Instituto Tecnológico y de Estudios Superiores de Monterrey

Campus Monterrey

School of Engineering and Sciences

Passive cooling strategies and performance of low energy residential buildings in semi-arid climate conditions

A thesis presented by

SeyedehNiloufar Mousavi

Submitted to the
School of Engineering and Sciences
in partial fulfillment of the requirements for the degree of

Master of Science

In

Engineering Science

Monterrey Nuevo León, June 15th, 2021

Dedication

To all the souls who wake up every day to make earth a better place.

I also dedicate this dissertation to my most loving parents, Fatemeh and Ebrahim Mousavi, and my precious sister, Niusha who were always there with their unconditional love and support and motivated me on this journey.

I would as well love to dedicate this to all professors that inspired me with their knowledge and guidance, Dr. Carlos Iván Rivera Solorio, and Dr. Miguel Ángel Gijón Rivera.

Acknowledgements

I am immensely grateful to my committee members who were more than generous with their expertise and precious time. A special thanks to Dr. Carlos Iván Rivera Solorio and Dr. Miguel Ángel Gijón Rivera as my advisors for their endless hours of guidance, direction, encouraging, and most of all patience throughout the entire process.

I would also like to thank my research group at CEDES, who thought me a lot about their culture and inspired me with their backgrounds, Grecia, Enrique, Ivan, Caribay, and Maria, who will always be a part of my life.

I am further grateful to all the teachers which thought me their experience and knowledge of engineering and building science and I commit to use them in improvement of our world. Special thanks to Dr. Jose Luis Lopez who thought me energy efficiency in buildings and more.

Finally, I deeply appreciate Tecnologico de Monterrey to cover all my tuition. I will always be in debt with all the administrative staff who enable this process and make it easier. I am special thankful with all the authorities who contribute to my tuition.

Lastly, gracious thanks to CONACYT for the support of my living cost.

Passive cooling strategies and performance of low energy residential buildings in semi-arid climate conditions

by

SeyedehNiloufar Mousavi

Abstract

This numerical study compares annual energy consumption of three building prototypes under semi-arid climate conditions of Monterrey. These common cases were selected based on Mexican housing classification of houses including, one story house, apartment of 4 story house, double story house, named C1, C2, and C3, which were simulated using DesignBuilder software. Based on literature reviews and availability of materials, 6 scenarios were defined for walls component, similarly 6 scenarios for the roof of all cases with the application of phase change material (PCM), reflective paint, and insulation. Regarding the opening envelope of cases 5 scenarios were defined including the application of double clear glazing, double low-e glazing, and reflective glazing coupled with shading. Selection factor to find the most efficient combination were based on annual energy and material cost of scenarios against each other and base case. Firstly, for wall component of envelope results showed that PCM with insulation (PI) outperformed other scenarios for all cases however with regards to its cost reflective paint with insulation (Ir) was more efficient, similar pattern was found for roof component for all cases where Ir scenario outperformed in term of cost and energy. Secondly, with regards to the opening scenarios loE double glazing coupled with horizontal shading outperformed others, consequently three selected scenarios were combined for all cases and formed the energy efficient configuration (EEC) to analyze the improvement in indoor thermal comfort, thermal improvement, carbon emission reduction, and economic benefit of their application. Various actions are carried out to perform these analyses; calibration of the model with experimental data and comparative ASHRAE benchmark case study 600FF, climate data simulations with TRNSYS software, and sensitivity analysis for PCM selection. Also, it was found that PCM was effective strategy if the thickness of material increases to similar thickness as insulation it could save up to 57% of energy for C1 which is the highest saving rate as compared to all other scenarios, however due to its high cost it is not economically efficient in local context.

The results demonstrate that EEC cases achieved total annual energy saving of around 53%, 55%, and 58% for C1, C2, and C3 cases, furthermore, concerning the thermal comfort improvement were around 45%, 33%, and 38% respectively. With regards to thermal performance during hottest day temperature, improvement was observed with averages of 5.9°C and 3.2°C for C1 and C3 whereas C2 had no improvement during this period, however during coldest day all cases had an average improvement of 2.4°C, 2°C, and 2.6°C. Concerning the Carbon footprints, reduction of emission for each case of C1, C2 and C3 were around 1578 Kg, 2798 Kg, and 3004 Kg annually, with 6 years, period of return for C1 and almost 3.5 years for C2 and C3. To conclude, the scenarios studied could be integrated with renewable sources of energy supply such as PV panels and result in net-zero building envelope, as all cases almost saved more than 50% of energy.

List of figures

List of tables

Contents

Acronyms and abbreviations

AB	Aerogel Blanket
ACH	Air Changes Per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATHM	Average Temperature in The Hottest Month
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent
COP	Coefficient of Performance
EEC	Energy-efficient Configuration
EPS	Expanded Polystyrene
EPW	EnergyPlus Weather File
ERV	Energy Recovery Ventilation
HCS	High-Cost Strategies
HRV	Heat Recovery Ventilation
HTF	Heat Transfer Fluid
ISO	International Standardization Organization
GF	Glass Fiber
GHG	Greenhouse Gases
LCA	Life Cycle Assessment
LCS	Low-Cost Strategies
Low-E	Low Emissivity
Mt	Million Tons

MVHR	Mechanical Ventilation Heat Recovery
NRP	National Research Program
PCM	Phase Changing Material
PECC	Programa Especial De Cambio Climático
PEC	Primary Energy Consumption
PHPP	Passive House Planning Package
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PU	Foamed Polyurethane
TES	Thermal Energy Storage
TRNSYS	Transient Systems Simulation Program
WWR	Window-To-Wall Ratio
XPS	Extruded Polystyrene

Nomenclature: Variables and Greek Letters

C	conduction and convection rate W/(m^2 K)
E	rate of heat loss by evaporation, respiration, and elimination, J s^-1
hc	convection coefficient, W m^-1 K^-1
hr	radiation coefficient, W m^-1 K^-1
M	metabolic rate, Met
R	radiation rate, W m^-2
r	mean Radiant Temperature, K or °C
S	body heat storage rate
To	operative Temperature, K or °C
Ta	air Temperature, K or °C

Chapter 1 Introduction

In this chapter most important problems in energy and building are discussed, as well as local and energy policies and organization in Mexico. Cooling energy consumption in buildings is analyzed and similar studies are reviewed. Finally aim and objective of study is presented with an overview of thesis structure.

1.1. Problem statement and the demand for passive cooling

The building sector is responsible for 40% of the total world electric energy consumption and 30% of the greenhouse gas (GHG) emissions [1]. Many studies have found that by 2100, the demand for cooling would increase by 350% and the demand for heating would decrease by 48% [2]. Therefore, cooling energy provision becomes an important area to improve. In many buildings, the energy usage can be significantly reduced by adopting passive strategies which aim at reducing energy demand by increasing the use of natural heating and cooling of environment or building component, as well as reducing the GHG emissions by decreasing the need for electricity and fossil fuel energy. Globally great number of organizations concerning the energy issues have set goals to reduce amount of energy consumption of building sectors with the assistance of envelope enhancement in five years by about 30%, as the demand for new construction rises along the comfort needs of occupants [3].

In August 2009, Mexico formulated a program dedicated for changes in Climate called PECC that defines more than 100 greenhouse gas (GHG) mitigation actions to cut down the emissions by a total of 51 Mt CO2e by 2012 across the country. This illustrates a 6% reduction compared to the current GHG trend of Mexico. The PECC also sets general guidelines to establish an ambitious Mexican GHG emission reduction pathway of 30% with respect to the past scenarios by 2020 that Mexico wants to pursue if a multilateral agreement at the UNFCCC is agreed and incorporates provisions for adequate technical and financial support for Mexico from the developed economy [4].

Energy efficiency traditionally has played an important role in improving building issues such as ventilation heat loss, fuel poverty, GHG emissions, health-based issues, and energy bills.

In general, human comfort is mainly affected by behavioral factors and environmental factors such as, thermal performance of space which commonly consume energy to provide the desired temperature for occupants in the room. Reducing the energy consumption of buildings while preserving users’ comfort can be achieved for new and existing buildings by improving building envelope performance and providing passive alternatives [5]. Effective and efficient building envelope design can be achieved by incorporating cost-effective passive solar strategies in windows, walls/roof insulation, daylighting, and heating–cooling systems. Primarily, the energy-efficient strategies in buildings must be focused on analyzing the interaction between local weather conditions and building envelope for the purpose of reducing the unwanted heat gains in summer and heat losses in winter. For instance, windows can be responsible for up to 40% of energy used for heating in cold climates while they yield between 60% and 80% higher cooling loads in hot climates [6]. For that reason, many efforts have been conducted to increase thermal performance on windows, and numerous thermal assessments for new glazing technologies are also needed. Similarly, incorporating PCM material into roof component illustrated a maximum of 12.9% reduction in indoor temperature during summer and average temperature fluctuation reduction of 8.4–9.5 °C [7]. Study in Mexico presented evidence that application of reflective white paint to basic gray roofs can decrease the daily heat gain up to 80% lower [8]. Single family house was studied to reveal the benefits of organic wool insulation application to walls of building in Spain and concluded that energy reduction of up to 40% could be achieved [9].

1.2. Local organizations and energy policies

According to OECD, it is estimated that by the end of 2050 Mexico will have a population of 121 million, hence there is a demand for 600,000 new residential units annually. With regards to the life duration of these building, efficient construction and housing will be remarkable investment in terms of both economic and environmental return. The NAMA as one of the organizations to develop sustainable housing in Mexico explore potential efficiency gain that can be achieved in this sector. There are few programs to promote this movements such as ‘Hipoteca Verde’ (‘Green Mortgage’) and ‘Ésta es tu casa’ (‘This is your house’) which are financial support on energy efficient appliances in residential sectors [10].

CONAVI (Comisión Nacional de Vivienda, Mexico's National Housing Commission) as a federal agency, has designed a set of building codes (Código de Edificación de la Vivienda, CEV) contribute by providing residential building efficiency guidelines but as voluntary level. To gain impact from these guidelines they need to be implied and enforced at state level but this body as agency is not able to enforce them. INFONAVIT (Instituto Fondo Nacional de la Vivienda para los Trabajadores) and SHF (Sociedad

Hipotecaria Federal) support CONAVI by providing funds to promote these codes and programs called “fondo de competitividad”.

The current mandatory norms related to energy efficient housing are:

a. Residential Building Envelope Standard, NOM-020-ENER-2011
b. Phase-out of inefficient (incandescent) lamps, NOM-028-ENER-2010
c. Energy efficiency standards for household appliances (some 20 standards).

Regardless of these norms and initiatives, there are extremely low number of endorsements of building codes, due to insufficient enforcement and monitoring. Some of the barriers that Mexico is facing to achieve low carbon residential units are mentioned as below [11]:

- Insufficient information and awareness on definition of energy efficient housing and application of building material.
- High cost of subsidized energy that supports low-income population but discourages the search for energy efficient houses. As well as high upfront cost for developers.

1.3. Local cooling energy consumption behavior per state

Annually, in summer season Mexican residential electricity consumption increases by 30% due to cooling needs. It was estimated in the whole country the cooling electricity consumption was 22.6 TWh in 2015 [12]. Accounting for losses, this represents about 9% of total generated electricity in that year. About half of cooling electricity is used in homes, with the remainder divided roughly evenly between small and large commercial and service buildings, and a small fraction in large industrial facilities. Summer electricity costs Mexican consumers about 31 billion pesos annually and incurs another 46 billion pesos in government subsidies in the residential sector. Because energy consumption for cooling is mostly concentrated in certain regions, months of the year and hours of the day, cooling can be cause weight to urban electricity grid, contributing to 7.5 GW to peak demand, equivalent to 15 500-MW power plants running at full capacity. In the warmest regions, cooling energy can rise to over a third of electricity in summer months and be responsible for over half of peak electricity demand.

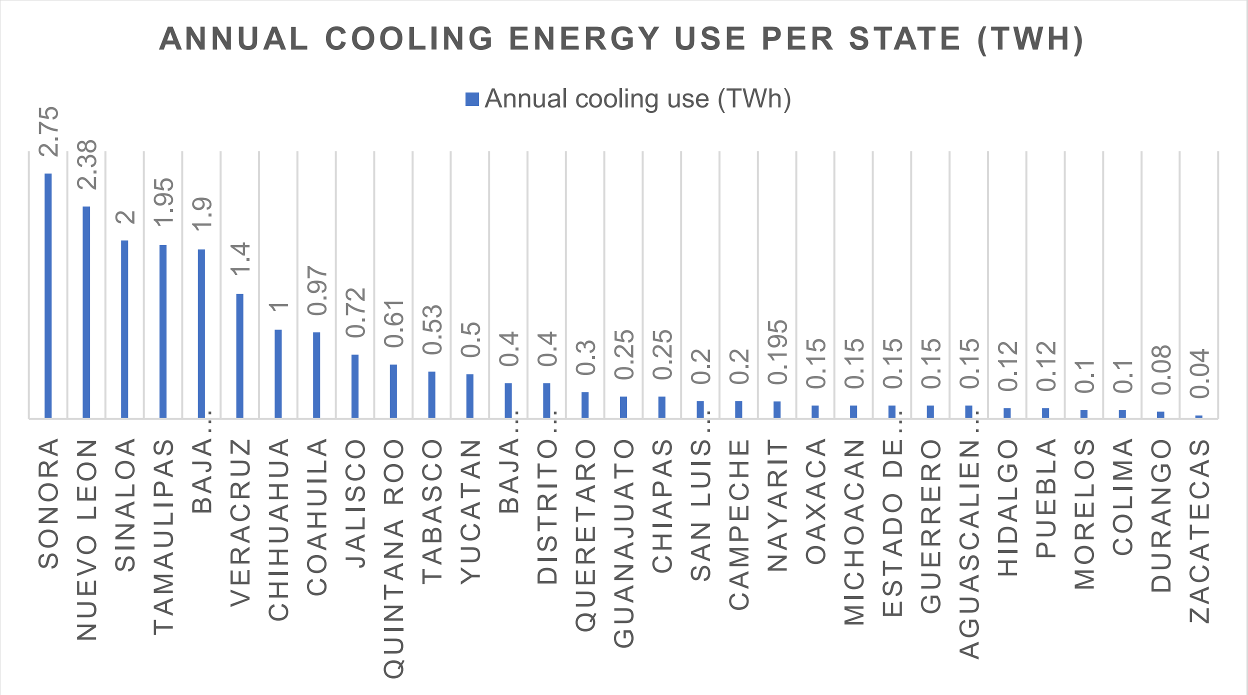


Fig 1. 1. Cooling energy consumption per states in Mexico [13]

Total cooling energy in TWh (bars) on the left axis and usage per customer in MWh on the right axis (line). The results show the expected effects of climate, with the Northern states showing very high cooling demand as in total and per user energy. Sonora is the most cooling-intensive state with over 2.5 TWh and 2.5 MWh per user. In contrast, the states of the central region of Mexico show very low cooling. The range is wide, with warm climate states using roughly an order of magnitude more cooling energy than the cool climate states and the top 5 cooling states (Sonora, Nuevo Leon, Sinaloa, Tamaulipas, and Baja California) using over half the cooling energy.

Hence, as can be seen in Fig 1.1 Nuevo Leon with representative City of Monterrey, with semi-arid climate and one of the top energy consuming zones regarding cooling energy was selected to be studied in this work.

1.4. Previous studies in passive cooling application

Latter literature review illustrates results of the application of PCM with other passive strategies in different climates around the globe using variety of simulation methods.

Chen et al. [14] investigated the performance of a hybrid passive cooling system (nocturnal radiative system integrated with microencapsulated PCM based energy storage system) in five typical cities of China. They performed their simulation analysis using ACCURACY model and MATLAB. The hybrid cooling system showed better performance for the climatic zones of Lanzhou and Urumqi cities with semi-arid and Mid-temperate climate condition. A desiccant enhanced evaporative cooling system integrated with the nocturnal radiative cooling panel could continuously satisfy the thermal comfort condition and the suggested system is more suitable for the areas with high humidity. A Canadian high-rise research lab integrated phase change material (PCMs) into walls and ceilings of apartment units with hybrid PCM system with a thickness of 2 cm composed of two PCM products with melting temperatures of 21.7 °C and 25 °C respectively, which demonstrated that the composite PCM system improves the indoor temperatures in both climates by reducing temperature fluctuations and balancing temperature peaks [15]. Overall, the adoption of this system results in the reduction of cooling energy demand by 6% in Toronto and 31.5% in Vancouver. Building envelope in Malaysia with tropical climate was studied to estimate the amount of energy saving potential of insulation in walls along with application of low-e glazing for windows through IES simulation software and it was found that 180,000 kWh of annual energy consumption can be saved.

In Mexico there have been a few studies regarding passive cooling strategies application to building envelope in the area of applied strategies a study was done regarding application of natural ventilation and for hot-dry weather, combining high thermal mass materials and natural ventilation in buildings achieve the lowest indoor temperature, whereas under hot-humid conditions, night ventilation combined with application of building materials with low heat capacity achieved the best results, 27 common cases were assessed based on the combination of different parametric building design, occupancy, and climate conditions [16]. The energy saving potential is analyzed by simulation in EnergyPlus. Then using a new assessment method suitable for large-scale scenarios using the actual number of air-conditioned dwellings distributed among the 27 cases. As a result, it is estimated that for year 2008, the saving is at US$ 900 M in cost and average mitigation of 2 Mt CO2eq from environment. However, there are limitations to the cases as the outputs will highly depend on realistic inputs building design and occupants behavior. Also, there are other strategies that could be imposed besides natural ventilation.

Another experimental study in Mexico was executed in Veracruz which is classified as a very hot climate zone in PHPP, a cooling-dominated climate, is being developed as part of a program by the SHF (2018) to incentivize energy efficiency in the housing sector in Mexico [17]. As part of the program, existing house prototypes were optimized to the Passive House standard. Given the high cooling requirements, the focus was to decrease solar heat gains. This was achieved using reflective painting in walls and roof, glazing with very high solar control (g-value of 28%), reduction of the window surface and additional interior shading during summer. The sensible cooling demand is further reduced using a highly efficient ventilation unit with heat recovery. The unit is in one of the bathrooms to reduce the exhaust and outdoor air ducts to the minimum length possible. When compared to the original prototype, the design achieves a reduction of 84 and 85% in cooling and primary energy demand, respectively. The construction costs of the existing prototype are a bit higher which is the downside of this but in long run it could save cost by less energy consumption.

Table 1.1 presents similar climatic condition studies that used simulation to analyze energy consumption impact of application of different passive cooling strategies in building envelope. Regarding opaque building component low-E glazing express potential of saving up to 6.4%, horizontal and other external shading can contribute to energy reduction of 6-11%, PCM integrated building components can save cooling energy demand from 10% to 60%, and application of reflective coat on roof can save from 15-30% of cooling energy annually.

Table 1. 1. Summary of previous studies in residential buildings of hot climate

Energy efficiency strategy	Climate	Research type	Outcome	**Year**	Reference
Study of tree shading	Hot humid	Numerical	10.3 % energy saving	2018	[18]

Triple glazing window	Hot humid	Simulation BIM	5.5% energy saving	2011	[19]
Single and double low-E glazing	Hot humid	Simulation IES	Double low-E best with energy saving of 6.4%	2011	[20]
Envelope shading	Hot humid	Simulation eQuest	11.3% energy saving	2007	[21]
External shading	Hot humid	Numerical	2.6-10% energy saving	2015	[25]
Horizontal & vertical shading	Hot dry	Simulation IES	6% energy saving	2013	[26]
20mm PCM interior roof surface	temperate oceanic	TRNSYS	39% cooling energy saving	2016	[27]
20mm PCM interior roof surface	Humid subtropical	TRNSYS	25% cooling energy saving	2014	[28]
40mm PCM (18-28) Applied interior surfaces	Warm climate	Simulation EnergyPlus	46%-62% cooling saving	2014	[29]
5mm PCM (21.7) external layer of mosaic	Subtropical	Simulation EnergyPlus	2.9% cooling energy saving	2011	[30]
10mm PCM (27) case 600 ASHRAE inner surface of wall and ceiling	Semi-arid	Simulation EnergyPlus	10-15% energy saving	2016	[28]

Reflective clay tiles	Mediterranean	Experimental	15% cooling energy saving	2014	[29]
Cool roof coat	Hot dry	Simulation	53% comfort improvement	2015	[30]
Cooling roof coating	Tropical	Simulation EPS	30% cooling energy saving	2015	[31]

In an investigation of micro-climate of four cities, it emerged that a reduction of 17% is possible in cooling energy consumption annually and in all climate PCM resulted best, by positioning it on the inner surface of building component [32]. Another study found that the most efficient way to incorporate PCM into building envelope is in the walls [33]. Experiment of integration of double layer of PCM into roof showed a total thickness of 6 cm of the material are required to maintain the temperature within comfort [34]. A study in Singapore, concluded that integration of PCM into the walls can function effectively in range of 21-32% annually specifically in tropical climate [35]. Selection of PCM Effectiveness of PCM materials in the envelope of building highly depends on the melting point of it and average daily temperature of the building site climate which is between 10–30 degrees.

The most optimum insulation thicknesses of the expanded polystyrene (EPS), extruded polystyrene (XPS), and foamed polyurethane (PU) varied from 0.053 m to 0.236 m while their payback periods varied from 1.9 to 4.7 years over a lifetime of 20 years [36].

Significant factors that impact the selection of thermal insulation in buildings are types of material and their thickness which affect the amount of energy consumption and costs. Pertaining to this issue, an article investigated five types of insulation with combining into three types of building materials in an office under humid subtropical climate and found out that the optimum insulation thickness of XPS, EPS, PU, GF (glass fiber), and AB (Aerogel blanket) for shale hollow brick is 42.6 mm, 77.0 mm, 49.0 mm, 41.0 mm, and 6.0 mm, respectively [37]. A paper compared two methods for positioning of insulation in walls of residential building, by using TRNSYS (numerical simulation) of one-story house with area of 99.6 m2 located at a mid-level of an apartment in Greece with climate of warm Mediterranean and temperate [38]. The outcome demonstrated that, while both external and internal application considerably reduced the energy consumption, but external insulation dominated the internal insulation application by 8 percent.

The author performed the study only for the Antalya province of Turkey and effectuated the calculations via the MATLAB program by using the finite difference method to find the effective thickness of insulation for warm climate [39]. Consequently, the author discovered that 3.6, 3.1, 4 and 4 cm insulation should be used for the south, north, east, and west, respectively.

Infrared reflective wall paint can lead to energy savings of more than 7% if the exterior wall obtains reflective coating only Coating on all exterior and interior walls leads to energy savings up to 18% [40].

Another urban study found that a controlled glass bubble volume concentration from 0 to 70% leads to a selective solar reflectivity increase from 0.06 to 0.92 while the mid-infrared emissivity remains above 0.85 [41]. Outdoor measurements show the polymer coating on a concrete surface can provide a temperature reduction up to 25 °C during the day when conduction and convection are limited and a net cooling power greater than 78 W/m2 at a cost less than $0.005/W. The impact of polymer coating on common buildings is estimated as potential annual energy savings of 2–12 MJ/m2 and CO2 emission savings of 0.3–1.5 kg/m2. Bubbles can have the solar reflectivity of 0.92 and emissivity of 0.85, which leads to significant radiative cooling. Also, its maximum sub-ambient cooling of 9 °C during the daytime. The associated annual cost savings and annual CO2 emission savings for representative buildings in Los Angeles are predicted to range from $0.05/m2 to $0.58/m2 and 0.26 kg/m2 to 1.45 kg/m2, respectively. The techno-economic analysis shows that the material costs for our cool white polymer coatings is estimated to be $0.39/m2 and $0.005/W.

Another study illustrated that to select the type of glazing is necessary to consider daylighting, thermal transmittance, the solar heat gain coefficient, and the visible transmittance parameters [42]. A study was done in tropical climate, four cities from south to north latitudes (Singapore, Hong Kong, Miami, and Houston) which, was based on different glazing types combined with interior and exterior shading elements, shown that between all different strategies, low-e had the highest performance with regards to its thermal behavior and daylighting ability, whereas the least performing was double-layer glazing [43][43]. In terms of shading selection, overhang surpassed the performance of interior blind. In Mexico, a research was conducted that studied the effect of room temperature and the incident solar radiation using numerical simulations [44]. They studied four types of glazing including clear glass double glazing, absorptive, low-e and reflective double glazing. Optical transmittance and specular reflectance were measured. The results showed that reflective coating reduces the heat flux to the indoors by up to 73%, with respect to clear double glazing, it is the best option for energy savings in a warm climate, where it is possible to save up to $20.29 USD per kW h per year. In addition, the payback period for this strategy is 3.7 years. Therefore, the use of reflective double pane window is highly recommended in Mexican warm climates.

As mentioned above passive cooling application for energy efficiency highly depend on climate and environmental condition as well as building design, great numbers of studies that employed different strategies to reduce energy and comfort but in previous studies there are single method of application, or under different climate condition and with different case study either imaginary. However, in this study, the aim is to consider common Mexican construction material and designs, under Semi-arid climate and apply combination of relevant and accessible strategies and analyze their impact not only in term of energy but also in terms of comfort and economical return, as code compliance usually recommends that there is a demand for conviction of users and builders by identifying the return of investment in terms of finances and environmental benefits.

1.5. Aim & objective

The aim of this thesis is to evaluate the most efficient application of passive cooling techniques in residential buildings compatible to the climate and construction of Mexico that can reduce energy consumption in buildings in semi-arid weather. Furthermore, to develop an economic and environmental benefit report.

In this order, the indoor thermal comfort will be improved while energy loads demand decreases through the following objectives, which will also give a holistic evaluation of residential Case study:

1. Perform bioclimatic analyzes to diagnose comfort requirement in the most populated climatic conditions of Mexico through analysis which is region of Monterrey.
2. To Verify the numerical results against experimental data and benchmark results.
3. To assess the thermal performance of different passive strategies such as glazing, insulation, shading, and PCM application in typical residential apartments in Mexico through performing building energy simulations and select the most efficient integration.
4. Conduct economic and environmental analysis of the enhanced cases

1.6. Thesis outline

Following the aims and objective of this project, the chapters are divided into six parts. Each chapter's outline as presented in Fig 1.2 are elaborated as follow:

Chapter 1. Introduction: This part discusses about the nature of problem, aim and objectives and illustrate the methods used in this study.

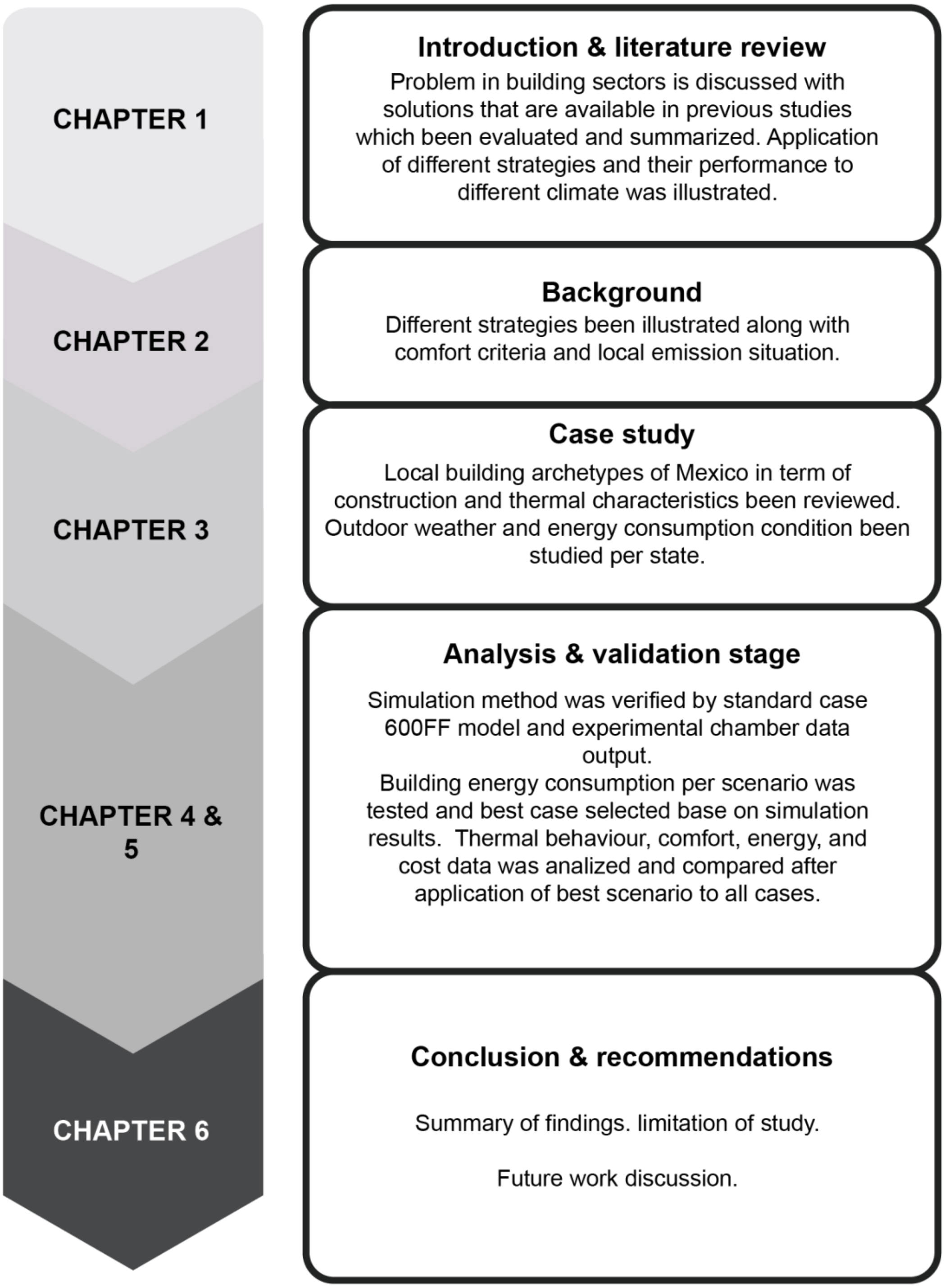
Chapter 2. Background: At this section different strategies application and performances in different climate as well as Mexican context is reviewed. Also, a short review of comfort parameters and standards concerning local climate are reviewed here.

Chapter 3. Case studies: Climate and building condition of Mexico is identified here and selected. Local construction and building material are discussed. Control case is designed here.

Chapter 4. Validation: This chapter explains about validation method and details and results of validation. A holistic view of building envelope simulation is presented and reasons for choice of the platform is considered.

Chapter 5. Results and discussion: In this chapter energy consumption reduction as well as thermal behavior of space is compared via simulation. All results are compared to optimize the most efficient selection of material for each climate and envelope.

Chapter 6. Conclusion: It concerns the summary of this thesis and express the general recommendations for future works.



Introduction & literature review

Problem in building sectors is discussed with solutions that are available in previous studies which been evaluated and summarized. Application of different strategies and their performance to different climate was illustrated.

Background

Different strategies been illustrated along with comfort criteria and local emission situation.

Case study

Local building archetypes of Mexico in term of construction and thermal characteristics been reviewed. Outdoor weather and energy consumption condition been studied per state.

Analysis & validation stage

Simulation method was verified by standard case 600FF model and experimental chamber data output.

Building energy consumption per scenario was tested and best case selected base on simulation results. Thermal behaviour, comfort, energy, and cost data was analized and compared after application of best scenario to all cases.

Conclusion & recommendations

Summary of findings. limitation of study.

Future work discussion.

Fig 1. 2. Visual illustration of thesis structure

Chapter 2 Background

Main variables and strategies of studies are defined in this chapter such as definition of PCM material and its properties. Other material such as insulation and different glazing for windows are explained. Finally comfort and its parameter is discussed based on ASHRAE standards.

2.1 General passive cooling categorization

Passive cooling uses free renewable sources of energy such as the sun and wind to provide cooling, ventilation, and lighting needs for a household. Classification of solar passive techniques for cooling applications is presented in Fig 2.1, Which will cut down the need for mechanical components. The thermal comfort will be provided by using the suitable technique and the indoor air quality will be enhanced for the occupants to function their daily lives and work in the space. By providing the thermal comfort, the need for electricity and unrenewable energy will drop and consequently there is less energy consumption and less Greenhouse gas emissions. Optimized building envelope can maximize the air flow and reduce the solar radiation to the building in summer [45]. There are many types of passive cooling strategies that can be recommended for use in hot semi-arid climates. Selection of passive strategies comes from the bioclimatic analysis and economical restrictions, for instance:

Low-cost solutions (LCS):

- Optimal window to wall ratio and orientation for windows
- Sun shading
- Insulation wall/roof
- Cool / reflective wall/roofs
- Glazing technologies: (double clear glazing)

High-cost solutions (HCS): select and implement one or two

- Evaporative cooling (roof pond)
- Natural Ventilation (cross ventilation, solar chimney, etc.)
- Vegetation wall/roof
- Glazing technologies: (double with selective coatings or absorbing windows)
- PCM technologies

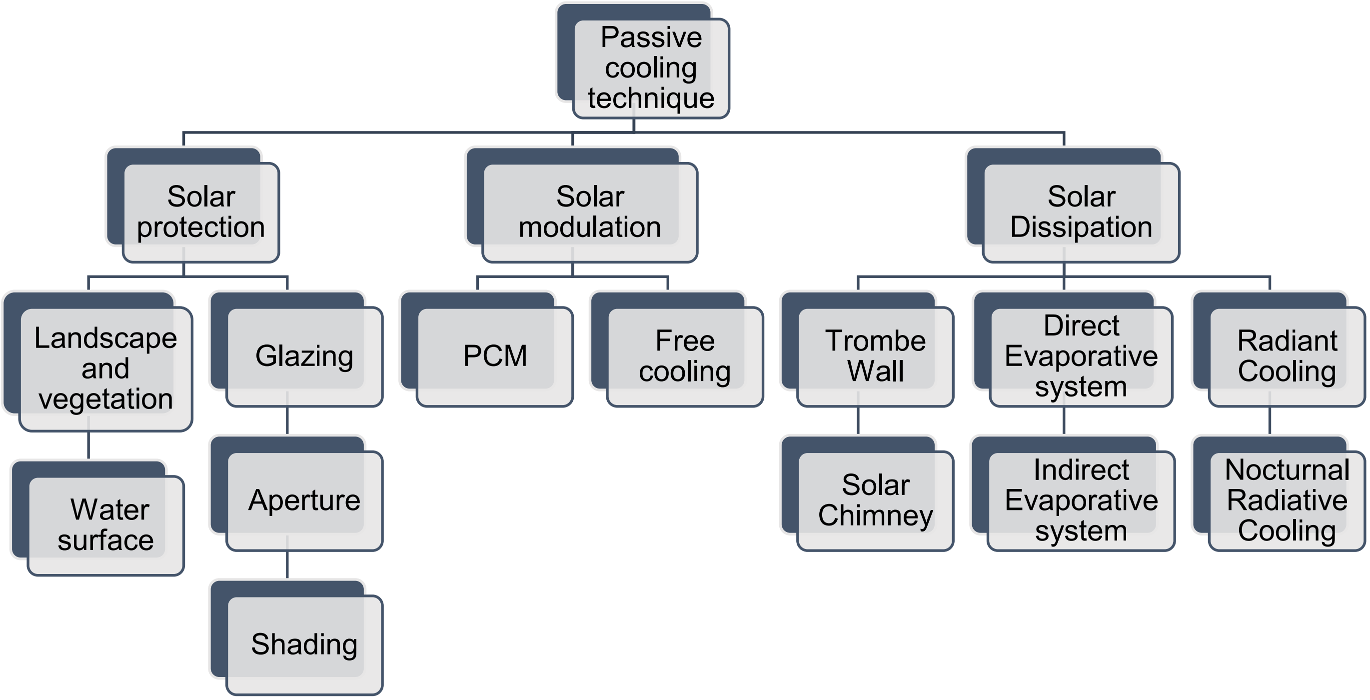


Fig 2. 1. Classification of passive cooling techniques

One of the pioneer agencies that contributed to passive cooling in buildings is The Passive House, which is a set of standards to optimize buildings performances with respect to corresponding local climate conditions. In this thesis the basic principles are illustrated along with three relatable different climatic examples [46].

