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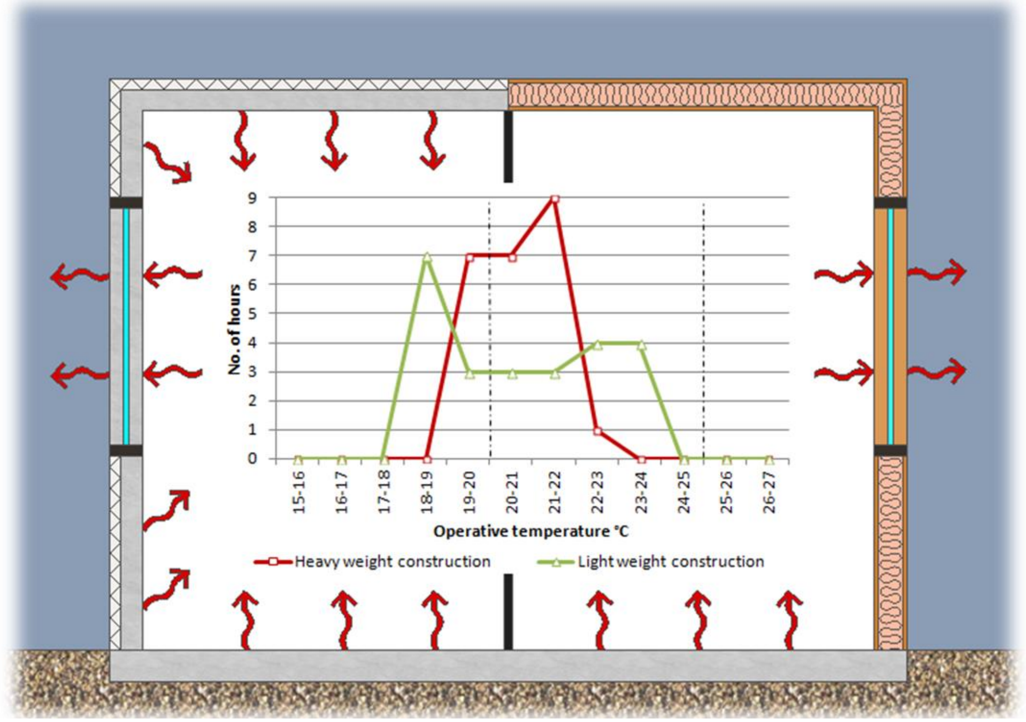

Impact of Thermal Mass on Energy and Comfort

A parametric study in a temperate and a tropical climate

Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology

CARLOS EDUARDO MORA JUAREZ

Department of Civil and Environmental Engineering
Division of Building Technology

Building Physics

CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis 2014:12

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Examensarbete / Institutionen för bygg- och miljöteknik,
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Cover:
Illustration of a heavy weight construction (left) and a light weight construction (right). Free running temperature response of both constructions in a typical winter day in a temperate climate are shown in the graph, see Section 3.2.1.

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ABSTRACT

The use of thermal mass in a building can result in an improved thermal comfort and energy savings. On the other hand, thermal mass can also be detrimental when it is not properly used. The outdoor climate is an important factor that influences the performance of thermal mass and will determine if a heavy weight or a light weight construction is desirable.

A shoebox model of one zone resembling a typical social house in Mexico is simulated in a temperate climate like Mexico city and a tropical climate corresponding to the city of Veracruz. It was analyzed how different parameters such as the type of glass, exterior shading, ground insulation, window size and natural ventilation affect the performance of thermal mass. Free running temperature simulations in typical seasonal days are conducted in order to describe comfort by means of the operative temperature. Annual year simulations are performed to estimate the energy demand. The most relevant simulation cases from the shoebox model are implemented in the real house.

The results show that thermal mass is beneficial in a temperate climate such as in Mexico city. Comparing with a light weight construction, thermal mass in a heavy weight building can compensate for the increase in temperature variations and energy demand due to a larger window area, or to a poor U-value of the windows.

In a tropical climate like Veracruz, a light weight construction with low thermal mass is preferable. Thermal mass is beneficial as soon as the free running temperature response of the building is within the comfort limits, otherwise it can be a liability and result in a larger energy demand.

Key words: Energy demand, energy savings, thermal comfort, thermal mass, temperature variations, parametric study, shoebox model, social housing in Mexico.

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Preface

This master thesis investigates the performance of thermal mass in two different climates in Mexico, and how it affects the energy demand and comfort in a typical social house model. Free running temperature simulations in typical seasonal days and annual energy simulations were conducted. This study was carried out from February 2013 to February 2014 in the group of Building Physics at Chalmers University of Technology, Sweden. This thesis was done with supervision and support from SP Technical Research Institute of Sweden (Sveriges Tekniska Forskningsinstitut).

I want to express my gratitude to my examiner Carl-Eric Hagentoft, Professor at Chalmers University for his great support and guidance along this project. I also want to thank my supervisor Harris Poirazis, PhD at SP for his tutoring sessions which were fundamental for the completion of this work, and for his advices for my future professional career. Likewise, I am very grateful to Jenny Sjöström and EQUA Simulation AB for providing me a license of IDA ICE 4.5.1 which was the simulation software used for this study.

Carlos Eduardo Mora Juarez

Göteborg, February 2014

Notations

Roman upper case letters

Aw	Climate classification: Equatorial / dry winter
C	Total heat capacity (J/K)
C_p	Specific heat capacity (J/m^3 K)
Cwb	Climate classification: Warm temperate / dry winter / warm summer
K	Thermal Conductance (W/K)
LT	Light transmittance (-)
R	Heat transmission resistance (m^2 K/W)
T	Primary solar transmittance (-)
T_{min}	Lowest monthly mean temperature in a year (°C)
U	Thermal transmittance (W/m^2 K)
V	Volume (m^3)

Roman lower case letters

a	Thermal diffusivity (m^2/s)
e^x	Exponential function
g	Solar transmittance (-)
l	Side length of shoebox model (m)
t	Time period
t_c	Time constant of the building (hr)

Greek upper case letters

Δx	Thickness (m)

Greek lower case letters

λ	Thermal conductivity (W/m K)
ρ	Density (kg/m^3)

Abbreviations

ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
HVAC	Heating Ventilation and Air Conditioning
IWEC	International Weather for Energy Calculations
Low-e	Glass with low emissivity coating
NAMA	Nationally Appropriate Mitigation Actions
SC	Glass with solar control
WWR	Window-Wall-Ratio

Definitions

Free running temperature:	Estimation of the indoor temperatures in a building without the aid of HVAC systems.

1 Introduction

1.1 Background

Over the last years there has been and increasing concern on sustainability in order to prevent global warming and depletion of natural resources. For this purpose, international organisms have been created, such as the United Nations Framework Convention on Climate Change (UNFCCC) which aim is to reduce the greenhouse gases emission. Every year the UNFCCC opens a space for negotiations and actions on climate change, this event is called Conference of the Parties. One of the mitigation actions addressed in the Conference of the Parties is to aim for more energy efficient buildings since they account for a large part of the total energy consumed (around 40% in developed countries). An important part of the energy used in a building corresponds to heating and cooling.

In Mexico, a number of studies and regulations have been done in order to reduce the energy demand for cooling and heating in the housing sector, one of them is the Official Norm for Energy Efficiency in Buildings (Secretaría de Energía, 2011). Most of these measures focus on limiting the heat gains into the house by reducing the heat transmission of the building envelope, nevertheless the effect of thermal mass is not addressed at all.

According to the design guidelines for passive housing in Australia from Reardon, et al. (2010), the appropriate use of thermal mass can result in large energy savings in heating and cooling. Therefore, it was considered that the impact of thermal mass on the energy demand in the housing sector in Mexico should be further investigated.

Another strong motivation for this study is the personal experience of the author of this thesis regarding indoor thermal comfort in houses in Mexico. *"In my personal experience in temperate climates, the use of heating or cooling devices are not so common in the housing sector. Houses are usually built with heavy weight materials such as clay or concrete bricks, but insulation is not placed on the building envelope, so the benefit of thermal mass is not used to its full extent. People use to wear warm clothes in winter inside the house since indoor temperatures are below the comfort zone most of the time. Nights in summer tend to be warm, and ceiling fans are not enough to provide acceptable temperatures. So I considered interesting to investigate how different parameters such as insulation, shading, etc. would affect the performance of thermal mass with the purpose to achieve an improved thermal comfort".*

1.2 Purpose

The purpose of this study is to investigate the performance of thermal mass in a temperate and a tropical climate, and how this affects the thermal comfort and energy demand in a house. The goal of the thesis is to analyze if thermal mass is desirable or not in such climates.

1.3 Scope

The scope of this thesis is limited to the housing sector with its respective internal loads and occupancy patrons. In other type of buildings, i.e. office buildings, working hours would affect the heating and cooling units' schedule, and as in consequence, energy demand would be different in comparison with a house.

The analysed model is of one storey level; the four facades and the roof are in contact with the outdoor climate while the floor is in contact with the ground. Results are not analysed by individual rooms but for the whole building. As it was mentioned previously, the focus of this work is to analyse if thermal mass is desirable or not in a temperate and a tropical climate. For other types of climate or detailed analyses on specific rooms, further studies should be done.

This thesis does not intend to design or optimize a house but to understand the performance of thermal mass in two climates.

An ideal heater and ideal cooler where used in order to measure the energy demand in the building. Energy sources, type of units and performance are not discussed in this work.

1.4 Method

The process in this thesis is divided in three steps:

Step 1: Definition the shoebox model

First of all, two locations with different climates were selected in order to be able to visualize differences in the performance of thermal mass. The cities of Mexico and Veracruz with temperate and tropical climates were selected. Typical climate days for simulation were chosen in winter, summer and a shoulder season.

It was chosen to analyse a single family house of one storey high. The reason of choosing this type of building was to simplify the modelling of the HVAC system, and focus on the effect of the thermal mass in energy and comfort, which is the purpose of this study.

A literature research was conducted in order to select a typical construction built in Mexico, and use it as reference building. A box model representing the thermal properties and window-wall-ratio of the typical house construction was suggested.

Three types of construction were selected, a heavy weight non-insulated building (reference), the same heavy weight construction with added insulation, and a light weight insulated building.

Step 2: Parametric study in the shoebox model

A parametric study was conducted in the proposed shoebox model in order to visualize how different variables affect the performance of thermal mass. The different parameters to be analysed were defined, and these were: type of glass, exterior shading, ground insulation, natural ventilation and window-wall-ratio. Dynamic simulations were carried out with the computer software IDA ICE 4.5.1 which stands for "Indoor Climate and Energy". Free running temperature simulations were conducted in the typical season days in the three selected types of construction; the operative temperature was used to capture thermal comfort and visualize the effect of the different parameters. In the same way, annual energy simulations were performed to estimate the energy demand.

Conclusions are drawn regarding the impact of thermal mass on energy and comfort in the two climates. These conclusions are to be implemented in the real typical house.

Step 3: Results implementation on the selected typical house

Based on the conclusions from the parametric study in Step 2, the most relevant parameters affecting thermal mass are analysed in the typical house. Annual energy demand is estimated in the three types of construction.

2 Definition of the Shoebox Model

The first step in this study consisted in defining the model to be analysed. Location, type of climate and days for simulation were selected. A typical building in the selected climates was chosen. A shoebox model of one single zone resembling the characteristics of the typical building was proposed. Three constructions with different temperature time response were defined.

2.1 Location and Climate

Mexico has a big variety of climates. The Köppen-Geiger climate classification system is one of the most widely used to characterise the climate conditions. In Figure 2.1 can be seen the different climatic regions in México.

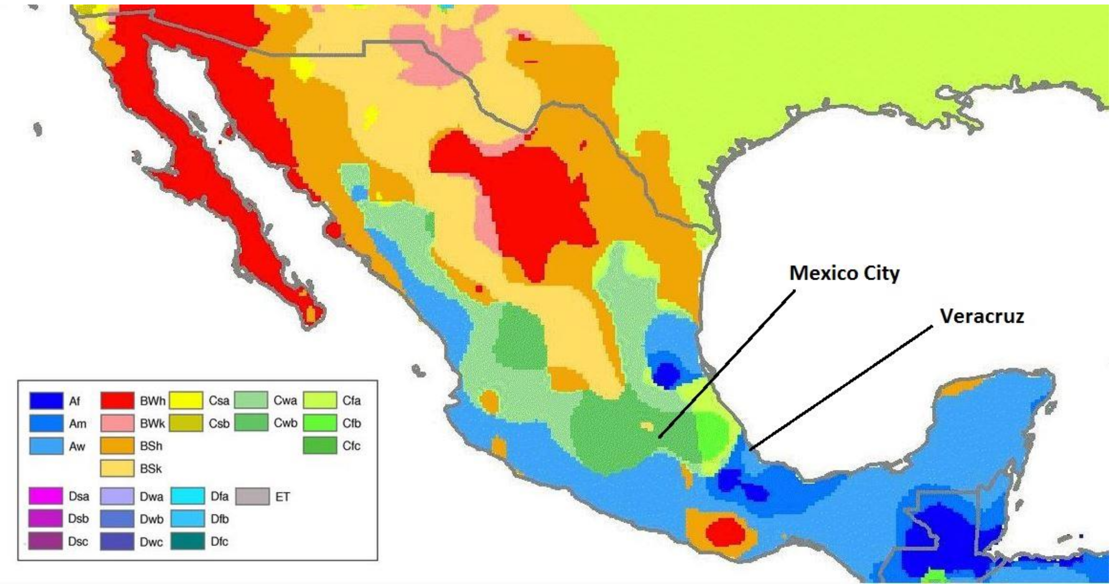


Figure 2.1 World map of Köppen-Geiger climate classification (Pidwirny, 2011).

The description to the nomenclature used to classify the climates is given in Table 2.1.

Table 2.1 Nomenclature description of Köppen-Geiger climate classification (Kottek, et al., 2006).

Main Climates	Precipitation	Temperature	
A: equatorial	W: desert	h: hot arid	F: polar frost
B: arid	S: stepe	k: cold arid	T: polar tundra
C: warm temperade	f: fully humid	a: hot summer	
D: snow	s: summer dry	b: warm summer	
E: polar	w: winter dry	c: cool summer	
	m: monosoonal	d: extremely continental	

The main climates Equatorial (A) and Arid (B) are also known as Tropical and Dry correspondingly (Pidwirny, 2011).

For the purpose of studying the performance of the thermal mass in different climates, two locations where selected, Mexico city and Veracruz, see Figure 2.1. The criterion to choose these two locations was that the main climates would be different enough among each other.

Mexico city with latitude 19.43 N, longitude 99.08 W and elevation 2234 m has a climate of the type ‘Cwb’, while Veracruz is a coastal city with latitude 19.2 N, longitude 96.13 W and elevation 14 m has a climate Aw.

Aw = Equatorial / dry winter

Cwb = Warm temperate / dry winter / warm summer

Climates of the type Cwb have mild winters with the mean temperature of the coldest month falling between – 3 °C and 18 °C. The lowest monthly mean temperature in tropical climates Aw is greater than 18 °C, see Table 2.2.

Table 2.2 Main climate characteristic for Mexico city and Veracruz.

	Mexico city	Veracruz
Classification	Cwb	Aw
Main climate	Temperate (C)	Tropical (A)
Mean temperature	$-3\ ^\circ\mathrm{C} < T_{min} < +18\ ^\circ\mathrm{C}$	$T_{min} \geq +18\ ^\circ\mathrm{C}$

Where:

T_{min} = Lowest monthly mean temperature in a year

2.2 Typical climate days

In order to measure the quality of thermal environment, free running temperature simulations are performed in a day time period. Three typical days are chosen; two days are selected from the coldest and warmest months of the year. The third day comes from a shoulder season, autumn or spring. The selected simulations days are shown in Table 2.3. The criteria to choose these days was that they would represent typical temperatures and solar radiation during that month. For a detailed explanation on how these days were selected, see Appendix 8.2.

Table 2.3 Typical climate days for the selected locations.

Typical days	Mexico city	Veracruz
Winter	30-December	15-January
Summer	18-May	07-May
Shoulder season	06-October	08-November

In Figure 2.2 it is shown the outdoor air temperature range in the selected typical days. Thermal mass is more effective in climates with big diurnal temperature variations. Temperature range in Mexico city is larger than in Veracruz, therefore it can be expected that thermal mass will be more beneficial in a temperate climate like Mexico city.

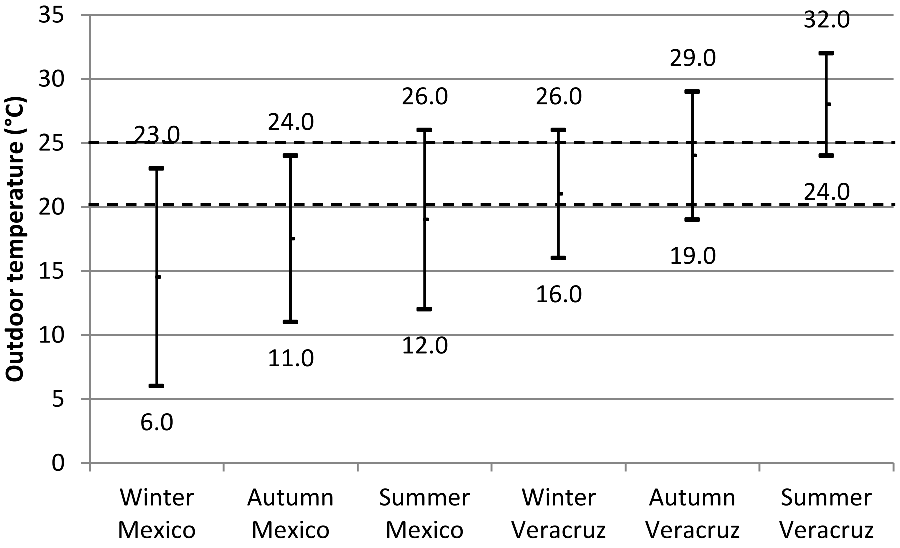


Figure 2.2 Outdoor air temperature range in typical days for Mexico city and Veracruz.