General principles according to this agency are as below:

- Proportionate ratio of exterior to living area.
- Facing openings to north and south.
- No thermal bridges.
- Mechanical Ventilation with Heat Recovery in very hot climate
- In humid summers ERV (Energy Recovery Ventilator) but in dry climates HRV (Heat Recovery Ventilation) with no humidity recovery.

Mexico has warm, hot, and very hot climate under this study. Criteria of passive house are as shown in table 2.1.

Table 2. 1. Passive house warm and hot bioclimatic general criteria [46].

Climate zone	U Win (W/$\mathbf{m^2K}$)	U Wall/roof (W/$\mathbf{m^2K}$)	Glazing
Warm	1.25	0.5	Double low e-glazing
Hot	1.25	0.5	Double Solar protective glazing
Very Hot	1.05	0.25	Triple Solar protective glazing

As PHA suggest that for hot climate, firstly Comfort assumption for temperature of 20°C in winter is to have 25°C room temperature with a maximum humidity ratio of 12 g/kg in summer which need to follow for more than 90% of year [46]. Similarly, a limit of 20% of the year applies for humidity ratios above 12 g/kg in passively cooled buildings.
Secondly, for purpose of cooling, if there is a need for active cooling it needs to be 46 and 13 kwh/m2 of sensible and latent cooling respectfully. Regarding the air tightness, maximum leakage of 0.6 air exchange per hour at 50 Pa and finally the primary energy needs to be around 120 kWh/$\mathbf{m^2}$ per year.

2.1.1. PCM as thermal storage integration in building envelope

Day after day the imminent approaches: the need to be energy efficient in addition to reducing dependence on fossil fuels. In both, heat and cold storage plays a very important role. For example, applying cold storage to control loads and energy demand in a refrigeration room would contribute to its efficiency, on the other hand, using solar collectors, and even more specialized salt tanks, is a smart alternative to take advantage of solar energy. One of the most significance of thermal storage lies in its capacity to store large amounts of energy at a relatively low cost. Application of these strategies is prominently wide, for instance, in residential and commercial buildings as heating and cooling solutions, in the industrial project as processes of cooling and heating, as well as a complement to the massive storage of energy for the electricity grid, these strategies have become extremely popular.

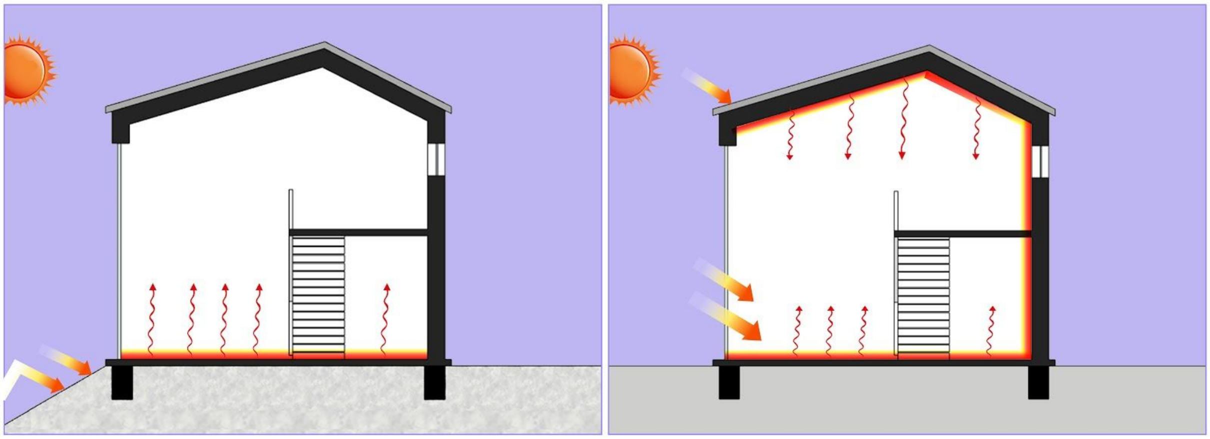


Fig 2. 2. illustration of direct and indirect radiation accumulation in building envelope.

Thermal Energy Storage (TES) allows the storage of heat or cold to be used later, for this to happen, the method is necessary to be reversible [47]. This is the possibility both of storing energy and of giving it to the environment, without the material losing properties. Thermal energy can be stored under three principles: using the sensible heat of the bodies, through the latent heat when changing from one phase to another, or through the energy involved in a chemical reaction.

Sensible heat storage is one of the most widely used strategies in building construction for centuries. When a medium transfers heat to a material, it increases its temperature (and the medium loses its energy). The amount of energy stored depends on the initial and final temperatures of the system, as well as the heat capacity of the material. Solid materials like concrete, clay bricks and stones or liquids like water can be used to store energy in the similar way. This passive strategy in buildings can be divided into two as illustrated in Fig 2.2. which are direct or indirect accumulation. In direct accumulation, solar radiation can strike directly on the mass of material which will be the accumulator element. The material must have a high thermal inertia, therefore, the relationship between thermal conductivity and its volumetric heat capacity is key for its selection. Indirect accumulation is defined when the collector element is both accumulator and regulator. In this case the entire building envelope acts as the heat storage system [48].

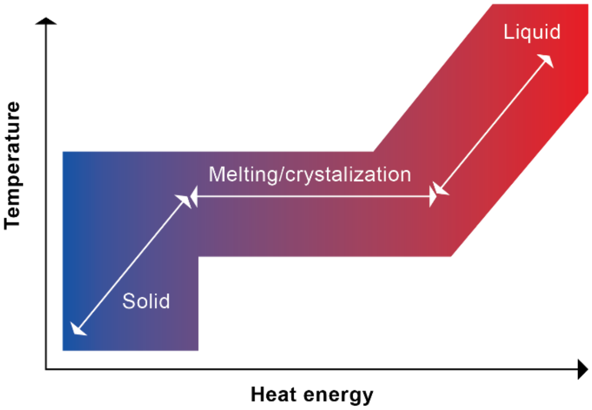


Fig 2. 3. Working principle of a phase change material (PCM)

However, latent heat storage is linked with phase changing materials utilize the thermal energy received to change from solid to liquid or liquid to gas. As Fig 2.3 presents how as temperature rises PCM melts and transform to liquid while as temperature drops and heat decreases material crystalize and transform back to solid form. Consequently, phase change materials such as paraffin wax can cause a delay in peak load duration period with their high thermal capacity as shown in Fig 2.4. The storage material is required to encompass a melting temperature in range of the charging and discharging temperatures of the Heat Transfer Fluid (HTF).

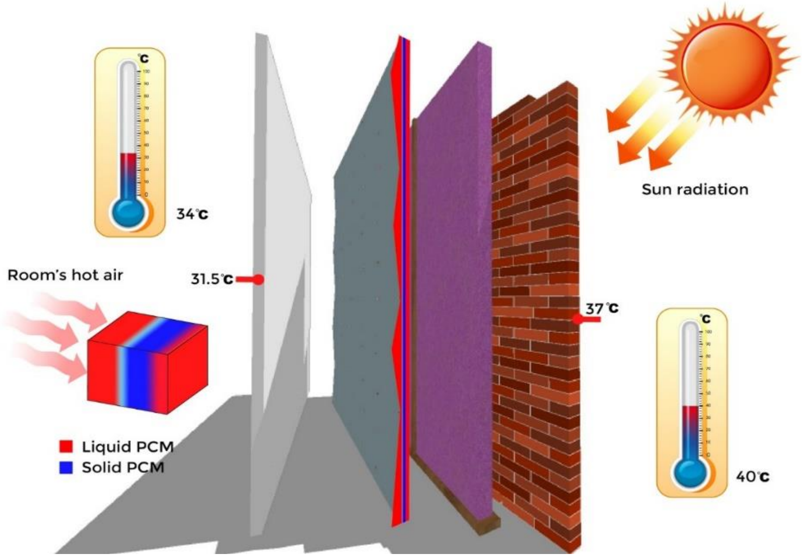


Fig 2. 4. Thermal behavior of PCM application on interior panels of wall

There are four measures for efficient building components which are thermal mass, thermal insulation, reflective roof, and window glazing. Thermal mass of building highly depends on the thermal storage of building materials [49]. Application of PCM in building components as a thermal storage has been used to improve performance of buildings by absorbing heat from inside surface and releasing it to the outside environment. When the ambient temperature rises above its melting point, a given PCM absorbs heat and turns to the liquid phase while remaining at an almost constant temperature. When the ambient temperature falls below the melting point, the PCM begins to release heat and solidify, again remaining at an almost constant temperature [50].

2.1.2. Insulation

For decades, insulations are integrated into building envelope to minimize the amount of heat transferred through the envelope (the transfer of thermal energy between objects at different temperatures), which will consequently, reduces the energy consumption in buildings [51]. During cold days, insulation protect the warm air from leaving indoor space, while in summer insulation will block the radiation absorbed from outside and reduces heat transfer through building envelope into space as shown in Fig 2.5.

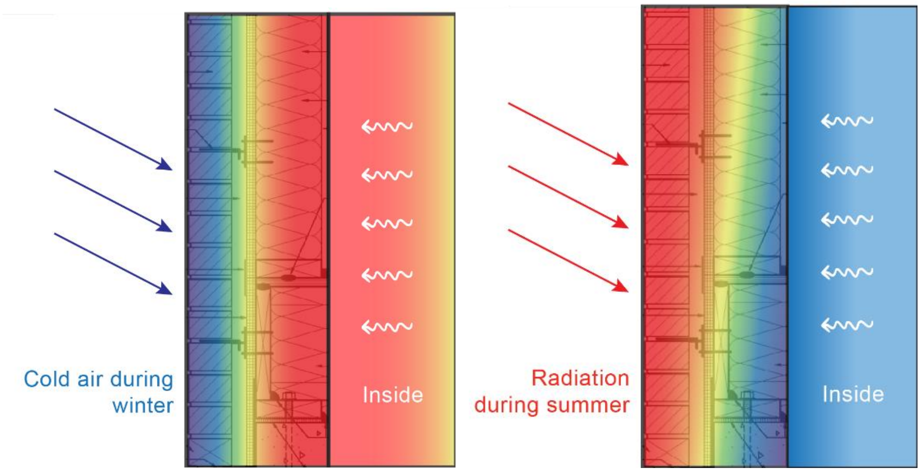


Fig 2. 5. Performance of insulation installed inner layer of brick wall during summer and winter

The insulating capacity of a material is determined by its thermal conductivity, low thermal conductivity is equivalent to a high insulating capacity (R-value) [52]. In thermal engineering, other important properties of insulating materials are product density (ρ) and specific heat capacity (c). There are mainly two types of insulation, firstly, convective, and conductive insulation or bulk insulation such as, fiberglass, mineral wool, and cellulose insulating material. the secondly type is radiant barrier insulator, for instance reflective aluminum insulation, which works best for hot climates that require cooling most of the year.

2.1.3. Reflective paint

Raising the albedo (solar reflectance) of a building's walls reduces unwanted solar heat gain in the cooling season. Reflective paint helps in cooling down the surface of building, due to its solar reflective characteristics. The layer of paint on the building component, reduces the heat transmission to indoor spaces consequently the indoor temperature will drop. This coating can reduce solar heat gain of any surface material such as tiles, felt, asphalt, wood, masonry, and concrete surfaces.

2.1.4. Window glazing and shading

Openings and windows are the main source of heat loss or gain in the building envelope, which influences the annual energy consumption of every home. Due to their lower thermal resistance, they contribute highly to solar heat gain of buildings. However, windows are crucial in providing residences with comfort and daylighting. In general glasses are defined by their solar absorptivity and number of layers for instance double or triple glazing. Typical construction of glazing includes glass or plastic that can transmit solar radiation. On average in residential buildings glazing contributes to one third of heat losses/gain [53]. There are few types of glazing and filling for windows, which the most common types are discussed below.

I) Clear double layer glazing window

Double layer glazed windows consist of two panes of glass, with an intermediate buffer zone, which act as insulation against radiation and outside temperatures. The clear glasses have no impact as insulation, but the space between them, in some cases the gap is filled with novel gases like argon.

II) Low-e double layer glazing window

Commonly outside surface of inner layer glass of double or triple layer window is coated with low-e coatings which was developed to minimize the amount of ultraviolet and infrared light that can pass through glass without compromising the amount of visible light that is transmitted. Figure 2.6 illustrates how this coating treats heat differently, for instance during summer days, light can pass through, but the longwave radiation will reflect to outdoor space, however during winter nights, heat energy inside the space tend to not leak out due to its emittance.

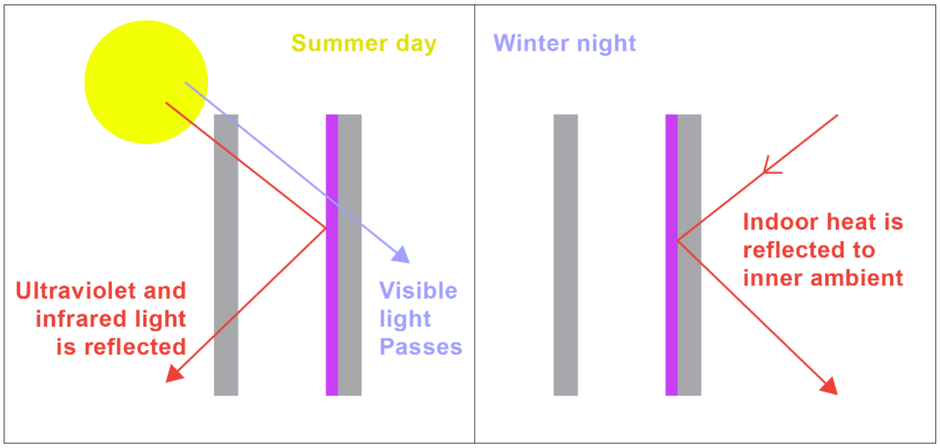


Fig 2. 6. Low-e glazing heat treatment during summer day and winter day

Low-E glass has a microscopically thin, transparent coating that reflects long-wave infrared radiation. Emissivity is the measure of an object's ability to emit infrared heat or energy the lower it is, less amount of radiation and heat can transfer through, for instance clear glass with emissivity of 0.84, has higher Solar heat gain coefficient than low-e glass with emissivity of 0.02. This is where low emissivity (or low-e glass) coatings gain its importance.

III) reflective double layer glazing window

Reflective glass is typically a metallic coating applied on simple clear float glass, that reflects solar radiation and work as a one-way mirror, preventing visibility from the outside.

Another method to decrease the amount of solar gain is through blocking direct radiation entering the window during the day. Commonly, there are internal and external shading, for instance, windows blinds are internally installed, whereas overhangs are placed on the outside of windows.

2.2. Adaptive comfort standard

2.2.1. Background of comfort in built environment

It is commonly believed that thermal comfort is related to direct temperature and moisture sensations from the skin, deep body temperatures, and the efforts necessary to regulate body temperature. Essentially, comfort occurs when human body temperature is between a slim range of human normal temperature with low skin's moisture, and minimum physiological effort of body regulation [54]. Quality of a space in terms of comfort is assessed based on performance of users within space, for instance deficient comfort conditioned room can results in various undesirable outcome for the users' work productivity, behavior, health [55]. Accordingly, occupants tend to adjust their environment to the norms of thermal comfort as in to reduce high ambient temperature, use air conditioning system which can reduce the temperature to that of comfort boundary. Similarly, in lower temperature a user might use a heater to increase the ambient temperature to the desired amount [56].

To establish the most applicable thermal comfort conditions, architects and engineers use international standards like ASHRAE Standard 55, and as well as, ISO Standard 7730. According to these standards, for different climate situation there are range of accepted comfort temperature defined. ASHRAE Standard 55 defines thermal comfort as a satisfactory space condition for users in the way that they feel nor too cold nor too hot, biologically maintaining the body temperature at around 37ºC. Comfort in environment does not limit to temperature only, but also concurrent regulation of humidity, air purity, and air movement of the ambient. Other factors include ambient odor and noise control.

Due to individuals' different physical characteristics such as health, gender, age, daily activity, type of clothing, and diet, there are no strict rules to follow for having a comfortable environmental condition. For instance, in the same space a young athlete man may experience warmer condition than an elder woman in the same condition. It was during 1970s that the basics of thermal comfort including accepted boundary of temperature, activity level and relative humidity, which resulted in shaping the ASHRAE Standard 55 in United states.

2.2.2. Thermal comfort principles

As a result of human metabolic rate, body continuously release heat to the environment, and thermal comfort is thermal balance between human body's heat generation and its release to ambient. Heat production is equal to heat loss which means body's heat gain and losses are equal as shown the relationship in (eq 2.1):

$$M = E \pm R \pm C \pm S \qquad \text{(eq. 2.1)}$$

where:

M = metabolic rate

E = rate of heat loss by evaporation, respiration, and elimination

R = radiation rate

C = conduction and convection rate

S = body heat storage rate

In general, there are four types of heat transfer between human body and environmental ambient which illustrated as follow [57]:

Convection: The transmission of heat from the body to the air in contact with the skin or apparel by characteristic convection flows or ventilation is a significant wellspring of cooling. The pace of convection heat loss is impacted by two components: speed of air development and air temperatures. The body's reaction to a cool climate is by confining blood flow to the skin, compulsory reflex activity like shuddering, or in outrageous cases, bringing down the internal heat level.

Conduction: Heat exchange which depends on property of materials in term of thermal conductivity while in contact with human skin and the environment. Particularly, conduction is the difference of temperature between any object in contact with skin such as clothing and the skin surface temperature. This rate insulation of the fabric that is worn on skin.

Evaporation: Heat is lost by insensible perspiration and sweat on the skin, as well as by respiration and exhalation in the lungs. Perspiration causes man to lose about one liter of water every day. The rate of evaporation is determined by the amount of moisture transferred as well as the relative humidity in the air.

Radiation: heat gain via solar radiation depends highly on the area of radiated surface, emissivity of surface and geometry of surfaces, hence, if a person is on the move in a room, he will experience different level of comfort dependent on the location of different surfaces in the room such as next to the glass or steel bar or wooden deck.

Principally, our body produces heat from consumption of food and process of digestion into energy, from which only about 20% of energy is used for activities and the remaining 80% need to be released to the environment. To maintain the basic body temperature at 37ºC, heat is expected to be concurrently released to the surrounding. Hyperthermia may occur if inadequate amount of heat is dissipated to environment which means body is overheating, and excessive amount of it ends in hypothermia which is low level of body temperature. Human minimum body temperature cannot fall below 28ºC as it will result in cardiac arrhythmia and death; likewise, if body temperature surpass 46ºC brain can be damaged irreversibly. Consequently, a precise regulation for human body temperature and health is necessary.

2.2.3. Factors affecting comfort

There are two major variables impacting comfort, which are personal and environmental factors together there are six parameters. These variables can affect the temperature, and the combined effect of these six variables can determine thermal comfort responses. In another study the variables that impact heat transfer from body and thermal comfort into groups of three sets as presented in table 2.2.

Table 2. 2. Factors that impact thermal comfort

Environmental variables	Personal variables	Contributing factors
Air temperature	Metabolic rate	Diet
Air movement	Clothing	Body shape
Humidity		Subcutaneous fat
Radiation		Age and gender
		State of health

According to ASHRAE 55 there are six basic factors that impact human comfort as below:

a) Metabolic rate

The rate at which energy is transferred from chemical to thermal form within the body is determined by metabolism, and the rate at which thermal energy is transported to the skin's surface is regulated by blood circulation. Each individual generated energy greatly depends on their level of activities, and the unit to illustrate this rate per unit of body surface area is the ‘met’, which is the heat produced by individual human with the values of 58 Watts produced for every square meter of the body surface area (i.e. 1.0 Met = 58.2 W/m^2)

Table 2. 3. Metabolic rate values

Activity	Met	W/m^2
Sleeping	0.7	40
Reclining, lying in bed	0.8	46
Seated, at rest	1.0	58
Standing, sedentary work	1.2	70
Very light work (i.e., shopping, cooking, light industry)	1.6	93
Medium light work (i.e., housework, machine tool work)	2.0	116

Steady medium work (i.e., jackhammer, social dancing)	3.0	175

b) Clothing insulation

Clothing insulation includes the amount of clothes that is worn by individuals and impacts their comfort. According to ASHRAE standard the clothing insulation is presented by clo value and some of the values are shown in table 2.4, for instance a person wearing short sleeves shirt with trouser has insulation of 0.57 clo.

Table 2. 4. ASHRAE 55 clothing insulation values

Clothing Description	Garments Included	Icl (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) Trousers, long-sleeve shirt, suit jacket	0.96
Skirt/Dresses	4) Knee-length skirt, short sleeve shirt (sandals)	0.54
	5) Knee-length skirt, long sleeve shirt, full slip	0.67
	6) Ankle-length skirt, long sleeve shirt, suit jacket	1.10
Shorts	7) Walking shorts, short sleeve shirt	0.36
Athletic	8) sweatpants, long sleeve sweatshirt	0.74
Sleepwear	9) Long-sleeve pajama tops, long pajama trousers, short ¾ length robe (slipper, no socks)	0.96

c) Air temperature

An average temperature that is surrounding the occupants with respect to time of the day and geographical location.

d) Radiant temperature

is defined as the temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with the occupant as the actual enclosure. It is a single value for the entire body and may be considered a spatial average of the temperature of surfaces surrounding the occupant weighted by their view factors with respect to the occupant

e) Air speed

Includes an average speed of air that occupant’s body is exposed to and the averaged time extend to three minutes.

f) Humidity

Humidity is illustrated as the amount of moisture in the surrounding air of occupants which consists of many factors such as pressure of vapor, humidity ratio and dewpoint temperature.

2.2.4. Determination of comfort criteria

Thermal comfort is determined based on values of different variables such as air temperature and immediate environment temperature, humidity and as well as speed of the air. Definition of thermal comfort in terms of operative system is measured by PMV and PPD index as illustrated below by Fangers [54].

2.2.4.1. Operative temperature

Regarding indoor ambient temperature, operative temperature (To) is defined as a tool to scale the amount of heat loss from occupants to space and as well as the limit measurement for thermal comfort boundary. To regulate a range of comfort operative temperature, radiant temperature performs a critical factor. Considering the dependency of operative temperature on outside climatic situation, it is also a variable of time.

Operative temperature can be calculated as shown in (eq. 2.2) below in cases when the relative air speed is small (<0.2 m/s, 40 feet per minute).

$$To = (Tr + (Ta \times \sqrt{10v})) / (1+\sqrt{10v}) \qquad \text{(eq. 2.2)}$$

Where;

To = operative temperature,

Ta = air temperature, and

Tr = mean radiant temperature.

Operative temperature can also be expressed by air temperature and mean radiant temperature with respect to heat transfer coefficients, whereas mean radiant temperature is a function of view factors such as location and can be illustrated as (eq. 2.3).

$$To = ((hr \times Tr)+(hc \times Ta))/(hr+hc) \qquad \text{(eq. 2.3)}$$

Where;

h_c = convection coefficient W/(m^2 K)

h_r = radiation coefficient W/(m^2 K)

For spaces that are naturally ventilated, occupant's sensation of comfort might differ than those in air-conditioned space, hence with use of operative temperature and other comfort variables, a range of accepted operative temperature is set with regards to outside temperature. To be regulated by this system, by refereeing to Fig 2.7 allowable area is shaded which is between satisfactory of 80% to 90%. When the information about the space is not comprehensive, we can use 80% range and 90% is used with higher standard of comfort.

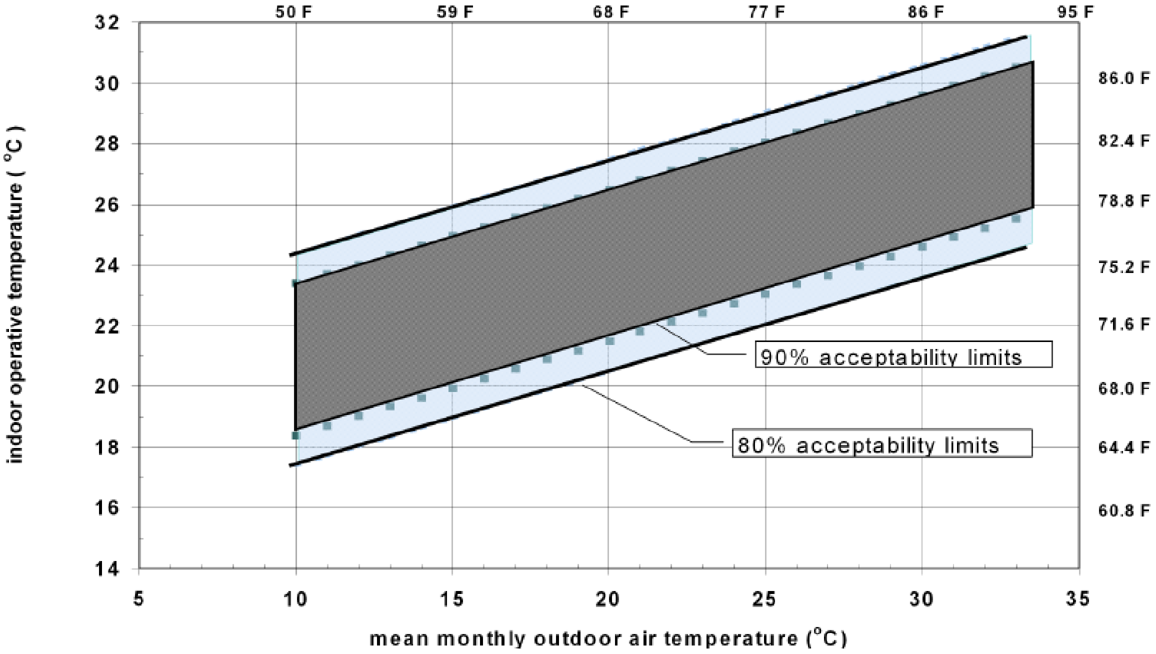


Fig 2. 7. Acceptable operative temperature ranges for naturally conditioned spaces with monthly mean outdoor temperature

2.2.5. Predicted mean vote (PMV)

Originally a model which incorporate all six variables of comfort into one index was developed during 1970s to predict the thermal comfort amount. In a steady state by inputting the precise personal and environmental values PMV index is determined accurately. This index scores based on ASHRAE sensational scale and measures the average feelings of a great number of users from cold to neutral and hot as presented in Fig 2.8.

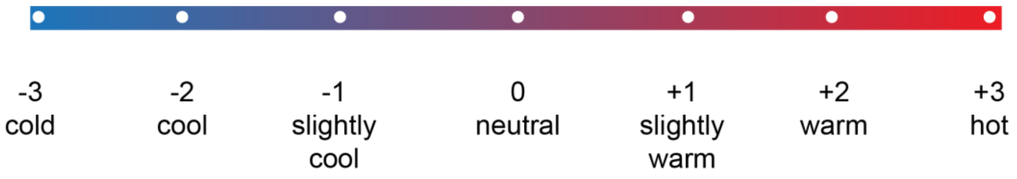


Fig 2. 8. ASHRAE scale of thermal sensation

ASHRAE presents three different classes of comfort as illustrated in table 2.5 (A, B and C) which they differ in their amount of PMV and PPD as the number of PPD increase means class C has the greatest number of unsatisfied occupants than class B and A.

Table 2. 5. Three classes of acceptable thermal environment for general comfort [54]

Comfort Class	PMV Range	PPD
A	-0.2 <PMV< +0.2	<6
B	-0.5 <PMV< +0.5	<10
C	-0.7 <PMV< +0.7	<15

2.2.6. Predicted percentage dissatisfied (PPD)

Another index to examine the thermal quality of the space is PPD index which relatively is also expressed by user voting scale of -3, -2, 2, and 3 from the scale of thermal environmental sensation. As people comfort satisfaction follow different sensation, even when PMV model is at 0 (which is the most satisfactory) there are still 5% PPD is reflected for those unsatisfied users with the space. Similarly, for PMV range of ±0.5 there are 10 % unsatisfied occupants. The unsatisfied amount is out of range of three classes of ASHRAE scales which is unacceptable in terms of thermal comfort. On contrary of PMV which responds to greater number of people, PPD is a range of individual responses. The relationship between PMV and PPD is expressed in Figure 2.9. The thermal neutral range is between -1≤ PMV ≤1.

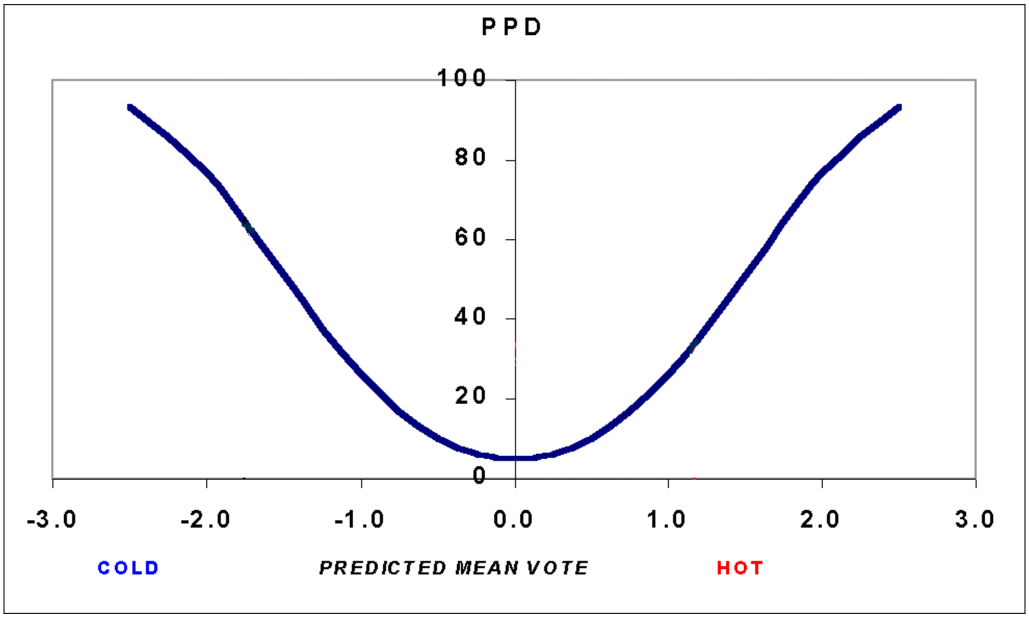


Fig 2. 9. Percentage of people dissatisfied as a function of mean vote.

2.2.7. ASHRAE versus ISO standard 7730

These standards were developed in parallel and both systems assess thermal comfort which measures comfort by adaptation of range of indexes named, predictive mean vote (PMV) and the predicted percentage of dissatisfied (PPD) to determine the thermal comfort boundary for different conditions. The main difference is that ISO is designed internationally for variety of weather condition however ASHRAE is better recognized within the United States. Also, as ISO is internationally organized, it goes beyond to consider cultural, national, and geographical differences to evaluate the free-cooling spaces.

2.3. Energy production emission rate in Mexico

In accordance with Article 12 of the Regulation of the Energy Transition Law, and having received and incorporated the observations to the methodology and its application by the Ministry of Environment and Natural Resources, the Establishments Subject to Report that the electricity emission factor of the National Electric System, for the calculation of indirect greenhouse gas emissions from electricity consumption corresponding to the year 2019, is 0.505 tCO_2e per MWh, which factor may be used for reporting purposes to the National Emissions Registry, considering that this factor considers the generation of power plants that deliver energy to the national electricity grid, in accordance with the provisions of section XLIV of Article 3 of the Electric Industry Law [58].

Chapter 3 Methodology and case study

In this chapter general methodology of research is discussed, as well as climate data, simulation process and case studies selection along with physical and thermal characteristics of cases.

3.1. Methodology

Process of work as stated in Fig 3.1 starts with data collection, first based on Mexican housing organization, the most common types were recognized and on the other hand climate data and reviewed strategies based on climate was analyzed. On the other hand, to validate the simulation method verification of modeling and simulation was performed using ASHRAE standard case 600FF and experimental data that was collected from PCM chambers.

Once cases were defined along most effective variables of improvement scenarios, relevant strategies were applied to different building envelope (Wall, roof, and openings) and thereafter annual energy consumption were calculated, which was the main deciding parameter for the selection of most optimum strategy, using EnergyPlus and Design Builder simulation.

Finally, impact of optimum scenario for each case was analyzed with respect to carbon emission, energy, cost saving, comfort analysis, and thermal performance.