Graphs with hourly mean outdoor temperatures and solar radiation in the selected typical days can be consulted in Appendix 8.2 in Figure 8.2 and Figure 8.3.

2.3 Reference house

In order to create the simulation model, a reference building was chosen. It was selected to use a house since the HVAC system is simple and this would allow to concentrate on the effect of thermal mass.

The house model adopted in this work is based on a typical social house built in Mexico in 2009. With the intention to reduce the energy consumption in the housing sector in Mexico, this same reference house has been used in energy efficiency studies conducted by government authorities. Two studies using this reference house are the Mexican NAMA (Nationally Appropriate Mitigation Actions) which was developed with the technical support of the German International Cooperation Agency (GIZ, 2012), and the other is Energy Efficiency Optimization in Social Housing by (Campos Arriaga, 2011).

This house is composed of 4 zones within the building envelope which are two dormitory rooms, one toilet and a public area where kitchen, dining room and living room are included, see Figure 2.3. The total construction is in one level and has an area of approximately 45 m^2. The interior area within the building envelope is 38 m^2. The roof slab is flat with a slope of 2 % for water drainage.

The house is of the type single detached which means that all facades are exposed to the outdoor climate conditions. It is assumed that there are not external shading bodies like trees or other buildings.

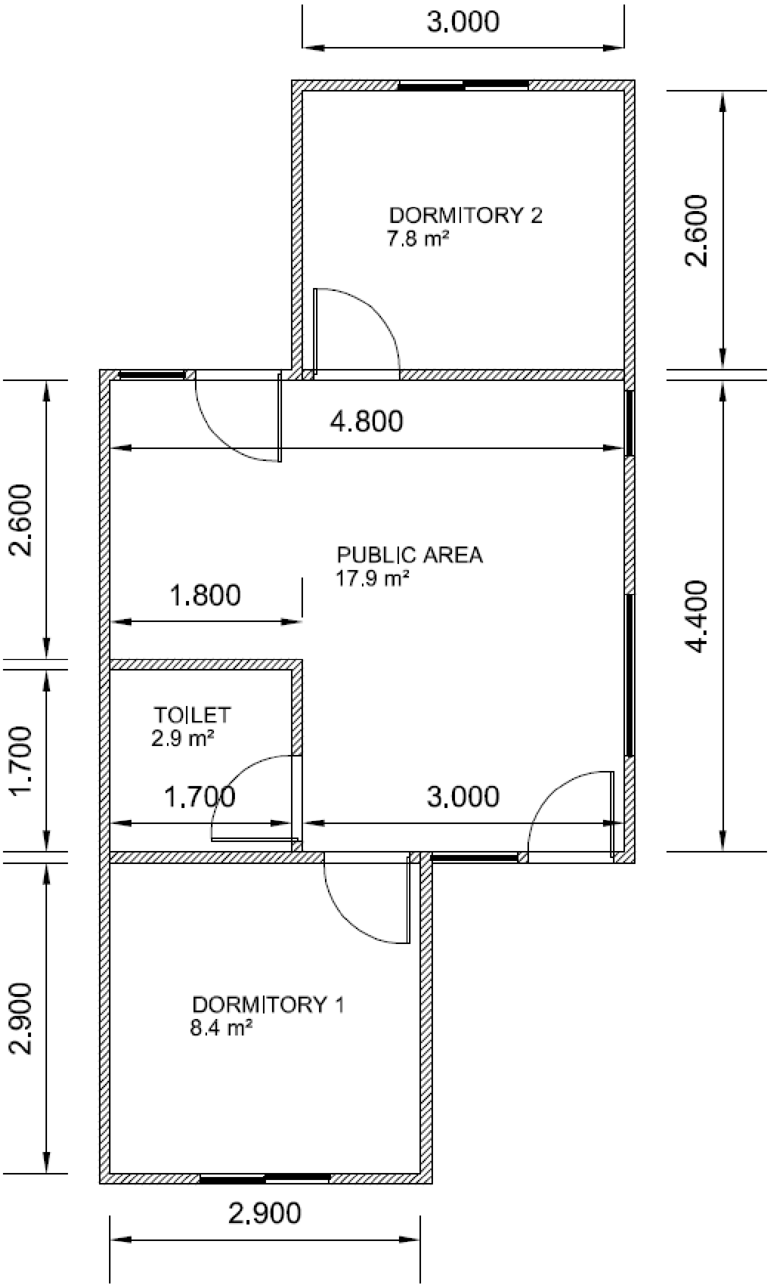


Figure 2.3 Plan view of a typical social house in Mexico.

Window dimensions are not specified neither in the NAMA nor in the energy efficiency study, so these dimensions were estimated based on the original plan view and the 3D model from (Campos Arriaga, 2011) in Appendix 8.3. The estimated window dimensions can be seen on the façade elevations in Figure 2.4. The height of the wall façade is assumed to be 2.80 m on the outside, and 2.50 m to the interior ceiling.

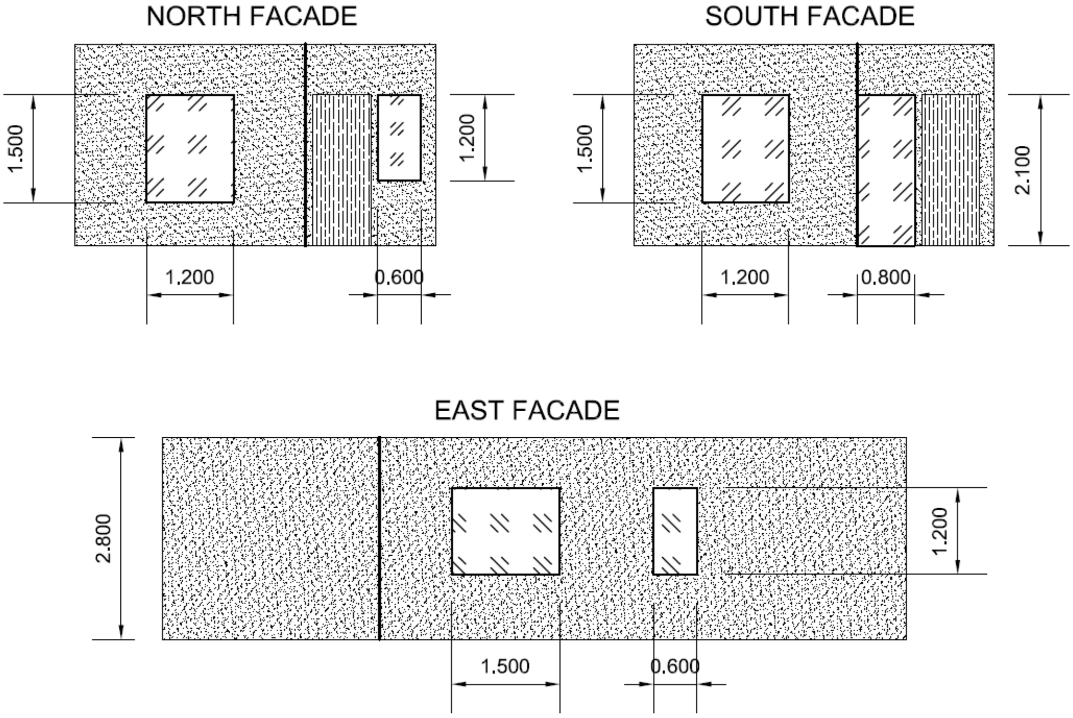


Figure 2.4 Window dimensions of reference house.

The interior wall areas and their corresponding window areas are summed up for every façade. In Table 2.4 it is shown the WWR for every façade and the overall WWR of 11% for the whole house.

Note: Zones in IDA ICE are defined by the interior dimensions of the building. Therefore, unless something different is specified, when referring to dimensions and areas it will be usually interior ones.

Table 2.4 Window wall ratio of reference house.

Reference House	Facade				All Facades
	South	East	West	North	
Wall Area (m^2)	12	25.25	25.25	12	74.5
Window Area (m^2)	3.48	2.52	0	2.52	8.52
WWR	0.29	0.10	0	0.21	**0.11**

2.4 Converting the reference house to the shoebox model

Simulation time can be greatly reduced when using a simplified model, therefore the house was transformed to a shoebox model of one single zone. It is important that the shoebox model resembles the thermal mass of the reference house. The criterion for suggesting the dimensions of the shoebox was that both models would have a similar conductance and heat capacity.

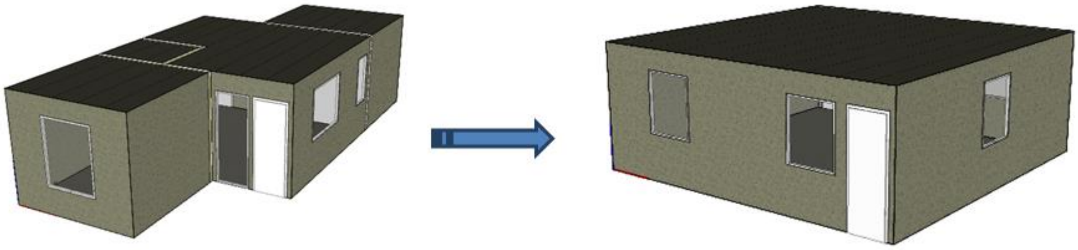


Figure 2.5 Conversion of the reference house to the shoebox model.

2.4.1 Thermal properties

The thermal properties of the construction elements of the building envelope are calculated in Table 2.5. Surface resistances are included; 0.04 m^2K/W (external surfaces), 0.13 m^2K/W (internal surfaces), 0.17 m^2K/W (internal floor). The properties of the individual materials can be found in Appendix 8.4. A section drawing of the walls, roof and floor is found in Section 2.5.1.

Total heat capacity is mainly attributed to the concrete elements since they are much thicker compared with the other layers. It should be noticed that in the reference house, the building envelope is not insulated, therefore there will be a great amount of heat exchange with the outside. Thermal mass becomes less efficient and heat storage will be much lower than the total heat capacity shown in Table 2.5.

Table 2.5 Thermal properties of exterior wall, roof and floor.

	Total Resistance $\sum$ R (m^2K/W)	Thermal transmittance U (W/m^2K)	Heat capacity / m^2 ρ*C_p*V (J/m^2K)	Total heat capacity / m^2 C (J/m^2K)
Wall construction				
Cement plaster with sand (ext)	0.41	2.45	2.97E+04	1.58E+05
Concrete block, medium weight			1.40E+05	
Gypsum plaster with sand (int)			1.83E+04	
Roof construction				
Plasticool layer (1.2 mm)	0.27	3.69	5.19E+02	2.43E+05
Reinforced concrete slab			2.43E+05	
Floor slab construction				
Tiles	0.23	4.26	7.60E+03	2.10E+05
Reinforced concrete slab			2.02E+05	

In order to define the dimensions of the shoebox model, equation (2.1) was proposed. The area of the floor, roof and perimeter walls of the shoebox are considered in $2l^2 + 10l$. The number, 150.5 represents these same areas in the reference house.

$$2l^2 + 10l = 150.5 \qquad (2.1)$$

The dimension of the shoebox is then $l = 6.5$ m. Consequently we find the areas for the shoebox which are shown in Table 2.6. The layout can be seen in Figure 2.6.

Table 2.6 Dimensions for shoebox and reference house.

Parameter	Shoebox	House
Wall length (m)	6.50	variable
Wall perimeter (m)	26.00	29.80
Height (m)	2.50	2.50
Wall area (m^2)	65.00	74.50
Roof area (m^2)	42.25	38.00
Floor area (m^2)	42.25	38.00

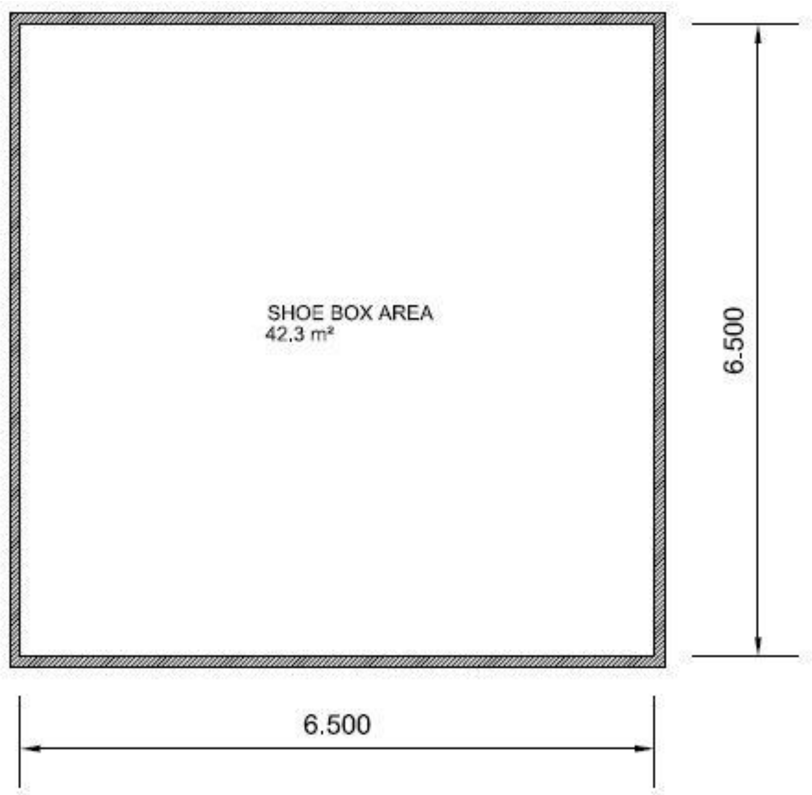


Figure 2.6 Plan view of shoebox model.

By using these dimensions for the shoebox, quite similar thermal conductance and heat storage capacities are obtained. In Table 2.7 can be seen that conductance and heat capacity differences with respect to the reference house are of 2.2% and 1.4%. Therefore the area of 6.5 x 6.5 m is considered to represent accurately enough the thermal properties of the building envelope of reference house.

Table 2.7 Thermal properties comparison between the shoebox and the reference house. All walls are solid, windows are not considered.

Construction element	Conductance K (W/K)		Total heat capacity C (J/K)	
	Shoebox	House	Shoebox	House
Wall	159.11	182.37	1.03E+07	1.18E+07
Roof	155.70	140.04	1.03E+07	9.23E+06
Floor	179.96	161.86	8.87E+06	7.98E+06
Total	494.77	484.26	2.94E+07	2.90E+07
Variation	2.2%		1.4%	

The thermal mass of the interior walls of the reference house should also be considered within the shoebox model. IDA ICE accounts for this walls by adding in the zone an ‘internal wall mass’ area. The area of the internal walls is 18.7 m^2, this area does not include the area of the doors, since they are taken in account as furniture.

2.4.2 Window-Wall-Ratio (WWR)

The area of windows in the shoebox should be also equivalent with the area of windows on the walls of the reference house. The criterion of window-wall-ratio is used, so this means that the percentage of windows in respect with the area of the walls should be the same in both models.

It was proposed to have less window area on the east and west façade since these orientations are more difficult to shade with fixed exterior shading devices. The WWR of 11% is satisfied by having two windows on the north and south facades, and one on the east and west as it can be seen in the plan drawing in Figure 2.7. The façade elevations with the window dimensions are shown in Figure 2.8.

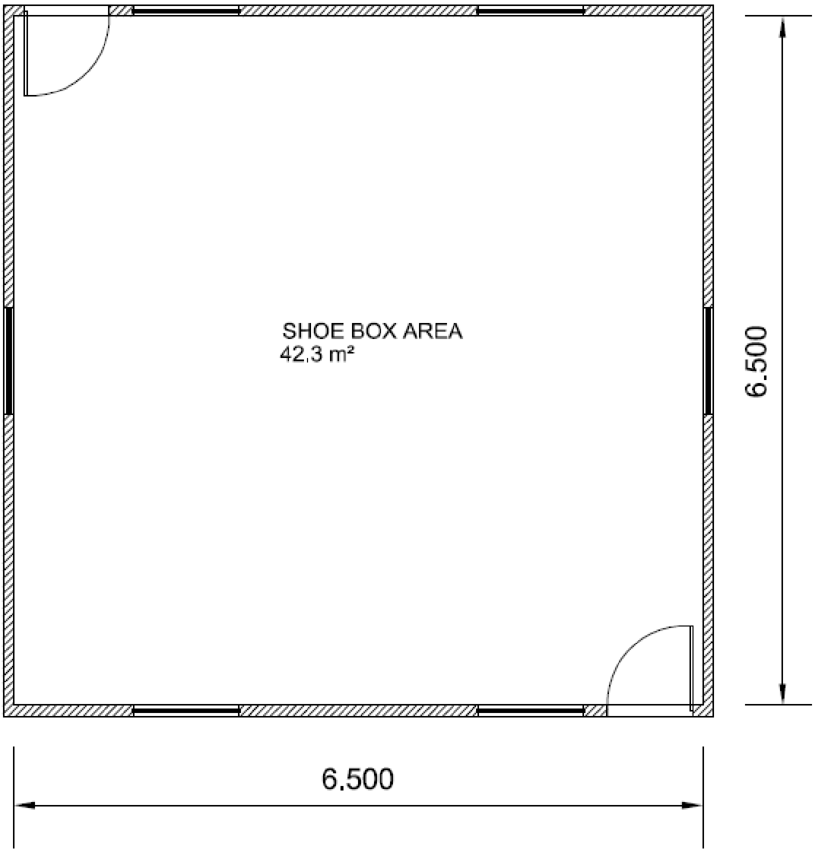


Figure 2.7 Plan view and window location in the shoebox model.

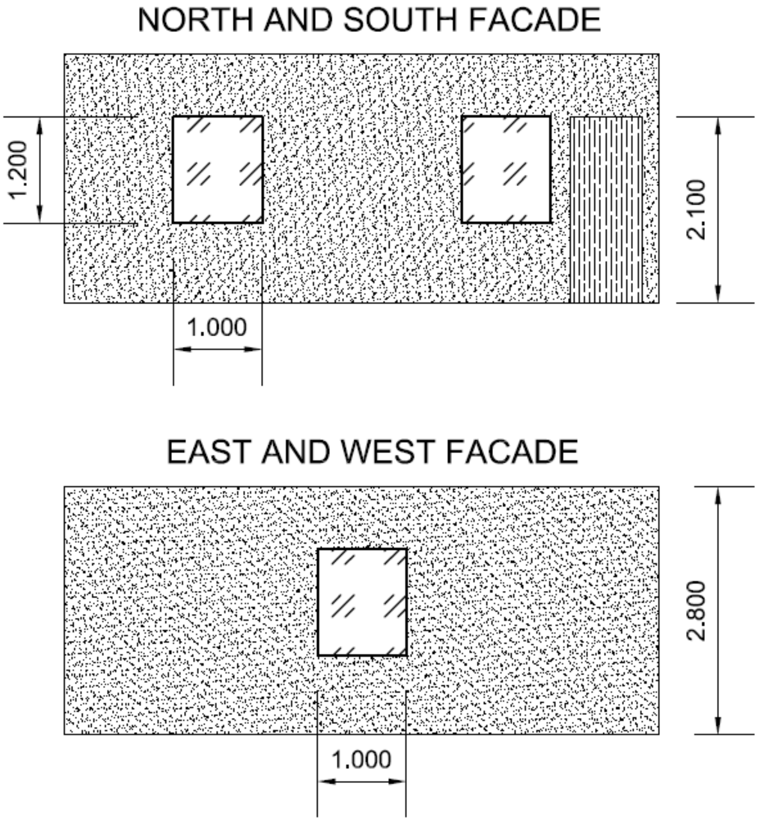


Figure 2.8 Façade elevations and window dimensions in shoebox model.

Table 2.8 Window-wall-ratio in the shoebox model.

Shoebox	Facade				All Facades
	South	East	West	North	
Wall Area (m^2)	16.25	16.25	16.25	16.25	65.00
Window Area (m^2)	2.40	1.20	1.20	2.40	7.20
WWR	0.15	0.07	0.07	0.15	**0.11**

2.4.3 Internal gains and occupancy patrons

According to the energy efficiency study from (Campos Arriaga, 2011), the studied house is intended for a family of two adults and two children. IDA ICE 4.5.1 considers by default an average adult with a body area of 1.8 m^2. Therefore the two children were considered as if they were one adult. The children room is Dormitory 2.

2.4.3.1 Reference house

Typical internal gains in a social type house and metabolic activity in different areas are given in Table 2.9.

Table 2.9 Metabolic rate and Internal gains, (Campos Arriaga, 2011).

Zone	Occupants (met)	Equipment (W/m^2)	Lighting (W/m^2)
Public Area	1.2	15	4
Dormitories	0.9	5	4

The internal gains produced by the equipment and lighting should be introduced in IDA ICE 4.5.1 in Watts as shown in Table 2.10.

Table 2.10 Internal gains in Watts.

Zone	Equipment (W/m^2)	Lighting (W/m^2)	Area (m^2)	Equipment (W)	Lighting (W)
Public Area	15	4	17.9	268.5	71.6
Dormitory 1	5	4	8.4	42	33.6
Dormitory 2	5	4	7.8	39	31.2

It is assumed that the electrical equipment will be used when the occupants are present, therefore the occupancy and equipment patron is the same.

Table 2.11 Occupancy and equipment patron for reference house.

	Time span	Occupancy factor	
		Weekdays	Weekend
Dorms	00:00 - 07:00	1	1
	07:00 - 22:00	0	0
	22:00 - 24:00	1	1
Public Area	00:00 - 07:00	0	0
	07:00 - 08:00	1	1
	08:00 - 14:00	0.25	1
	14:00 - 18:00	0.50	1
	18:00 - 22:00	1	1
	22:00 - 24:00	0	0

The use of electrical lighting is shown in Table 2.12. It is assumed that patrons are the same during the weekdays and weekend.

Table 2.12 Lighting patron for reference house.

	Time span	Lighting factor
		All week
Dormitories	00:00 - 06:00	0
	06:00 - 07:00	1
	07:00 - 22:00	0
	22:00 - 23:00	1
	23:00 - 24:00	0
Public Area	00:00 - 07:00	0
	07:00 - 08:00	1
	08:00 - 17:00	0
	17:00 - 22:00	1
	22:00 - 24:00	0

2.4.3.2 Shoebox

Given that the shoebox is composed of one single zone, it is necessary to convert the internal loads from the multi-zone house in such a way that they are both equivalent. Only one internal gain value can be used for the occupants, one for the equipment and one for the lighting. The occupancy and usage factors are adjusted in order to compensate for the modification in the internal gain, and it is done as follows:

0.9 / 1.2 = 0.75 (Occupant)

81 / 268.5 = 0.30 (Equipment)

64.8 / 71.6 = 0.91 (Lighting)

The sum of the internal loads in both dormitories for the equipment and lighting were obtained from Table 2.10. And these are 81 W and 64.8 W accordingly. From Table 2.13 to Table 2.15 it is shown the conversion of the internal loads from the multi-zone house to the single zone shoebox model.

Table 2.13 Conversion of internal gains from house to shoebox (Occupant).

Time span	Reference house				Shoebox (one zone)		
	Zone	Occupancy factor		Occupant	Occupancy factor		Occupant
		Weekday	Weekend	(met)	Weekday	Weekend	(met)
00:00 - 07:00	Dorms	1	1	0.9	0.75	0.75	1.2
07:00 - 08:00	Public	1	1	1.2	1	1	1.2
08:00 - 14:00	Public	0.25	1	1.2	0.25	1	1.2
14:00 - 18:00	Public	0.50	1	1.2	0.50	1	1.2
18:00 - 22:00	Public	1	1	1.2	1	1	1.2
22:00 - 24:00	Dorms	1	1	0.9	0.75	0.75	1.2

Table 2.14 Conversion of internal gains from house to shoebox (Equipment).

Time span	Reference house				Shoebox (one zone)		
	Zone	Usage factor		Equipment (W)	Usage factor		Equipment (W)
		Weekday	Weekend		Weekday	Weekend	
00:00 - 07:00	Dorms	1	1	81	0.30	0.30	268.5
07:00 - 08:00	Public	1	1	268.5	1	1	268.5
08:00 - 14:00	Public	0.25	1	268.5	0.25	1	268.5
14:00 - 18:00	Public	0.50	1	268.5	0.50	1	268.5
18:00 - 22:00	Public	1	1	268.5	1	1	268.5
22:00 - 24:00	Dorms	1	1	81	0.30	0.30	268.5

Table 2.15 Conversion of internal gains from house to shoebox (Lighting).

Time span	Reference house			Shoebox (one zone)	
	Zone	Usage factor	Lighting (W)	Usage factor	Lighting (W)
00:00 - 06:00	All	0	-	0	-
06:00 - 07:00	Dormitories	1	64.8	0.91	71.6
07:00 - 08:00	Public Area	1	71.6	1	71.6
08:00 - 17:00	All	0	-	0	-
17:00 - 22:00	Public Area	1	71.6	1	71.6
22:00 - 23:00	Dormitories	1	64.8	0.91	71.6
23:00 - 24:00	All	0	-	0	-

2.5 Base constructions

In order to analyse the effect of thermal mass, three different constructions are proposed. One of them is the construction of the reference building, the second is the same reference construction with added EPS insulation on the exterior, and the third is a wooden frame construction with batt insulation. The nomenclature for the base constructions will be regarded as *heavy (reference)* for the reference building, *heavy_ins* for the heavy weight insulated construction and *light_ins* for the light weight insulated building. The three base constructions have a single clear glass, and no exterior shading elements are used.

2.5.1 Heavy weight non-insulated building (reference)

The walls are built with a 10 cm concrete block which is covered on the exterior face with a cement plaster, and on the interior a gypsum layer is applied. The roof consists of a reinforced concrete slab of 12 cm which is sealed on the top with a plastic membrane. The floor is not insulated, the concrete slab is casted on top of a backfill material, and the floor finish is assumed to be tiles.

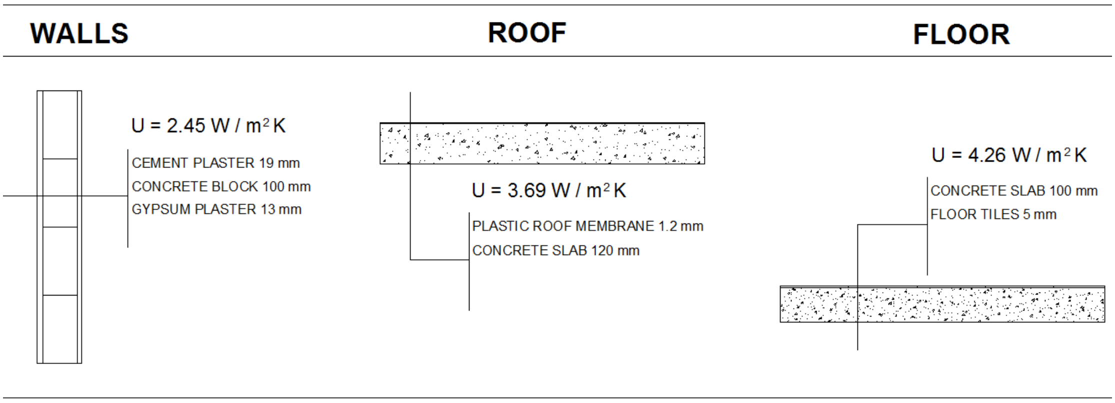


Figure 2.9 Wall, roof and floor construction of the heavy weight non-insulated building (reference).

2.5.2 Heavy weight insulated building

The same construction as in the reference building is used. EPS insulation is added on the exterior of the walls, on top of the roof slab, and in between the ground and the floor slab. The thermal transmittance is greatly reduced when insulation is placed. The amount of thermal mass is the same, but it will become much more effective since the exterior insulation will prevent heat transmittance, and the concrete elements will be able to store more heat.

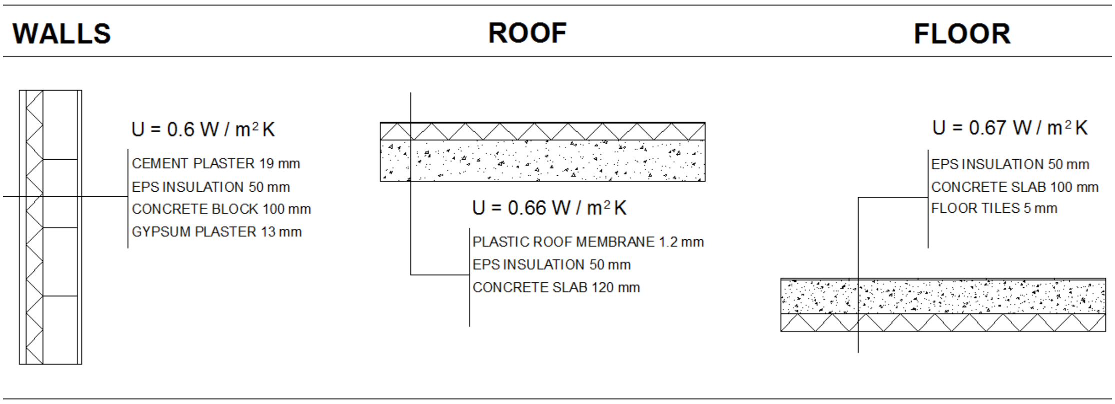


Figure 2.10 Wall, roof and floor construction of the heavy weight insulated building.

2.5.3 Light weight insulated building

A third construction with a lower thermal mass is proposed. Walls and roof are made of a wooden frame structure with batt insulation. Walls and roof were inspired from frame construction details from Thallon (2000) The floor slab is considered to be made out of concrete.

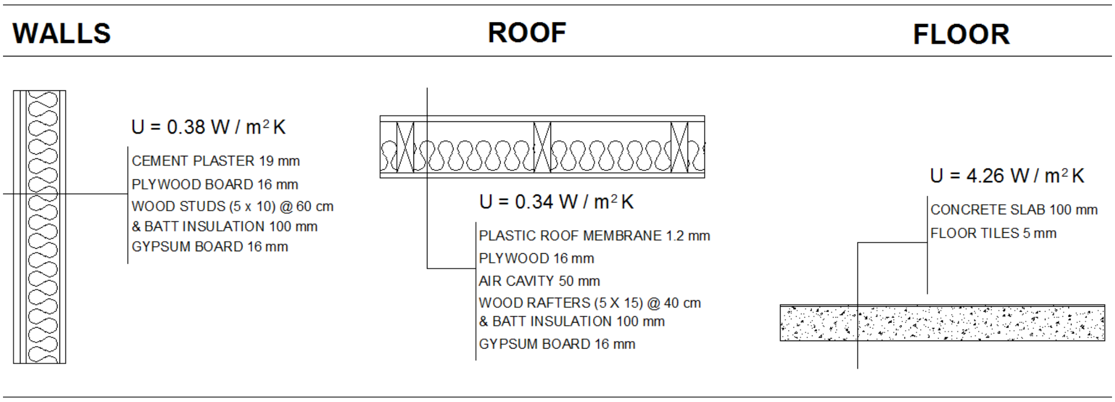


Figure 2.11 Wall, roof and floor construction of the light weight insulated building.

2.5.4 Temperature time response of the base constructions

In order to visualize the temperature response of the three constructions, the time constant of the buildings is estimated using the software IDA ICE 4.5.1. The indoor temperature was maintained at 10 °C until equilibrium was reached. A temperature step change was introduced so the outdoor temperature was suddenly dropped down to 0 °C. According to (Hagentoft, 2001) the time constant can be estimated by the following expression: $\left(1 - e^{-t/t_c}\right)$. Where t is the time period of study and t_c is the time constant of the building. Assuming that $t = t_c$ then the expression becomes $(1 - e^{-1})$ which corresponds to a 63 % temperature decay.

The temperature response of the reference building is faster than in the other two constructions as it was expected, see Figure 2.12. Something interesting is that the light weight insulated building has a larger time constant than the heavy weight insulated building. The reason for this is because the light weight insulated building is not insulated from the ground, see Section 2.5.3.

Thermal mass is in equilibrium when the indoor temperature is constant at 10 °C. At the moment when the outdoor temperature is dropped down to 0 °C, thermal mass will start releasing the stored heat to the air. The floor slab of the heavy weight insulated building will reach thermal equilibrium faster, and will stop providing heat to the room after some hours. The slab in the light weight construction is not insulated, therefore it will continue heating the space by transferring heat stored in the ground to the air in the room. This means that in the long term, the temperature response in the light weight construction is slower than in the heavy weight

Nevertheless, comfort is studied by the temperature variations in a day, and it can be observed that within a time period of 24 hours the temperature drop of the light weight insulated building will be faster than in the heavy weight insulated.