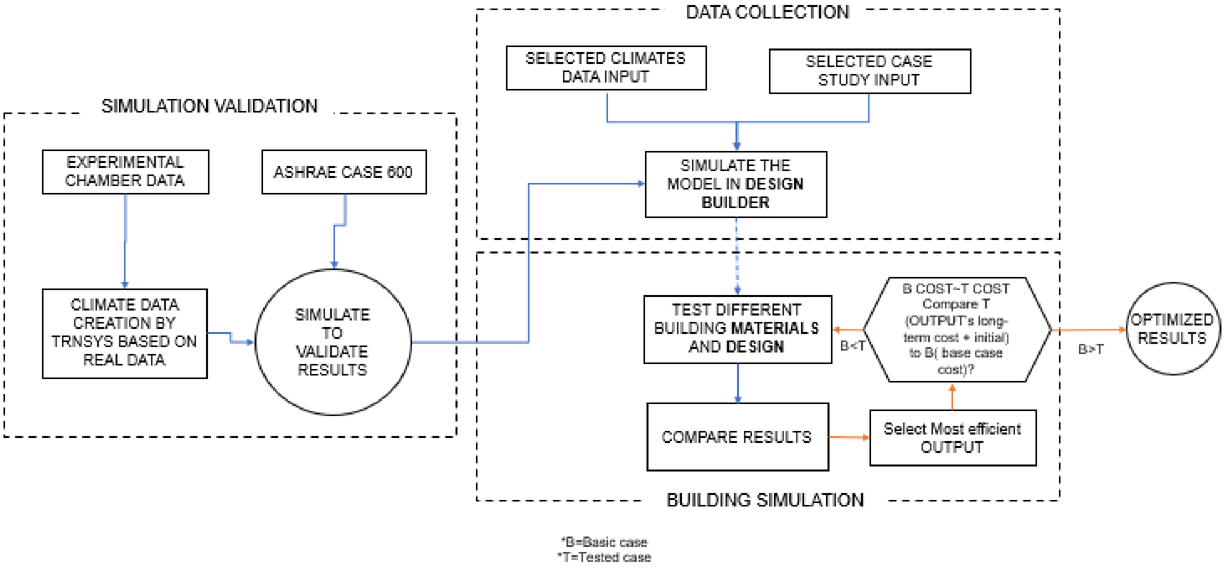


Fig 3. 1 Research flowchart

Software's that was used in this project are:

Microsoft Excel: To analyze the exported data from simulation and measure data.

EnergyPlus: As the primary simulation engine to simulate performance of strategies.

Design Builder: It was used as interface that graphically demonstrate EnergyPlus engine.

ELEMENTS: Create EPW files.

Climate Consultant: Analyze weather data.

TRNSYS: To calculate radiation from measure global radiation.

3.2. Location and climate

Monterrey belongs to the state of Nuevo León, Mexico at an altitude of 515 meters above sea level under semi-arid climate zone. The city is in the north of the country at a latitude of 25 N and a longitude of -100 west [59]. Figure 3.2 indicates the location of the City of Monterrey with a red mark.

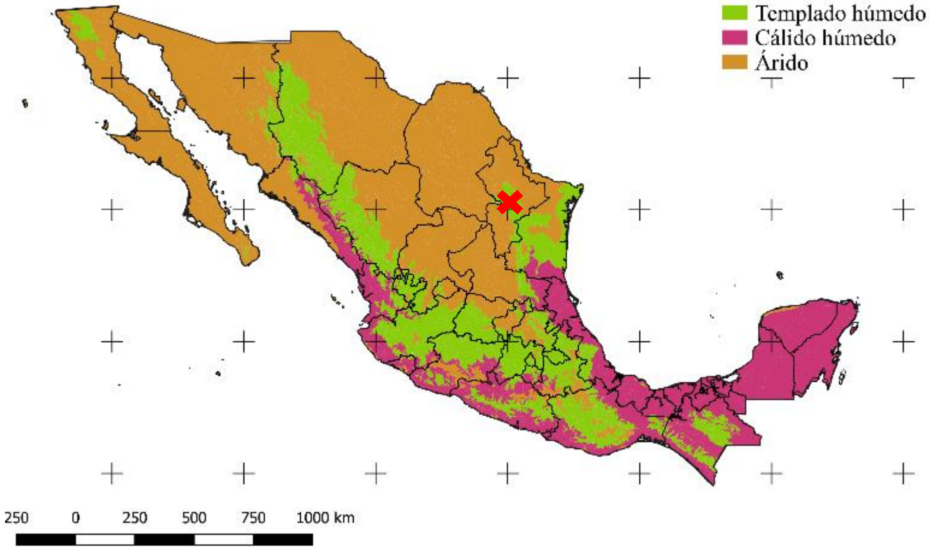


Fig 3. 1. Climate Classification of Mexico [60]

The City of Monterrey belong to the climatic group “B” (semi-arid) of the Köppen scale modified by García within the subgroup “BSx” which refers to a type of semi-dry or steppe climate with little abundant rainfall in all seasons [59]. The following table present a summary of climatic characteristic of each city. As table 3.1 presents, Monterrey has on average 3386 hours in a year a temperature more than 25 degrees and the highest temperature on average is 35°C. Also, other parameters such as dry bulb temperatures, relative humidity, global, direct, and diffuse radiation, are presented in graphs which are based on the data used in the simulation of this study. The information reported represents hourly values for the entire year divided into the hot period (May - October) and the cold period (November - April).

Table 3. 1. Typical annual climatic characteristics of Monterrey

Zone	City	Main Index °C	NHAT25	Latitude	Humidity %	Annual wind Speed m/s
Semi-arid	Monterrey	ATHM=35	3386	25.68	65.3%	3.48

ATHM average temperature in the hottest month; NHAT25 number of hours that average temperature is above 25°C.

3.2.1. Hot period

The dry bulb temperature during this period presents minimums of 15°C in the month of October and maximums of 35°C in the month of July. The hottest months are June, July, and August with average temperatures of 29.8°C, 30.5°C and 30.29°C. As can be seen in Fig 3.3 starting in September, the temperature begins to drop until it reaches an average of 24.17°C in the month of October.

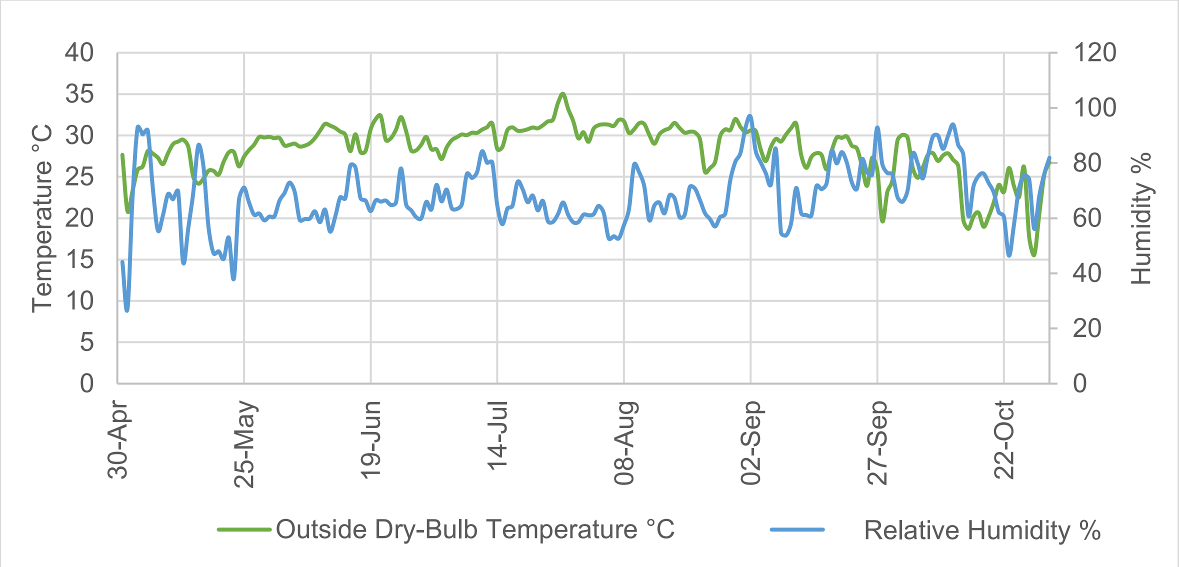


Fig 3. 2. Average temperature and humidity level during hot season in Monterrey

Relative humidity presents minimums of 35% in the month of May and maximums of 95% in the months of September, October, and early May. The months with the lowest relative humidity level on average are from May to August with values between 60% and 65%.

On the other hand, the months with the highest average relative humidity are September and October with values of 70% and 75%.

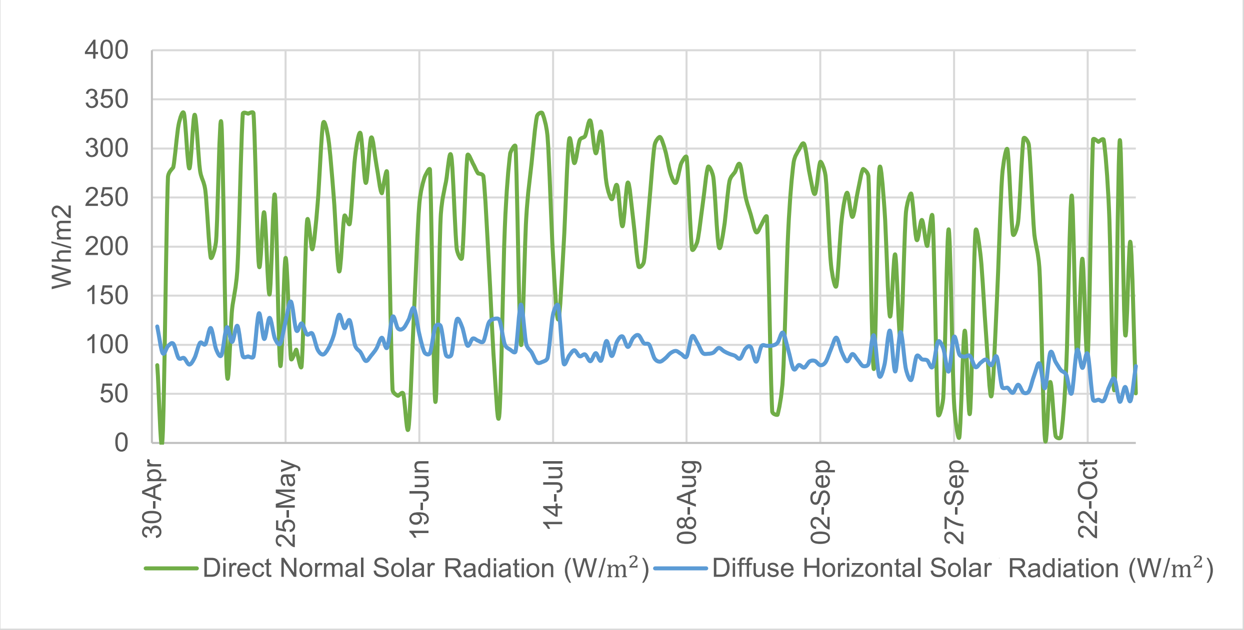


Fig 3. 3. Average daily direct and diffuse solar radiation during hot season in Monterrey

Normal direct solar radiation with minimum of 8 Wh/$\mathbf{m^2}$ and maximum of 340 Wh/$\mathbf{m^2}$ is illustrated in Fig 3.4. On average, the month with the least direct solar radiation is September with 280.1 Wh/$\mathbf{m^2}$ and the month with the highest direct radiation is 394.4 Wh/$\mathbf{m^2}$. Diffuse solar radiation presents minimums of 133.9 Wh/$\mathbf{m^2}$ and maximums of 284.4 Wh/$\mathbf{m^2}$. The month with the lowest diffuse radiation on average is October with 198.2 Wh/$\mathbf{m^2}$, while the highest month is September with 219.7 Wh/$\mathbf{m^2}$.

3.2.2. Cold period

During this period, the dry bulb temperature presents minimums of 4.1°C in the month of December and maximums of 29.9°C in the month of April as shown in Fig 3.5. The months with the lowest temperatures are December, January, and February with average temperatures of 14.25°C, 13.81°C and 15.1°C while the months with the highest temperatures are March and April with average temperatures of 19.54°C and 23.9°C.

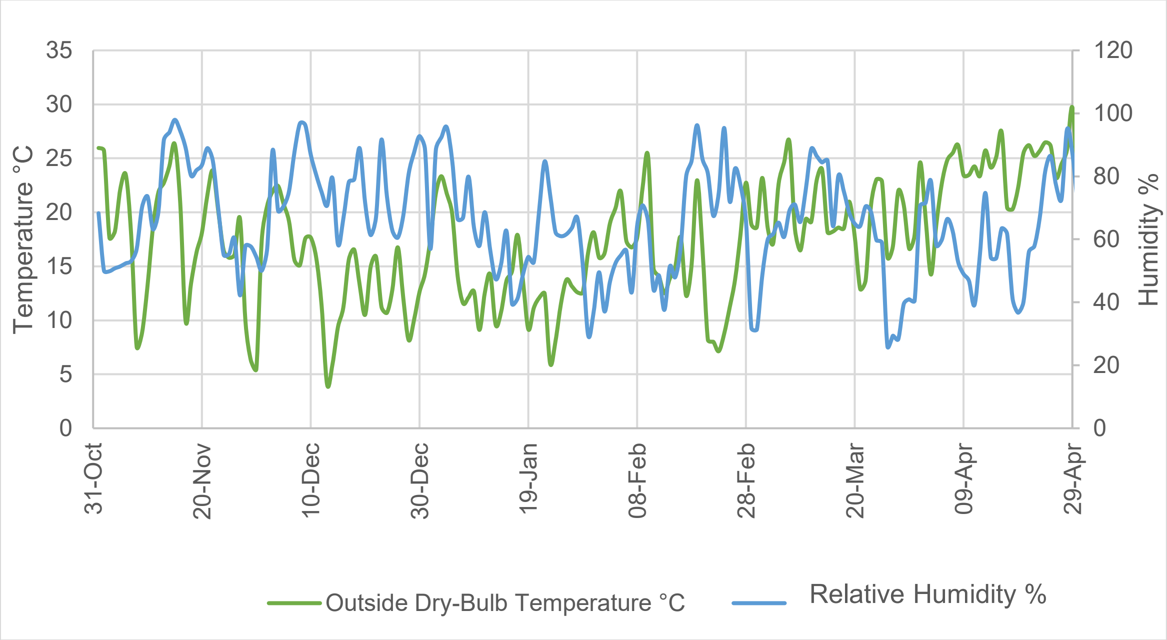


Fig 3. 4. Average temperature and humidity level during cold season in Monterrey

Relative humidity presents minimums of 26% in March and maximums of 95% in November, December, February, and April. The months with the highest relative humidity on average are November and December with 68.2% and 76.1%, while the months with the lowest humidity on average are from January to April with values between 60% and 62%.

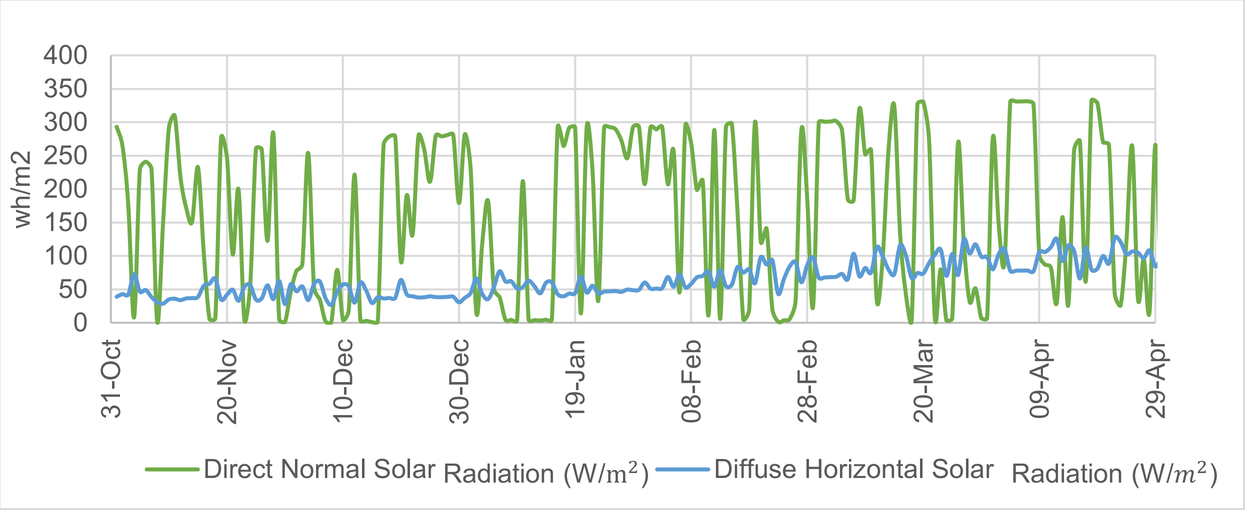


Fig 3. 5. Average daily direct and diffuse solar radiation during cold season in Monterrey

Direct and diffuse solar radiation during a cold season is presented in Fig 3.6 and accordingly, horizontal direct solar radiation during this period is in a range with minimums of 139.3 Wh/$\mathbf{m^2}$and maximums of 613.4 Wh/$\mathbf{m^2}$. Direct radiation is found to present minimums of 9.7 Wh/$\mathbf{m^2}$ and maximums of 778.5 Wh/m2. On average, the month with the least direct solar radiation is January with 287.5 Wh/$\mathbf{m^2}$, while the month with the highest direct radiation is February with 417.3 Wh/$\mathbf{m^2}$. Diffuse solar radiation shows minimums of 114.6 W Wh/$\mathbf{m^2}$ and maximums of 286.35 Wh/$\mathbf{m^2}$. The month with the lowest average diffuse solar radiation is December with 145.8 Wh/m2 while the month with the highest diffuse radiation is April with 201.3 Wh/$\mathbf{m^2}$.

3.3. Identification and selection of building types

The class of the house is determined by the value of the house according to Infonavit financial plan of 2016-2020 [61]. With regards to Fig 3.7, class 1, 2.1, 5 and 6 have the lowest living rate. Whereas, class 2.2, 2.3 and 3 which respectively are, type Popular B2, Popular B3 and Traditional have the highest rate of living as residential homes.

Table 3.2. Residential buildings classification of Mexico according to Infonavit 2020 [61].

Class	Segment	Minimum VSMM*	Maximum VSMM*	Average price
1	Economica	<118	118	MXN 203,291
2.1	Popular B1	118	128	MXN 235,772
2.2	Popular B2	128	158	MXN 277,616
2.3	Popular B3	158	200	MXN 342,894
3	Tradicional	200	350	MXN 495,985
4	Media	350	750	MXN 963,191
5	Residential	750	1500	MXN 1,909,953
*Times the monthly minimum wage				

Also, State of Nuevo Leon has the highest residential houses in the country followed by Jalisco. Consequently, type Popular B2 and B3 and Traditional were chosen as case study of this project [62].

Housing class

A. ECONOMICA	B.1 POPULAR 128	B.2 POPULAR 158	B.3 POPULAR 200	C. TRADICIONAL	D. MEDIA	E. RESIDENCIAL	F. RESIDENCIAL +
2.40%	1.53%	16.77%	23.88%	33.37%	18.95%	2.89%	0.20%

Number of bedroom

Dos o más	Una recámara
99.00%	1.00%

Housing size

Superficie construida

MENOR A 38	MENOR A 45	MENOR A 60	MENOR A 80	MAYOR A 80
0.19%	8.54%	49.94%	18.22%	23.11%

Housing types

Horizontal	Vertical
71.22%	28.78%

Fig 3. 6. Popularity of different residential units based on RUV (Registro Único de Vivienda)

3.4. Simulation method and case studies

Firstly, the city, which best represent as one of the highest cooling energy consuming and populated locations of Mexico was selected. Then by using climate consultant will further analyze the existing weather detail such as temperature, wind speed and humidity to estimate the thermal comfort criteria in that area.

Secondly, a complete collection of all passive cooling technologies will be studied. Consequently, with regards to the climate condition and considering the economical availability, will select and test the most suitable passive techniques. The most affordable, efficient strategy will be recommended accordingly to the climatic condition of site and building type. This test will be applied using a simulation program, Energy Plus. Three types of building based on Mexican most common housing are selected as a control unit with respect to Mexican norms. Subsequently, each strategy is added to different component of building envelope and then the new building's annual energy consumption is compared to the base case, most optimum combinations of strategy is selected based on the reduction in energy consumption. A cost analysis is then applied to understand the duration of return of investment. Every detail of materials and design input is inserted in the simulation platform of energy plus and design builder.

For the validation of simulation, there are two methods used, first through comparison against BESTEST benchmark case of 600FF based on ASHRAE Standard in Design Builder and, secondly, a PCM chamber was built with weather station to be the benchmark of experimental data and then be compared to simulation results of the same unit case. This lab consists of control unit chamber and a treatment chamber which PCM and insulation is applied to walls and roof inner surface. The weather data is collected using Davis Vantage Pro2 which is a Weather Station console that shows and records the weather data collected at the lab. Further details about validation data are presented in chapter 4.

Lastly, with regards to the established data and results, a set of guidelines for building materials and strategy will be developed suited to each kind of building envelope. This guideline could be used by Architects and designers, also governments of similar weather countries can use the data to develop building policies and rules for betterment of environment and a sustainable city development. In conclusion, it is intended that the present thesis can serve as a base guideline for improving indoor thermal performance in the residential buildings of Mexico, new techniques in designing and operating unconditioned buildings in warm or hot climates that can also enhance indoor comfort conditions.

Table 3.3 presents the characteristics of base cases which are the common type of houses construction in Mexico, where C1 represent Popular B2 type of building, C2 represent Popular B3, and C3 is Tradicional type of house.

Table 3. 3. Characteristics of the building systems for all cases

Characteristics	Description C1	Description C2	Description C3
Location	Monterrey, 25.6866° North, 100.3161° West		

Orientation	Main façade facing west	Main façade facing west	Main façade facing west
Plan shape	Rectangle	Rectangle	Rectangle
Number of floors	1 floor	4 floors	2 floors
Floor to floor Height	3 m	2.7 m	2.7 m
Gross wall area	66.13 $\mathbf{m^2}$	61.56 $\mathbf{m^2}$	99.16 $\mathbf{m^2}$
Window area	9.98 $\mathbf{m^2}$	10.44 $\mathbf{m^2}$	9.95 $\mathbf{m^2}$
Type of glass	6 mm Single glass	6 mm Single glass	6 mm Single glass
Solar absorptance	0.5 for wall / 0.6 for roof		
Occupancy density	3 persons	2 persons	5 persons
Infiltration	0.5 ACH	0.5 ACH	0.5 ACH
System type	Package DX	Package DX	Package DX
Thermostat setting	Cooling = 25°C / Heating = 21°C		
COP	2.5	2.5	2.5

3.4.1. Case 1 (Popular B2)

The model consists of single-story building with main façade oriented facing towards west east. A rectangular geometry of 4.5 x 8 m. and 3 m. high on the ground floor. This floor consists of four windows with area of 1.5 $\mathbf{m^2}$, 4.8 $\mathbf{m^2}$, 2.18 $\mathbf{m^2}$, and 1.5 $\mathbf{m^2}$. Basic characteristics and systems of envelope is presented in table 3.3 and the material thermal characteristics is shown in table 3.4 and openings size is expresses in table 3.5.

The house is located between two adjacent neighbors hence only the walls with windows (façade and back) has contact with the outside air. The remaining two surfaces are adjacent to spaces of equal temperature. Therefore, all surfaces facing north, and south are adiabatic. Zoning of the floor plan and building elevation is expressed in Fig 3.8 and Fig 3.9.

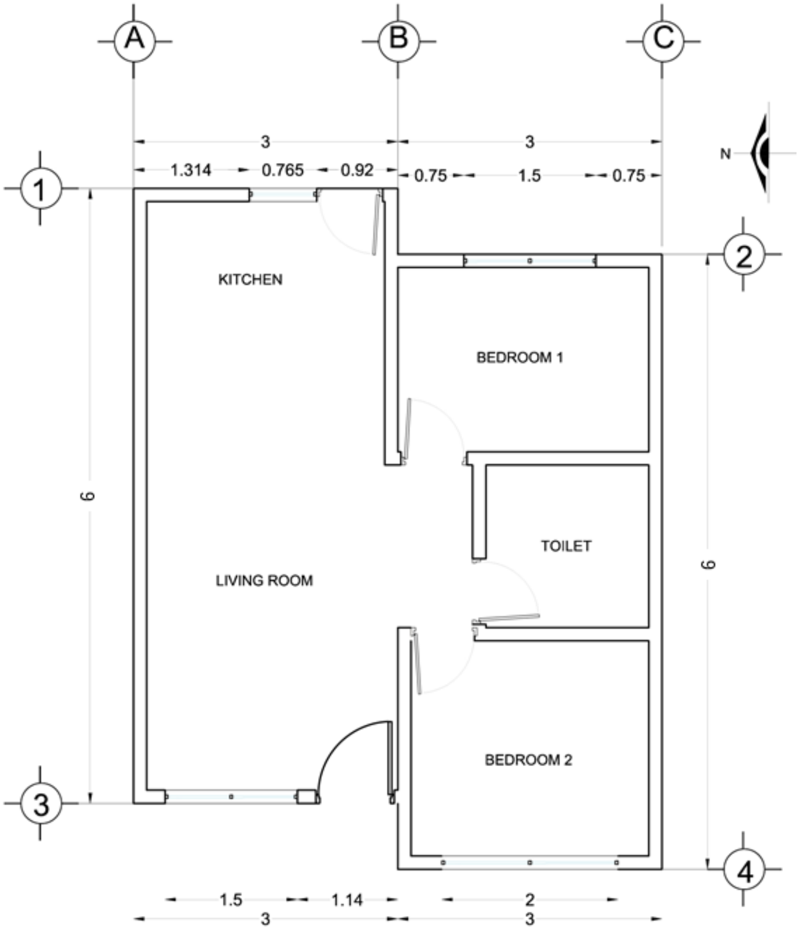


Fig 3. 7. Floor plan of case 1 (all measurements are in meter)

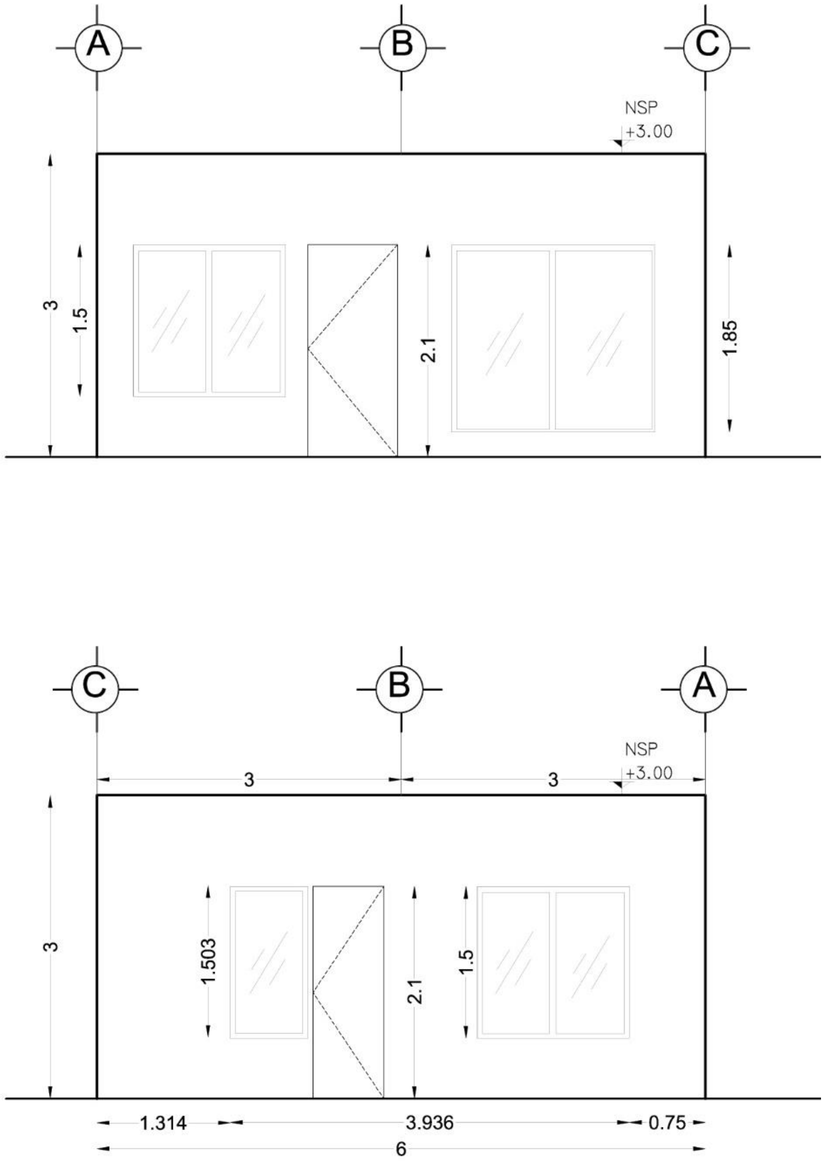


Fig 3. 8. Elevation drawing of case 1 showing the openings size and positioning (all measurements are in meter)

In the context of this study thermal absorptance (emissivity) represents the fraction of incident long wavelength radiation that is absorbed by the material. This parameter is used when calculating the long wavelength radiant exchange between various surfaces and affects the surface heat balances (both inside and outside as appropriate). While solar absorptance represents the fraction of incident solar radiation that is absorbed by the material. Solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths. This parameter is used when calculating the amount of incident solar radiation absorbed by various surfaces and affects the surface heat balances (both inside and outside as appropriate). Values for this field must be between 0.0 and 1.0.

Table 3. 4. Thermal and material characteristics of base case 1

Component	Material	Thickness	Thermal absorptance	Solar absorptance	Thermal conductivity W/mk
External Wall					
Outer most	Plaster lightweight	0.013	0.9	0.5	0.16
Layer 2	Single Brick work	0.1	0.9	0.7	0.84
Inner most	Plaster lightweight	0.013	0.9	0.5	0.16
Partitions					
Outer most	Plaster lightweight	0.013	0.9	0.5	0.16
Layer 2	Single Brick work	0.1	0.9	0.7	0.84
Inner most	Plaster lightweight	0.013	0.9	0.5	0.16
Window					
Frame	Aluminum no break	0.04	0.3	0.3	160
Glass	Single blue glass	0.006			
Floor					
Outer most	Concrete	0.1	0.9	0.6	1.13
Layer 2	Floor Screed	0.07	0.9	0.73	0.41
Inner most	Clay Ceramic Tiles	0.03	0.9	0.6	1.2
Roof					
Outer most	Concrete slab	0.2	0.9	0.6	0.6
Inner most	Plaster Board	0.013	0.9	0.5	0.5
External					
Doors	Plywood	0.006	0.9	0.78	0.15
Outer most	Air gap	0.028	0.9	0.7	
Layer 2	Plywood	0.006	0.9	0.78	0.15

Inner most					
Internal					
Doors	Plywood	0.006	0.9	0.78	0.15
Outer most	Air gap	0.028	0.9	0.7	
Layer 2	Plywood	0.006	0.9	0.78	0.15
Inner most					

Table 3. 5. Opening’s size and schedule case 1

Component	Location	Area
Window 1	Zone 1, Bedroom	1.5 $\mathbf{m^2}$
Window 2	Zone 2, Bedroom	4.8 $\mathbf{m^2}$
Window 3	Zone 1, Living room	2.18 $\mathbf{m^2}$
Window 4	Zone 3, Living room	1.5 $\mathbf{m^2}$
External Door	Zone 3, Living room	1.89 $\mathbf{m^2}$
Door 1	Zoon 1, Bedroom	1.47 $\mathbf{m^2}$
Door 2	Zoon 4, Bedroom	1.47 $\mathbf{m^2}$
Door 3	Zone 2, Toilet	1.47 $\mathbf{m^2}$

3.4.2. Case 2 (Popular B3)

The model consists of four-story building. Each house is a rectangular geometry of 6 x 7 m and 2.7 m high block with four detached levels with area of 42 m^2, and volume of 113.4 m^3. Each house consists of two bedrooms with material characteristics as shown in table 3.6, and five windows with dimensions as shown in table 3.7. Building layout and zones are displayed in Fig 3.10 and façade view and windows positioning are presented in Fig 3.11.