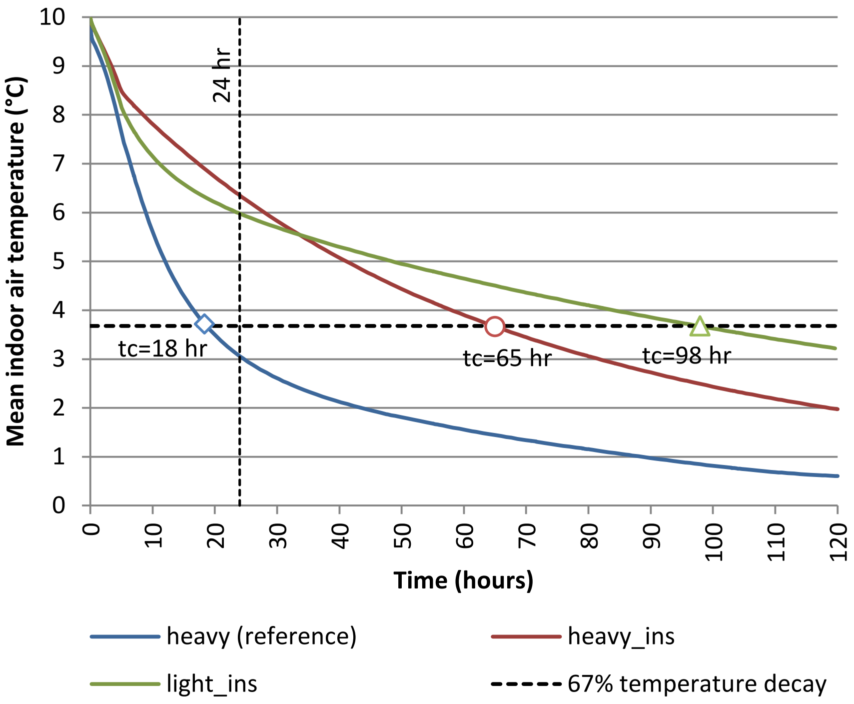


Figure 2.12 Temperature response for the three base constructions.

2.6 General considerations

2.6.1 Defining comfort

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment" (Szokolay, 2004). Thermal comfort depends on physiological and psychological factors which are illustrated in Table 2.16. As we can see, thermal comfort is influenced by a number of variables given by the climate conditions, type of clothing, and physical activity among others. The perception of thermal comfort is not easy to determine and it varies from person to person.

Table 2.16 Variables affecting thermal comfort (Szokolay, 2004).

Environmental	Personal	Contributing factors
Air temperature	Metabolic rate (activity)	Food and drink
Air movement	Clothing	Body shape
Humidity	State of health	Subcutaneous fat
Radiation	Acclimatisation	Age and gender

The parameter that will be used in order to measure the impact of thermal mass on indoor thermal comfort is the operative temperature which considers the air temperature and the mean radiant temperature of the surrounding surfaces.

A temperature comfort zone should be defined in order to assess the quality of thermal environment depending on the number of hours for which the operative temperature is within this temperature range. For this study, the comfort zone is considered to be between 20 °C and 25 °C.

2.6.2 Type of soil

There is a large variety of type of soils from place to place, the properties can be totally different close to a body of water and a few hundred meters away at the foot of a rocky hill. According to (FAO, 2009), Regosols are a common type of soil in the area of Mexico city while in Veracruz, Acrisols are dominant. Regosols are classified as a 'sandy loam' composed by roughly 70 % sand, Acrisols are refered as 'clay (heavy)' containing nearly 80 % of clay and silt. According to these soil descriptions it is chosen to use the thermal properties illustrated in Table 2.17.

Traditionally in Mexico the top layer of organic soil is removed and replaced by a compacted backfill, and on top of it the concrete floor slab is poured. It is assumed a backfill of 30 cm with properties similar to a 'sand or gravel soil'.

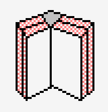
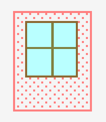
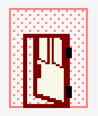
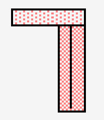
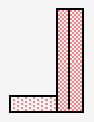
Table 2.17 Soil thermal properties (Hagentoft, 2001).

City	Type of soil	Density	Specific Heat	Thermal conductivity	Thermal diffusivity
		ρ (Kg/m^3)	C_p (J/kg K)	λ (W/m K)	a (m^2/s)
Mexico City	Sand or Gravel	2000	1000	2.00	1.00E-06
Veracruz	Clay or Silt	1600	1875	1.50	5.00E-07

2.6.3 Thermal bridges

Typical thermal bridges are considered for the heavy weight and light weight insulated constructions, see Table 2.18. The reference building does not have any insulation, therefore it is assumed that transmission through the envelope will be much greater, so thermal bridges can be disregarded.

Table 2.18 Typical thermal bridges (IDA ICE 4.5.1).

Type of thermal bridge	Loss factor	Image
External wall / external wall (W/K/m joint)	0.08	
External windows perimeter (W/K/m perim)	0.03	
External doors perimeter (W/K/m perim)	0.03	
Roof / external walls (W/K/m joint)	0.09	
External slab / external walls (W/K/m joint)	0.14	

Insulated wooden doors with U-value of 1 W/m^{2}K are considered for the insulated constructions. Doors in the reference building are not insulated and have a U-value of 2.4 W/m^{2}K.

2.6.4 Air infiltration through the building envelope

It is assumed a constant air flow rate of 0.5 * 1/h (air changes per hour). This value is used for a typical house in Mexico for the energy calculations of the Mexican NAMA (GIZ, 2012).

3 Parametric Study

In this section it is analysed the impact of thermal mass in energy and comfort. Free running temperature simulations in typical days are carried out in the shoebox model; comfort is analysed by means of the operative temperatures. Annual simulations are performed to estimate the energy demand.

The three base constructions described in Section 2.5 are investigated in a preliminary study. Later on, different parameters are implemented into the base constructions. It is discussed how varying these parameters affects the performance of thermal mass.

3.1 Parameters

3.1.1 Type of glass

Four different types of glass constructions are analysed with the purpose to vary the heat gains by transmission and solar radiation into the shoebox zone. The properties of the clear glass are those of the glass in the reference house. The other three types of glass are taken from data sheets from Saint-Gobain glass. The low emissivity and the solar control glass have a double pane glass construction with 15 mm argon gas insulation in between. The tinted glass is single pane with green colour. It is assumed that the window frame is 10 % of the window area with a U-value of 2.0 W/m^{2}K for the insulated glasses and 5.5 W/m^{2}K. for the single glasses.

Table 3.1 Glass properties (Saint-Gobain Emmaboda Glas).

Glass properties	Single clear	Low-e	Solar control	Single tinted
Built up (mm)	3	4-15-4	6-15-4	5
Thermal transmittance U (W/m^2 K)	5.6	1.1	1.1	5.8
Solar transmittance g (-)	0.87	0.63	0.41	0.63
Primary transmittance T (-)	0.83	0.54	0.38	0.53
Light transmittance LT (-)	0.9	0.79	0.68	0.77

3.1.2 Exterior shading

According to (Reardon, et al., 2010), in a temperate climate, solar radiation heat gains are desirable in winter in order to heat the space, but not in summer since temperatures can be too high. On the other hand, in a warm climate, solar radiation should be avoided all year round. Therefore two different shading strategies are proposed, one for a temperate climate (Mexico city), and the other for a tropical climate (Veracruz), see Table 3.2. The size of the shading elements was suggested by using a graphic method where shading masks were drawn on stereographic diagrams, for a detailed explanation see Appendix 8.6.

Table 3.2 Length of exterior shading elements in Mexico city and Veracruz.

Exterior shading length (cm)					
Location	Type	South	North	East	West
Mexico city	Horizontal	41	-	-	-
	Vertical	-	30	-	-
Veracruz	Horizontal	80	-	80	80
	Vertical	-	30	-	-

It should be noticed that the size of the shading elements depends on the dimensions of the window. The shading sizes in Table 3.2 are designed for the type of window used in the shoebox model which has dimensions of 1.00 x 1.20 m. In Figure 3.1 it is shown the shading strategy on the south and north facades in Mexico city.

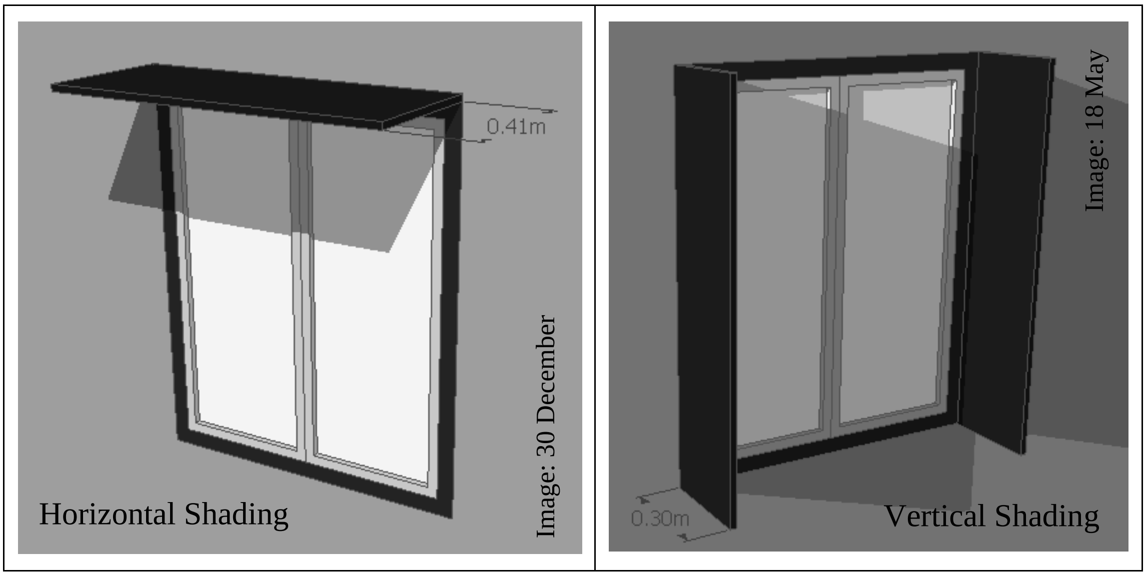


Figure 3.1 Horizontal and vertical exterior shading elements, Mexico city.

3.1.3 Natural ventilation

Temperature induced natural ventilation is also investigated. It is assumed that windows open at 18:00 hr. in the evening and they remain open until 08:00 hr. in the morning the next day when people go to work. The strategy for Mexico city is to open two windows, one in the north and one in the south façade as it is shown in Figure 3.2. For the city of Veracruz, all windows in the north and south façades are opened. It should be noticed that air velocity pressure coefficients are not considered.

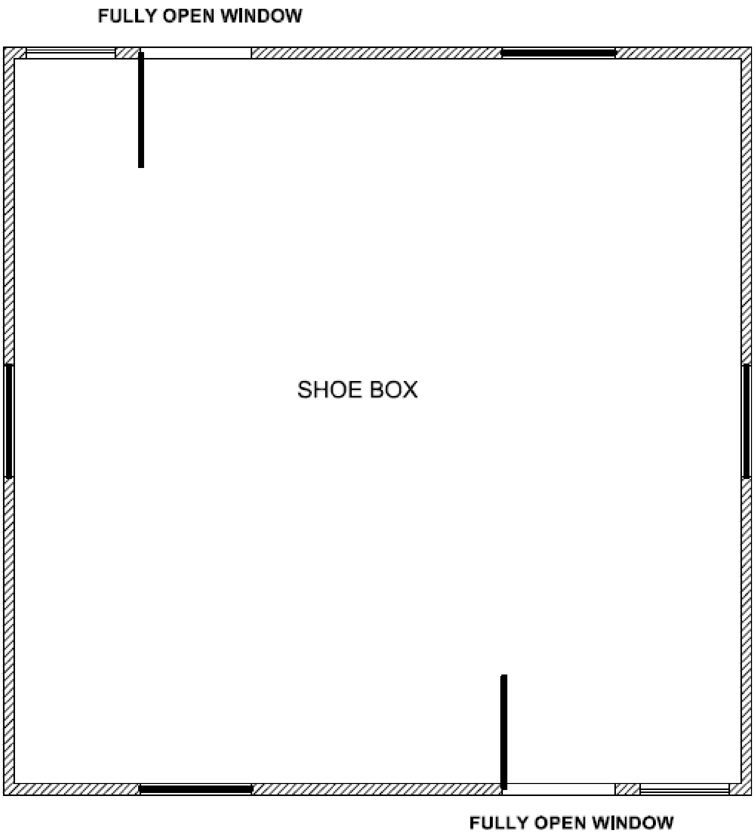


Figure 3.2 Window opening for natural ventilation, Mexico city.

3.1.4 Window-Wall-Ratio (WWR)

Now it is investigated at which extent an increase in window size would affect the energy and comfort in constructions with different thermal mass. The area of the windows is increased 80 %. The windows in the shoebox model had a width of 1 m, so now they are increased to 1.80 m as it is shown in Figure 3.3.

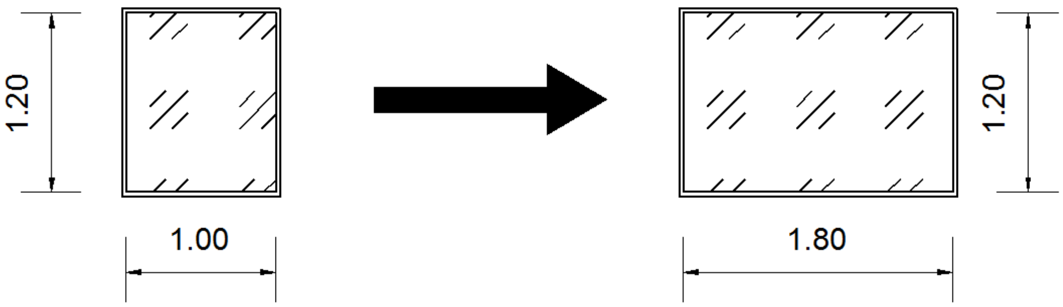


Figure 3.3 Window area increase to 80 %.

An area increase of 80 % in all windows will result in a 20 % window-wall ratio, see Table 3.3.

Table 3.3 Window-wall-ratio with an increased window area of 80%.

Shoebox	Facade				All Facades
	South	East	West	North	
Wall Area (m^2)	16.25	16.25	16.25	16.25	65.00
Window Area (m^2)	2.40	1.20	1.20	2.40	7.20
WWR reference	0.15	0.07	0.07	0.15	**0.11**
(+) 80% window area (m^2)	4.32	2.16	2.16	4.32	12.96
WWR	0.27	0.13	0.13	0.27	**0.20**

3.2 Temperate climate, Mexico city.

3.2.1 Preliminary study

The number of hours in a typical season day that operative temperature falls within an acceptable comfort range of 20 to 25 °C is shown in Figure 3.4. The heavy weight insulated building achieves more time within the comfort range than the other two constructions in winter and autumn, however, in summer the indoor temperature is too high falling above 25 °C all the time.

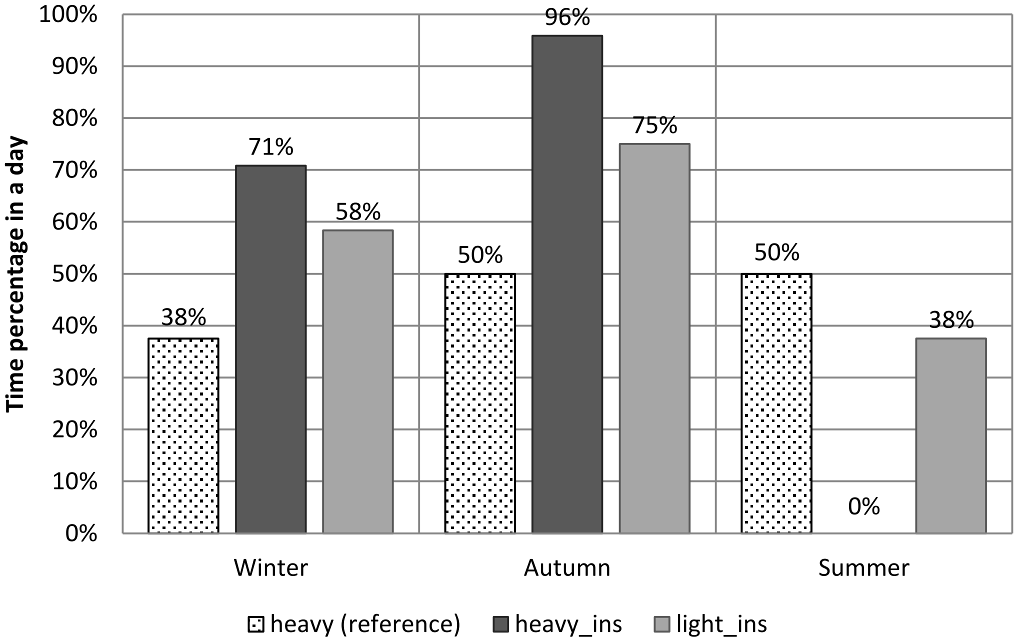


Figure 3.4 Time percentage in a typical season day when operative temperature is within the range of 20 to 25 °C. Free running temperature, Mexico city.

The relation between the outdoor climate and the temperature response in the three buildings is shown in Figure 3.5. The indoor temperature is more stable in the heavy weight insulated building due to its higher thermal mass which will regulate the temperature variations.