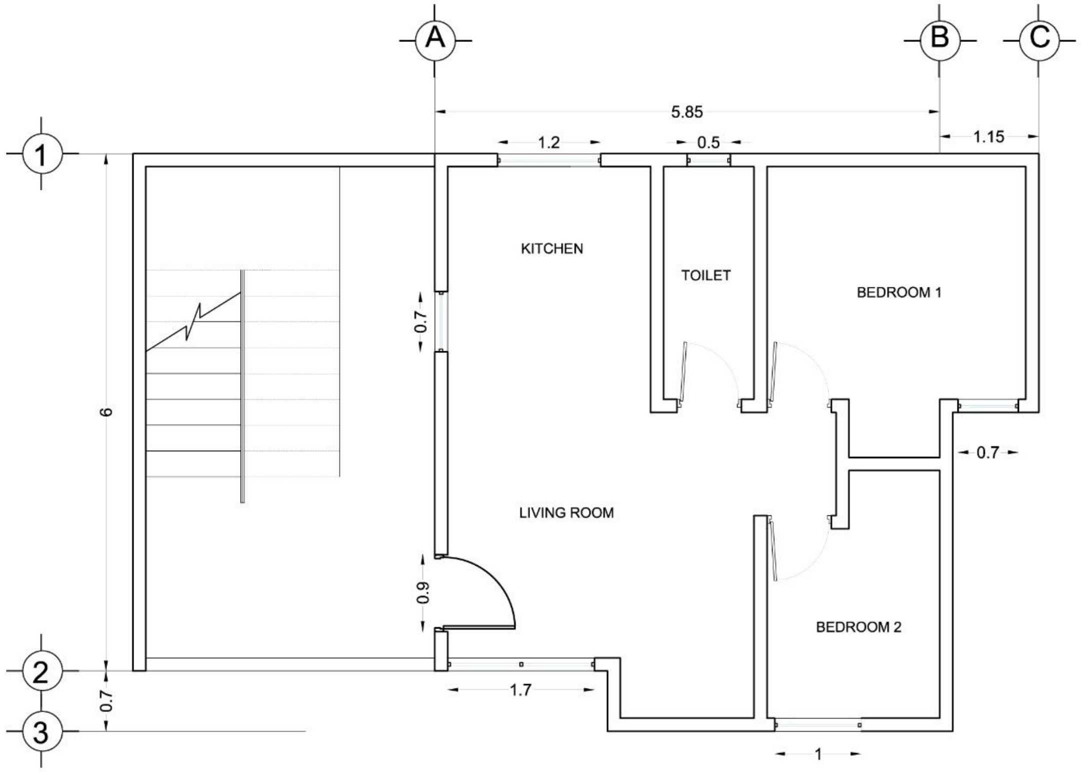


Fig 3. 9. Floor plan of case 2 (all measurements are in meter)

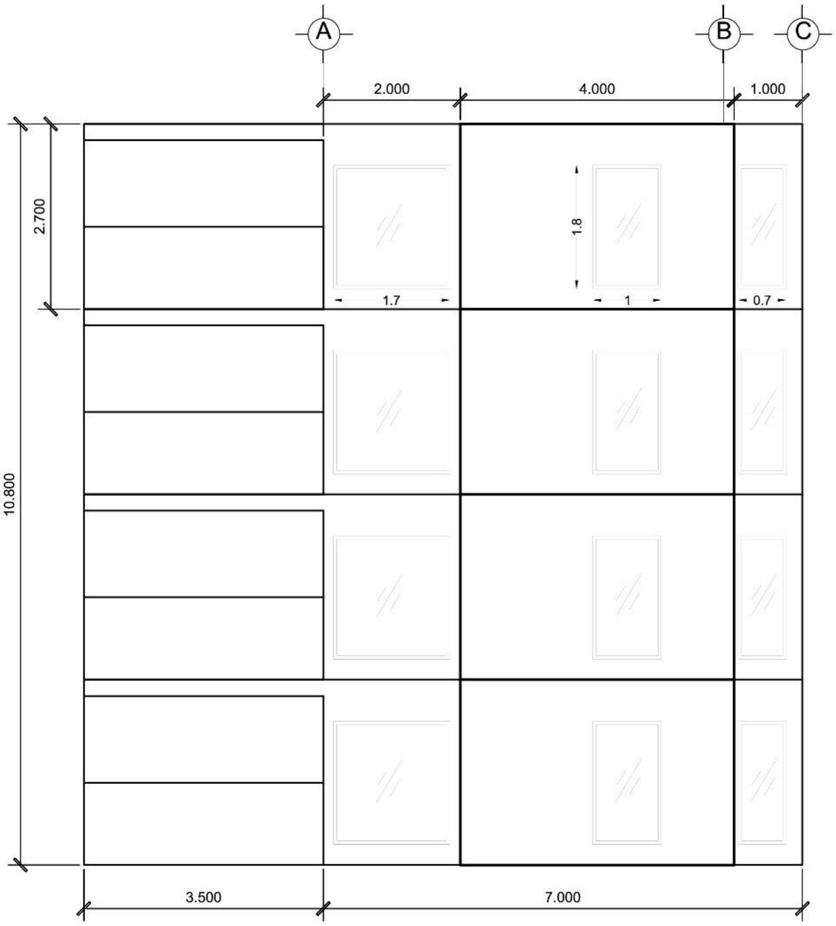


Fig 3. 10. Elevation drawing of case 2 showing the openings size and positioning (all measurements are in meter)

Table 3. 6. Thermal and material characteristics of base case 2

Component	Material	Thickness	Thermal absorptance	Solar absorptance	Thermal conductivity W/mk
External Wall					
Outer most	Plaster	0.013	0.9	0.5	0.16
Layer 2	lightweight	0.1	0.9	0.7	0.84
Inner most	Single Brick work	0.013	0.9	0.5	0.16

	Plaster lightweight				
Partitions Outer most Layer 2 Inner most	Plaster lightweight Single Brick work Plaster lightweight	0.013 0.1 0.013	0.9 0.9 0.9	0.5 0.7 0.5	0.16 0.84 0.16
Window Frame Glass	Aluminum no break Single blue glass	0.04 0.006	0.3	0.3	
Floor Outer most Layer 2 Inner most	Concrete Floor Screed Clay Ceramic Tiles	0.1 0.07 0.03	0.9 0.9 0.9	0.6 0.73 0.6	1.13 0.41 1.2
Roof Outer most Inner most	Concrete slab Plaster Board	0.2 0.013	0.9 0.9	0.6 0.5	0.6 0.5
External Doors Outer most Layer 2 Inner most	Plywood Air gap Plywood	0.006 0.028 0.006	0.9 0.9 0.9	0.78 0.7 0.78	0.15 0.15
Internal Doors Outer most Layer 2	Plywood Air gap Plywood	0.006 0.028 0.006	0.9 0.9 0.9	0.78 0.7 0.78	0.15 0.15

Inner most					

Table 3. 7. Opening’s size and schedule case 2

Component	Location	Area
Window 1	Zone 1, Bedroom	1.26 $\mathbf{m}^2$
Window 2	Zone 4, Bedroom	1.8 $\mathbf{m}^2$
Window 3	Zone 3, Living room	3.06 $\mathbf{m}^2$
Window 4	Zone 3, Living room	3.06 $\mathbf{m}^2$
Window 5	Zone 3, Kitchen	1.8 $\mathbf{m}^2$
Window 6	Zone 2, Toilet	0.9 $\mathbf{m}^2$
External Door	Zone 3, Living room	1.89 $\mathbf{m}^2$
Door 1	Zoon 1, Bedroom	1.47 $\mathbf{m}^2$
Door 2	Zoon 4, Bedroom	1.47 $\mathbf{m}^2$
Door 3	Zone 2, Toilet	1.47 $\mathbf{m}^2$

3.4.3. Case 3 (Traditional)

The model consists of double story building. A rectangular geometry of 4.5 x 8 m. and 2.7 m. high on the ground floor with area of 80 m^2, and as well as rectangular geometry of 4.5 x 10 m and 2.7 m in height on the second floor as Fig 3.13 illustrates the zones. In total the envelope consists of six windows, which of those two of 1.5 x 2 m and 1.5 x 0.5 m on the west face, as well as on the east face with same dimensions as shown in Fig 3.12.

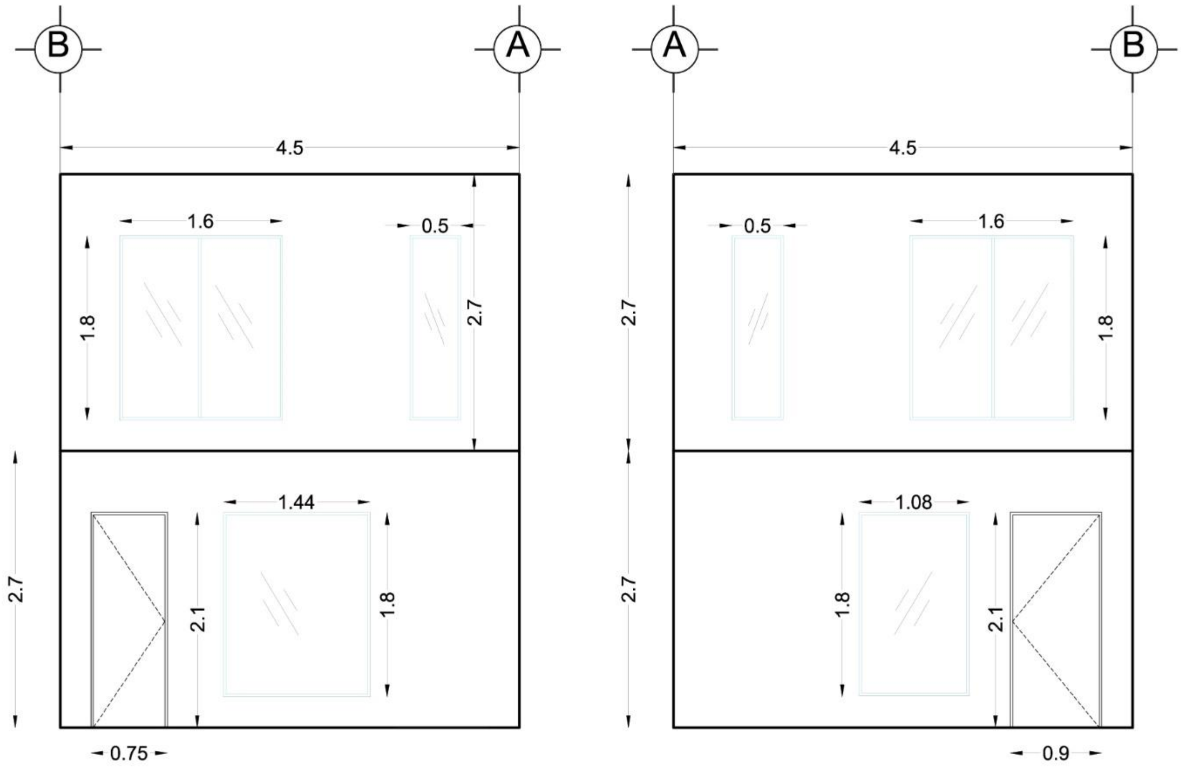


Fig 3. 11. Elevation drawing of case 3 showing the openings size and positioning (all measurements are in meter)

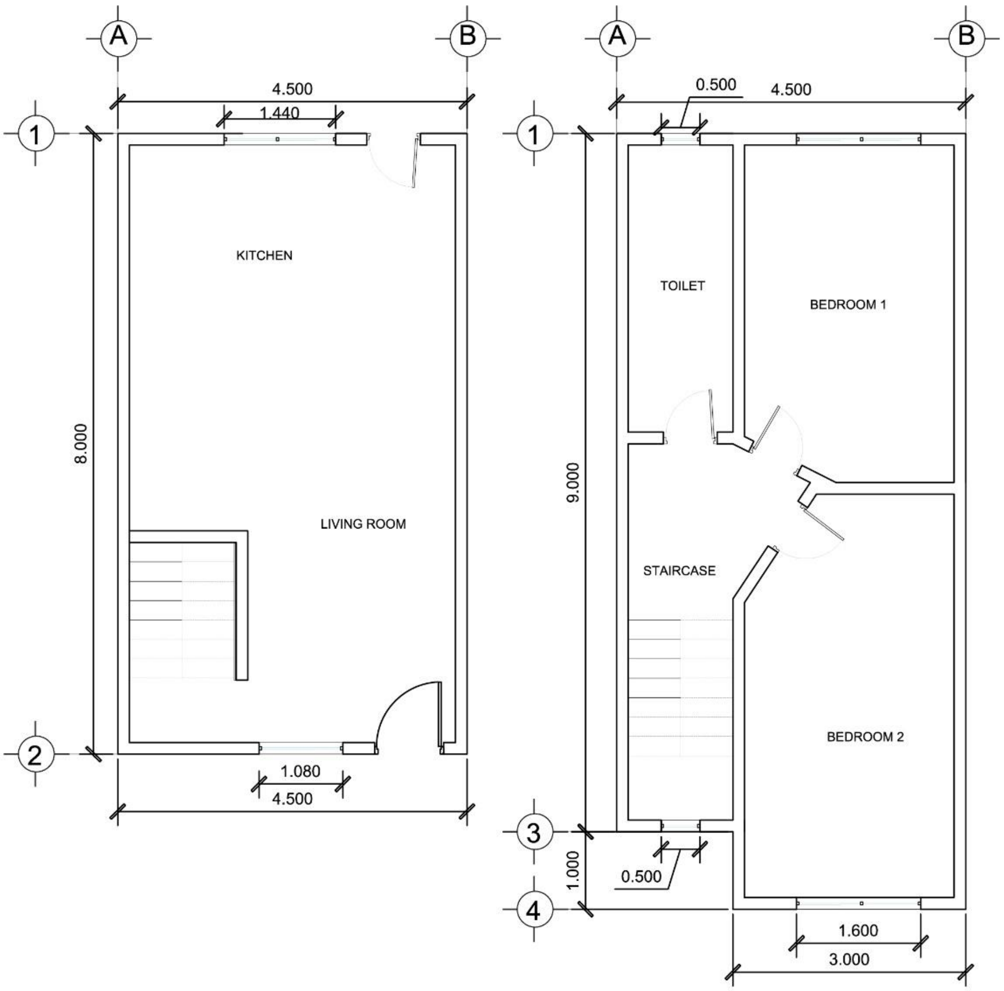


Fig 3. 12. Floor plan of case 3 (all measurements are in meter)

Table 3. 8. Thermal and material characteristics of base case 3

Component	Material	Thickness	Thermal absorptance	Solar absorptance	Thermal conductivity W/mk
External Wall					
Outer most	Plaster	0.013	0.9	0.5	0.16
Layer 2	lightweight	0.1	0.9	0.7	0.84
Inner most	Single Brick work	0.013	0.9	0.5	0.16

	Plaster lightweight				
Partitions					
Outer most	Plaster lightweight	0.013	0.9	0.5	0.16
Layer 2	Single Brick work	0.1	0.9	0.7	0.84
Inner most	Plaster lightweight	0.013	0.9	0.5	0.16
Window					
Frame	Aluminum no break	0.04	0.3	0.3	
Glass	Single blue glass	0.006			
Floor					
Outer most	Concrete	0.1	0.9	0.6	1.13
Layer 2	Floor Screed	0.07	0.9	0.73	0.41
Inner most	Clay Ceramic Tiles	0.03	0.9	0.6	1.2
Roof					
Outer most	Concrete slab	0.2	0.9	0.6	0.6
Inner most	Plaster Board	0.013	0.9	0.5	0.5
External Doors					
Outer most	Plywood	0.006	0.9	0.78	0.15
Layer 2	Air gap	0.028	0.9	0.7	
Inner most	Plywood	0.006	0.9	0.78	0.15
Internal Doors					
Outer most	Plywood	0.006	0.9	0.78	0.15
Layer 2	Air gap	0.028	0.9	0.7	
Inner most	Plywood	0.006	0.9	0.78	0.15

Table 3. 9. Opening's size and schedule case 3

Component	Location	Area ($\mathrm{m^2}$)
Window 1	Zone 1, Living room	1.08 $\mathrm{m^2}$
Window 2	Zone 1, Kitchen	1.44 $\mathrm{m^2}$
Window 3	Zone 2, Bedroom	3.00 $\mathrm{m^2}$
Window 4	Zone 4, Bedroom	3.00 $\mathrm{m^2}$
Window 5	Zone 3, Stairs	0.75 $\mathrm{m^2}$
Window 6	Zone 1, Toilet	0.68 $\mathrm{m^2}$
External Door	Zone 3, Living room	1.89 $\mathrm{m^2}$
Door 1	Zone 3, Living room	1.47 $\mathrm{m^2}$
Door 2	Zoon 1, Bedroom	1.47 $\mathrm{m^2}$
Door 3	Zoon 4, Bedroom	1.47 $\mathrm{m^2}$
Door 4	Zone 2, Toilet	1.47 $\mathrm{m^2}$

3.5. Applied strategies specification

PCM selection was executed based on average hourly temperature of the city which the most common temperature with higher number of repetitions annually was selected as the most optimum PCM. As PCM starts to melt at its melting point, The most common temperature throughout the year is selected to perform better for instance if most of the year temperature is around 25 and we select a PCM 19 which melts by the time temperature reaches 19 we have the material at its liquid form throughout the day and PCM is not performing as thermal storage, on the contrary if we choose PCM 25 and the temperature never reaches above 25 our PCM is not melting to change form and release the heat at cooler time, hence the average hours are critical. Moreover, the availability of PCM is vital, in Mexico the only brand available is Infiniti PCM 21, 25, and 29, hence we compare the melting points based on available PCM. As it is shown in Table 3.10 most of the year temperature is above 25 degrees which results in selection of PCM 25.

Table 3. 10. Average hourly temperature analysis for Monterrey in one year

Temperature range	21<T<25	25<T<29	T>29

Number of hours in a year	1479	2049	2031

All the simulations are based on the three cases described above, but is extended by adding PCM, reflective white paint and insulation into walls and roof, as well as different glazing for window and overhang shading. The material properties are presented in table 3.11.

Table 3. 11. Thermal characteristics of passive strategies applied in different scenarios

Material	Thickness (m)	Conductivity (W/m.K)	Specific Heat (J/kg.K)	Density (Kg/m^3)
Reflective white paint	0.005	.20	1400	1250
PCM 25	0.012	0.815	3140	929
Insulation	0.0762	.034	1400	35

Window	Thickness (m)	SHGC	Light transmission	Solar reflectance	Visible reflectance
Double clear glass with air gap	0.025	0.497	0.505	0.05	0.06
Double low-e glass with air gap	0.025	0.26	0.137	0.059	0.453
Double reflective glass with air gap	0.025	0.35	0.591	0.22	0.25
Overhang Shading	0.125			0.75m	

Wall are abbreviate to W, roof to R, and openings to O, alongside six scenarios which are designed for building component of wall, as defined in table 3.12 which indicates that based on U-value factor, scenario W.Ir and W.PI with the lowest U-value are expected to have the most optimum impact.

Table 3. 12. Description of scenarios for the wall component

Scenario	Type	U-Value

		(W/m^2K)
Scenario W.P	Base case wall + PCM 25	1.93
Scenario W.r	Base case wall + Reflective paint	2.45
Scenario W.I	Base case wall + Insulation	0.78
Scenario W.Ir	Base case wall +Insulation + Reflective Paint	0.73
Scenario W.Pr	Base case wall + PCM 25+ Reflective Paint	2.03
Scenario W.PI	Base case wall + PCM 25+ Insulation	0.74

As can be seen in table 3.13, scenario R.I, R.Ir and R.PI has the lowest U-value of around 0.8 and are expected to have greater impact.

Table 3. 13. Description of scenarios for the roof component

Scenario	Type	U-Value (W/m^2K)
Scenario R.P	Base case roof + PCM 25	1.93
Scenario R.r	Base case roof + Reflective paint	2.45
Scenario R.I	Base case roof + Insulation	0.82
Scenario R.Ir	Base case roof +Insulation + Reflective Paint	0.80
Scenario R.Pr	Base case roof + PCM 25+ Reflective Paint	2.67
Scenario R.PI	Base case roof + PCM 25+ Insulation	0.81

There are three types of glazing that are expressed in table 3.14, which scenario O.DBLE has the lowest U-value of 1.27 compared to other scenarios, hence anticipated to have superior influence on energy efficiency of envelope.

Table 3. 14. Description of scenarios for the opening component

Scenario	Type	U-Value (W/m^2K)
Scenario O.DBC	Double clear glazing with air gap	2.66
Scenario O.DBR	Double Reflective coating air gap	1.76

Scenario O.DBLE	Double with Low-E coating air gap	1.27
Scenario O.SH	Overhang Shading	-
Scenario O.SHDBLE	Overhang shading + Double with Low-E coating air gap	-

Figure 3.14 illustrate construction detail of scenario R.PI where insulation and PCM was applied to the roof component and Insulation absorbs the heat conducted through concrete slab, whereas PCM absorbs the heat radiation from room and then conducted through Plaster board to it, and store the heat.

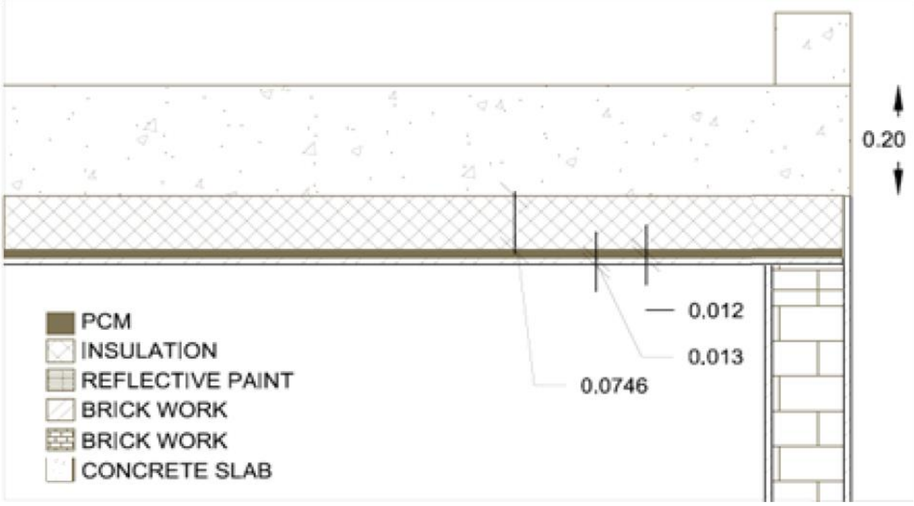


Fig 3. 13. Roof configuration with Insulation + PCM 25

Shading device is installed horizontally above openings of the building envelope as Fig 3.15 shows its application on single layer glass window. Similarly in Fig 3.16 shading is installed but in combination with double layer window with low-e glazing.

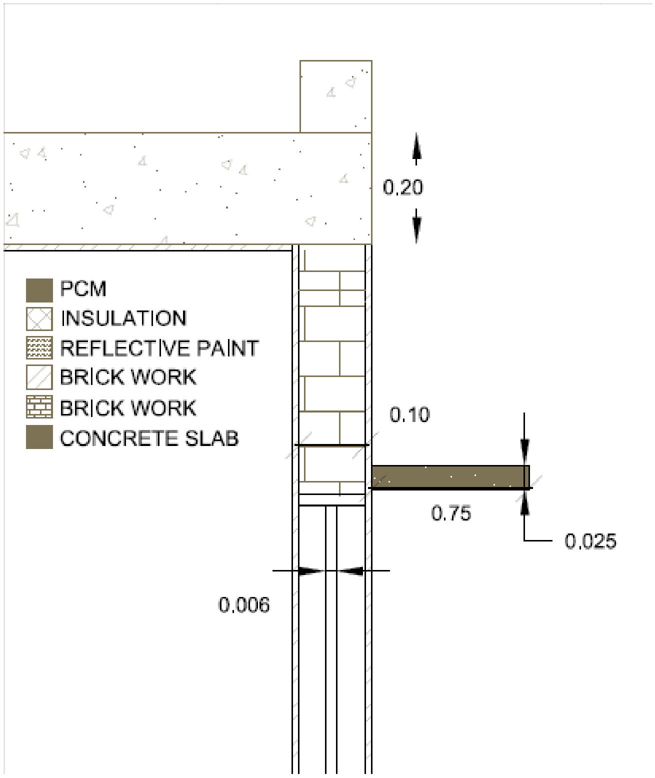


Fig 3. 14.Window configuration of single glass glazing with overhang shading

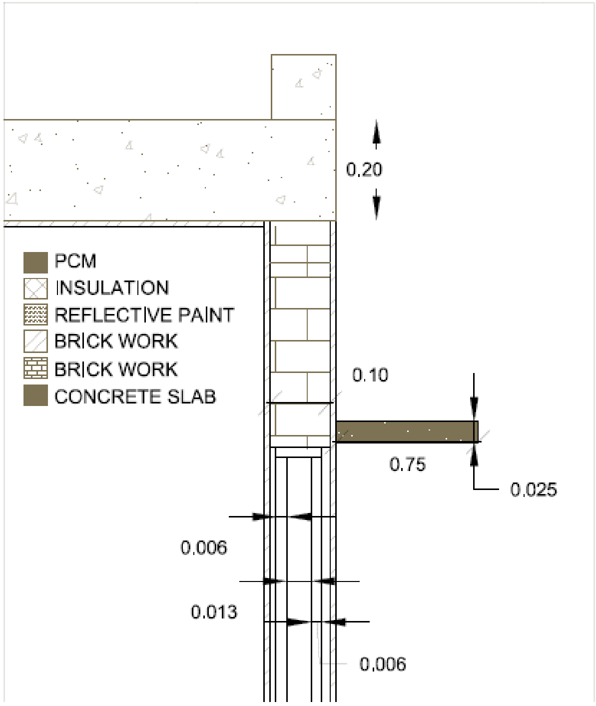


Fig 3. 15. Window configuration of double layer glass low-E glazing with overhang shading

Chapter 4 Validation

Validation of simulation method is presented here, firstly the benchmark case 600FF is introduced and simulated to compare the results, secondly an experimental test is carried out and results are compared to verify the method. Finally, as the error rate is less than 1% the building simulation is verified and highly credible to run DesignBuilder simulation in the analysis stage.

To validate the building simulations model was conducted using DesignBuilder V.60.1 program, in which the exercises "the BESTEST benchmark case 600 FF" of the ANSI / ASHRAE 140-2001 standard were replicated. This standard is used as a test method for the evaluation of computer programs for energy analysis in buildings. The results obtained were compared with those reported by other energy simulation programs, among which are DOE21D and an older version of DesignBuilder. The results of these last two programs are used as a reference to calculate and report the error percentage obtained with the most recent version of DesignBuilder used in this thesis.

Furthermore, to evaluate the behavior of PCM and insulation in Mexican climate, two experimental chambers was created one as a control unit and the other treatment with applied PCM and insulation on its wall and roof.

4.1. Building design and simulation capability

Originally, buildings are a system that create our environment and impact our ecosystems, hence the process of idea generation and inclusion of efficiency estimation regarding their envelope performance is key. Recently, building simulation tools been used by professionals to recognize the most feasible designs in respect with energy efficiency of buildings [63]. There have been many platforms as can be seen in table 4.1, which between all, as Crawley et al. [64] suggests that EnergyPlus has one of the most proficiency.

Table 4. 1. Simulation software comparison

Program	Source	Capabilities	Comments
eQUEST	www.doe2.com/equest	Performs an hourly simulation of the building based on walls, windows, glass, people, plug loads, and ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices.	The building creation wizard walks a user through the process of creating a building model within eQUEST, DOE-2.2
TRNSYS	http://apps1.eere.energy.gov/buildings/tools_directory/software.	Analysis and sizing HVAC, Multi-zone airflow analyses, electric power simulation, solar design, building thermal performance, analysis of	Useful for research applications and industry cases where a new or innovative

	cfm/ID=58/pagename=alp ha_list	control schemes, differing levels of complexity, extensive documentation on component routines, including explanation, background.	system model is required.
EnergyPlus	http://apps1.eere.energy.gov/buildings/tools_ directory/software.cfm/ID=287/pagename=al pha_list	EnergyPlus engine that is based on DOE-2, BLAST, and COMIS software. EnergyPlus engine that is based on DOE-2, BLAST, and COMIS software. Time-steps less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems.	EnergyPlus is a complicated program in which to develop or adjust building models.
ECOTECT	http://apps1.eere.energy.gov/buildings/tools_ directory/software.cfm/ID=391/pagename_menu=pc/contacts_landing.cfm	Thermal energy, lighting, shading, acoustics, Tools for climatic analysis.	Real-time animation features are provided along with interactive acoustic and solar ray tracing that updates in real time with changes to building geometry and material properties.
TAS	http://www.edsl.net/main/	Dynamic thermal performance of buildings and their systems, accessing environmental performance, conducting a natural ventilation analysis	
ESP-r	http://www.esru.strath.ac.uk/Programs/ESP- r.htm	An integrated energy modelling tool for the simulation of the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with associated environmental control systems.	Useful for research applications where high degree of accuracy is required.
Energy-10	http://www.nrel.gov/buildings/energy10.html	Whole-building analysis, evaluating the energy and cost savings that can be achieved by applying energy-efficient strategies such as day lighting, passive solar heating, and high-performance windows and lighting systems, natural ventilation.	The simulation software is suitable for examining small commercial and residential buildings that are characterized by one or two thermal zones.
DesignBuilder	http://apps1.eere.energy.gov/buildings/tools_ directory/software.cfm/ID=486/pagename_menu=united_kingdom/contacts_landing.cfm	EnergyPlus Engine that is based on DOE-2, BLAST, and COMIS software. Calculates CO2 emissions, solar shading, comfort studies, CFD, HVAC, naturally ventilated buildings, buildings with day lighting control, facades, advanced solar shading strategies.	The DesignBuilder approach to natural ventilation allows detailed models of natural ventilation air flows.

Chiefly, EnergyPlus is designed according to ASHRAE standard which is solid for warm and semi-arid climate. Respectively, DesignBuilder software uses the basic concept of sequential simulation of EnergyPlus, and here are some of parameters that resulted in selection of this software for this research:

Performance: The multi-zones approach to modelling allows flexibility in both the types of system that can be modelled and the level of detail. The modeler can describe a building and its systems abstractly and then add more detailed zone descriptions as required. For example, the most basic energy simulation would involve only one domain in a model which are the geometry and fabric of the building. If more functionalities were required, the model could be augmented with air flow, CFD and HVAC.

Separation of engine and interface: DesignBuilder interface allows simulation engine to work in mainstream of allowed input-output data without the need for request redesign of the models. Hence, while the model can be constructed from many different and diverse zones, the zones of the building model are connected, and they form a consistent mathematical description of the building.

Integrated simulation: DesignBuilder performs a comprehensive simulation. A typical model of a building consists of several coupled polyhedral zones that describe the geometry and fabric of the building envelope. Augmenting these zones are a series of networks, each of which describes an individual zone: heating, air conditioning plant and air flow. This multi-zone modelling approach is efficient in terms of both the complexity of the model and the numerical solution. The requirements of a particular simulation will dictate time-steps from 15-minutes to 1-hour [65].

In conclusion, the selection of DesignBuilder is based on:

Validity 101: This program enable user to model any building and calculates its internal heat gain, amount of radiation through windows and other façade components. Furthermore, it can measure energy consumption through lighting, cooling, and heating of building as well as naturally ventilated load, different types of HVAC from simple to complex systems. In addition, simulator can use CTF or Finite difference for special materials like PCM, also times steps are available for less than hour, trees and vegetation is integrated within and thermal comfort of many types such as Fangers are available.

Validity 102: DB comprises all parameters of the structure. Platform of DB provides variety of regions, material, and geometries for location input, weather data and building variable inputs.

4.2. Design builder simulation verification by BESTEST benchmark case 600FF

This test consists of building a simple model of light mass without internal partitions with two windows on the south face. The output data obtained in this test are the minimum and maximum temperature in the area.

4.2.1. The input data

Location

A climate file of the City of Denver belonging to the State of Colorado in the United States in EPW format was used. The automatic weather station where this information comes from is located at Stapleton International Airport. It is located at a latitude of 39.75° and a longitude of -104.87°. It belongs to the climatic group B of the Köppen scale, which classifies as an arid type of climate.

Geometry and orientation

The model consists of a rectangular geometry of 6 x 8 m and 2.7 m high with a volume of 129.6 $\mathbf{m^3}$, with two windows of 3 x 2 m on the south face, as shown in Fig 4.1.

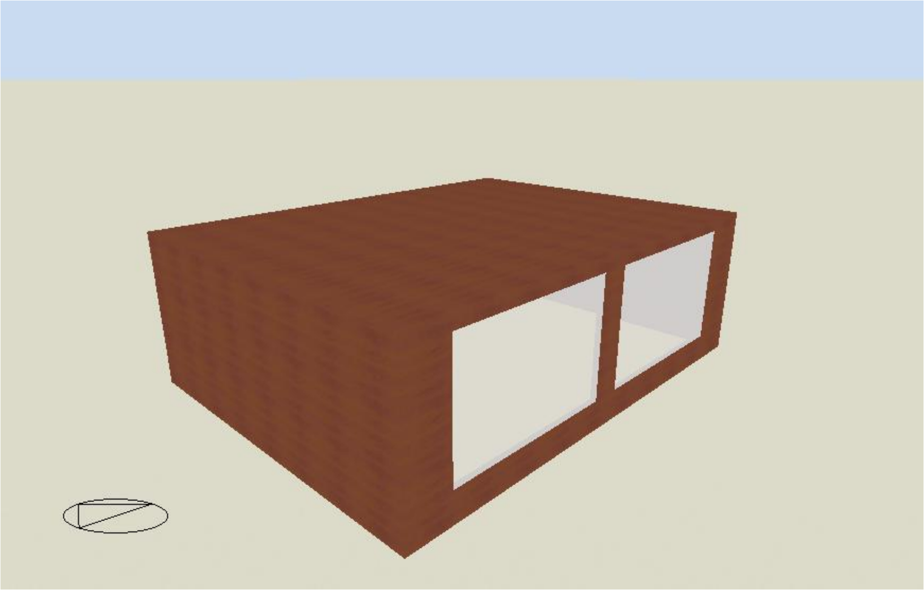


Fig 4. 1. Case 600FF perspective view

Materials

Roof: It is made up of an outer covering of 0.019 m, fiberglass of 0.1118 m and an inner layer of plaster of 0.010 m with thermal properties as presented in table 4.2.

Table 4. 2. Case 600FF roof construction thermophysical properties

Element	K (W/m-K)	Thickness (m)	U (W/m^{2}-K)	R (m^{2}-K/W)	ρ (kg/m^{3})	Cp (J/kg-K)
Int. Surface Coeff.	-	-	8.290	0.121	-	-
Plasterboard	0.160	0.010	16.000	0.063	950	840
Fiberglass Quilt	0.040	0.1118	0.358	2.794	12	840
Roof deck	0.140	0.019	7.368	0.136	530	900
Ext. Surface Coat	-	-	29.300	0.034	-	-

Walls: They are made up of a 0.009 m wooden exterior cladding, followed by 0.066 m fiberglass and a 0.012 m thick layer of plaster on the inside of the model. Table 4.3 shows the thermophysical properties of the materials that make up each layer.

Table 4. 3. Case 600FF wall construction thermophysical properties

Element	K (W/m-K)	Thickness (m)	U ($W/m^{2-}K$)	R (m^2-K/W)	ρ (kg/m^3)	Cp (J/kg-K)
Int. Surface Coeff.	-	-	8.290	0.121	-	-
Plasterboard	0.160	0.012	13.333	0.075	950	840
Fiberglass Quilt	0.040	0.066	0.606	1.650	12	840
Wood Siding	0.140	0.009	15.556	0.064	530	900
Ext. Surface Coat	-	-	29.300	0.034	-	-

Floor: The model as can be seen in table 4.4 has wooden floor with thickness of 0.025 m and a 1.003 m layer of insulation. The soil temperature is 10°C continuous during all months of the year.

Table 4. 4. Case 600FF floor construction thermophysical properties

Element	K (W/mK)	Thickness (m)	U ($W/m^{2-}K$)	R (m^2-K/W)	ρ (kg/m^3)	Cp (J/kg-K)
Int. Surface Coeff.	-	-	8.290	0.121	-	-
Timber Flooring	0.140	0.025	5.600	0.179	650	1200
Insulation	0.040	1.003	0.040	25.075	-	-

Windows: Both windows feature 3.175 mm thick double glass separated by a 13 mm thick air gap which the frame and glass properties are displayed in table 4.5 and 4.6.