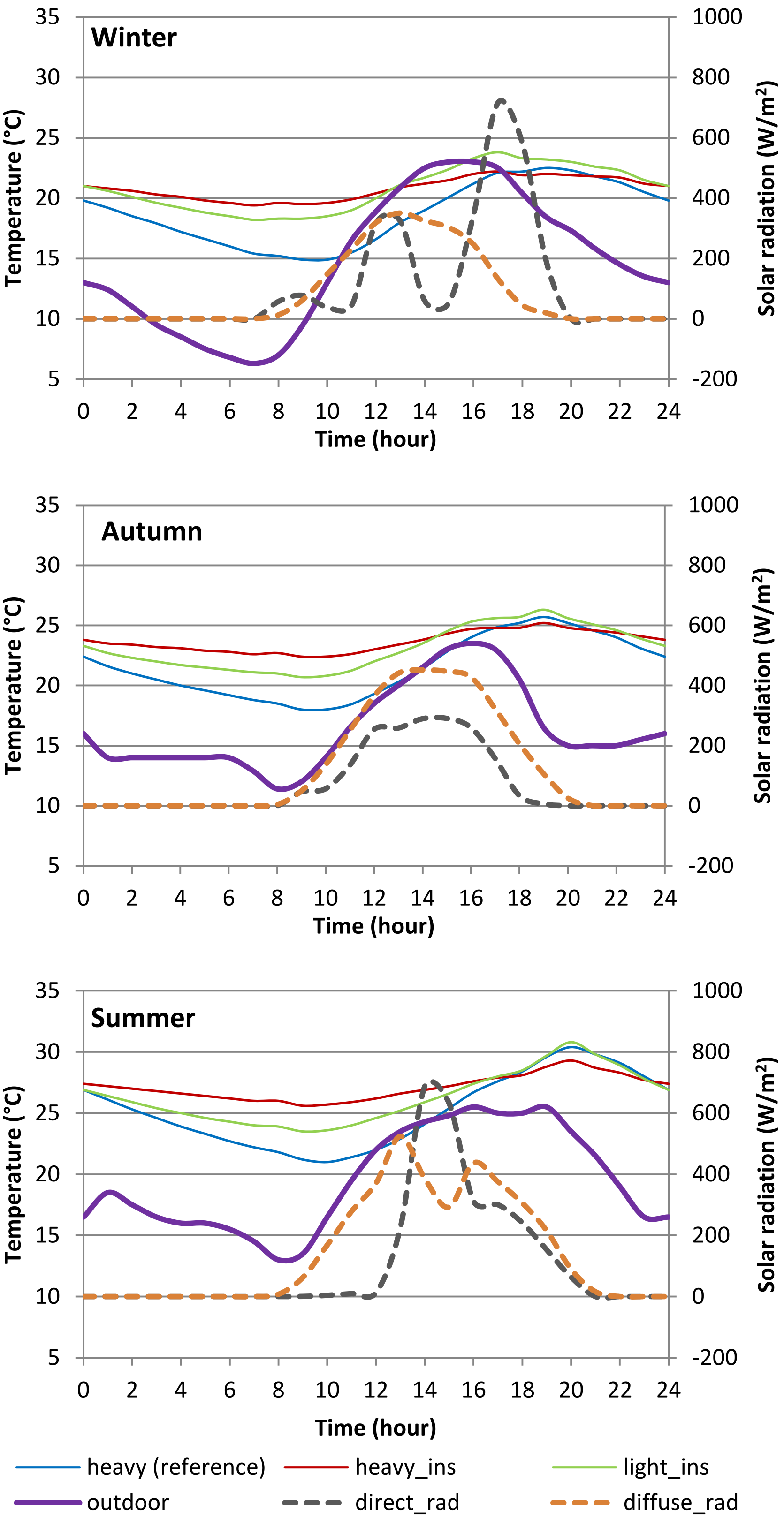


Figure 3.5 *Indoor operative temperature response in the three base constructions. Outdoor climate (mean air temperature, direct solar radiation and diffuse solar radiation on horizontal surface). Free running temperature simulations, Mexico city.*

Operative temperature distribution for the three base constructions over a typical winter, autumn, and summer day is shown from Figure 3.6 to Figure 3.8. The heavy weight insulated construction has a slower time temperature response which allows a narrow distribution and thus a more stable temperature range. In contrast the heavy weight non-insulated construction has a faster response being the reason that the temperature distribution over a day is so large.

In winter, the higher thermal mass of the heavy weight insulated building is beneficial. Thermal mass stores heat from the air and from incoming solar radiation during the day, and releases this heat back to the room at night when the outdoor temperature is lower. In this way a more stable indoor temperature is achieved, and more number of hours falling within the comfort range are met.

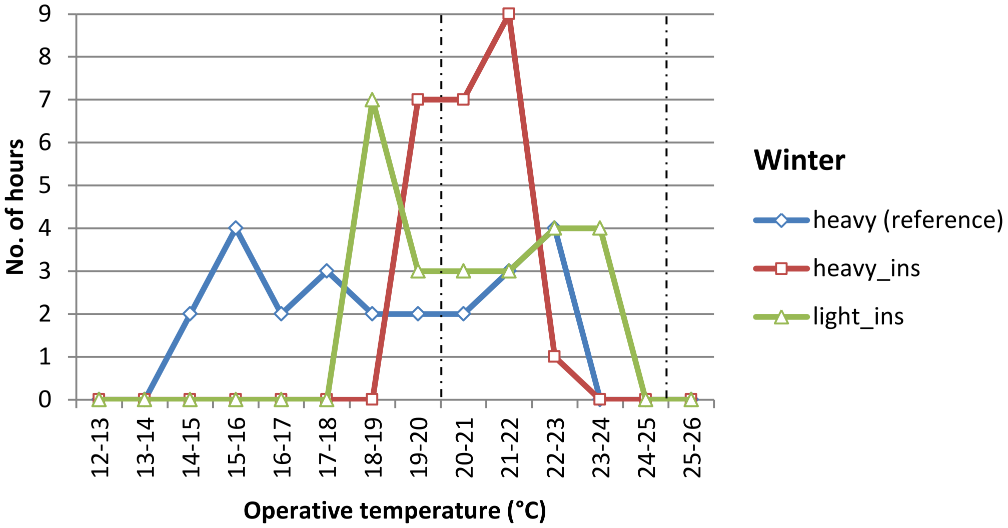


Figure 3.6 Number of hours distribution of operative temperatures in a typical winter day. Free running temperature, Mexico city.

More comfort hours are achieved during the shoulder seasons of autumn and spring. The heavy weight insulated construction will keep operative temperatures within the comfort limits most of the time, see Figure 3.7.

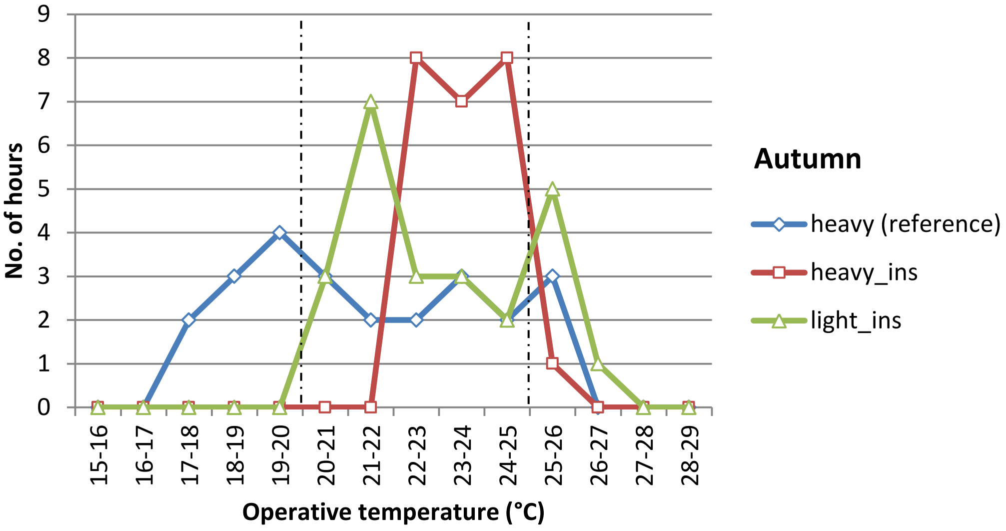


Figure 3.7 *Number of hours distribution of operative temperatures in a typical autumn day. Free running temperature, Mexico city.*

In summer, the temperature in the heavy weight insulated construction falls above the comfort limit of 25 °C all the time. Even though thermal mass helps to reduce temperature variations, it is only beneficial as soon as it provides a temperature within the comfort limits. The reference building would be preferable in summer, since it achieves more hours within the temperature comfort range.

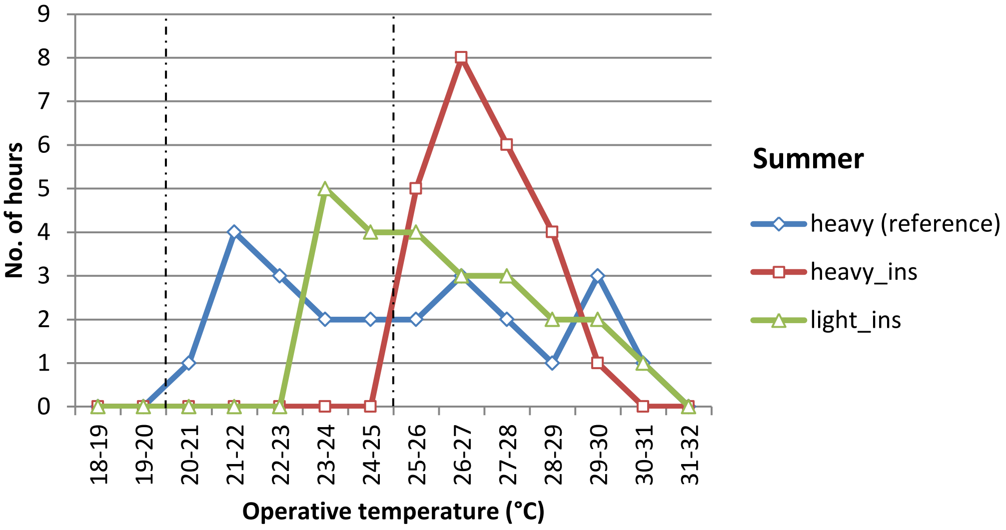


Figure 3.8 *Number of hours distribution of operative temperatures in a typical summer day. Free running temperature, Mexico city.*

From these distributions is implied that in a climate like Mexico city there is a demand for heating in winter and cooling in summer. Annual energy demand in the three construction types is estimated by adding heating and cooling devices and running simulations over the whole year, see Figure 3.9.

In a heavy weight non-insulated construction as it is the reference building, heating is much larger compared with the insulated constructions. The added insulation will considerably decrease both the heating and cooling demand, therefore insulation is so important.

From Figure 3.7 and Figure 3.8 it was seen that the heavy weight insulated building is warmer in summer but cooler in the shoulder seasons of spring and autumn. In consequence, the cooling demand of the heavy weight insulated building over a whole year period will be less than in the light weight insulated building as it can be seen in Figure 3.9.

Thermal mass helps to reduce the energy demand since it assists the cooling and heating units by absorbing and storing heat during the day, and releasing it back to the air at night.

Another advantage of thermal mass is that the size of cooling and heating devices can be smaller. As it was seen from Figure 3.6 to Figure 3.8, the minimum and maximum temperatures in the reference building and the light weight insulated building are larger than in the heavy weight insulated building, thus they might need as well larger cooling and heating units with a higher capacity.

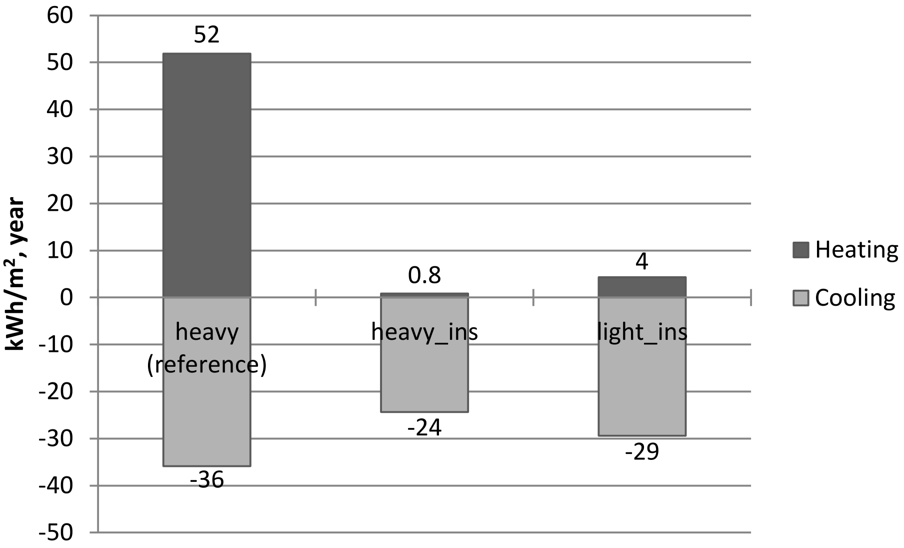


Figure 3.9 Annual energy demand in the three base constructions. Air temperature control set points: 20 – 25 °C, Mexico city.

The monthly energy demand of the insulated constructions is shown with bars on the left vertical axis in Figure 3.10. The energy used by the light weight building is subtracted from the energy used by the heavy weight building, in this way the lines “heating difference” and “cooling difference” are obtained. When these lines are positive on the right vertical axis, then the heavy weight insulated construction performs better since it demands less energy. When the lines are negative, the light weight building demands less energy. As it can be seen in the graph, the performance of the heavy weight insulated building is better over the whole year, it is just in May and June when the light weight insulated building requires less cooling energy.

From this graph can be confirmed that the selection of typical days was correct since December, October, and May are representative months of the energy consumed in low, middle and high temperature seasons. It is important to mention that seven months along the year have a behavior as that of a middle season, so temperatures will be within the comfort limits most of the time as it was seen from Figure 3.7. December and January behave like a winter season, while April, May and June represent the summer.

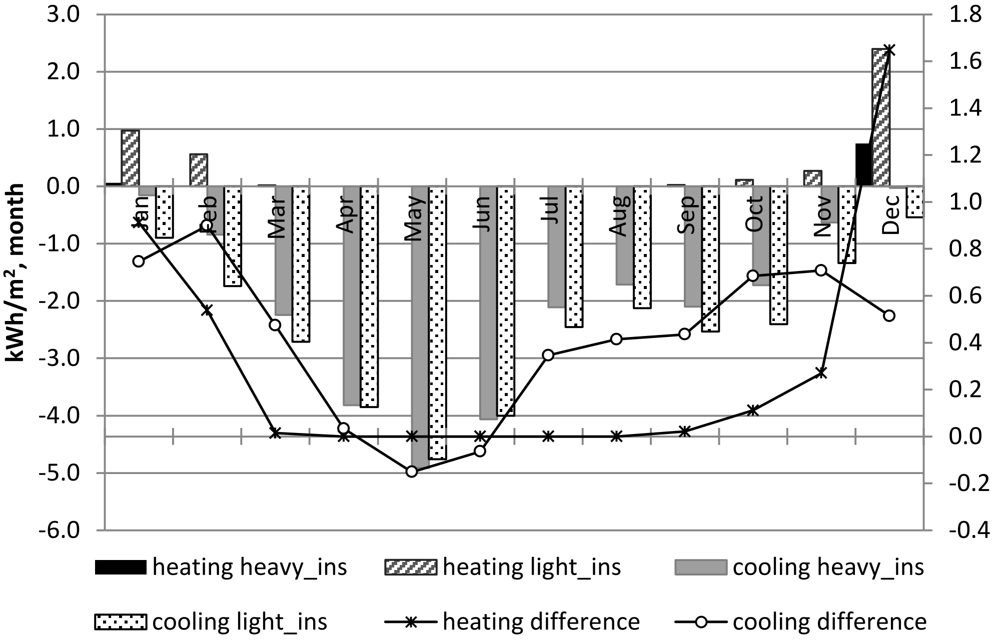


Figure 3.10 Monthly energy demand in a heavy weight insulated and a light weight insulated building. Air temperature control set points: 20-25 °C, Mexico city.

From this section has been found that in this type of climate, thermal mass is beneficial since it increases the number of comfort hours, and consequently it reduces the energy demand along the year. Temperatures tend to be more time above the upper comfort limit so more cooling than heating is needed. In the following sections will be investigated how the different parameters can be used on the insulated constructions in order to bring temperatures down to the comfort limits.

3.2.2 Type of glass

The four different types of glass described in Section 3.1.1 are analysed in the heavy weight insulated and light weight insulated constructions. Typical day simulations are done in order to study how the type of glass affects the heat gain of thermal mass and consequently affects the operative temperatures. In Figure 3.11 it is shown the range of temperatures obtained with the different glasses, so only the glasses achieving lower and higher temperatures are shown. In Appendix 8.5 can be found the figure showing the temperatures achieved with all four glasses.

The low-e glass will allow solar radiation to enter the building and heat the thermal mass. Its insulated double glass will prevent heat going out, similar to a green-house effect. This will make the low-e glass to generate higher indoor temperatures than other types of glass, therefore it is the one achieving more comfort time in winter but less in summer.

The solar control glass will decrease heat gains from solar radiation and in consequence it will achieve lower temperatures in summer than other glasses. Its performance in winter is poor since solar radiation is desirable in this season of the year, but it is still better than the tinted glass since its insulated double glass will decrease heat losses to the outside. From Figure 3.9 can be seen that annual cooling demand is larger than heating, thus glass performance in the middle seasons and summer is of greater importance than in winter; this will make the solar control glass a better option regarding energy savings.

Single clear glass has a poor performance both in winter and summer since its high U-value allows more heat exchange with the exterior, furthermore it does not have a solar reduction factor. Tinted glass has the poorest performance in winter since it deacreases the sun radiation coming in, and also allows heat losses going out through its single pane glass.