Table 4. 5. Case 600FF windows thermophysical properties

Window Properties	
Extinction coefficient 0.0196/mm	0.0196 / mm
Number of panes 2	2
Pane thickness 3.175 mm	3.175 mm

Air-gap thickness 13 mm	13 mm
Index of refraction 1.526	1.526
Normal direct-beam transmittance through one pane 0.86156	0.86156
Thermal Conductivity of glass 1.06 W/mK	1.06 W/m-K
Conductance of each glass pane 333 W/m2K	333 W/m^{2}K
Combined radiative and convective coefficient of air gap 6.297 W/ m2K	6.297 W/m^{2}K
Exterior combined surface coefficient 21.00 W/ m2K	21.00 W/m^{2}K
Interior combined surface coefficient 8.29 W/ m2K	8.29 W/m^{2}K
U-value from interior air to ambient air 3.0 W/ m2K	3.0 W/m^{2}K
Hemispherical infrared emittance of ordinary uncoated glass 0.9	0.9
Density of glass 2500 kg/m3	2500 kg/m^3
Specific heat of glass 750 J/kgK	750 J/kg-K
Interior shade devices None	Ninguno
Double pane shading coefficient at normal incidence 0.907	0.907
Double-pane solar heat gain coefficient at normal incidence	0.789

Table 4. 6. Case 600FF thermal and optical properties of glass

Material of window glass	
Solar transmittance at normal incidence	0.86156
Solar reflectance at normal incidence: front side	0.07846
Solar reflectance at normal incidence: back side	0.07846
Visible transmittance at normal	0.91325
Visible reflectance at normal incidence: Front	0.08200
Visible reflectance at normal incidence: Back	0.08200
Transmittance at normal incident	0
Emittance: Front	0.84
Emittance: Back	0.84

HVAC System Configuration

In this model, the HVAC system is deactivated, therefore, it does not have cooling or heating. For this reason, the letters “FF” were added to the name of this test, which are the abbreviation in English of “Free Float”. It receives this name since the test consists of analyzing the temperatures that the building reaches freely since it does not have the air flows provided by the cooling, heating, or mechanical ventilation systems. All cases maintained an air infiltration of 0.5 air change per hour and soil temperature was at 10°C continuously.

4.2.2. The output data

The results obtained in the simulation of the BESTEST case 600FF which are shown below using bar graphs. Each graph represents an output data. The grey bars indicate the values obtained by other simulation programs, while the green bars indicate the result obtained in this validation process using DesignBuilder V.60.1.19 software.

Air temperatures in the area

The following graphs show the values of the maximum, minimum and average temperatures in the area. Recalling that the model is a single zone, the temperatures shown below are an average of the air temperature within the model, since if the reading were taken at different points in the room, the air temperature would vary from one side to the other.

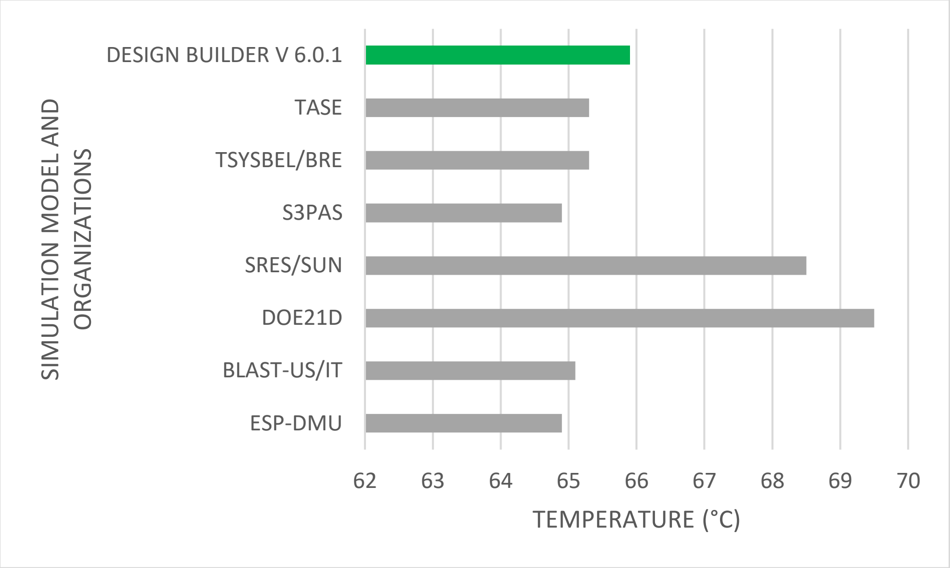


Fig 4. 2. Comparison of maximum annual hourly temperature of simulation

The maximum temperature inside the model was 68.9°C on October 17 at 3:00 p.m. Same time and day that is reported with DOE21D, which has an error rate of 5%. The DesignBuilder V.6.0.1 result report a maximum temperature on October 16 at 4:00 p.m. with an error rate of 0%. The other programs report results of between 64.9°C and 69.5°C between October 16 and 17 at times from 15:00 and 16:00 hours a day, as can be seen in Fig 4.2.

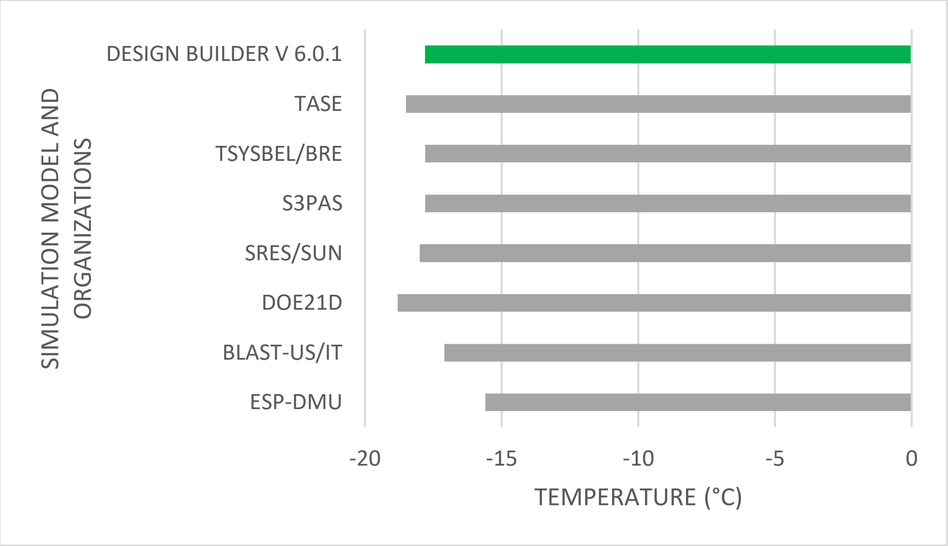


Fig 4. 3. Comparison of minimum annual hourly temperature of simulation

The minimum temperature recorded was -17.9°C on January 4 at 8:00 a.m. Same day and time as that reported by DOE21D and DesignBuilder V.6.0.1, with which an error rate of 5% and 1% respectively was obtained. The temperature range reported by the other programs varies between -15.6°C and -18.5°C on January 4 and 8 with times of 7:00 and 8:00 a.m. as shown in the following graph of Fig 4.3.

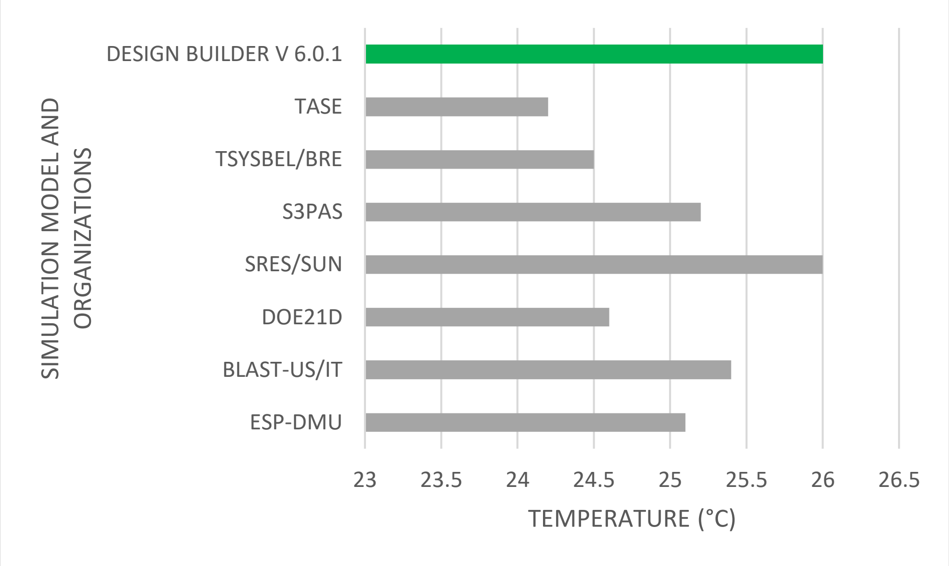


Fig 4. 4. Comparison of average annual hourly temperature of simulation

The result of the average temperature within the zone during a year was 26°C. An error rate of 4% was obtained compared to DOE-2 and 0% with DesignBuilder V.6.0.1. The other programs reported results between 24°C and 26°C as shown in the graph in Fig 4.4.

4.3. Validation through experimental chamber

The units are located at Garza Sada with coordination of 25°38'52.3"N 100°17'26.4"W with total area of 3.08 $\mathbf{m^2}$. The units are located on the 4th level which is a roof top with dimensions of 2.2 m by 1.4 m. Figure 4.5 illustrates actual impression of units and PCM applications. There are two identical blocks with same building components. One unit was used as control unit with no PCM application, while in the second test unit PCM material was applied to roof and wall A. In both case HVAC was installed but for the free flow measurement in the simulated time frame, it was disabled. Building envelope materials and dimensions are presented in table 4.7.

Fig 4. 5. Actual site photos of interior and exterior view of the units

Table 4. 7. Experimental chambers materials and dimensions

Components Lab					
Concept	No.	Size	No.	Components	width
Walls	1	2.20 m x 1.52 m	1	gypsum	5 mm
			2	Glass rey	1.27 cm
			3	iron structure	3.5 cm
			4	Glass rey	1.27 cm
			5	gypsum	5 mm
	2	2.20 m x 1.185 m	1	gypsum	5 mm
			2	Glass rey	2.54cm
			3	iron structure	3.5 cm
			4	Glass rey	2.54 cm
			5	gypsum	5 mm
Floor	1	2.20 m x 1.40 m	1	plywood	4.20 mm
			2	Foamular	2.54 cm
			3	wood	10 mm
Roof	1	2.20 m x 1.40 m	1	galvanized sheet	46 mm
			2	extended polish	2.54 cm

			1	galvanized sheet	46 mm

Every sensor's positioning is as shown in Fig 4.6, accordingly, sensors 1-4 are measuring ambient temperature and humidity, whereas sensors 5-13 measures the surface values of properties. The data were collected from July 3rd, 2020 to September 2020, without any occupants and HVAC system. During the first period, doors were closed at all the time.

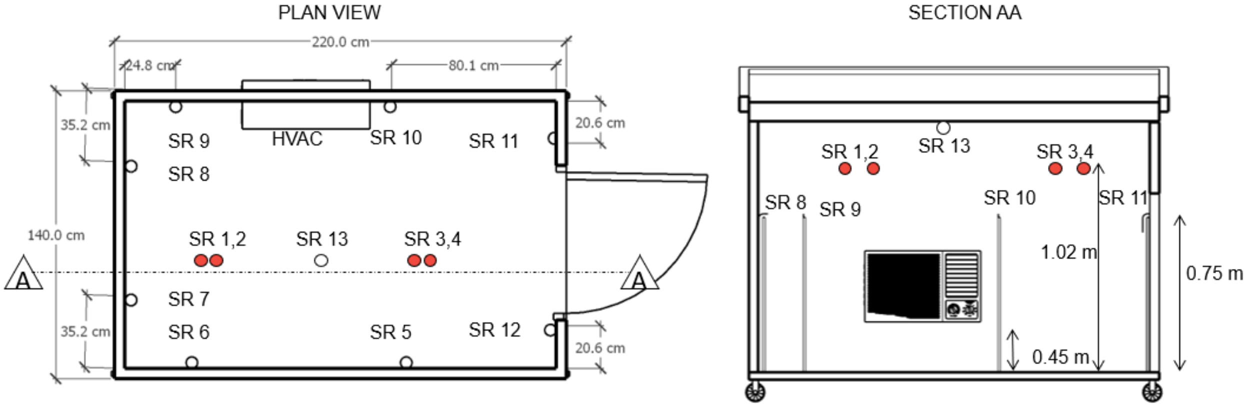


Fig 4. 6. Plan and section view of sensors layout in the experimental units

HVAC detail:

The HVAC unit is 0.5 tons of refrigeration, and the model is Mirage macc0511.

4.3.1. Weather data

Weather data consists of hourly values of representative climate components such as radiation, temperature, and wind, etc. DesignBuilder program reads EPW files that is self-generated or available on energy plus website. However, as this test is to validate real data, it was crucial to create an EPW file from real collected data from station near chambers.

The weather data was collected using Davis Vantage Pro2 which is a Weather Station console that shows and records the weather data collected at the lab. This solar pyranometer, measures global radiation, the sum at the point of measurement of both the direct and diffuse components of solar irradiance. On the other hand, to simulate the exact temperature DB (DesignBuilder) uses Direct and diffuse radiation as a parameter, hence TRNSYS was used to calculate from global radiation, the amount of direct and diffuse. Then, the data from station which was saved in CSV (Comma separated values format) excel format, along another CSV from TRNSYS was combined using ELEMENTS application which can create EPW (EnergyPlus weather) files. EnergyPlus weather converter in DB was then used to read the new EPW file. The new EPW contained all parameters of Monterrey 2020 real data in solar time and local standard time, dry bulb temperature / dew-point temperature / relative humidity / atmospheric pressure, direct radiation and diffused radiation, Wind data (Wind speed and direction).

4.3.2. Comparison of real data and simulation

The experimental unit's geometry was created in DesignBuilder as shown in Fig 4.7 with the materials and dimension given and the results have been compared as below.

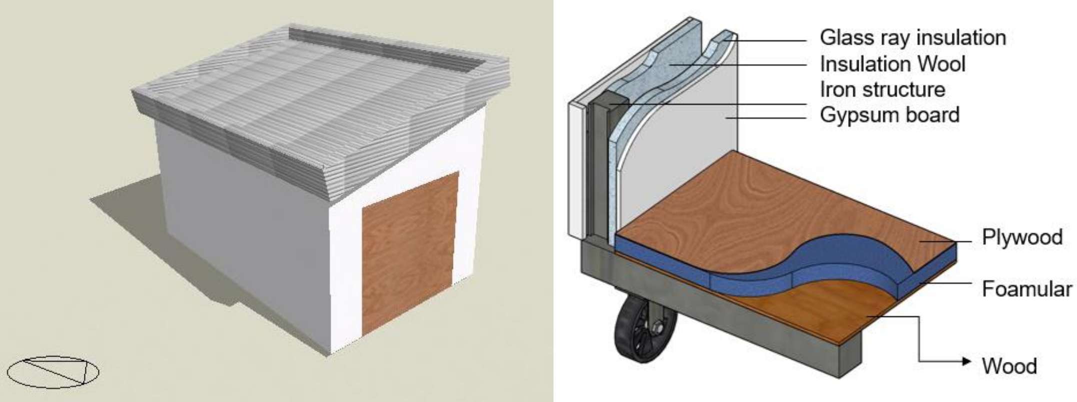


Fig 4. 7. Perspective view of experimental chamber in DB simulation software on left and sectional material illustration in SketchUp modeling software on right

From the weather station data was collected in CSV format for 3 day of August 2020 from 4th-6th. After calculating the direct and diffuse radiation via TRNSYS by inputting the exact weather data into ELEMENTS to convert the CSV to EPW file. Consequently, the EPW file was used to simulate the indoor temperature of chamber. The model was built according to material list of chambers. The result as shown in Fig 4.8 and Fig 4.9 indicated that, according to ambient and surface temperature analysis of simulated model in compared with real data, there was only an error deviation of below 5% from experimental data, which can be considered due to the uncertainty levels of the weather sensors which is around ± 0.5%.

The method to calculate the uncertainty and error of data RMSE and RMSPE was performed, which is calculated as the eq. 4.1 and eq. 4.2 presents below

$$\boldsymbol{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(yi' - yi)^2}{n}} \qquad \textbf{(eq. 4.1)}$$

$$\boldsymbol{RMSPE} = \sqrt{\sum_{i=1}^{n} \left(\frac{yi - yi'}{yi}\right)^2} \qquad \textbf{(eq. 4.2)}$$

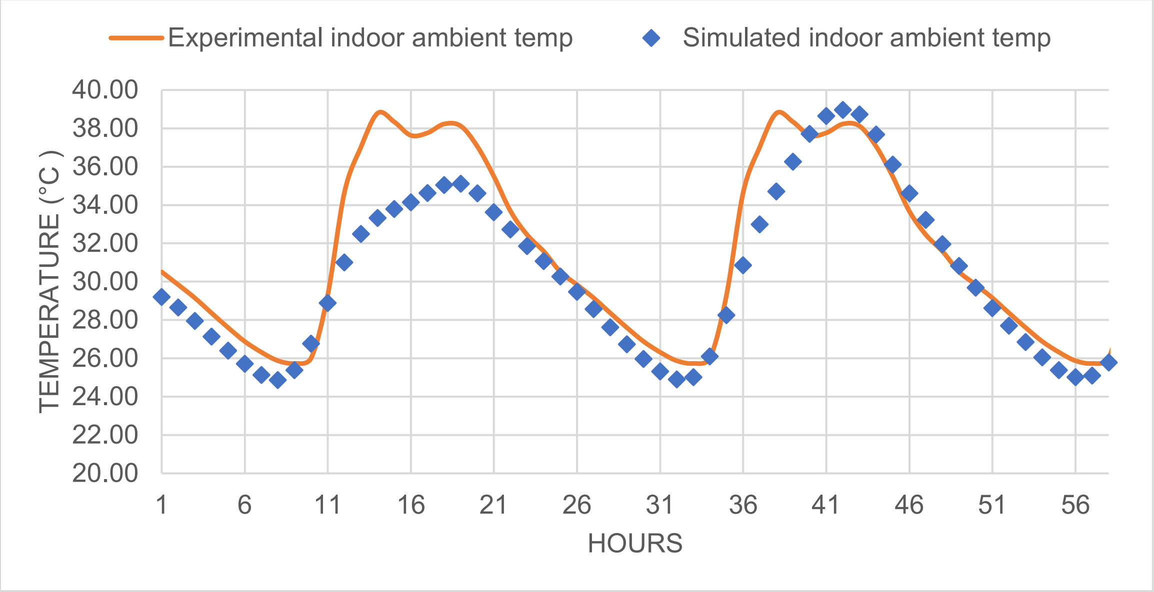


Fig 4. 8. Comparison of indoor temperature of simulated versus experimental unit

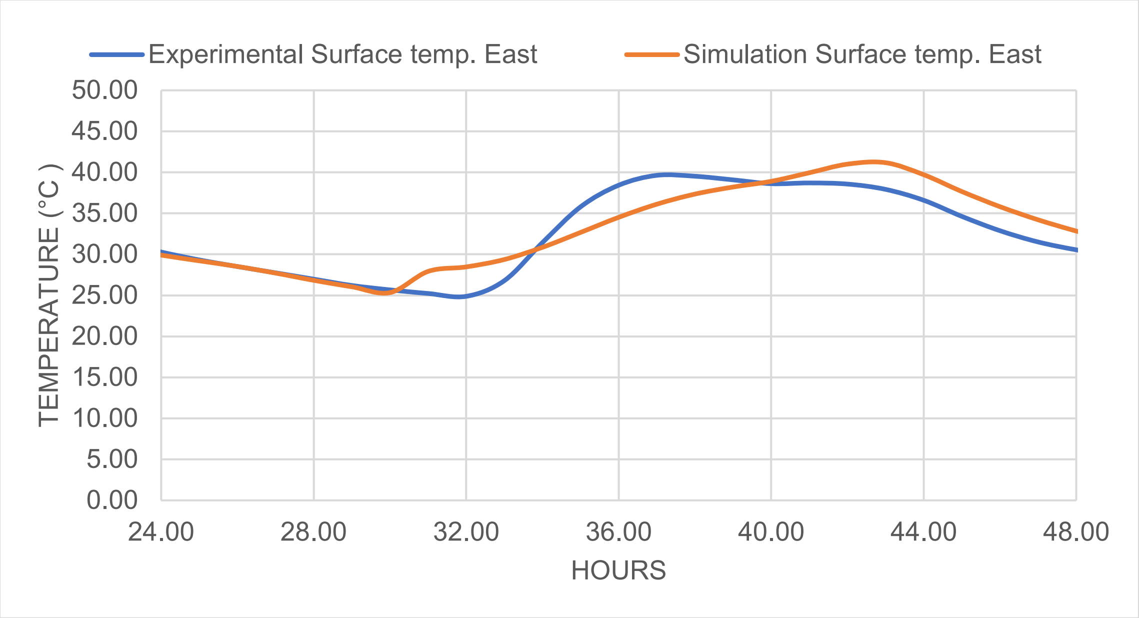


Fig 4. 9. Comparison of east wall surface's temperature of simulated versus experimental unit

4.4. Conclusions of the validation

The BESTEST case 600FF has been verified using DesignBuilder V.60.1.19 software to simulate with EnergyPlus calculation engine. As expected, the results between the programs are not the same due to the mathematical models with which the simulations are solved, the versions, among other possible assumptions. However, the results obtained by replicating the tests were very similar to those reported by the other programs.

When comparing the results obtained with DesignBuilder version 6.0 used to replicate the tests and those reported by version 4.2, error rates of 1% and 2% were obtained. It is considered that one of the reasons why the results could differ in this minimum percentage is due to the model materials. The 140-2001 standard lists the materials that make up each layer and most of its properties. Most of the materials listed are in the DesingBuilder library, so when selecting them it is necessary to check that the properties match or otherwise modify them according to the standard. However, when the indicated material is not found and a similar one is chosen, there is a risk of not being able to configure it properly if some data on the properties of the materials are unknown. Such was the case of the external layer of the roof since the values of the absorbing and reflective properties of walls and ceilings are not specified. Beyond any doubt, the

DesignBuilder simulation test had error of 0% and is calibrated to carry on simulations for new models and cases.

Experimental chamber with surface temperature sensors and weather station recorded real data. Afterward a model was created using DB, weather file with EPW format was created using TRNSYS to simulate the same amount of radiation and temperature. Finally, EnergyPlus engine was used to simulate the results and was compared against real data and found that RMSPE was around 1%, which further confirmed that the simulation is calibrated as the error rate was only below allowed 5% error amount which is due to devices miscues.

All in all, the relationship between the measured data and simulated results data in DesignBuilder demonstrate an extremely strong positive result in the accuracy of simulation algorithms based on the virtual model of building construction and the physical properties of building materials with respect to building orientation and natural ventilation. The error calculated for RMSD (Root-mean-square error) was at 2.6℃ and RMSPE (Root mean squared error of prediction) of 1%. Altogether, this gives confidence and adequate matching with the real building data that gives high credibility to run DesignBuilder simulation in the analysis stage.

Chapter 5 Results and discussion

Simulation results and selection factors is discussed in this chapter. Energy impact of each scenario is calculated and compared against each other with respect to their cost and then selection is made according to both factors. Subsequently, the most optimum scenario is analyzed in respect to comfort, thermal behavior, energy, and carbon footprint, as well as payback period. The scenarios are described based on the following nomenclature.

Nomenclature scenarios naming

C1	Case 1	DBRE	Double reflective glazing	P	PCM
C2	Case 2	I	Insulation	PI	PCM + Insulation
C3	Case 3	Ir	Insulation + Reflective Paint	Pr	PCM + reflective Paint
DB	Double clear glazing	MP	Melting point	R	Roof
DBLE	Double low-e glazing	O	Opening	W	Wall

Impact of passive cooling strategies in building envelope in semi-arid climate of Mexico is investigated by testing different scenarios and factors to reduce heat gain by solar radiation in different building parameters such as walls, roof, and windows as well as to increase building heat storage capacity by installation of PCM into opaque envelope to reduce energy consumption of building and improve comfort inside the house. Building models are simulated and enhanced based on three base cases as shown in Fig 5.1 and tested with different scenarios as discussed in chapter 3. Moreover, Fig 5.2 presents an overview to all the scenarios that were tested, each building component (wall, roof, and openings) were improved separately as table 5.1 to 5.3 demonstrate each strategy and its U-value, and most optimum scenario was selected to combine with each other. In the result section energy savings, comfort improvement and carbon emission reduction are analyzed as we apply the optimum strategy for each case. In the cost analysis we calculate the period of return on investment and the generated profit after the period.

POPULAR B2
CASE 1
Area of 36 m^2

POPULAR B3
CASE 2
Area of 42 m^2

TRADITIONAL
CASE 3
Area of 81 m^2

Fig 5. 1. Base cases 3D model

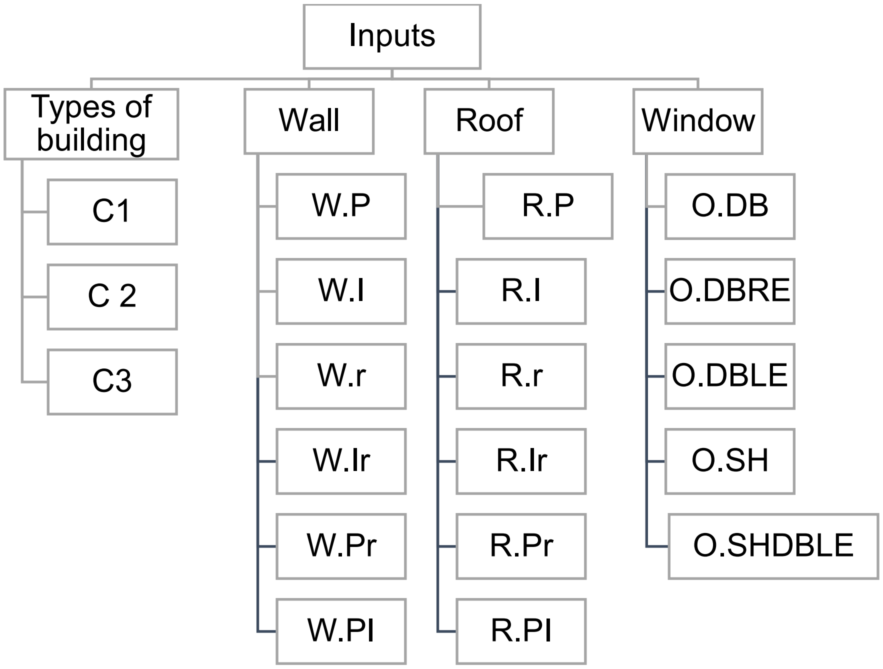


Fig 5. 2. Summary of application of strategies and scenarios definition

5.1. Assumptions of study

In this analysis there are a few assumptions which are defined as below:

- Regarding the apartment case only the top floor of apartment prototype was studied.
- Orientation of all cases were limited to east-west position of main façade.
- Calculation of energy and bills was based on Nuevo Leon state as there are different tariffs for different states of Mexico.

The duration of the simulation is annual for energy calculation, PMV analysis and cost analysis. Regarding the thermal analysis the simulation is for 2 days of the year with the most extreme situation which are hottest day (27 July) and coldest day (13 Dec) based on climate data that is used. Moreover, it is critical to analyze the thermal behavior and comfort of building without HVAC system. Ultimately, the optimal solution can be defined as the case where a satisfying thermal comfort is achieved with the lower energy consumption and cost.

5.2. Parameter integration and energy consumption comparison

Each building component, wall, roof, and openings were tested separately and best performed scenarios were combined.

5.2.1. Wall improvement

To select the most optimum scenario, annual energy consumption parameter was the deciding factor. The results of wall enhancement scenarios as presented in Fig 5.3 to Fig 5.5, which shows the total cooling energy load per strategy in compared to base case consumption. Overall, all cases indicated that reflective paint in combination with PCM and insulation have the highest cooling energy saving consequences, as light blue and dark blue line illustrate. On the contrary, with respect to heating energy saving green line which represent scenario W.PI proved most efficient, as reflective coating has inverse effect due to its high reflectivity, during winter blocks heat gain from sun radiation in the roof surface and causes the internal ambient to cool down and require more energy to heat up the space.

Total cooling energy saving for cases C1, C2, and C3 were highest at 600 kWh, 1380 kWh, and 945 kWh for scenario W.Pr, where reflective paint on the surface reflects most of radiation and reduces the heat gain through walls, and furthermore PCM absorbs the heat from internal ambient and store it till melting state and then release the heat at night when outside temperature drops. The difference in the amount of saving is due to total area of C3 is larger than the other cases, as well as base case energy consumption in apartment is greater. The lower impact scenarios in regards with cooling was scenario W.r with low saving of 320 kWh, and 350 kWh, for C1 and C2, whereas lowest impact scenario was W.P for C3 with the value of 550 kWh energy saving.

Nonetheless, with respect to heating energy saving, scenario W.PI outperformed others in all cases with values of 290 kWh, 850 kWh, and 500 kWh for C1, C2, and C3.

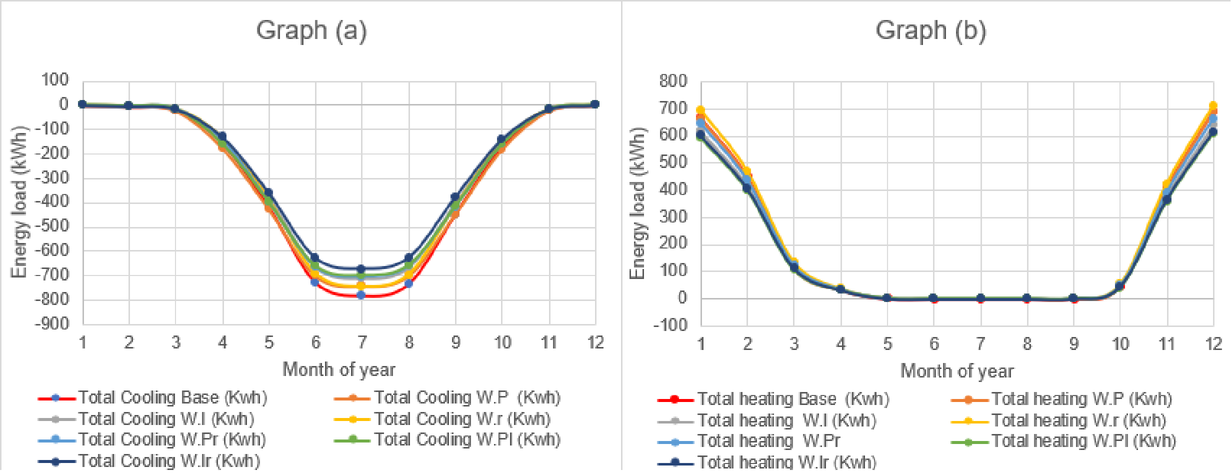


Fig 5. 3. Energy consumption reduction for different wall scenarios: (a) total cooling load, (b) total heating load (Case 1).

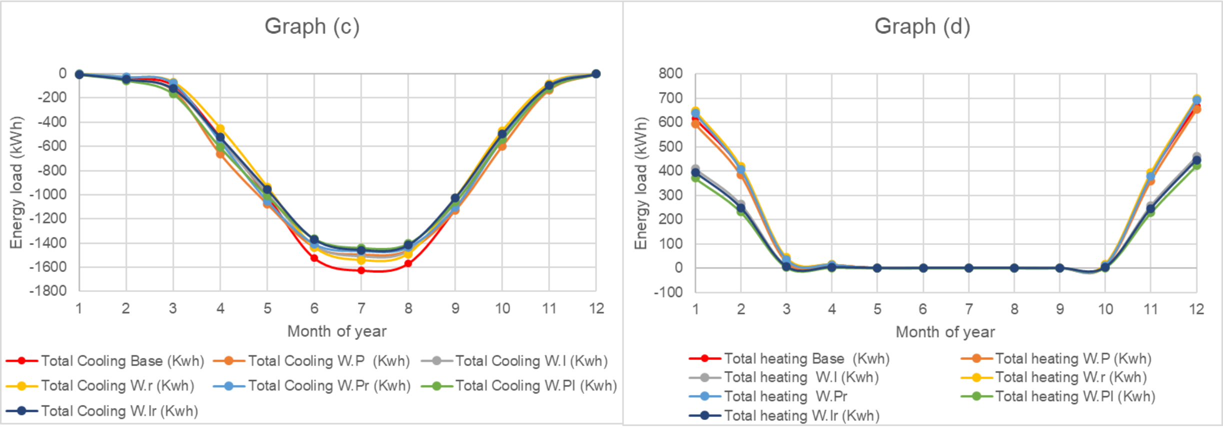


Fig 5. 4. Energy consumption reduction for different wall scenarios: (c) total cooling load, (d) total heating load (Case 2).

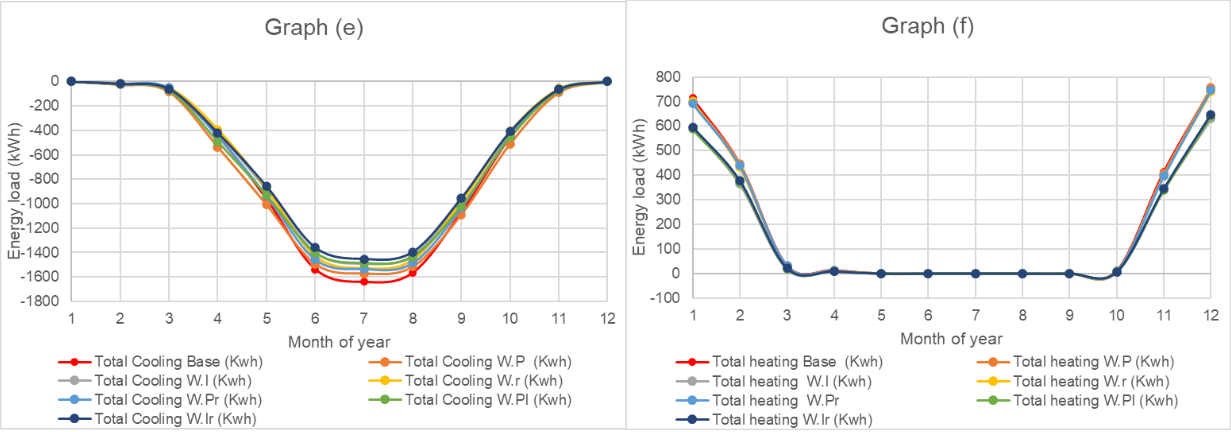


Fig 5. 5. Energy consumption reduction for different wall scenarios: (e) total cooling load, (f) total heating load (Case 3).

Total cooling and heating energy consumption was analyzed in percent total saving as is shown in Fig 5.5 for selection of each scenario and combination decision. Reflective paint and insulation W.IP and W.Ir had the highest impact in all three cases, with respect to economic value and negligible difference in W.IP superiority, W.Ir was preferred.

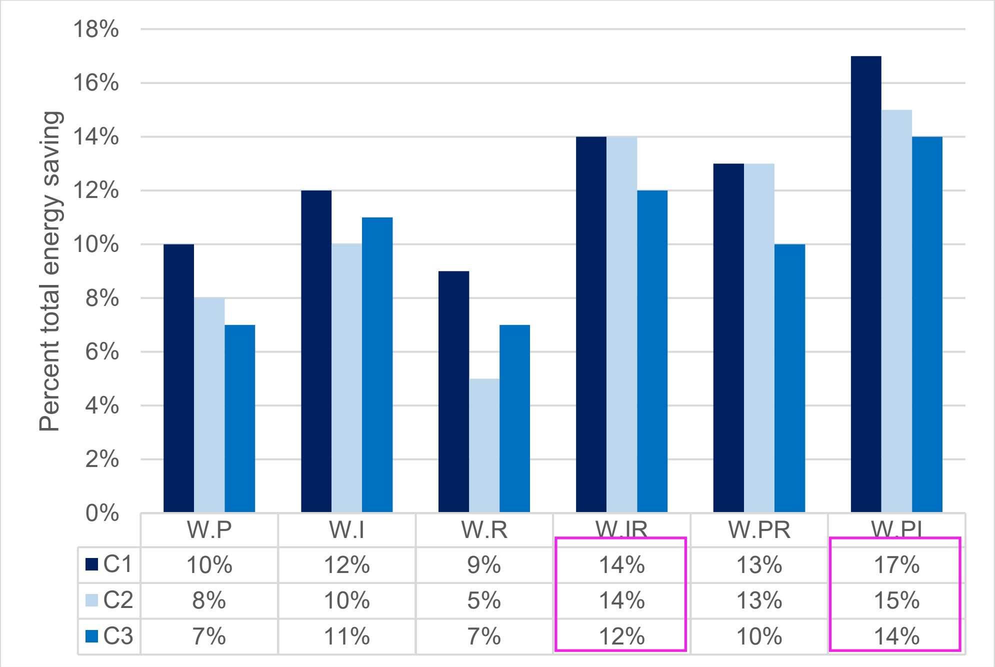


Fig 5. 6. Total annual energy saving comparison for different wall scenarios

5.2.2. Roof improvement

Annual cooling load of enhanced envelope with applied scenarios are presented in Fig 5.7, 5.8, and 5.9 and compared against the base case on the left and annual heating load chart on the right for cases C1, C2, and C3. Almost in all cases as demonstrates by the charts, reflective paint paired with insulation or PCM has the highest cooling energy saving impact as light blue and dark blue line presents. On the other hand, with regards to heating energy saving green line which represent scenario R.PI has the highest influence, as reflective coating has inverse effect due to its high reflectivity, during winter blocks heat gain from sun radiation in the roof surface and causes the internal ambient to cool down and require more energy to heat up the space.

Total cooling energy saving for cases C1, C2, and C3 were highest at 1100 kWh, 1800 kWh, and 2500 kWh for scenario R.Pr, where reflective paint on roof surface reflects most of radiation and reduces the heat gain through roof, and furthermore PCM absorbs the heat from internal ambient and store it till melting state and then release the heat at night when outside temperature drops. The saving reduction of this scenario is close to scenario R.Ir with values of 1047 kWh, 1150 kWh, 2150 kWh for C1, C2, and C3 cases, respectively. The difference in the amount of saving is due to total area of C3 is larger than the other cases, as well as base case energy consumption in apartment is greater. The lower impact scenarios in regards with cooling was scenario R.P with deep of 430 kWh, 440 kWh, and 740 kWh energy saving for cases C1, C2, and C3 respectively. Nonetheless, with respect to heating energy saving, scenario R.PI outperformed others in all cases with values of 500 kWh, 770 kWh, and 830 kWh for C1, C2, and C3. In winter thermal insulation maintains the heat indoor and prevents the roof from losing heat from inside to outside environment, and PCM stores warmth (through melting) during night and discharges the heat (by freezing) during daytime [66].

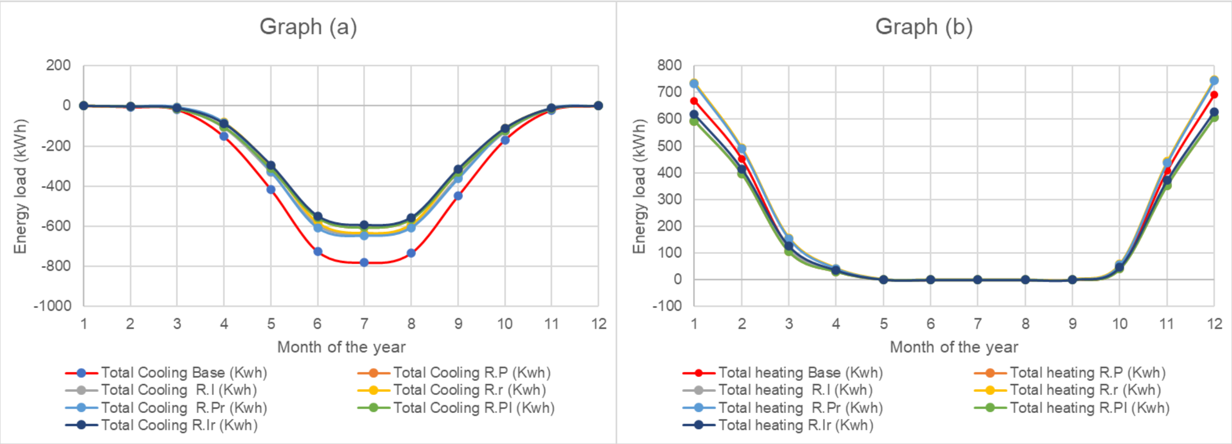


Fig 5. 7. Energy consumption reduction for different roof scenarios: (a) total cooling load, (b) total heating load (Case 1).

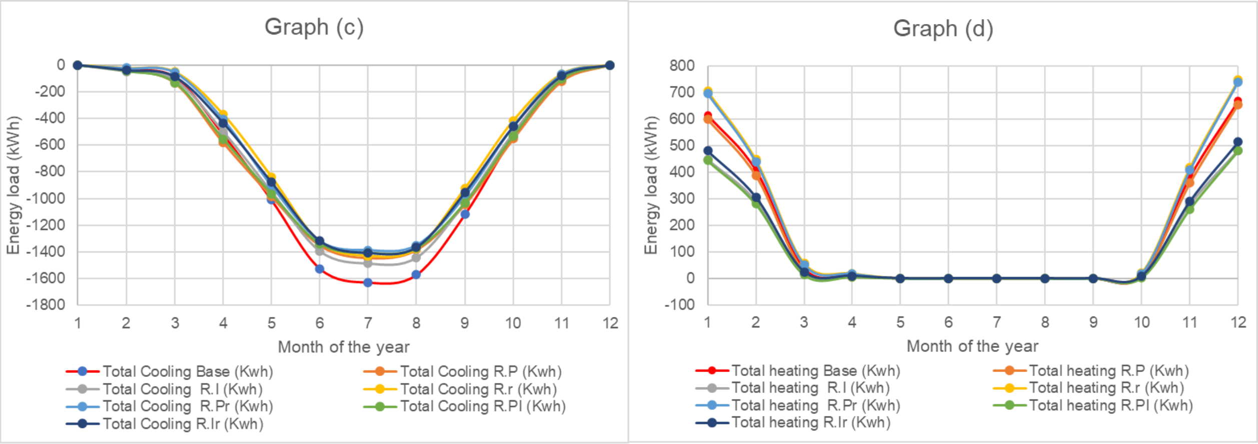


Fig 5. 8. Energy consumption reduction for different roof scenarios: (a) total cooling load, (b) total heating load (Case 2).

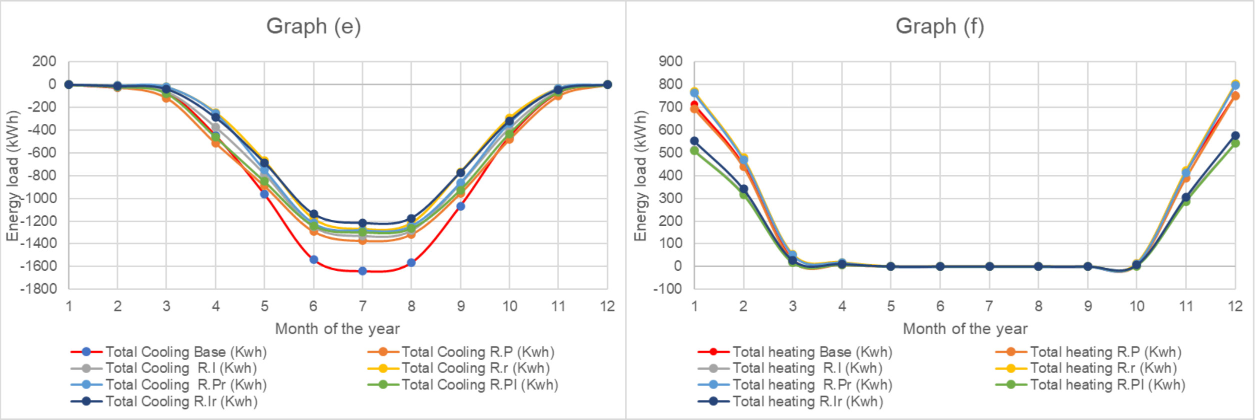
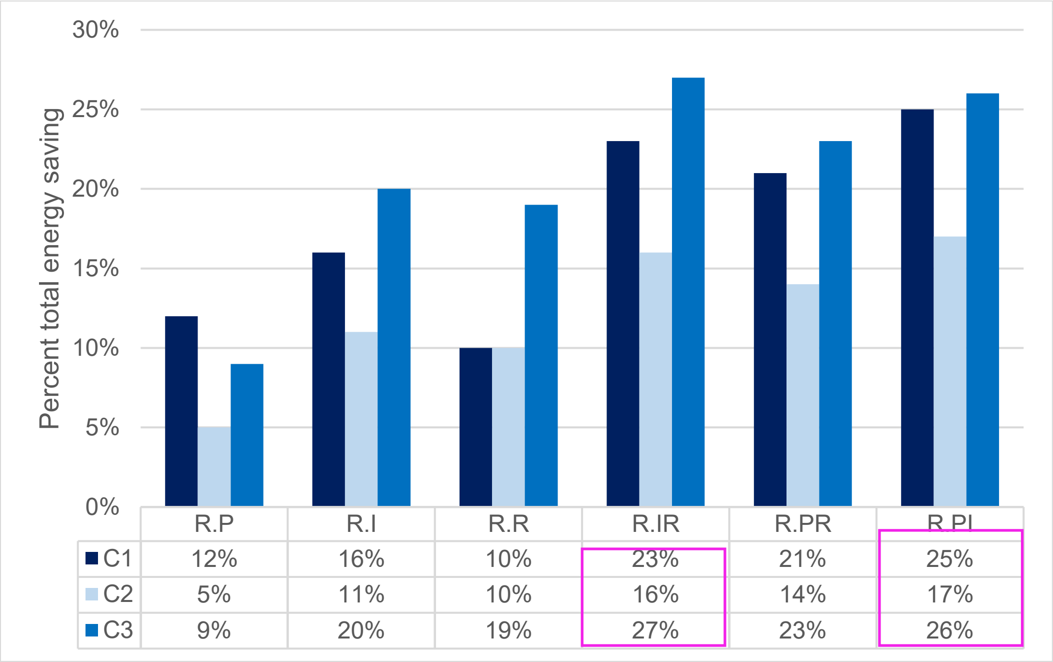


Fig 5. 9. Energy consumption reduction for different roof scenarios: (a) total cooling load, (b) total heating load (Case 3).

All in all, single material application has the lowest impact as Fig 5.10 illustrate the total energy saving in percentage for three cases in all 6 scenarios for roof improvement. Another conclusion that is driven from the chart is that case C2 has the lowest level of impact with regards to its total floor area, and that is due to its height from ground and the exposure to heat radiation during the day. Scenario R.Ir (Insulation and reflective paint) and R.PI showed similar results and outperformed the other scenarios for all cases. Regarding case C1 scenario R.r had the lowest impact by 10%, whereas for C2 and C3 R.P had the bottom percentage of 5% and 9% respectively. Considering economical cost of each strategy scenario R.Ir has the lower value and therefore is favored over R.IP.



	R.P	R.I	R.R	R.IR	R.PR	R.PI
■ C1	12%	16%	10%	23%	21%	25%
■ C2	5%	11%	10%	16%	14%	17%
■ C3	9%	20%	19%	27%	23%	26%

Fig 5. 10. Total annual energy saving comparison for different roof scenarios

5.2.3. Opening’s improvement

All in all, in all cases as Fig 5.11, 5.12, and 5.13 illustrate, double glazing with clear glass had the least energy saving for all cases and Low-E coated double glazed window had the highest impact accompanied by cantilever shading.

Double clear glazing had total cooling saving of 410 kWh, 9 kWh and 310 kWh for C, C2, and C3 respectively, whereas Low-E coated double glazed window had total cooling saving of 880 kWh, 500 kWh, 900 kWh, almost saves energy by twofold. The impact is due to low emissivity of O. DBLE scenario, long wavelength heat radiation in summer will be reflected, consequently the coating prevents heat gain in the room and during winter it will reflects the internal ambient temperatures back inside, which results in warm ambient.

Shading device addition to windows had almost a similar cooling reduction around 400 kWh for all cases, however heating energy demand increased by 80 kWh for C3 and almost 0 kWh saving for C2 and C1 due to lower sun radiation absorption by building envelope. Considering Low-E coating as the most outperforming option, once combined with cantilever shading, it presented cooling saving of 1100 kWh, 1000 kWh, 1200 kWh for C1, C2, and C3, and an average heating saving of 110 kWh for all cases.

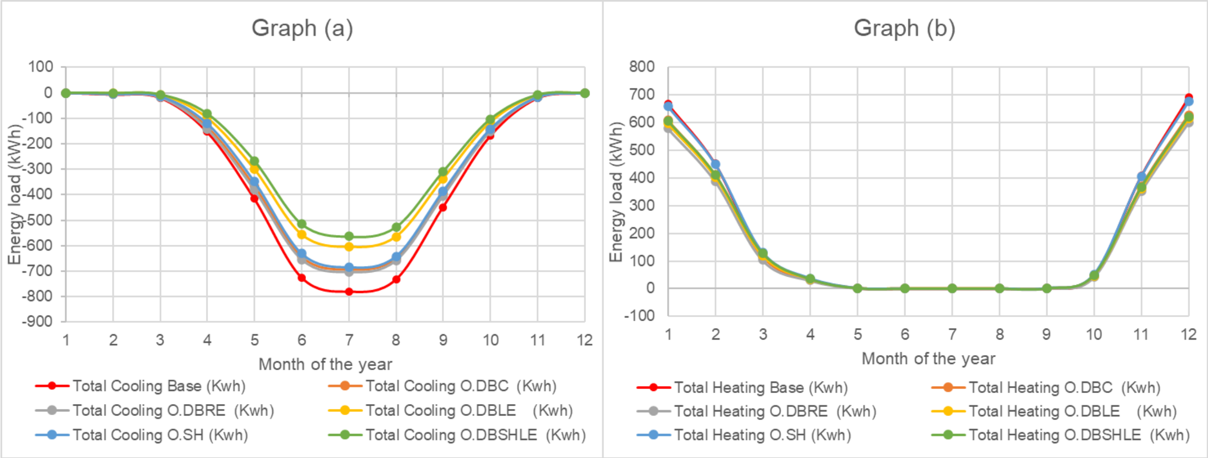


Fig 5. 11. Energy consumption reduction for different opening scenarios: (a) total cooling load, (b) total heating load (Case 1).

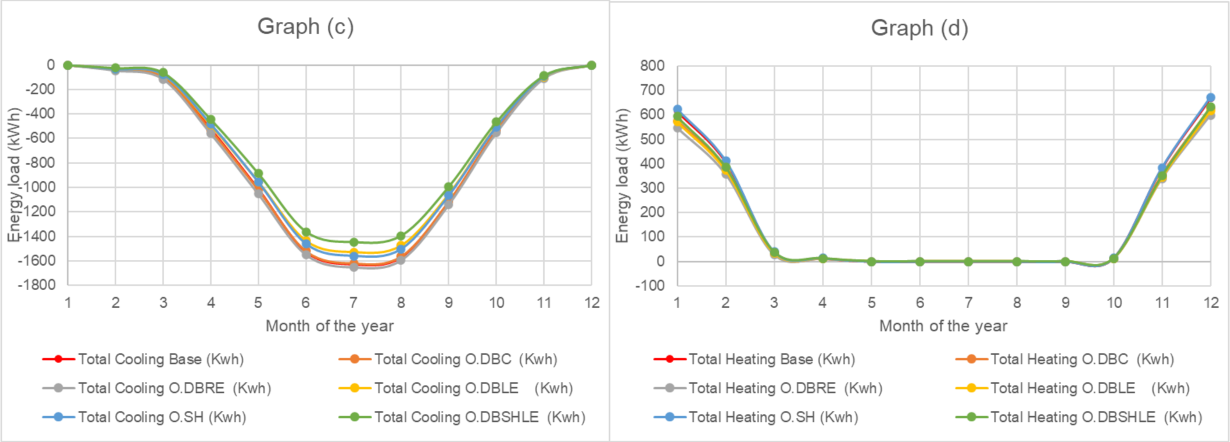


Fig 5. 12. Energy consumption reduction for different opening scenarios: (a) total cooling load, (b) total heating load (Case 2).

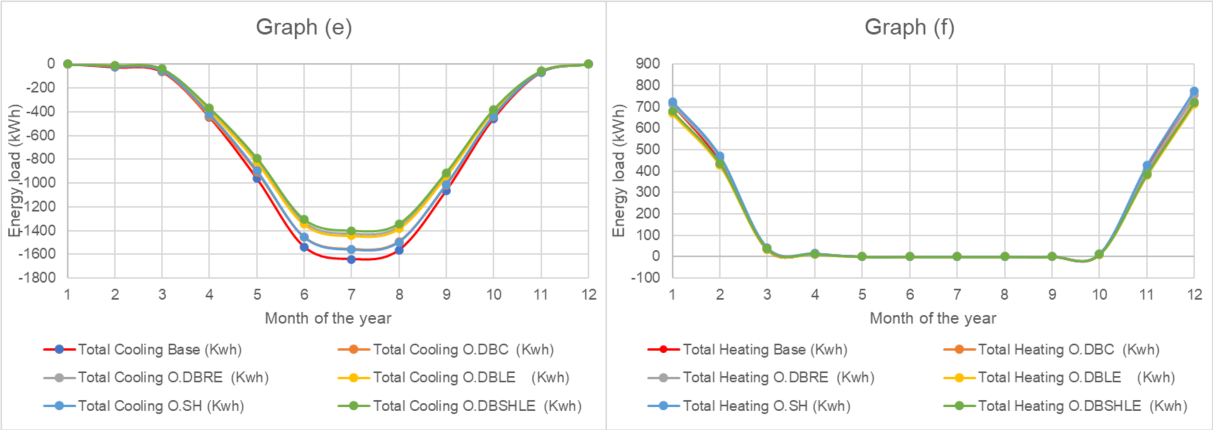


Fig 5. 13. Energy consumption reduction for different opening scenarios: (a) total cooling load, (b) total heating load (Case 3).

As can be seen in Fig 5.14 the total annual energy saving per scenario for all cases, and chiefly between three glazing, low-E coating outperformed others in all cases with value of 19%, 7% and 11% saving in C1, C2, and C3, while combined with shading these saving reach up to 22%, 11%, and 13% annually. All scenarios can be applied during retrofit, thereupon there are only one set of scenarios selected.

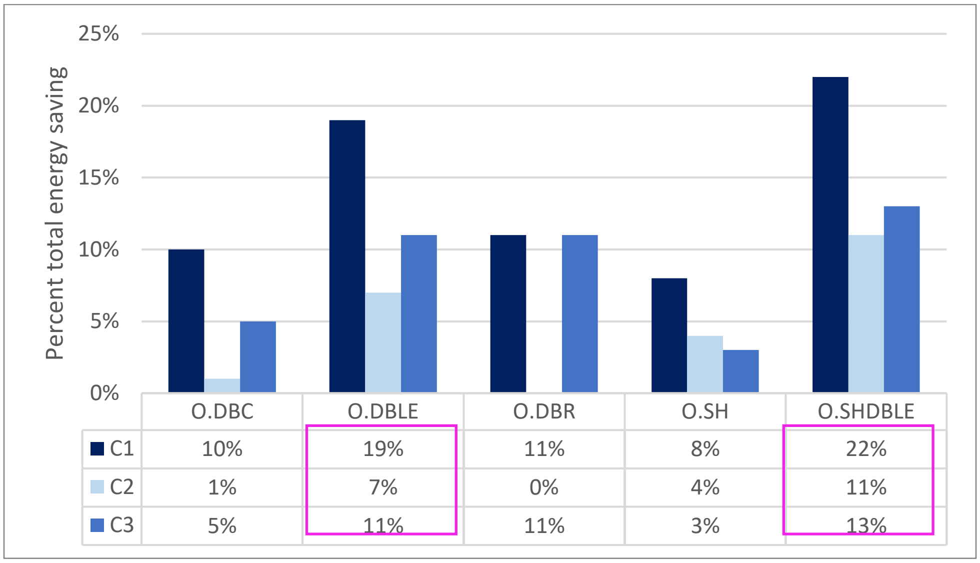


Fig 5. 14. Total annual energy saving comparison for different opening scenarios

Based on the results above, the most energy saving scenarios were applied as in table 5.1 Roof envelope of building had the most impact on the saving parameter of energy as the building has adiabatic neighbors to protect the side walls.

Table 5. 1. Optimum scenarios selection

Cases	Wall Scenario	Percent saving	Roof	Percent saving	Opening	Percent saving	Total
C1	W.Ir	14%	R.Ir	23%	O.SHDBLE	22%	53%
C2	W.Ir	14%	R.Ir	16%	O.SHDBLE	11%	55%
C3	W.Ir	12%	R.Ir	27%	O.SHDBLE	13%	58%

5.3. Thermal comfort analysis

Table 5.2 illustrate average amount of solar gain in each zone and indoor temperature to find the most critical zones in each case as shown in Fig 5.15, Zone 2 was the most critical in three cases, due to its exposure to radiation as it is pushed outward.

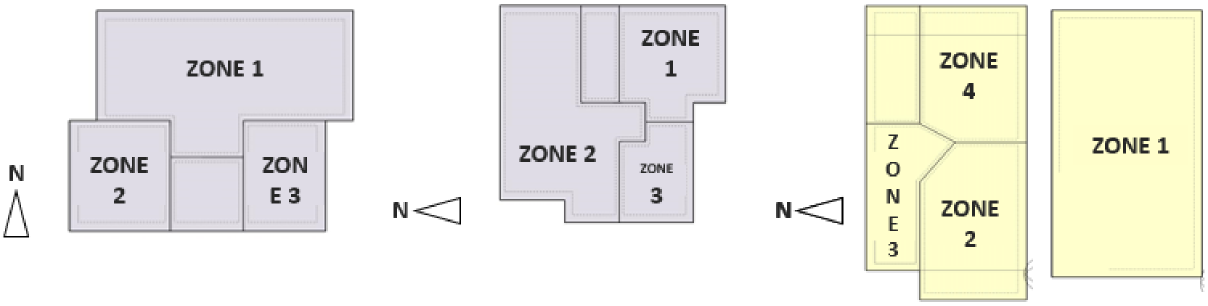


Fig 5. 15. C1 zoning plan, C2 zoning plan, and C3 zoning plan from left to right

Table 5. 2. Comparison of average summer week's thermal and solar characteristics of each zone

Zones		Solar gain (W)	Indoor temperature (°C)
C1	Z2	211.42	32.45
	Z1	144.27	29.96
	Z3	113.32	32.19
C2	Z1	22.06	35.03
	Z2	141.51	36
	Z3	41	35.32
C3	Z1	160.6	31.15
	Z2	322.4	36.31
	Z3	172.17	35.44

Figure 5.16-5.18 displays 8670 hours of the year in zone 2 of cases C1-C3. Blue dots are the hours of base case and orange dots present the optimum case hours based on PMV method. According to Fanger's PMV method, human comfort PMV is between -1 to 1

which light green bar is highlighting in the Figures. As can be seen C1 had the highest amount of improvement due to being single story and smaller surface area. Optimized line in C1 almost flattened into the green bar, which is the comfort area. Case C2 has the greatest number of hours out of comfort zones, the curve in C3 had the drop of almost quarter from base case. C1, C2, and C3 have improvement of 45%, 32%, and 38% respectively for zone 2.

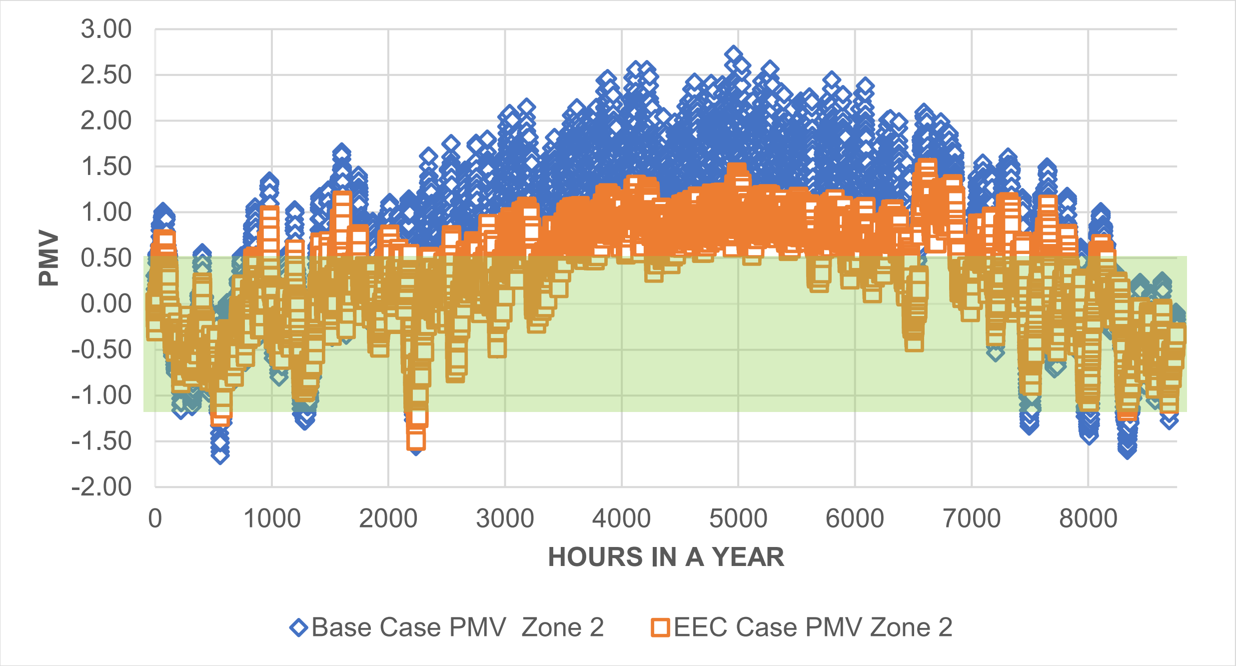


Fig 5. 16. Annual PMV comfort analysis of zone 2 for C1

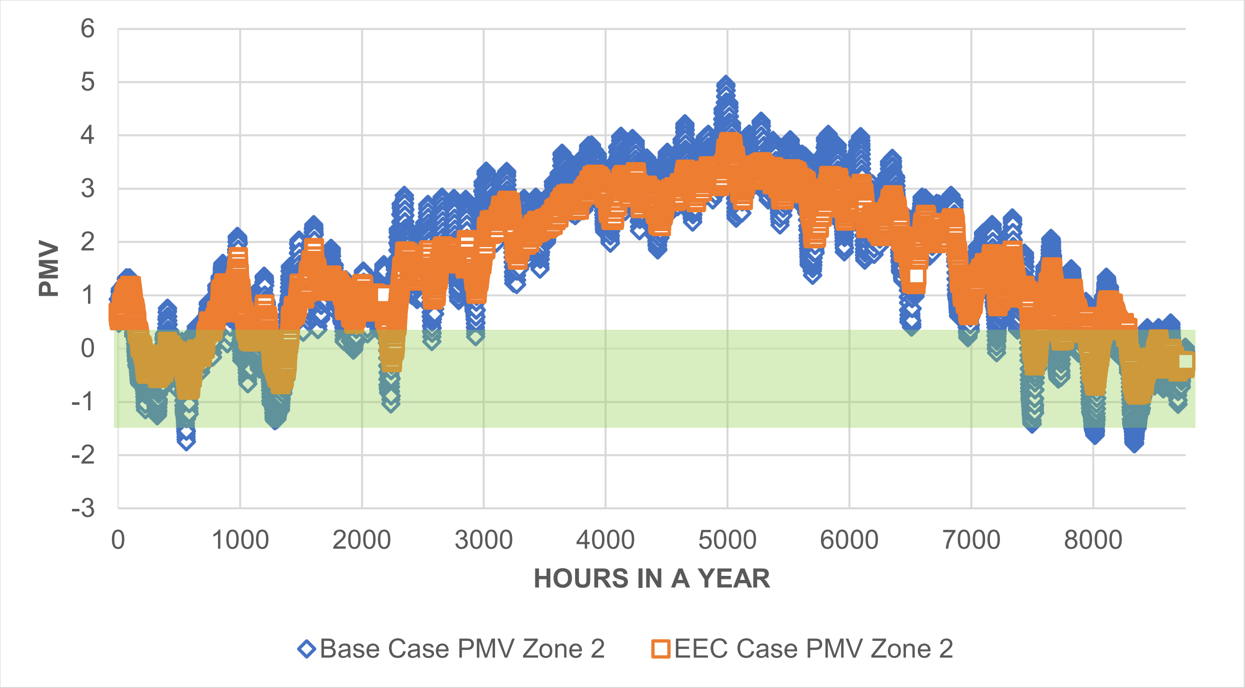


Fig 5. 17. Annual PMV comfort analysis of zone 2 in C2

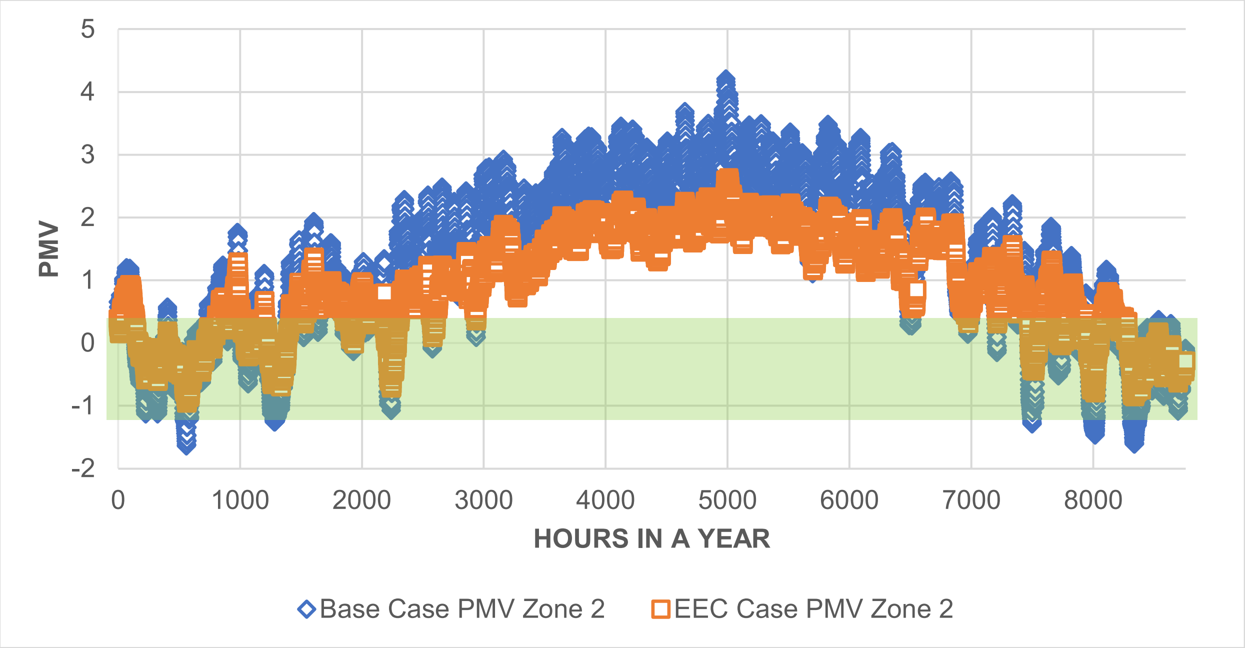
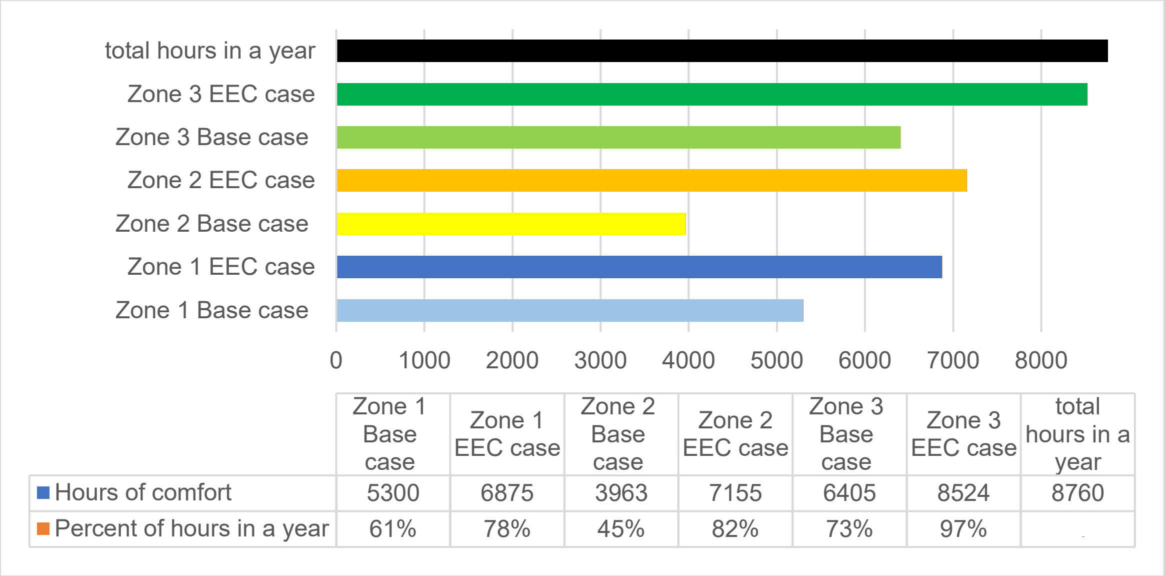


Fig 5. 18. Annual PMV comfort analysis of zone 2 in C3

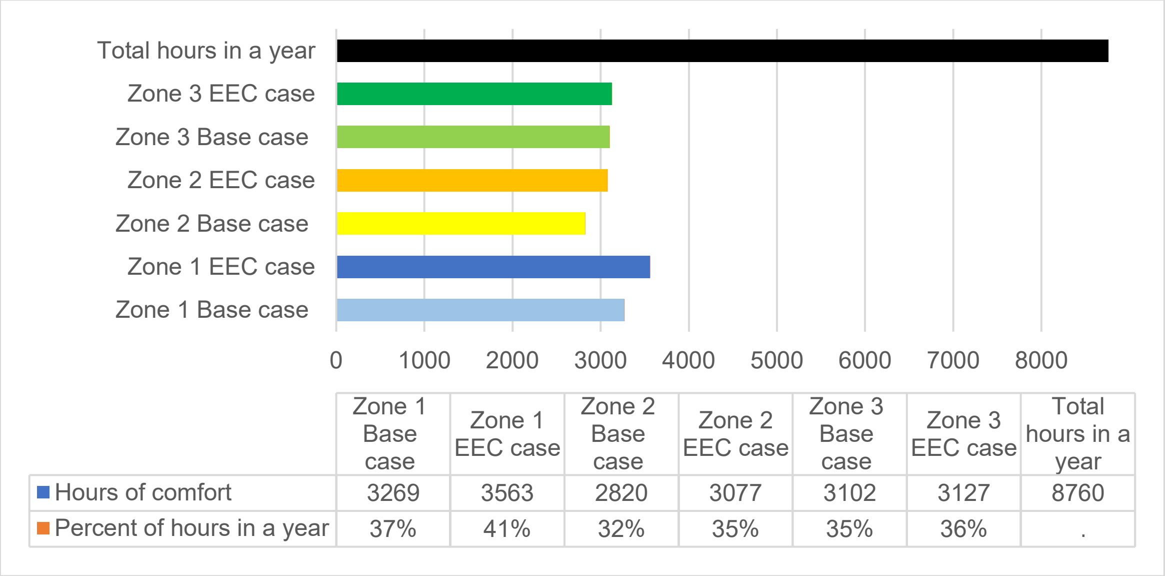
Overall, Fig 5.19 illustrate, C1 with the highest improvement of the number of comfort hours around 45% against the base case and zone 2 with the highest hours of improvement from 45% to 82% comfortable hours, as the most critical zone, which is due to its aerial position which is positioned half meter outside and consequently receives more radiation towards its wall and opening.