As it can be observed, the lines of the light weight building are more inclined than those of the heavy weight building, which means that the temperature span over the day is larger in a light weight construction. A heavy weight building will give more comfort time in winter and middle seasons while a light weight counstruction will achieve more comfort hours in summer.

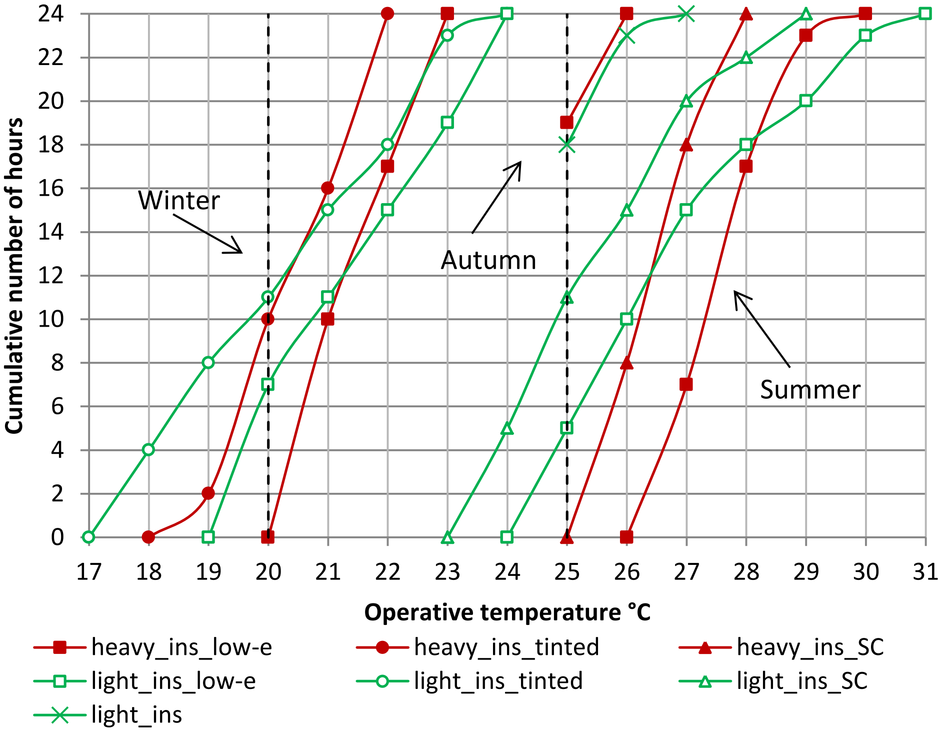


Figure 3.11 Cumulative number of hours of operative temperatures with different types of glass. Free running temperature simulations in a typical winter and summer day, Mexico city.

From the energy simulations results in Figure 3.12, it can be observed that thermal mass can compensate for the poor U-value performance of single pane glasses. By comparing the two constructions with tinted glass, it can be observed that a heavy weight building with a higher thermal mass will demand less energy than a light weight building. Single pane glasses will allow more heat leaving and coming into the room, so temperature variations in the room will be larger. Thermal mass stores heat and compensates for the larger temperature variations produced by single pane glasses.

Another important issue from Figure 3.12 is that the benefit of thermal mass is reduced when a better performing glass is in place. As it can be observed, the energy demand of both types of construction is nearly the same when solar control glass is used. So thermal mass shows to be more effective in combination with a single glass when temperature variations are larger.

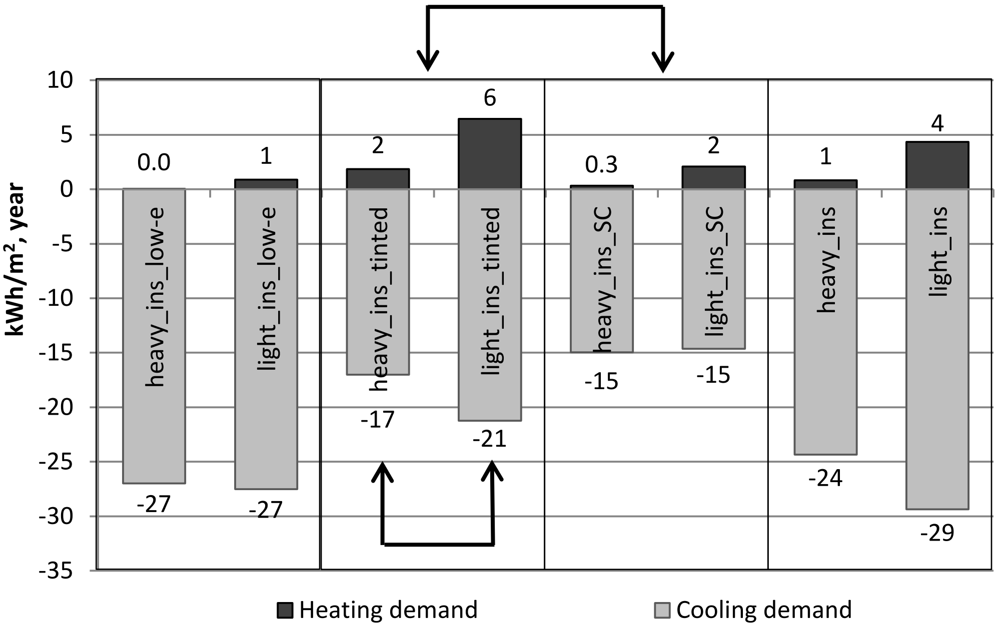


Figure 3.12 Annual energy demand in the heavy and light weight insulated buildings with different types of glass; mean air temperature control set points: 20 – 25 °C, Mexico city.

3.2.3 Ground insulation

Previous simulations have been done with an insulated floor slab in the heavy weight insulated construction (heavy_ins) and a non-insulated floor slab in the light weight insulated building (light_ins), see Section 2.5.

The effect of the ground insulation was analysed and it was found that a non-insulated slab will reduce indoor temperatures by removing heat to the ground. The temperature of the ground under the floor slab should be something in between the annual mean and the monthly mean outdoor temperatures, which would be approximately 15 °C in winter and 18 °C in summer. Considering that indoor temperatures are higher than the ground temperature according to Figure 3.5, then a non-insulated floor slab will allow a constant heat outflow through the ground which will be lower in winter and higher in summer due to the temperature driving potential in every season.

In Figure 3.13 it is shown the energy demand comparison in the heavy weight insulated building with or without ground insulation. It can be observed that with an insulated slab the heating demand is lower in December, January and February. By removing the ground insulation, the cooling demand will be lower all year round. The overall energy demand is less with a non-insulated floor slab, therefore for further analysis in Mexico city, insulation will be removed from the heavy weight insulated construction.

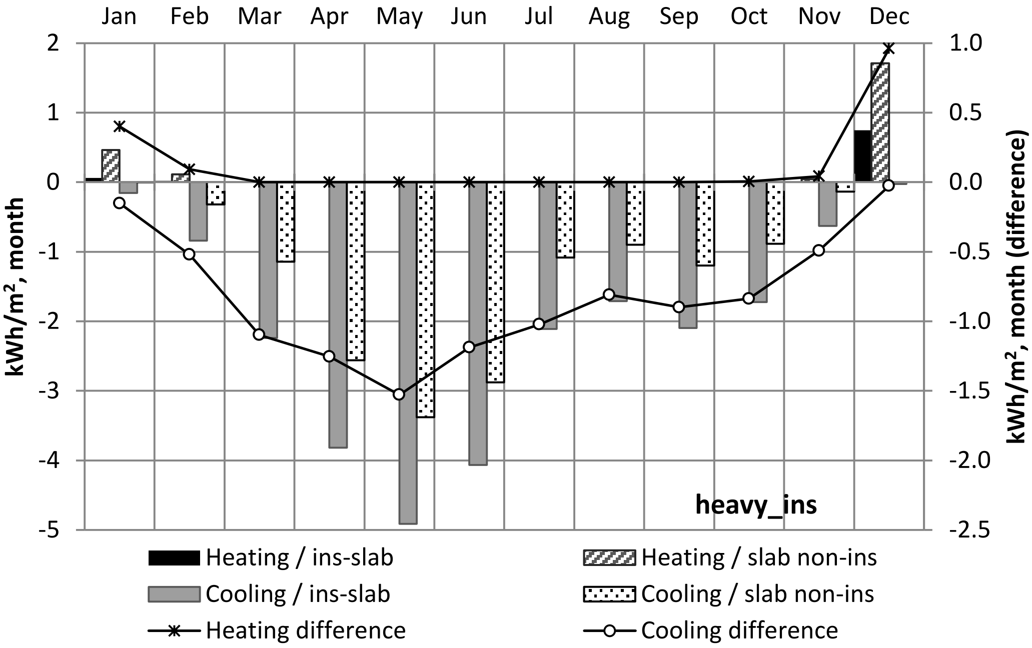


Figure 3.13 Annual energy demand in the heavy weight insulated construction with or without ground slab insulation. Mean air temperature control set points: 20 – 25 °C, Mexico city.

3.2.4 Exterior shading

It was discussed previously that in a temperate climate like Mexico city, the winter sun is desirable in order to heat the thermal mass inside the room. A solar shading technique intended to shade the summer sun and let the winter sun in was proposed in Section 3.1.2. Nevertheless, the exterior shading devices will also shade a small portion of the direct and diffuse solar radiation in winter.

Exterior solar shading reduces indoor temperatures in summer by reducing the solar heat gains, therefore comfort time in summer will increase. Temperatures will also be reduced in winter, so comfort time will decrease in this season. In autumn, temperatures in the light weight construction will be slightly below the comfort limit for a small portion of time when using a tinted glass, see Figure 3.14.

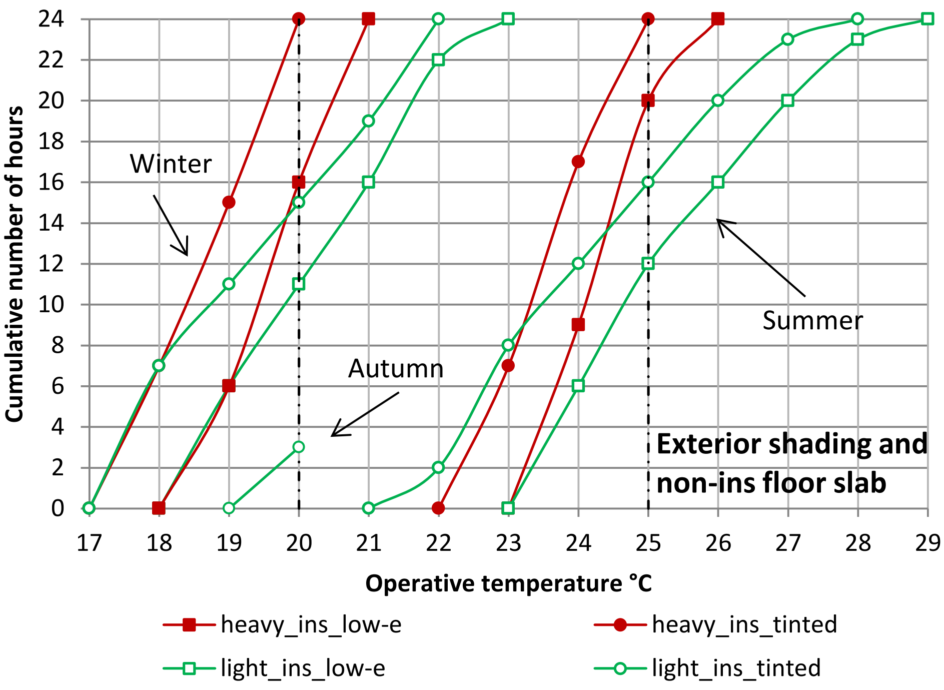


Figure 3.14 Cumulative number of hours of operative temperatures with different types of glass and exterior shading. Non-insulated ground slab. Free running temperature simulations in typical days, Mexico city.

Exterior shading will increase the heating demand in winter and reduce the cooling in summer, see Figure 3.15. The increment in heating is nearly the same in both constructions. The reduction in cooling demand is larger in the light weight insulated construction than in the heavy weight. This confirms again that thermal mass is less effective when temperature variations are reduced. By adding the solar shading, the solar heat gains are reduced and temperatures become more stable so the benefit of thermal mass is less.

The increase in heating demand is larger in the single pane glasses since they will allow larger heat losses to the outside than the insulated low-e and solar control glasses. The shading is more effective in reducing the cooling demand when it is used on clear and low-e glasses which do not have a solar protection factor.

The reduction on cooling is larger than the increment on heating therefore exterior shading is considered to be beneficial.

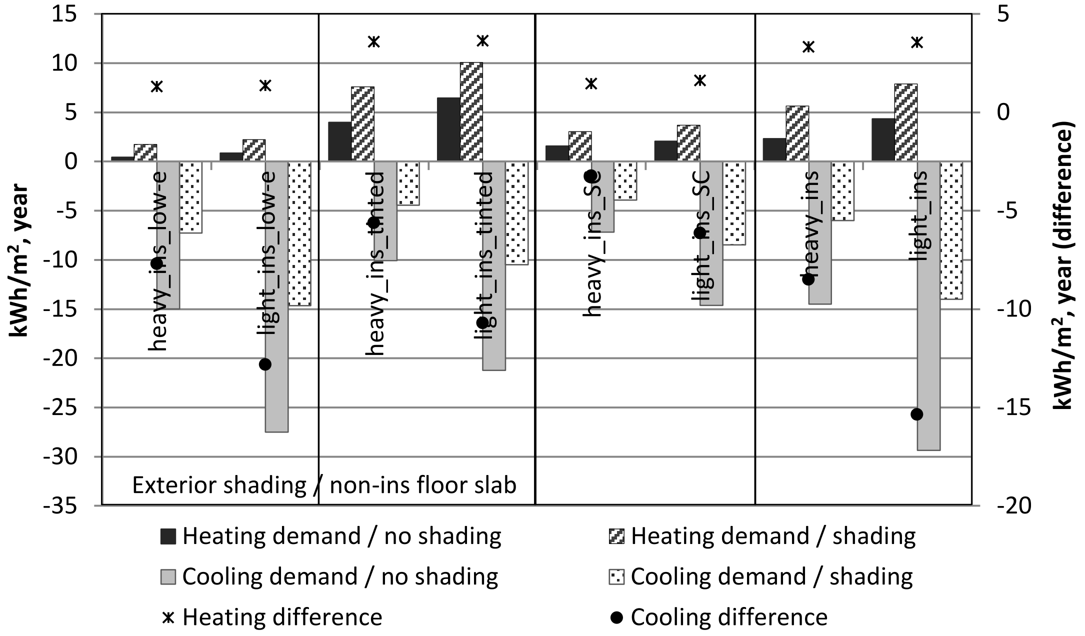


Figure 3.15 Annual energy demand with and without exterior shading. Non-insulated ground. Mean air temperature control set points: 20 – 25 °C, Mexico city.

3.2.5 Natural ventilation

In this section it is analysed the possibility to cool down the building by natural ventilation in summer. The construction with low-e glass is considered suitable for this analysis since it is the one with higher indoor temperatures in summer, so if it is possible to cool down the building with this type of glass down to 25 °C, then the other glasses will be possible as well.

In order to visualize how fast can be cooled down the two types of construction, a dynamic simulation is performed from the 17th to 19th of May. It is assumed that windows have been closed during the 17th of May and suddenly natural ventilation is introduced by opening the windows on May 18th at 18:00 hr. when people are back from work, and they remain open till the next day at 8:00 hr. in the morning when they go to work, see Figure 3.16. The light weight building cools down faster, but temperature variations are larger, so it goes up to 27 °C and down to 19 °C. The temperature response of the heavy weight building is sufficient to achieve comfort and it will keep more stable temperatures.

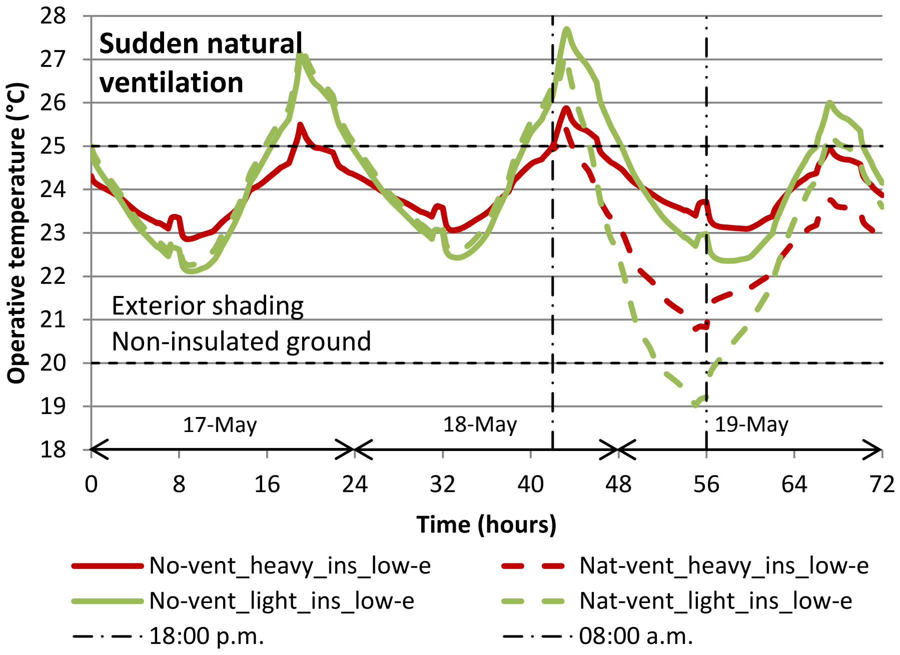


Figure 3.16 Operative temperature response from suddenly introducing natural ventilation by opening windows on May 18th at 18:00 hr. and closing them at 08:00 hr. on May 19th. Mexico city.