	Zone 1 Base case	Zone 1 EEC case	Zone 2 Base case	Zone 2 EEC case	Zone 3 Base case	Zone 3 EEC case	total hours in a year
🟦 Hours of comfort	5300	6875	3963	7155	6405	8524	8760
🟧 Percent of hours in a year	61%	78%	45%	82%	73%	97%	.

Fig 5. 19. Comparison of number of comfort hours between zones of C1

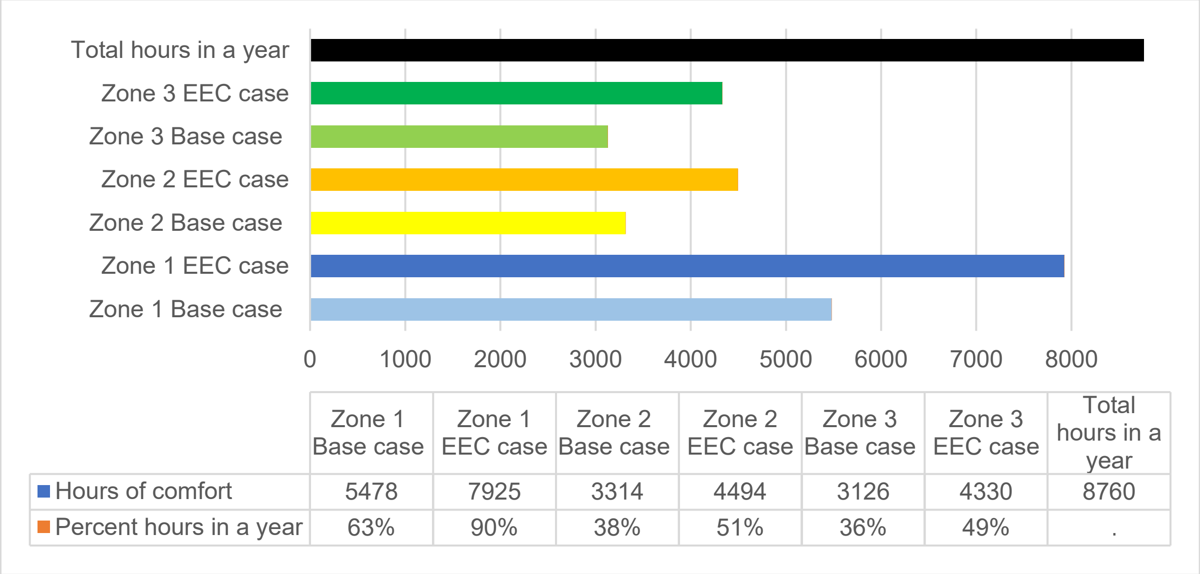
Number of comforts hours for C2 is presented in Fig 5.20 and similarly the most critical zone is zone 2 with only 32% hours of comfort in base case and 3% improvement, owning to its number of openings compared to other zones. Additionally, zone 1 had the greatest number of hours of comfort which is 3563 hours of comfort as compared to base case of 3269 hours (4% improvement). On average improvement in all cases were around 32% improvement, which makes this case the least improved case in comfort factor.



	Zone 1 Base case	Zone 1 EEC case	Zone 2 Base case	Zone 2 EEC case	Zone 3 Base case	Zone 3 EEC case	Total hours in a year
🟦 Hours of comfort	3269	3563	2820	3077	3102	3127	8760
🟧 Percent of hours in a year	37%	41%	32%	35%	35%	36%	.

Fig 5. 20. Comparison of number of comfort hours between zones of C2

As can be seen in Fig 5.21 zone 1 had the greatest number of improvements from 63% to 90% hours of comfort, an increase by one third, in C3 to 7925 hours out of total 8760 hours in the year, because of being in the lower ground and receiving less direct radiation, insulation resulted better in keeping the temperature in desired level. This also means most of the year there is no demand for mechanical ventilation in zone 1. Comfort hours in zones 2 and 3 had increase by one quarter which is up to 51% and 49% respectively.



	Zone 1 Base case	Zone 1 EEC case	Zone 2 Base case	Zone 2 EEC case	Zone 3 Base case	Zone 3 EEC case	Total hours in a year
🟦 Hours of comfort	5478	7925	3314	4494	3126	4330	8760
🟧 Percent hours in a year	63%	90%	38%	51%	36%	49%	.

Fig 5. 21. Comparison of number of comfort hours between zones of C3

5.4. Thermal analysis

5.4.1. Thermal analysis of the hottest day

Figure 5.22 shows that regarding C1, in zone 2, the most critical zone, at the hottest day the room temperature improved with a maximum difference of 8.8°C and an average minimum temperature difference of 5.9°C. According to simple Fanger accepted comfort temperature for free-cooling room with no mechanical system while internal Operative temperature need to be between 20°C to 26°C during summer, which is shown with the green horizontal bar, where improved case falls outside the comfort range temperature. Regarding the PCM 25 application, during the hottest day it is illustrated that the temperature does not drop below 25 in any of hours which means PCM will only melt and will not be able to solidify, hence during these days PCM 25 is not effective.

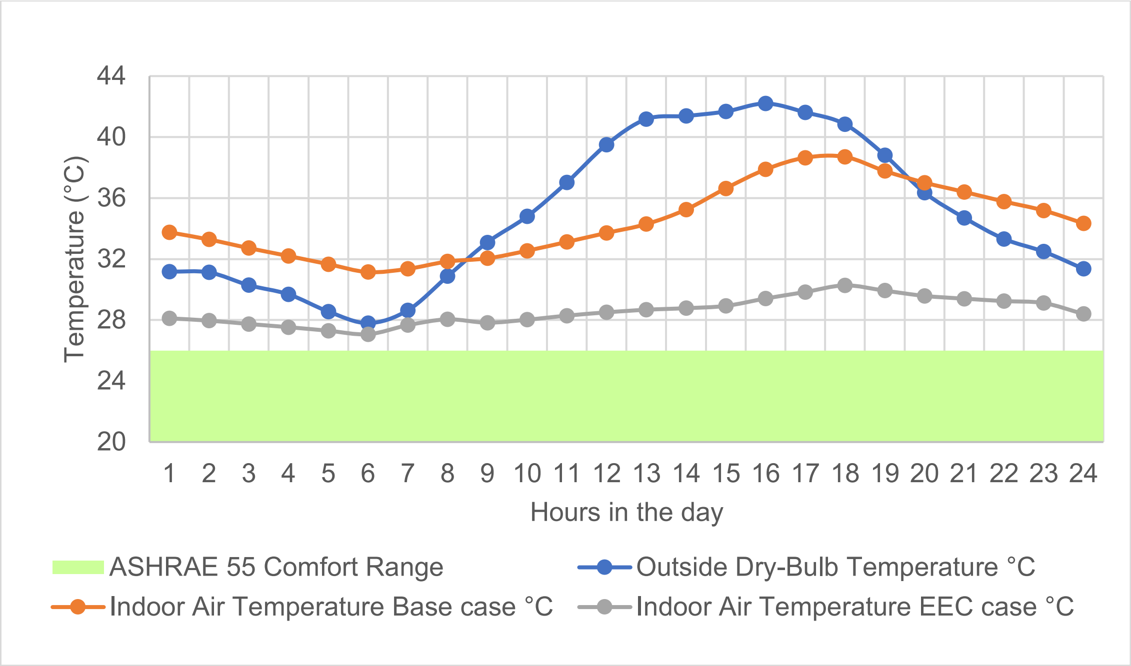


Fig 5. 22. Zone 2 indoor temperature comparison for hottest day in C1

Zone 2 indoor temperature of EEC case is compared against base case in Fig 4.23, for C2 on the day of 27th July, hottest day in the year, in relation to outside temperature. Overall, the maximum temperature difference of improvement was around 1.4 °C and an average temperature difference of -0.1 °C, which is way beyond the comfort temperature range.

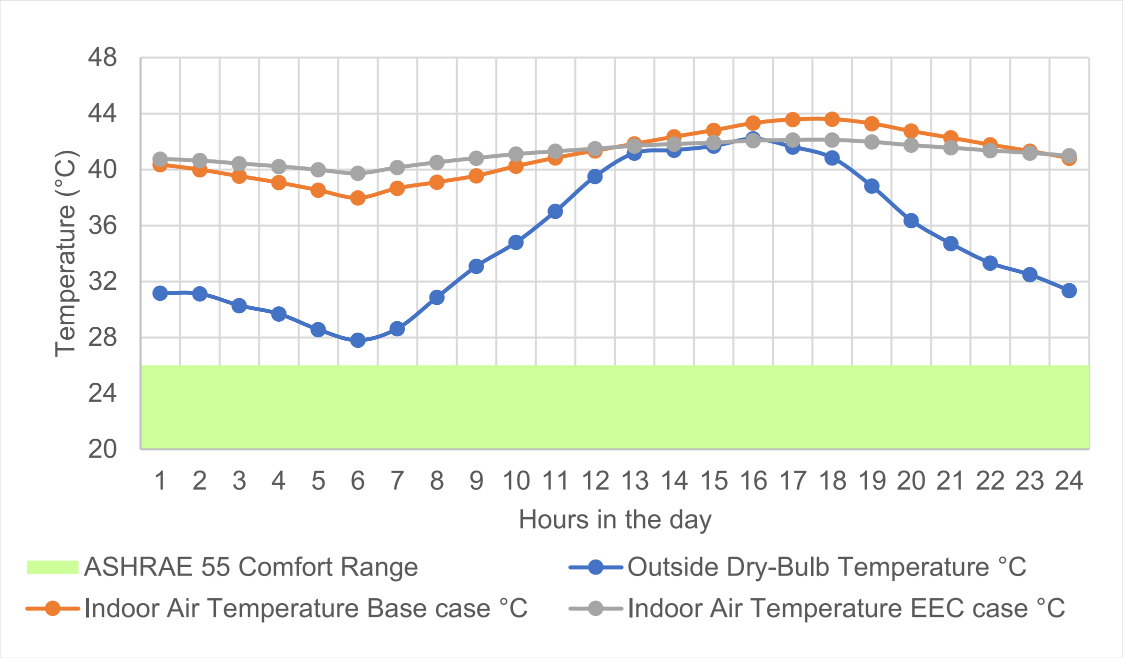


Fig 5. 23. Zone 2 indoor temperature comparison for hottest day in C2

As can be seen in Fig 5.24 case C3, had a steadier improvement than C2. The indoor temperature improved at maximum difference of 5.8°C and an average temperature difference of 3.2°C, but during the hottest day it does not maintain the comfort level of temperature and hence there is a need for mechanical ventilation.

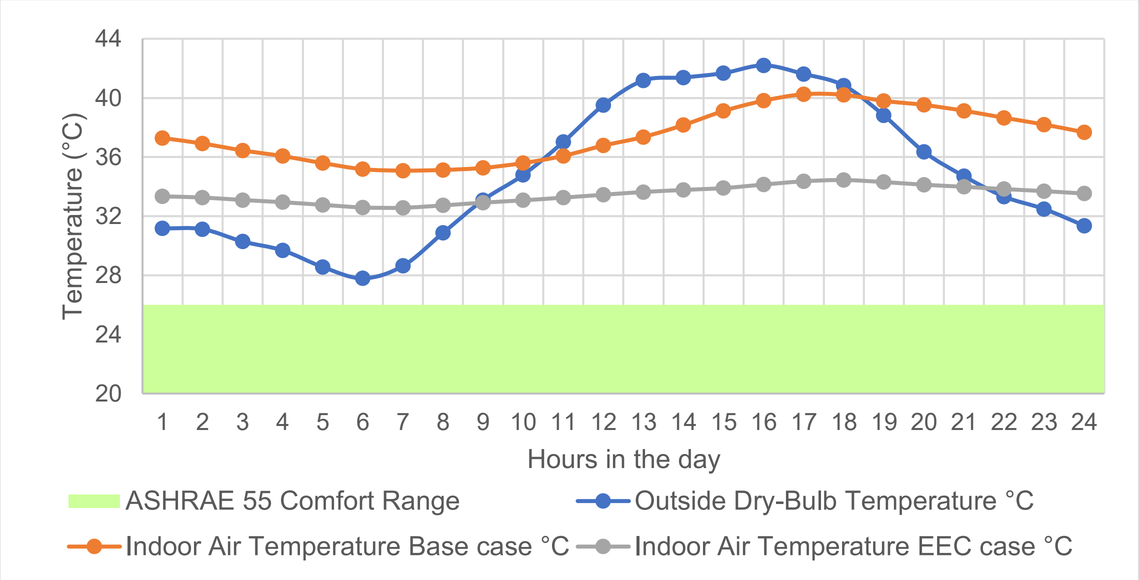


Fig 5. 24. Zone 2 indoor temperature comparison for hottest day in C3

5.4.2. Thermal analysis of coldest day

Figure 5.25 presents the coldest day indoor temperature behavior of optimum case zone 2 in relation to base case and outdoor temperature, where the room temperature improved at maximum difference of 2.98°C and an average temperature difference of 2.44°C. The green bar illustrates the range of comfort temperature which is 20°C -24°C for winter and illustrates that EEC case and base case both fall out the comfort at this day and require mechanical system to provide comfort for occupants.

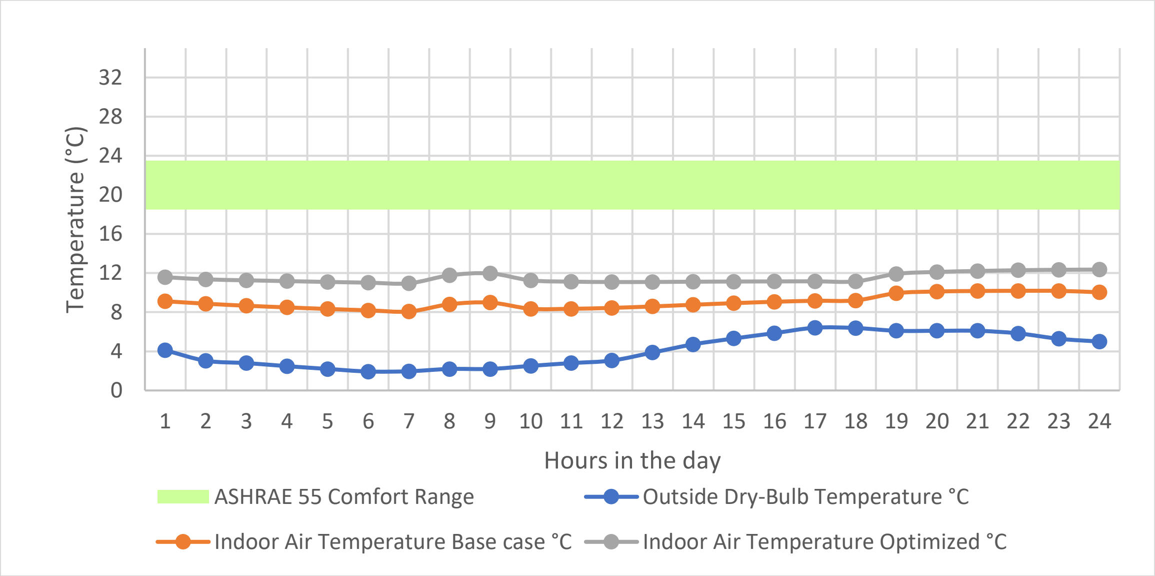


Fig 5. 25. Zone 2 indoor temperature comparison for coldest day in C1

As Fig 5.26 reveals that C2 with temperature improvement around an average of 2°C improvement in indoor temperature and a maximum amount of 2.6°C, which is still outside the comfort range.

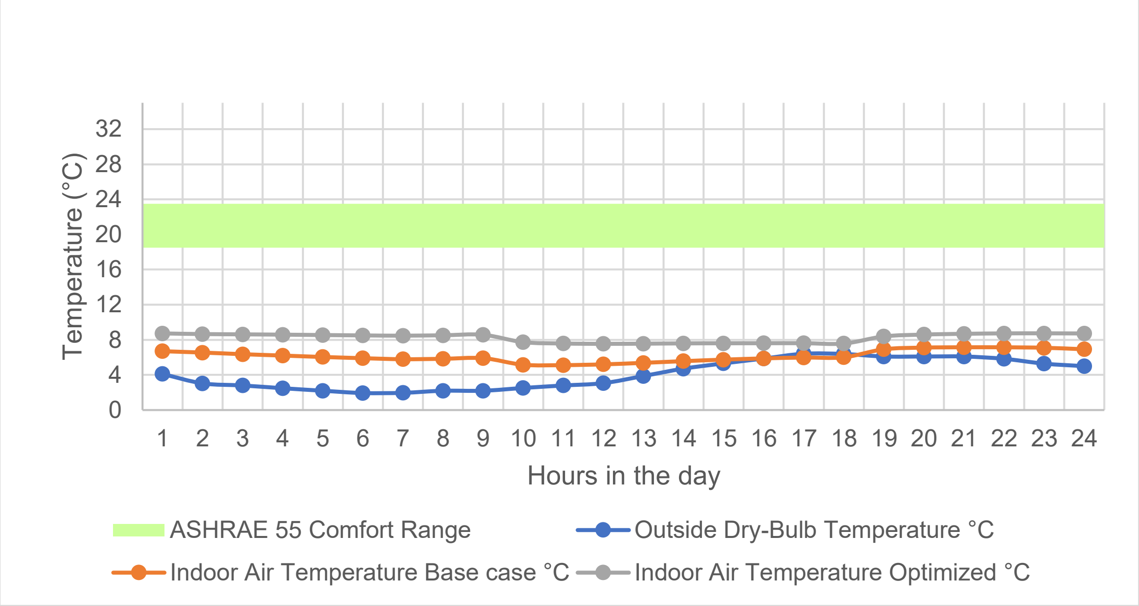


Fig 5. 26. Zone 2 indoor temperature comparison for coldest day in C2

It is observed as Fig 5.27 shows that, EEC envelope of C3 reduced the indoor temperature steadily with an average of 2.6°C and maximum temperature difference of 3.23°C.

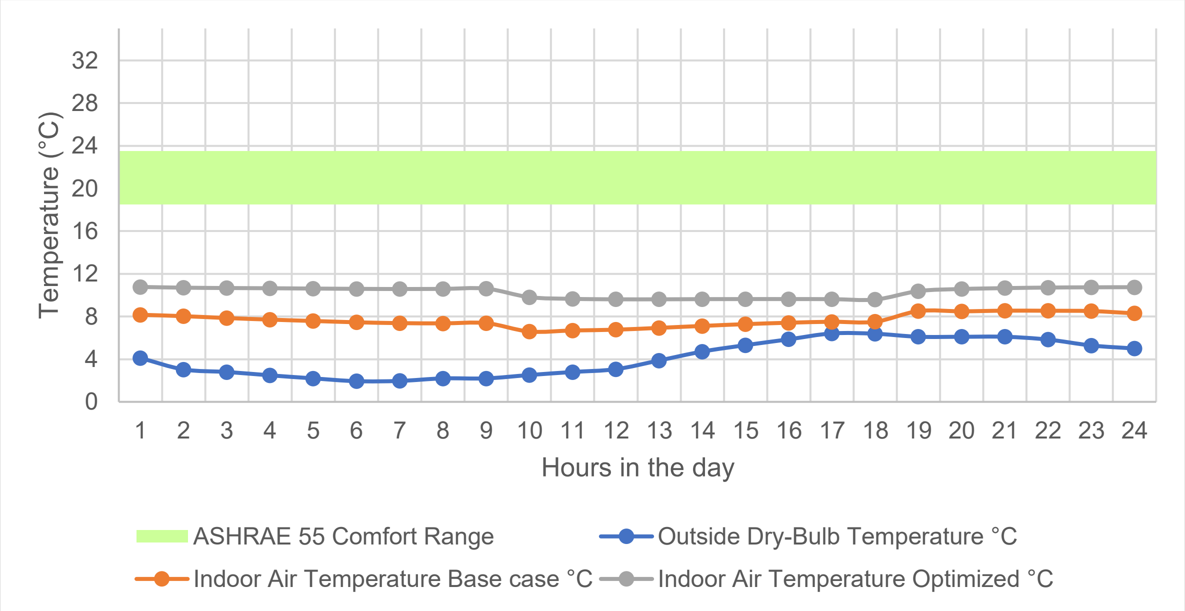


Fig 5. 27. Zone 2 indoor temperature comparison for coldest day in C3

5.5. EEC case energy analysis

Figures 5.28-5.30 present the cooling and heating energy consumption reduction in EEC (Energy-efficient configuration) compared with their base case’s consumption in a year using the optimized building envelope for C1, C2 and C3. The total cooling energy, after application of all strategies, was almost reduced by three forth (2635 kWh) for C1, and halved for C2 and C3, around 4261 kWh,3521 kWh, respectively. Whereas, regarding heating energy reduction, C1 had less improvement by around one fifth of base case only 515 kwh, C2 and C3 experienced larger percent around 4100 kWh and 1289 kWh.

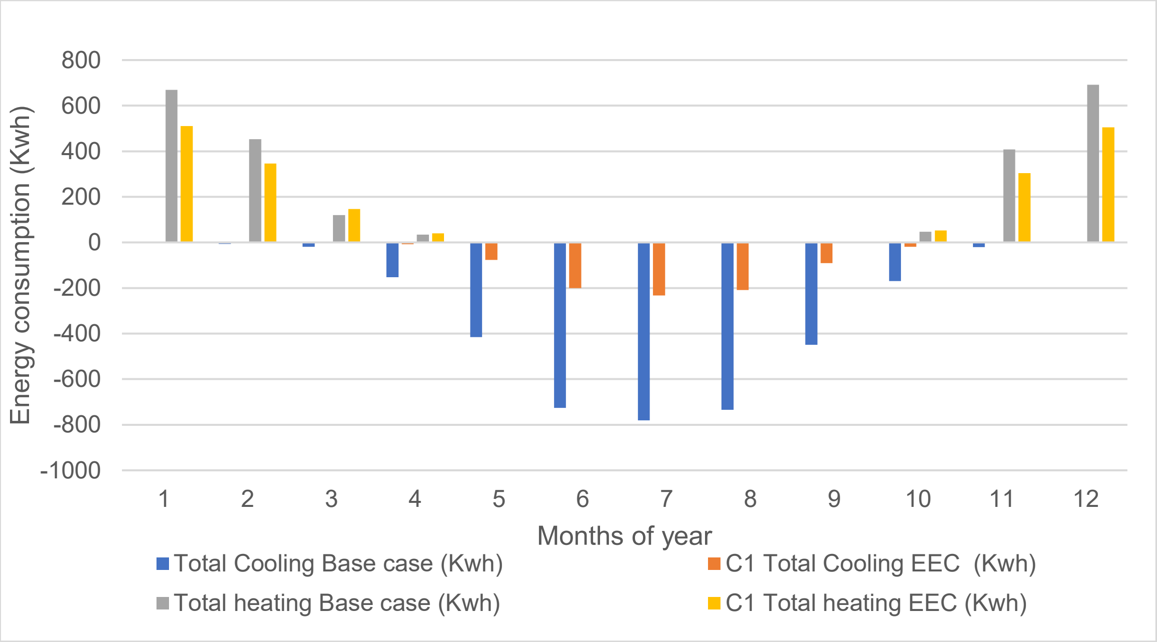


Fig 5. 28. Annual energy consumption comparison of EEC envelope against base case for C1

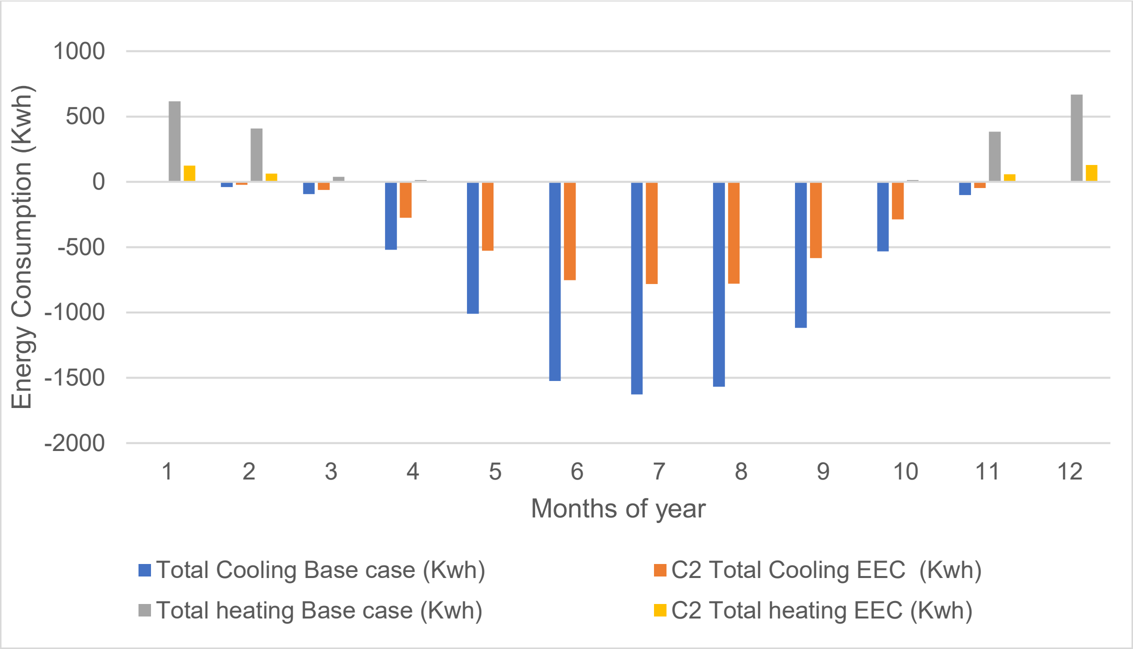


Fig 5. 29. Annual energy consumption comparison of EEC envelope against base case for C2

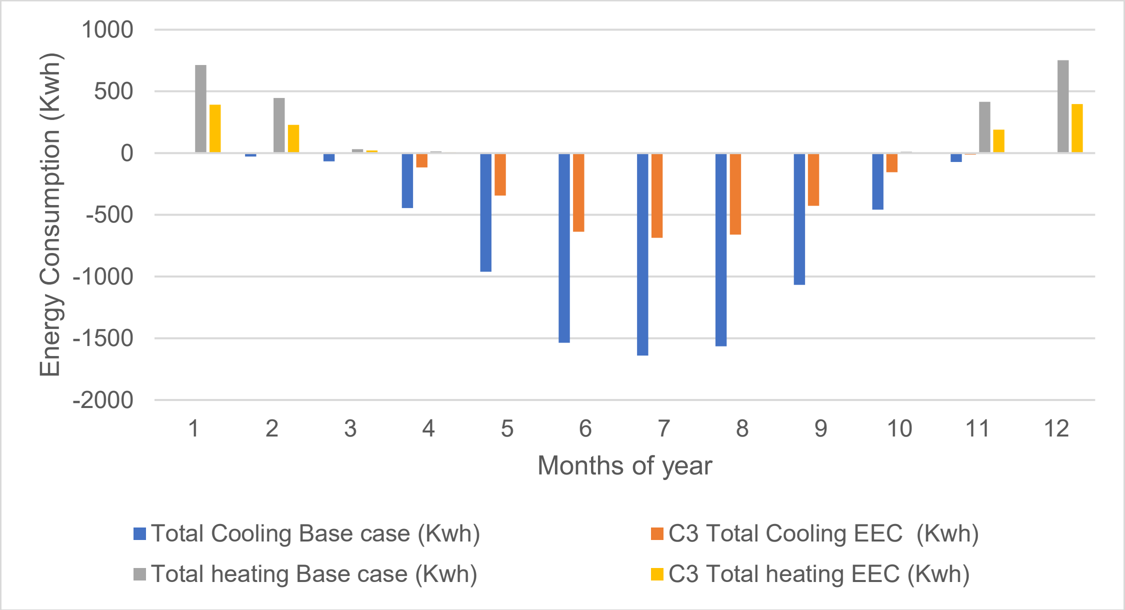


Fig 5. 30. Annual energy consumption comparison of EEC envelope against base case for C3

As Fig 5.31 illustrate the total percentage of energy saving per month for each case, C2 was the only one that had more saving during winter than in summer, however for C1 and

C3 summer saving was higher, due to their heigh, as the building height increased the heating load demand decreased more effectively than cooling.

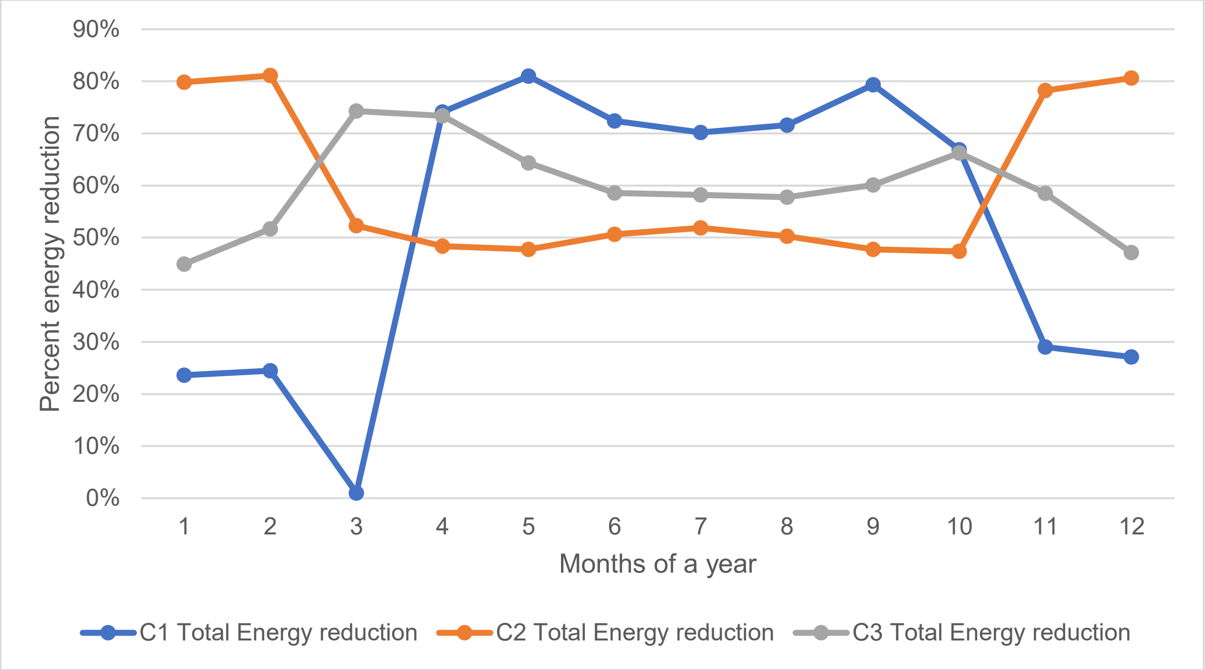


Fig 5. 31. Total cooling and heating energy saving comparison of different cases in percentage

The total energy reduction for C1, C2, and C3, as shown in table 5.3, were similar with each other, around 55% with total values of 3150 kWh, 5542 kWh, 5929 kWh, respectively. For apartment, with higher distance from ground, the heating reduction is greater than cooling.

Table 5. 3. Summary of total energy saving per combined strategies for each case

Cases	Base case (kWh)	Optimum case (kWh)	Energy Saving(kWh)	Percent saving
C1	5896	2746	3150	53%
C2	10,119	4577	5542	55%
C3	10,229	4280	5948	58%

5.6. Emission impact analysis

As discussed in chapter 1 according to Commission of energy regulation of Mexico (CRE) for every Megawatt hour of electricity there are 0.505 tons of CO2 emission produced. With respect to this fraction we have:

0.505 tCO2e/MWh = 0.505 kgCO2e/kWh

For C1:

Total area of 36 $\mathbf{m}^{\mathbf{2}}$, Annual loads of saving energy: 3150.1 kWh

Total Annual Carbon emission reduction = 1578.1 kgCO2e

Total Carbon emission reduction per SQM: 44 kgCO2/$\mathbf{m}^{\mathbf{2}}$

For C2:

Total area of 42 $\mathbf{m}^{\mathbf{2}}$, Annual loads of saving energy: 5542 kWh

Total Annual Carbon emission reduction = 2798.7 kgCO2e

Total Carbon emission reduction per SQM: 66.6 kgCO2/$\mathbf{m}^{\mathbf{2}}$

For C3:

Total area of 81 $\mathbf{m}^{\mathbf{2}}$, Annual loads of saving energy: 5,948 kWh

Total Annual Carbon emission reduction = 3004.1 kgCO2e

Total Carbon emission reduction per SQM: 37.1 kgCO2/m2

As calculated above for C1, C2 and C3 there regarding the Carbon emission, by application of optimum envelope we can save around 1578 Kg, 2798 Kg and 3004 Kg of emission annually for each building. Below Fig 5.32 presents both fraction of emission saving due to cooling and heating energy reduction. Concerning to C1 cooling energy had a higher contribution about five times more whereas regarding cases C2 and C3 the heating emission reduction contributed by more than one third of cooling.

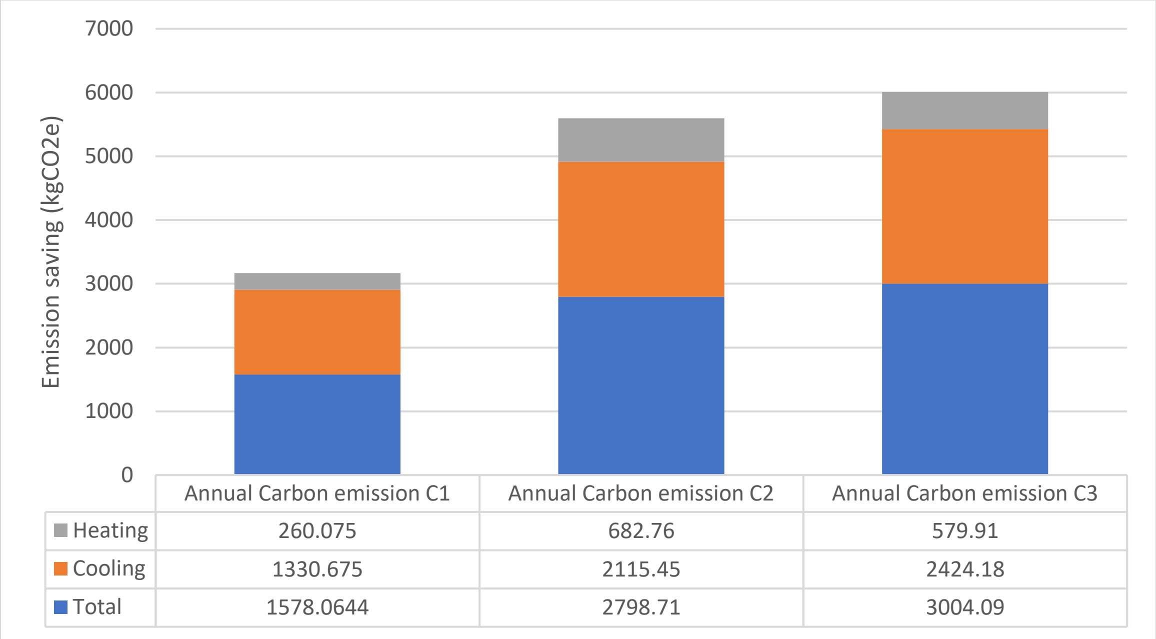


Fig 5. 32.Total Carbon dioxide (CO2) emission and its distribution for cooling and heating consumption of EEC cases (Kg)

Annually each tree can absorb 21 Kg of CO2 [67], consequently by considering the amount of emission saving for C1, C2 and C3 it is assumed that we are planting 76, 101 and 143 trees respectively, annually per house. Furthermore, one of the main sources of Mexico power supply is oil [68], in 2019, it was responsible for 45% of total annual power supply. Due to this we can also translate the reduction of energy into oil barrels, which that every 42-gallon barrel can produce 1700 kWh energy, hence we save 2, 3.2 and 3.5 barrels of oil for C1, C2 and C3 annually to produce 3150 kWh, 5542 kWh and 5948 kWh of energy which are the amount of energy reduced by the optimized building envelope [69].

5.7. EEC case cost analysis

The static payback period (SPP) is a period that invested amount of capital is returned based on the profit earned out of investment, for construction application we use the formula below:

$$SPP=\frac{Cin}{S}$$

SPP is a static payback period,

Cin is Initial investment for combined strategy,
S is the profit due to energy saving per strategy

Table 5.4 presents initial cost of improvement combination strategies for each case as well as annual profit per energy saving and the period of return of investment. Case C1 experience the longest period to recover as its initial energy consumption is lower than other houses due to its size and single level positioning. Case C2 and C3 similarly have period of almost 3.5 years of return which is valuable for house owners to consider, after this period C2 and C3 have a profit of almost MXN 16,000 and MXN 17,000 per annum.

Table 5. 4. Cost analysis of EEC cases and payback period

	Annual Energy Cost reduction (MXN)	Material Cost (MXN)	Return of investment (Years)
C1	8,496.5	50,621.4	5.96
C2	15,845.5	56,607	3.57
C3	16,902.8	57,905.6	3.43

Share of each material in total cost is presented in Fig 5.33, which indicates that almost half of cost is due to glazing improvement and the second larger portion belongs to insulation material.

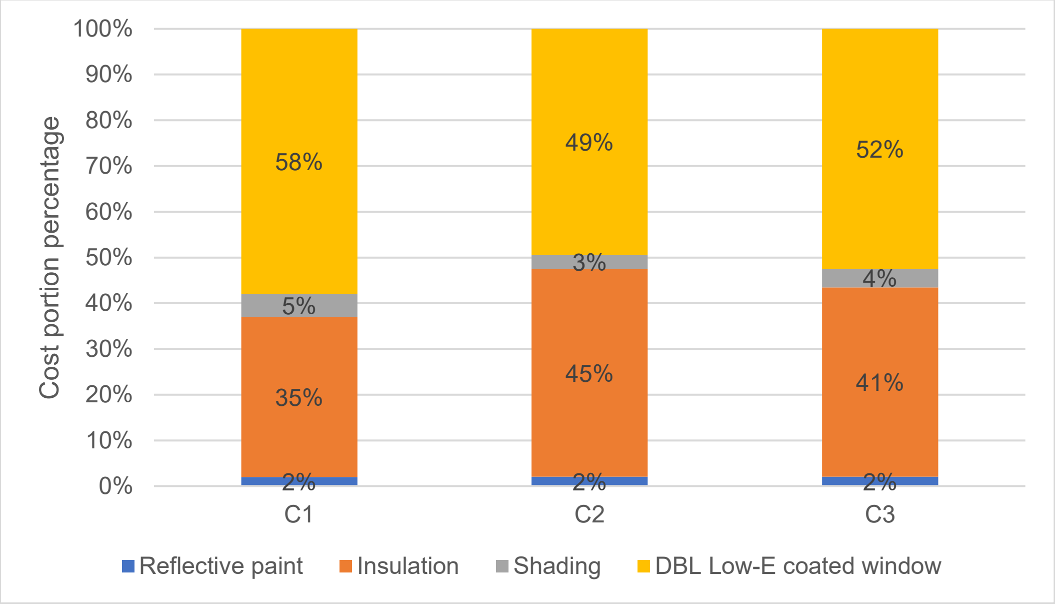


Fig 5. 33. Cost distribution percentage per material for all cases

5.8. PCM thickness and type analysis

Numerical study, which was conducted in Spain, evaluated the economic impact of different types and thickness of PCM and found that the one with 27◦C melting point temperature achieved the highest annual energy savings in CSA climate condition (warm temperate weather). Furthermore, between 5mm and 10 mm thickness of PCM 10 mm presented higher saving and shorter payback period of 3 years for residential buildings. Hence in this section, different melting point of PCM for Semi-arid climate is tested along with different thickness that Infinite PCM (available product in Mexico) provides. In Mexico momentarily only a few suppliers are available which one is Infinite R but it has limitation of thickness and melting point, for instance melting point of 27 is not available and only a thickness of 12 mm is available. Consequently, in Table 6.1 only 3 melting point of PCM was analyzed, as melting point of 27 is not available, the base case is C1 and PCM is applied to roof and walls.

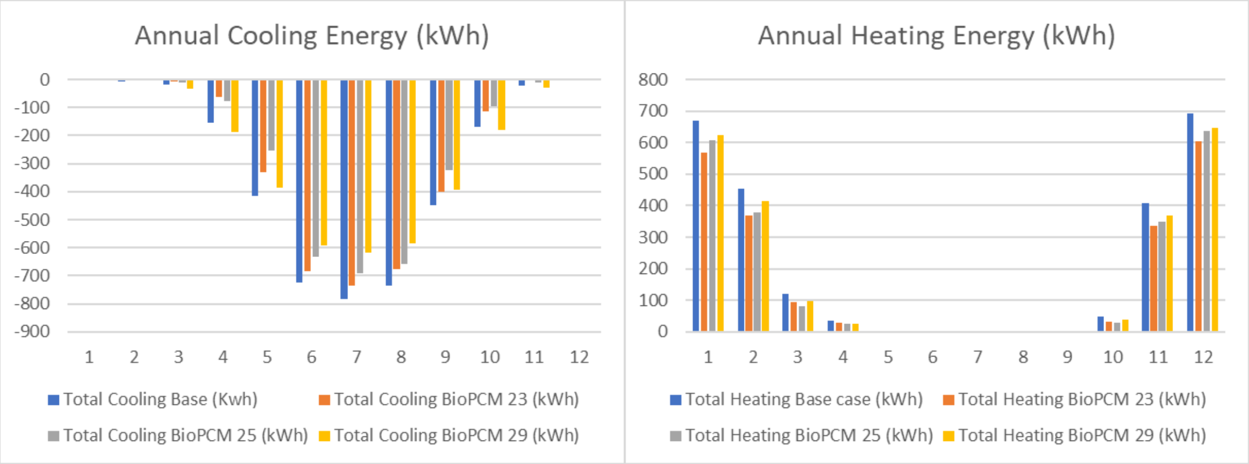


Fig 5. 34. Annual heating and cooling energy demand of base case compared to application of different melting point of PCM

As can be seen, Fig 6.1 presents annual cooling and heating load of different melting points PCM compared to base case energy loads. Generally, PCM application reduces the need for cooling more than heating load demand, on the right cooling load illustrates that during colder months such as April, May, September, and October PCM 29 performed lowest, whereas PCM 25 worked best and during hotter months June, July, and August PCM 29 outperformed others, this is due to higher average hourly temperature in hot months that higher melting point express higher thermal storage capacity. On the contrary, during heat demanding months PCM 23 outperformed others due to its lower melting point and less demand for thermal storage during this time.

All in all, table 6.1 illustrates that PCM with melting point of 25 outperformed others in total energy saving by 18% annual saving compared to PCM 23 and 29 with energy saving of 14% and 11% respectively.

Table 5. 5. Percent of total energy saving per different PCM melting's point

Different melting points	PCM MP @23	PCM MP @25	PCM MP @29
Total Energy saving	14%	18%	11%

Figure 6.2 shows comparison of 3 scenarios, whereas openings are optimum, but walls and roof are tested once with insulation (D= 7cm), PCM 25 of thickness 12cm and another

case with PCM with thickness of 7cm to equalize with insulation thickness. The result illustrates that by increasing the thickness of PCM to match insulation thickness, PCM 25 outperformed insulation by 15%, which is as well equal to optimum case in chapter 5 insulation combined with reflective paint, hence if PCM prices reduce, PCM alone could perform the same amount of energy reduction as insulation with white paint combined.

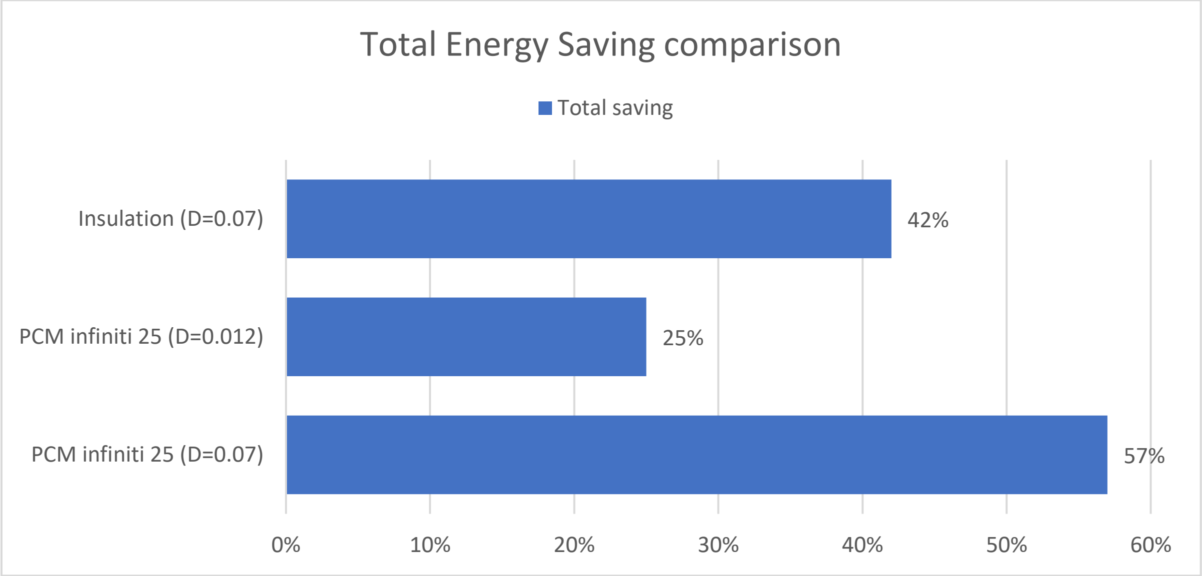


Fig 5. 35. PCM thickness comparison between similar thickness to Insulation and basic Infinite R thickness (along with optimum opening scenario)

Chapter 6 Conclusion

In conclusion, the study was based on a numerical model, using EnergyPlus engine and DesignBuilder, which was validated by BESTEST case 600FF and experimental chamber within 5% error of devices, to simulate the performance of different building envelope scenario that are recommended based on literature for residential buildings compatible to semi-arid climate. Six different wall and roof construction types, with different material, insulation and PCM and reflective paint were analyzed with different U-Values and simulated along with four different opening scenarios, low-e coating, reflective coating, clear double glazing, and horizontal shading. Selection of EEC (Energy-efficient configuration) was established with respect to energy and cost efficiency of the scenarios. Ultimately, thermal comfort improvement, energy, payback period and emission impact were discussed.

6.1. EEC scenario selection

A description of variety of strategies with regards to semi-arid climate as well as literature review showed that for wall and roof component, insulation, PCM and reflective paint are accessible and effective, along with low-E and reflective glazing and horizontal shading devices for opening component of buildings. It is however critical to remember application of such strategies depends on many factors, for instance occupant’s behavior, location and building design. In this study we consider some of the most extreme cases in terms of apartments, highest level of radiation exposure as only considered the top floor.

- Through the analysis it was found that scenario W.PI outperformed the others scenario but with regards to cost analysis W.Ir was selected.
- Regarding the roof component of building similar results were found that R.Ir was the most energy and cost efficient scenario for all cases.
- However, PCM due to its price is integrated in building industry with slim thickness of 0.012 which showed lower impact but with an increase in its thickness it had a better impact, for instance by increasing PCM thickness to similar number of insulation (0.07 m) and applying to roof and walls, 57% energy reduction could be achieved in C1.
- Glazing was responsible for higher cost of envelope, which O.DBLE glazing outperformed O.DBRE and O.DB. It was then combined with horizontal shading and resulted in 22%, 11%, and 13% reduction in energy for C1, C2, and C3.
- Overall, it is desirable for all cases to employ reflective paint and insulation into wall and roof component of buildings to reduce heat gain during the day. EEC scenario consisted of W.Ir, R.Ir, and O.DBLE which estimated a drop in annual energy consumption of 53%, 55%, and 58% for C1, C2, and C3 respectively.

6.2. Impact of EEC application

Figure 6.1 summarize 5 parameters of this study, cooling energy reduction, heating energy reduction, Carbon reduction, Comfort improvement, and payback years of three cases C1, C2, and C3. It is observed that the proposed scenarios had the highest impact on cooling energy demand, and comfort level had the lowest ratio of improvement.

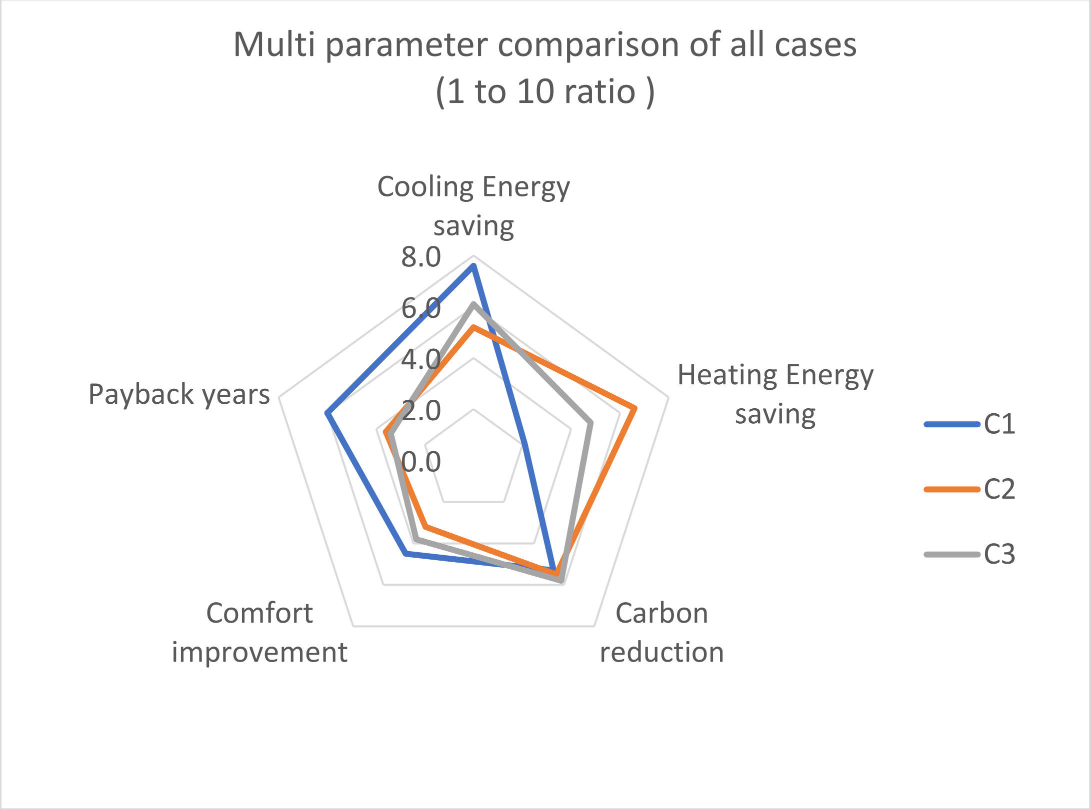


Fig 6. 1. Multi-parameter comparison of all cases based on ratio 1-10

- Cooling demand was reduced to almost one fifth of base case for C1 and for C2 and C3 to almost half.
- Case C1 had the lowest heating energy demand improvement, whereas C2 on the contrary had the highest improvement.
- Carbon emission in 3 cases were similarly dropped by more than half, emission for each case of C1, C2 and C3 can be reduced by 1578 Kg, 2798 Kg, and 3004 Kg annually, with 6 years, period of return for C1 and almost 3.5 years for C2 and C3.
- With regards to thermal performance during hottest day temperature, improvement was observed with averages of 5.9°C and 3.2°C for C1 and C3 whereas C2 had no improvement during this period, however during coldest day all cases had an average improvement of 2.4°C, 2°C, and 2.6°C.
- Comfort level showed higher improvement in C1 by 45%, for C2 and C3 an improvement of 33% and 38% in hours of comfort.

- Payback period for C1 was the highest at 5.9 years, whereas C2 and C3 return the investment in almost half of C1 period around 3.6 and 3.4 years, respectively.

6.3. Recommendation and future work

- PCM alone can increase energy saving impact in semi-arid climate up to 57% instead of 53% in most cases but due to its high price is less applicable, it is favorable with the drop in its price, PCM could add high value to energy efficiency of buildings.
- Other climate of Mexico can be studied to extrapolate the cases of studies and have a more realistic estimation of cost and emission saving throughout the country.
- Experimental approach of scenarios application should further investigate on the impact of their integration into building.

Bibliography

[1]. Buildings – Topics - IEA. (2021). Retrieved 22 January 2021, from https://www.iea.org/topics/buildings

[2]. Zmeureanu, R., & Renaud, G. (2008). Estimation of potential impact of climate change on the heating energy use of existing houses. Energy policy, 36(1), 303-310.

[3]. IEA, (2021). Retrieved 13 April 2021, from https://www.oecd.org/about/publishing/Corrigendum_EnergyTechnologyPerspectives2017.pdf

[4]. (2021). Retrieved 13 April 2021, from https://unfccc.int/files/national_reports/non-annex_i_parties/biennial_update_reports/application/pdf/executive_summary.pdf

[5]. Reddy, T. A., Kreider, J. F., Curtiss, P. S., & Rabl, A. (2016). Heating and cooling of buildings: principles and practice of energy efficient design. CRC press.

[6]. Us Department of Energy. (2021). Retrieved 23 January 2021, from https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter5.pdf

[7]. Al-Yasiri, Q., & Szabó, M. (2021). Experimental evaluation of the optimal position of a macroencapsulated phase change material incorporated composite roof under hot climate conditions. Sustainable Energy Technologies and Assessments, 45, 101121.

[8]. Hernández-Pérez, I., Xamán, J., Macías-Melo, E. V., Aguilar-Castro, K. M., Zavala-Guillén, I., Hernández-López, I., & Simá, E. (2018). Experimental thermal evaluation of building roofs with conventional and reflective coatings. Energy and Buildings, 158, 569-579.

[9]. Braulio-Gonzalo, M., & Bovea, M. D. (2017). Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation. Energy and Buildings, 150, 527-545.

[10]. Organisation for Economic Co-operation and Development. (2015). OECD Urban Policy Reviews: Mexico 2015: Transforming Urban Policy and Housing Finance. OECD Publishing.

[11]. Robert Kaineg, R. S. (2012, November 1). viviendasustentable. Retrieved 2020, from:

https://www.conavi.gob.mx/images/documentos/sustentabilidad/2_NAMA_for_Sustainable_New_Housing_with_Technical_Annex.pdf

[12]. Oropeza-Perez, I., & Petzold-Rodriguez, A. H. (2018). Analysis of the energy use in the Mexican residential sector by using two approaches regarding the behavior of the occupants. Applied Sciences, 8(11), 2136.

[13]. cemiegeo. (2021). Mexico space cooling electricity Impacts and mitigation strategies. http://cemiegeo.org/images/noticias/mexico_cooling_fact_book-usaid_lbnl.pdf

[14]. Chen, L., Zhang, K., Ma, M., Tang, S., Li, F., & Niu, X. (2020, July). Sub-ambient radiative cooling and its application in buildings. In Building Simulation (pp. 1-25). Tsinghua University Press.

[15]. Berardi, U., & Soudian, S. (2018, August). Benefits of latent thermal energy storage in the retrofit of Canadian high-rise residential buildings. In Building Simulation (Vol. 11, No. 4, pp. 709-723). Tsinghua University Press.

[16]. Oropeza-Perez, I., & Østergaard, P. A. (2014). Energy saving potential of utilizing natural ventilation under warm conditions–A case study of Mexico. Applied energy, 130, 20-32.

[17]. Schnieders, J., Feist, W., & Rongen, L. (2015). Passive Houses for different climate zones. Energy and Buildings, 105, 71-87.

[18]. Hsieh, C. M., Li, J. J., Zhang, L., & Schwegler, B. (2018). Effects of tree shading and transpiration on building cooling energy use. Energy and Buildings, 159, 382-397.

[19]. Tahmasebi, M. M., Banihashemi, S., & Hassanabadi, M. S. (2011). Assessment of the variation impacts of window on energy consumption and carbon footprint. Procedia engineering, 21, 820-828.

[20]. S. Sadrzadehrafiei , K. Sopian , S. Mat , C. Lim , Application of advanced glazing to mid-rise office buildings in Malaysia, in: Proc 9th WSEAS Int Conf Environ Ecosyst Dev, 2011, pp. 197–201 .

[21]. N.H. Wong, S. Li, A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore, Build. Environ. 42 (2007) 1395–1405, doi: 10.1016/j.buildenv.2005.11.032 .

[22]. Kim, M., Leigh, S. B., Kim, T., & Cho, S. (2015). A study on external shading devices for reducing cooling loads and improving daylighting in office buildings. Journal of Asian Architecture and Building Engineering, 14(3), 687-694.

[23]. Awadh, P.B. Abuhijleh, The Impact of external shading and windows' glazing and frame on thermal performance of residential house in Abu-Dhabi 2013:3–10.

[24]. Jayalath A, Aye L, Mendis P, Ngo T. Effects of phase change material roof layers on thermal performance of a residential building in Melbourne and Sydney. Energy Build 2016;121:152–8.

[25]. Alam M, Jamil H, Sanjayan J, Wilson J. Energy saving potential of phase change materials in major Australian cities. Energy Build 2014;78:192–201.

[26]. Soares N, Gaspar aR, Santos P, Costa JJ. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. Energy Build 2014;70:411–21.

[27]. Chan ALS. Energy and environmental performance of building facades integrated with phase change material in subtropical Hong Kong. Energy Build 2011;43:2947–55.

[28]. Saffari M, de Gracia A, Ushak S, Cabeza LF. Economic impact of integrating PCM as passive system in buildings using Fanger comfort model. Energy Build 2016;112:159–72.

[29]. Pisello, A. L., & Cotana, F. (2014). The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring. Energy and Buildings, 69, 154-164.

[30]. Dabaieh, M., Wanas, O., Hegazy, M. A., & Johansson, E. (2015). Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings. Energy and Buildings, 89, 142-152.

[31]. Zingre, K. T., Wan, M. P., Wong, S. K., Toh, W. B. T., & Lee, I. Y. L. (2015). Modelling of cool roof performance for double-skin roofs in tropical climate. Energy, 82, 813-826.

[32]. Raoux, S. (2009). Phase change materials. Annual Review of Materials Research, 39, 25-48.

[33]. Han, Y., & Taylor, J. E. (2016). Simulating the Inter-Building Effect on energy consumption from embedding phase change materials in building envelopes. Sustainable cities and society, 27, 287-295.

[34]. Akeiber, H., Nejat, P., Majid, M. Z. A., Wahid, M. A., Jomehzadeh, F., Famileh, I. Z., ... & Zaki, S. A. (2016). A review on phase change material (PCM) for sustainable passive cooling in building envelopes. Renewable and Sustainable Energy Reviews, 60, 1470-1497.

[35]. Pasupathy, A., & Velraj, R. (2008). Effect of double layer phase change material in building roof for year round thermal management. Energy and Buildings, 40(3), 193-203.

[36]. Yu, J., Yang, C., Tian, L., & Liao, D. (2009). Evaluation on energy and thermal performance for residential envelopes in hot summer and cold winter zone of China. Applied Energy, 86(10), 1970-1985.

[37]. Huang, H., Zhou, Y., Huang, R., Wu, H., Sun, Y., Huang, G., & Xu, T. (2020). Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. Sustainable Cities and Society, 52, 101840.

[38]. Kolaitis, D. I., Malliotakis, E., Kontogeorgos, D. A., Mandilaras, I., Katsourinis, D. I., & Founti, M. A. (2013). Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings. Energy and Buildings, 64, 123-131.

[39]. Ozel, M. (2011). Thermal performance and optimum insulation thickness of building walls with different structure materials. Applied Thermal Engineering, 31(17-18), 3854-3863.

[40]. Malz, S., Krenkel, W., & Steffens, O. (2020). Infrared reflective wall paint in buildings: Energy saving potentials and thermal comfort. Energy and Buildings, 224, 110212.

[41]. Synnefa, A., Santamouris, M., & Livada, I. (2006). A study of the thermal performance of reflective coatings for the urban environment. Solar Energy, 80(8), 968-981.

[42]. Ávila-Delgado, J., Robador, M. D., Barrera-Vera, J. A., & Marrero, M. (2021). Glazing selection procedure for office building retrofitting in the Mediterranean climate in Spain. Journal of Building Engineering, 33, 101448.

[43]. Huang, Y., Niu, J. L., & Chung, T. M. (2014). Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. Applied energy, 134, 215-228.

[44]. Aguilar, J. O., Xamán, J., Olazo-Gómez, Y., Hernández-López, I., Becerra, G., & Jaramillo, O. A. (2017). Thermal performance of a room with a double-glazing window using glazing available in Mexican market. Applied Thermal Engineering, 119, 505-515.

[45]. Bhamare, D. K., Rathod, M. K., & Banerjee, J. (2019). Passive cooling techniques for building and their applicability in different climatic zones—The state of art. Energy and Buildings, 198, 467-490.

[46]. Institute, P. (2021). PassivhausInstitut. Retrieved 3 February 2021, from https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm

[47]. Mehling, H., Cabeza, L. (2010) Heat and cold storage with PCM - An up to date introduction into basics and applications. Springer. Berling, Germany.

[48]. García de Diego, M., Raymundo, A., Hernandez, J., Bango, M. (2011) Estrategias de Diseño. Consultado el 28 de enero de 2021 de 14. ESTRATEGIAS DE DISEÑO by Ramón ITC - issuu

[49]. Li, D. H., Yang, L., & Lam, J. C. (2013). Zero energy buildings and sustainable development implications–A review. Energy, 54, 1-10.

[50]. Lei, J., Yang, J., & Yang, E. H. (2016). Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore. Applied energy, 162, 207-217.

[51]. Latif, E., Bevan, R., & Woolley, T. (2019). Thermal Insulation Materials for Building Applications: The complete guide. ICE Publishing.

[52]. Eshrar Latif, R. B. (2019). Thermal insulation materials for building application. Inst of Civil Engineers Pub.

[53]. Reddy, T. A., Kreider, J. F., Curtiss, P. S., & Rabl, A. (2017). Heating and cooling of buildings: Design for Efficiency. CRC Pr I Llc.

[54]. ANSI, A., & ASHRAE, M. (2004). Standard 55—Thermal Environmental Conditions for Human Occupancy. ASHRAE, Atlanta.

[55]. Kaynakli, O., Pulat, E., & Kilic, M. U. H. S. İ. N. (2005). Thermal comfort during heating and cooling periods in an automobile. Heat and mass transfer, 41(5), 449-458.

[56]. Andamon, M. (2006). Thermal comfort standards and building energy use in philippine office environments. In 40th Annual Conference of the Architectural Science Association ANZAScA (pp. 66-72).

[57]. Guyton, A. C., & Hall, J. E. (2006). Medical physiology. Gökhan N, Çavuşoğlu H (Çeviren), 3.

[58]. Emiliano Zapata, (2021). Retrieved 12 April 2021, from https://www.gob.mx/cms/uploads/attachment/file/442910/Aviso_Factor_de_Emisiones_2018.pdf

[59]. García, E.-Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO),(1998).'Climas' (clasificación de Koppen, modificado por García). Escala 1:1000000.México

[60]. Mapa Digital de México en línea. (2021). Retrieved 26 May 2021, from http://gaia.inegi.org.mx/mdm6/?v=bGF0OjIyLjg1MTU2LGxvbjotMTAxLjUwMDAwLHo6MQ

[61]. Infonavit, (2020). Retrieved 31 March 2020, from **https://infonavit.janium.net/janium/Documentos/65547.pdf**

[62]. Cifras básicas RUV – RUV – Registro Único de Vivienda. (2020). Retrieved 31 March 2020, from http://portal.ruv.org.mx/index.php/cifras-basicas-ruv

[63]. Lam, K. (2013). Sustainability performance simulation tools building design simulation tools for building design building design. Sustainable Built Environments, Springer, New York, 526-594.

[64]. Crawley, Drury B., Hand, Jon W., Kummert, Michael and GriffIth, Brent T ,

(2005). Contrasting the capabilities of building energy performance simulation programs. In Ninth International IBPSA Conference. Montréal, Canada, 15-18 August 2005. International Building Performance Simulation Association . 231 - 238.

[65]. Analytics, G. A. R. D. (2004). EnergyPlus Testing with ANSI/ASHRAE Standard 140-2001 (BESTEST).

[66]. Pasupathy, A., Velraj, R., & Seeniraj, R. V. (2008). Phase change material-based building architecture for thermal management in residential and commercial establishments. Renewable and Sustainable Energy Reviews, 12(1), 39-64.

[67]. Specialist Heating Advice, T., absorb, H., absorb, H., boiler?, H., & help?, W. (2021). How much CO2 does a tree absorb?. Retrieved 20 February 2021, from **https://www.viessmann.co.uk/heating-advice/how-much-co2-does-tree-absorb#:~:text=A%20typical%20tree%20can%20absorb,around%20a%20tonne%20of%20CO2**.

[68]. Mexico - Countries & Regions - IEA. (2021). Retrieved 20 February 2021, from https://www.iea.org/countries/mexico

[69]. Greenhouse Gases Equivalencies Calculator - Calculations and References | US EPA. (2015). Retrieved 20 February 2021, from https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

Curriculum Vitae

SeyedehNiloufar Mousavi was born in Tehran, Iran, on July 28th, 1991. She earned her Bachelor of Science in Architecture Technology degree from the University UCSI Malaysia, in July 2014. She was accepted in the graduate programs in Science Engineering in August 2019.

This document was typed in using Microsoft Word by SeyedehNiloufar Mousavi.