On Figure 3.17 it is shown how the heavy weight and light weight buildings respond to a periodic natural ventilation on the selected typical summer day in Mexico city (May 18th). It is assumed that windows are open between 18:00 hr. in the evening and 08:00 hr. in the morning. Thermal mass of the heavy weight building helps to maintain a more stable temperature and keep it within the comfort limits of 20 – 25 °C. The light weight building has a faster time response, consequently its temperature variations are larger and shows a few hours above and below the comfort temperature range.

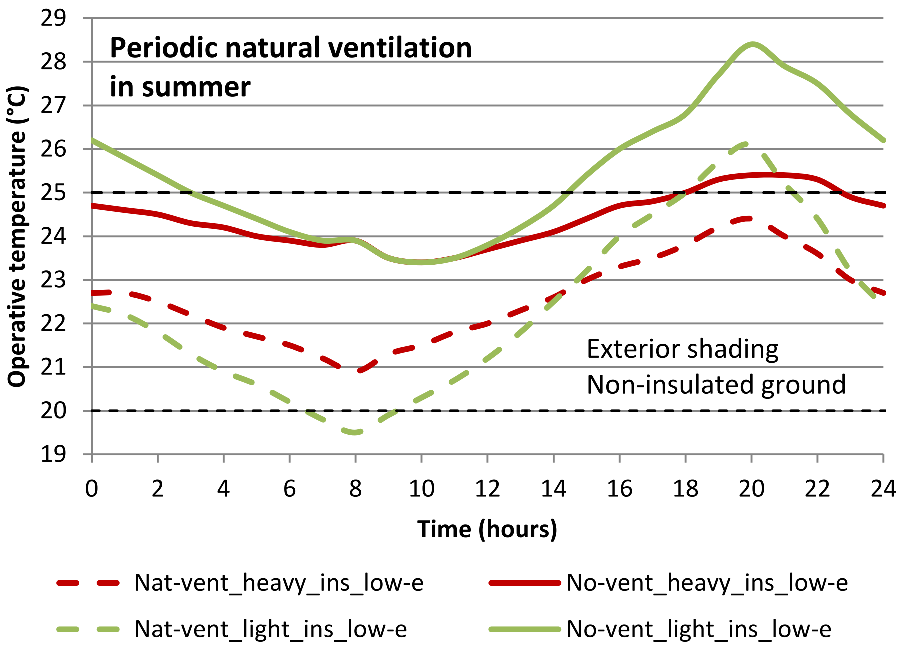


Figure 3.17 Operative temperature in a heavy and light weight insulated building with exterior shading and without ground insulation. Typical summer day with and without natural ventilation from 0:00 to 8:00 hr. and from 18:00 to 24:00 hr. Mexico city.

Temperature distribution over a typical summer day with natural ventilation is shown in Figure 3.18. The heavy weight building fits well within the comfort range while the light weight construction shows some hours outside the comfort limits of 20-25 °C.

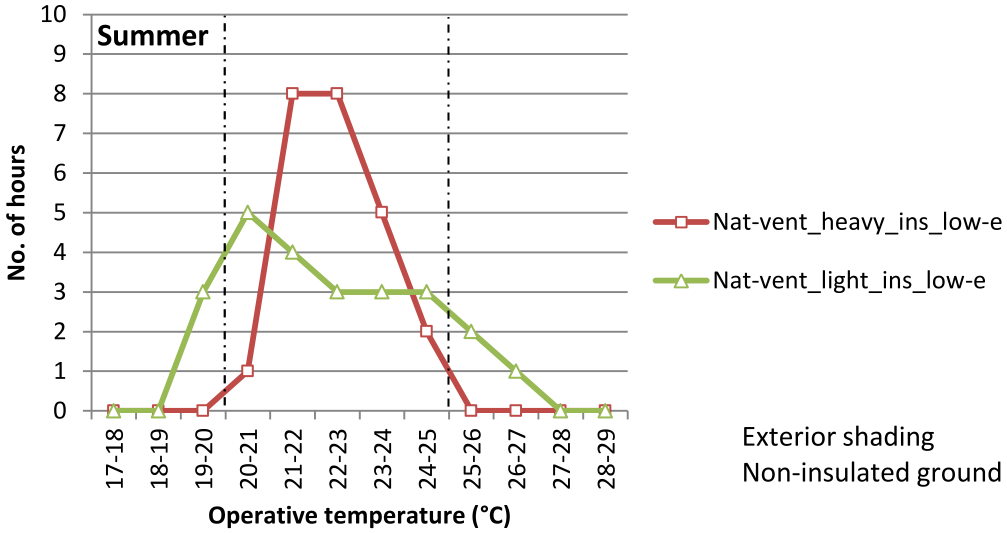


Figure 3.18 Number of hours distribution of operative temperatures in a typical summer day with natural ventilation from 0:00 to 8:00 hr. and from 18:00 to 24:00 hr. Mexico city.

3.2.6 Window-Wall-Ratio (WWR)

Assuming a possible scenario that a high glass façade building is required, then in this section it is investigated how the increase on window size affects a heavy weight and a light weight constructions. It has been discussed in the previous sections that thermal mass is more effective when temperature variations are larger, therefore in order to see the impact of thermal mass, it is chosen a model with clear glass windows, no exterior shading and a non-insulated ground. The reference building has a window wall ratio of 11 % which is increased to 20 %. After the increase in window size, also the thickness of the walls and roof will be increased from 10 and 12 cm to 20 cm each.

According to results in Figure 3.19, the light weight building is much more sensible to the increment in window size, it reaches much higher temperatures than the heavy weight construction. Increasing the window size makes temperature variations become larger, since heat gains during the day and heat losses at night are increased. Bigger windows represent less area of thermal mass, so this also contributes to increase the temperature span. When increasing the wall thickness in the heavy weight construction, it can be observed that thermal mass will slightly reduce temperatures. Further increase in the construction thickness is not helpful since the penetration depth of concrete is about 15 cm, therefore another solution could be to increase the thermal mass area by adding more internal walls.

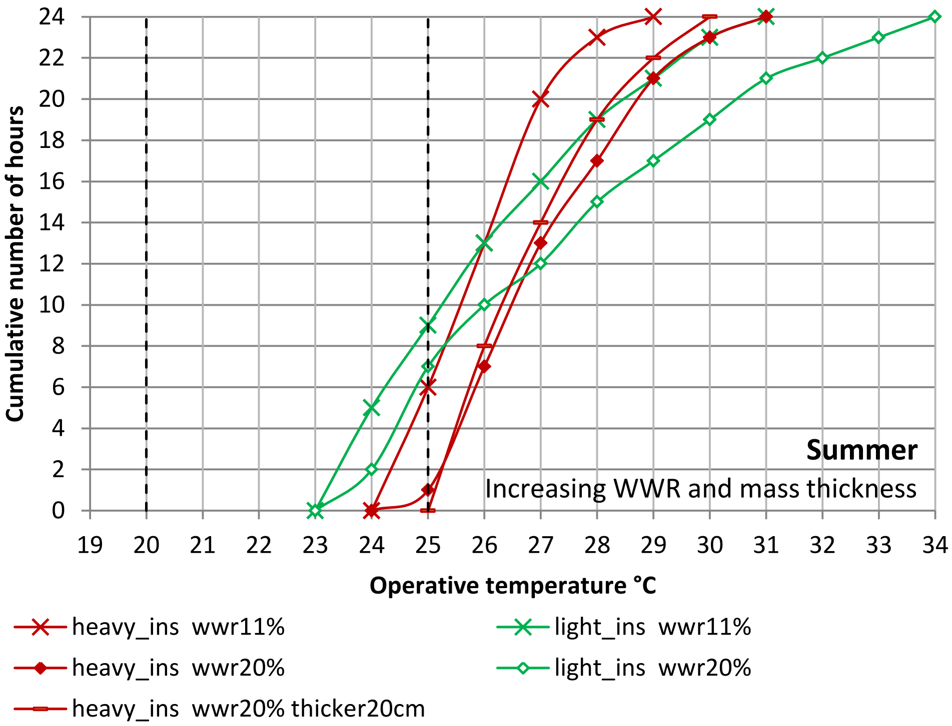


Figure 3.19 Cumulative number of hours of operative temperatures with increasing window wall ratio and thermal mass thickness. A single clear glass is used, no exterior shading and non-insulated ground. Free running temperature simulations in a typical summer day, Mexico city.

The annual energy demand of increasing the window size is shown in Figure 3.20. The energy demand increase is much less in the heavy weight construction compared with the light weight building. A heavy weight construction with a WWR of 20% demands approximately the same energy as a light weight building with a WWR of 11%. Thermal mass helps to compensate for the increased temperature variations from larger windows. Therefore, in the case of a high glass façade building, it is recommended to use thermal mass to achieve energy savings.

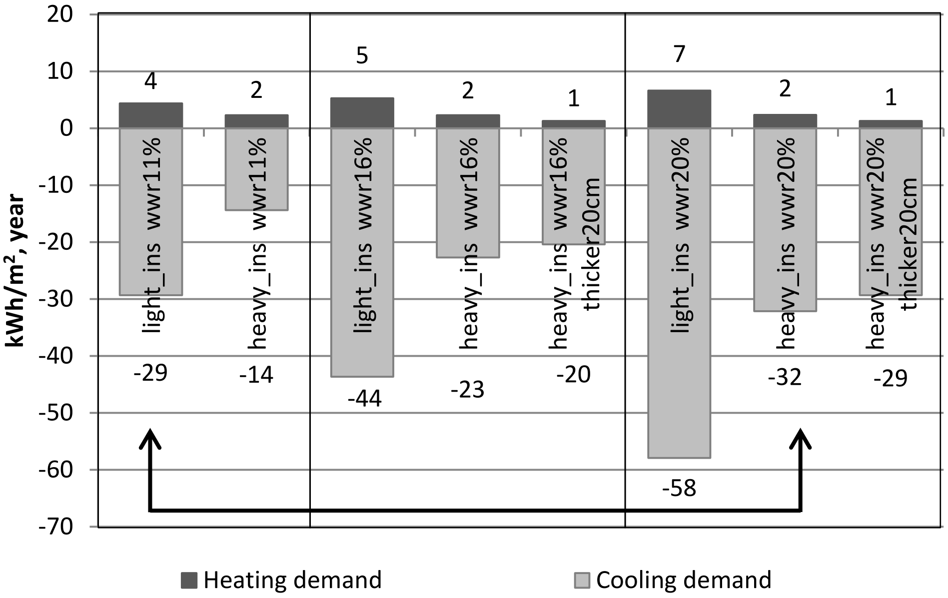


Figure 3.20 Annual energy demand in the heavy weight and light constructions with increasing window wall ratio and thermal mass thickness. A single clear glass is used, no exterior shading and non-insulated ground. Mean air temperature control set points: 20 – 25 °C, Mexico city.

3.2.7 Summary temperate climate

In a temperate climate like in Mexico city it is beneficial to use thermal mass. Indoor temperatures in winter and summer fluctuate around the acceptable comfort temperature range. Thermal mass will help to reduce temperature variations and in this way more time within the comfort limits will be achieved.

A non-insulated slab is desirable to allow heat losses to the ground and reduce the overall year energy demand.

The benefit of thermal mass is reduced when temperature variations decrease. Consequently, exterior solar shading is less effective in a heavy weight construction compared with a light weight building, yet shading is necessary to lower down temperatures within the comfort range.

Single clear glass is a good option for a temperate climate. Cooling in summer can be managed with natural ventilation. Heating can be provided with a movable electrical heater where and when it is needed. Double glass units demand less heating in winter, but the heating savings are not large enough to justify for the cost difference.

Thermal mass helps to reduce energy demand in a high glass facade building.

3.3 Tropical climate, Veracruz

3.3.1 Preliminary study

Winter is the season in Veracruz with more time falling within the comfort temperature range of 20 – 25 °C. The reference building with a heavy non-insulated construction achieves more time within the comfort range than the insulated constructions, see Figure 3.21. Temperatures in summer are too high therefore indoor comfort is not achieved for any type of construction in this season.

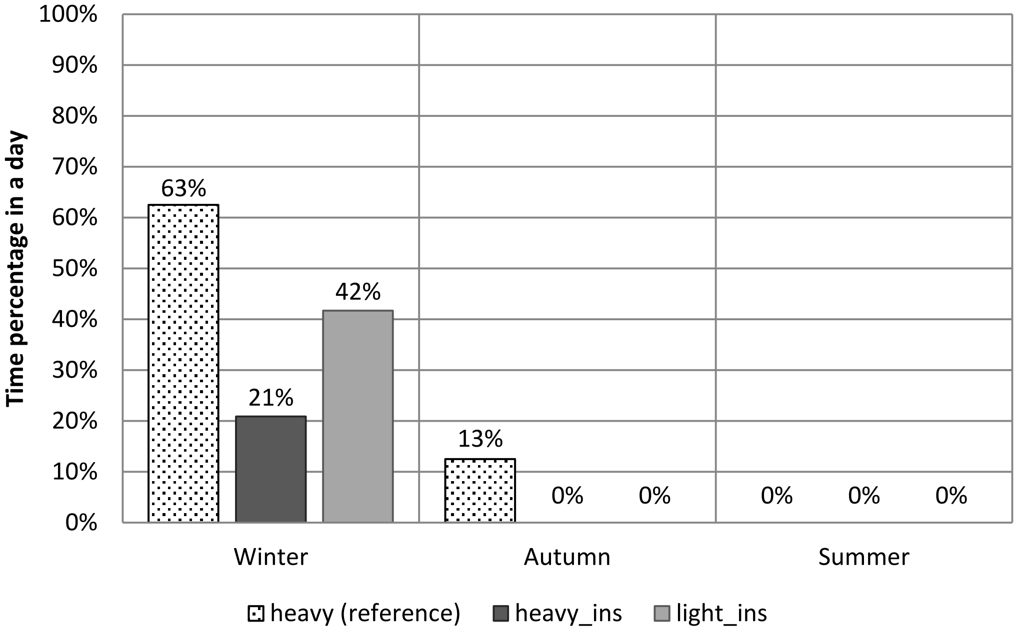


Figure 3.21 Time percentage in a typical season day when operative temperature is within the range of 20 to 25 °C. Free running temperature, Veracruz.

The relation between outdoor climate and indoor operative temperatures in winter and summer is shown in Figure 3.22. The light weight insulated building seems to be a good option, since in summer its temperature amplitude is smaller than in the reference building and lower operative temperatures are accomplished compared with the heavy weight insulated building.

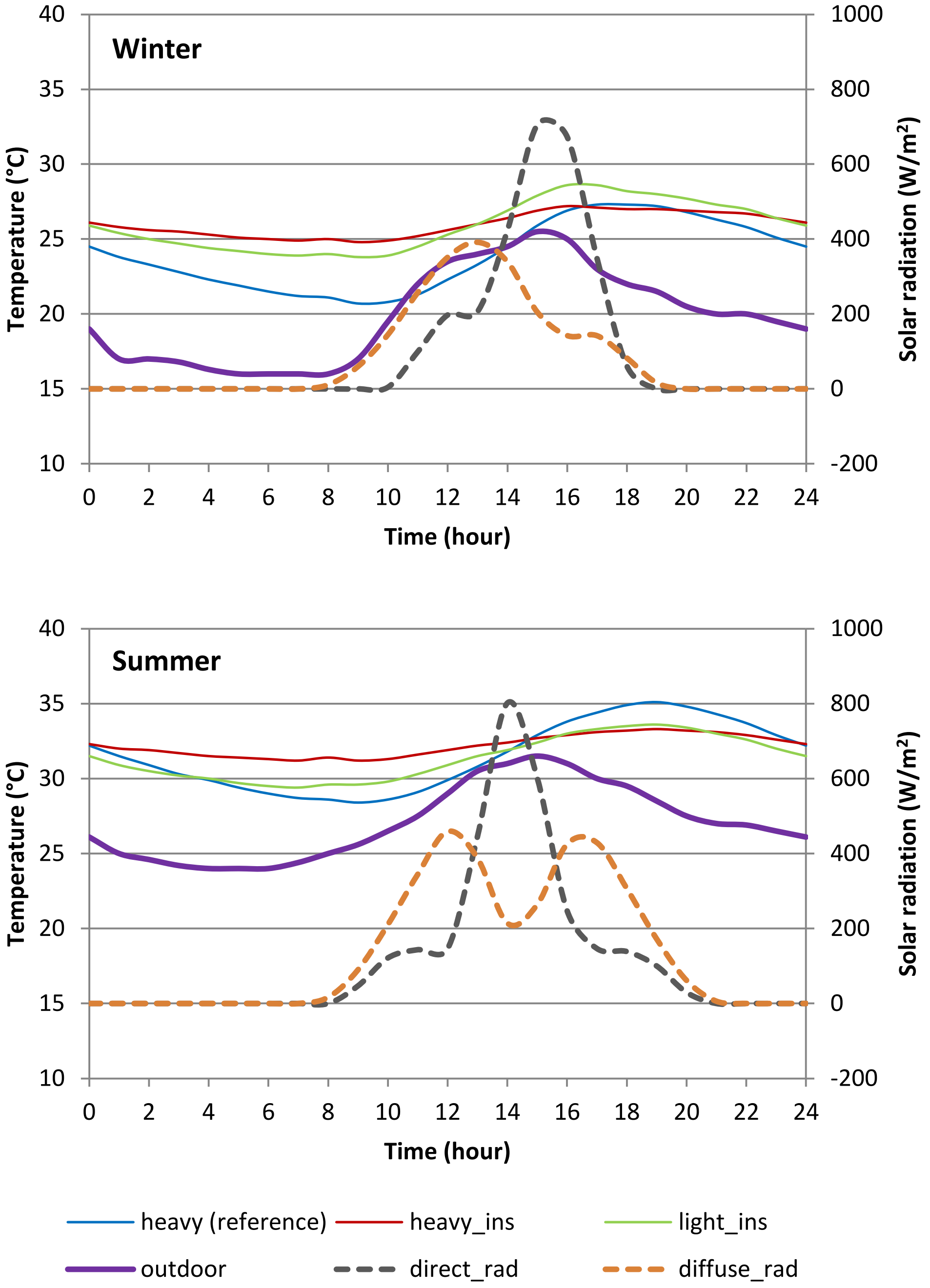


Figure 3.22 Indoor operative temperature response in the three base constructions. Outdoor climate (mean air temperature, direct solar radiation and diffuse solar radiation on horizontal surface). Free running temperature simulations, Veracruz.

The temperature distribution in the three constructions in typical winter and summer days is shown in Figure 3.23 and Figure 3.24. The winter in Veracruz has a similar behaviour as the summer in Mexico city. It is clearly shown in these graphs that in a climate like Veracruz, there will be a high demand for cooling.

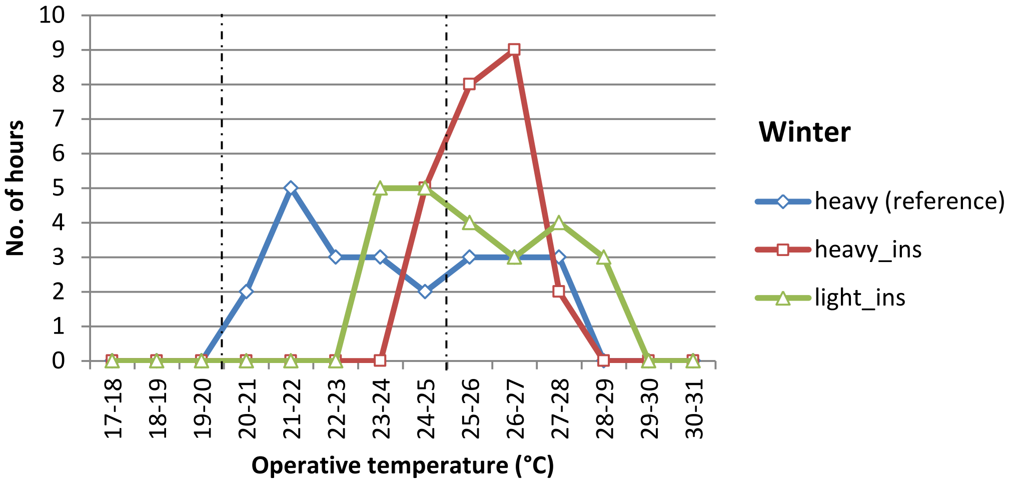


Figure 3.23 Number of hours distribution of operative temperatures in a typical winter day, Veracruz.

In the analysed typical day in summer can be observed that the highest operative temperatures for the heavy weight and light weight insulated buildings are in the same range of 33 – 34 °C, therefore the cooling unit will be of the same size. The light weight building shows to have more hours with lower temperatures; this is because low thermal mass stores less heat, therefore the building cools down faster. It should be investigated if adding features like solar shading, solar control glass, and removing the ground insulation will shift temperatures down to the comfort zone. Otherwise, thermal mass will not be useful, and a light weight construction would be preferable.

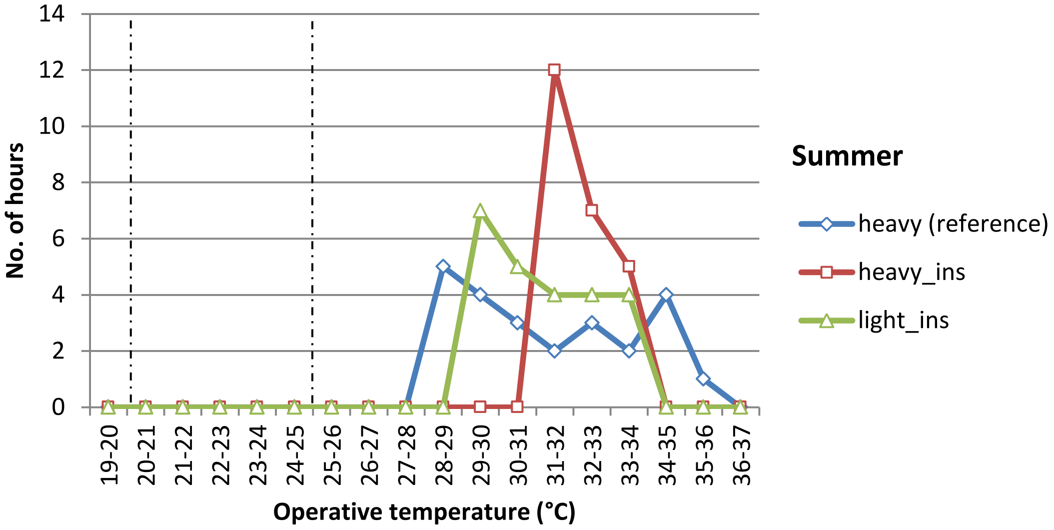


Figure 3.24 Number of hours distribution of operative temperatures in a typical summer day, Veracruz.

Annual energy demand for the three base constructions is shown in Figure 3.25. It can be observed that there is a high demand for cooling and no heating is needed. The cooling demand in the reference building is much larger because this construction is not insulated so the cooling devices need to compensate for the losses, therefore insulation is needed when introducing cooling devices.

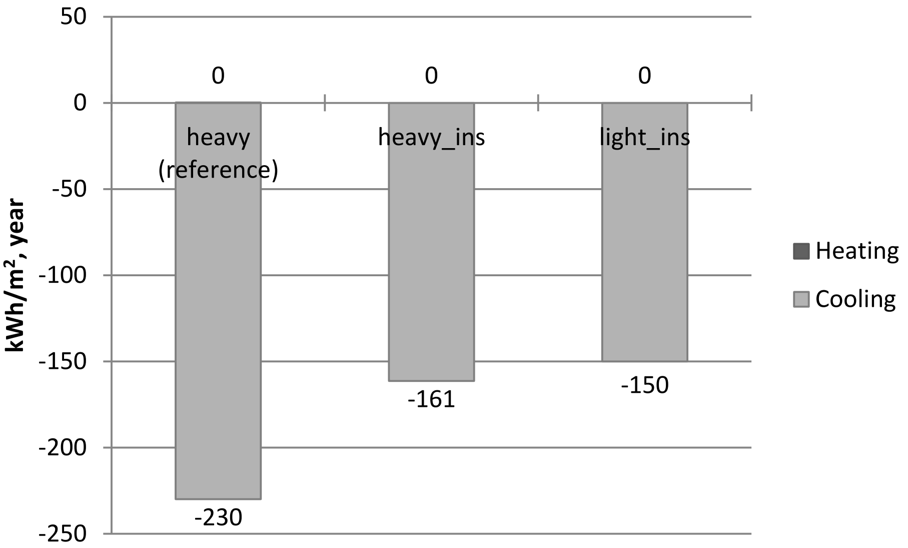


Figure 3.25 Annual energy demand in the three base constructions, Veracruz. Air temperature control set points: 20 – 25 °C.

The monthly energy demand for the insulated construction is shown in Figure 3.26. The cooling demand difference between the heavy weight insulated and light weight insulated buildings is shown on the right axis. When the difference is positive, the energy demand of the heavy weight building is lower, and when is negative then the demand in the light weight building is less. The light weight insulated construction performs better over the whole year except in the month of January, therefore the light weight construction seems to be appropriate for a warm climate like in Veracruz.

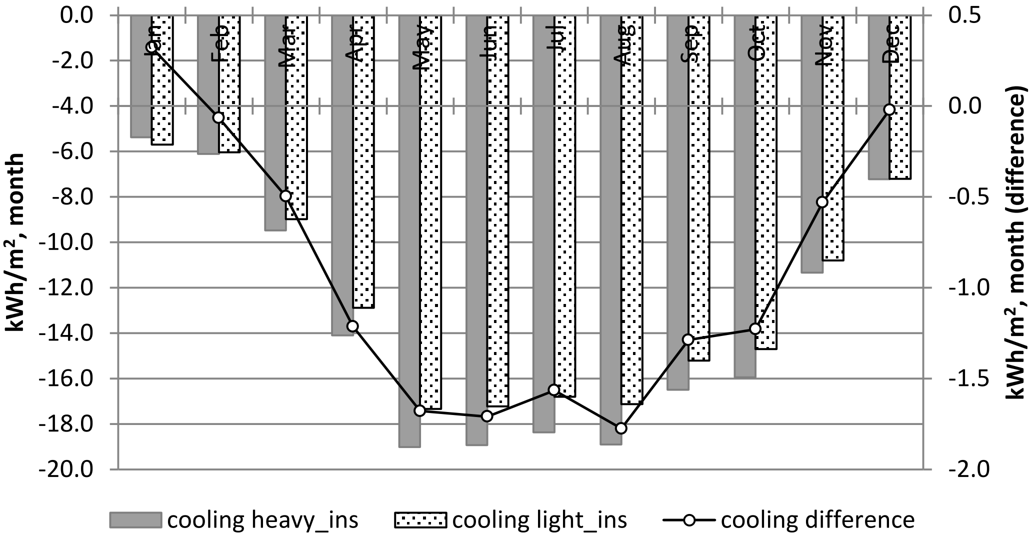


Figure 3.26 Monthly energy demand in a heavy weight insulated and a light weight insulated building. Air temperature control set points: 20-25 °C, Veracruz.

3.3.2 Parameters implementation

In this section it is investigated if it is possible to lower down the temperature response in the buildings down to the comfort limits. The results obtained from Section 3.2, are used in order to predict how the type of glass, exterior shading and ground insulation will affect energy and comfort in a tropical climate like Veracruz.

Low-e glass and single clear glass performed good in winter in Mexico city since these glasses allowed more solar radiation into the room to heat the thermal mass. In Veracruz, as it can be seen from Figure 3.26, there is a demand of cooling all the year round, so for this type of climate a solar control glass or a tinted glass are a better option since these will reduce the solar heat gains. Exterior shading is applied to these glasses, the selected shading for Veracruz should intend to shade both winter and summer, see Section 3.1.2. Energy savings from a non-insulated ground slab are very small in Veracruz compared with Mexico city. A non-insulated slab is beneficial from October to April since a lower ground temperature will allow heat losses, but from May to September the temperature of the ground will be above the upper comfort limit of 25 °C, so heat gains will come into the room, and extra cooling will be needed. It is decided to leave the ground slab without insulation since a non-insulated slab is beneficial in the winter and the middle seasons when natural ventilation can be used to cool the building.

Results in Figure 3.27 show that operative temperatures in winter will be lower in a heavy weight construction. Nevertheless, temperatures in summer are still too high even after applying the improvements mentioned previously.

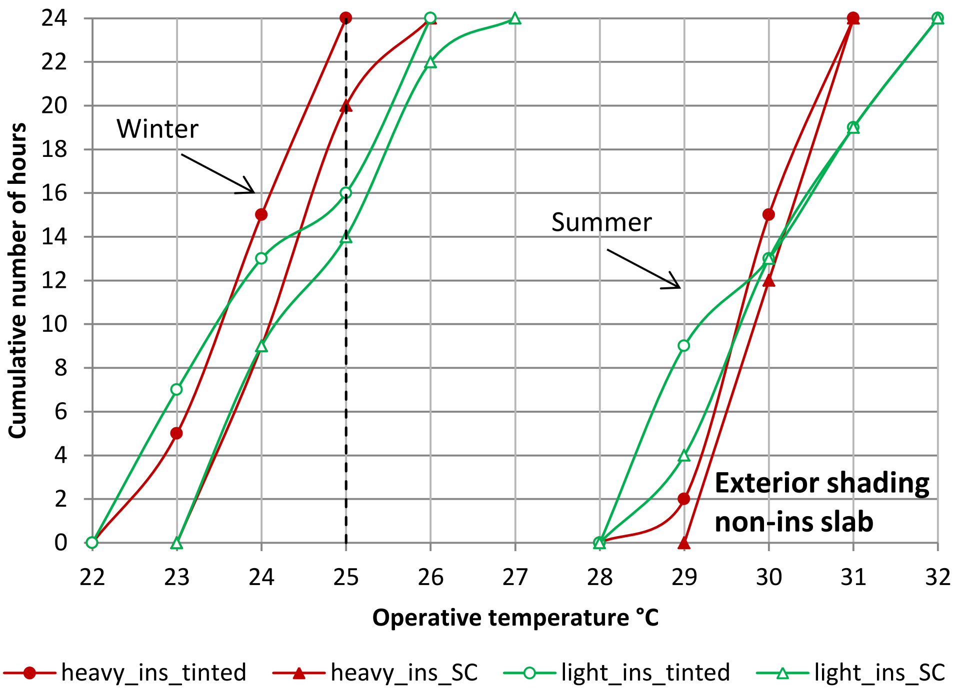


Figure 3.27 Cumulative number of hours of operative temperatures with tinted and solar control glass. Exterior shading is applied, and floor slab is not insulated. Free running temperature simulations in a typical winter and summer day, Veracruz.

The energy demand in the light weight building is less than in the heavy weight construction according to Figure 3.28. A low mass construction would be better in order not to store heat, lower down the temperature faster and achieve energy savings.

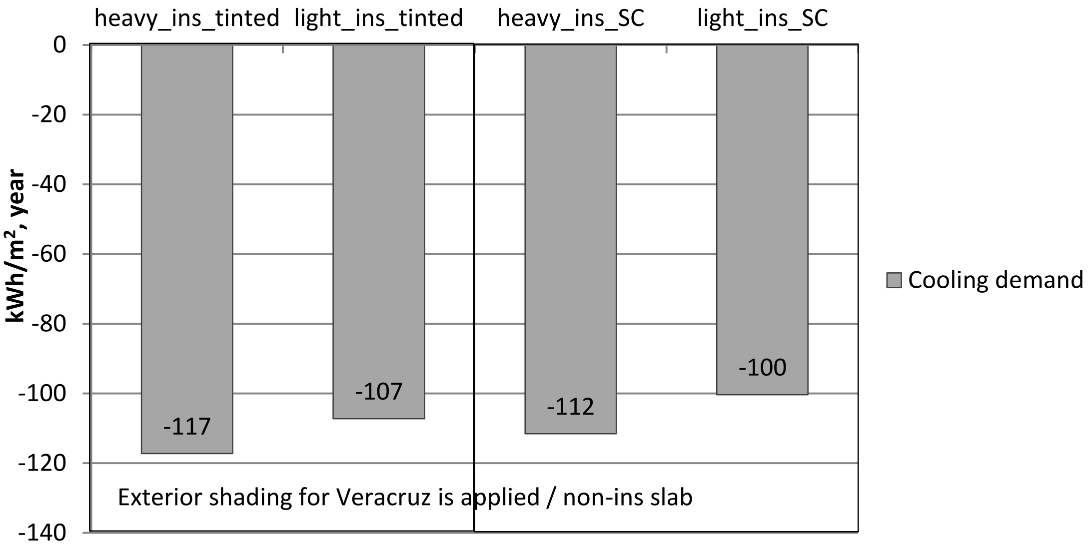


Figure 3.28 Annual cooling energy demand in the heavy and light weight insulated buildings. Exterior shading is applied, and floor slab is not insulated. Air temperature control set points: 20 – 25 °C, Veracruz.

Something to be noticed from Figure 3.27 and Figure 3.28 is that lower temperatures are achieved with the tinted glass, but when cooling is used this same glass will require more energy. The explanation to it is that heat will be transmitted to the outside through a single pane glass but a double glass insulated unit will prevent heat leaving the room, therefore indoor temperatures will be slightly lower with a single glass. Outdoor temperatures in Veracruz are usually higher than the comfort limit of 25 °C so when cooling is introduced there will be a constant heat inflow into the room, and this heat transmission will be lower with an insulated glass, consequently the solar control glass will require less cooling than the tinted glass.

In Figure 3.29, can be observed that the heavy weight construction demands less cooling in winter from December to February, but during the rest of the months a light weight construction will perform better.

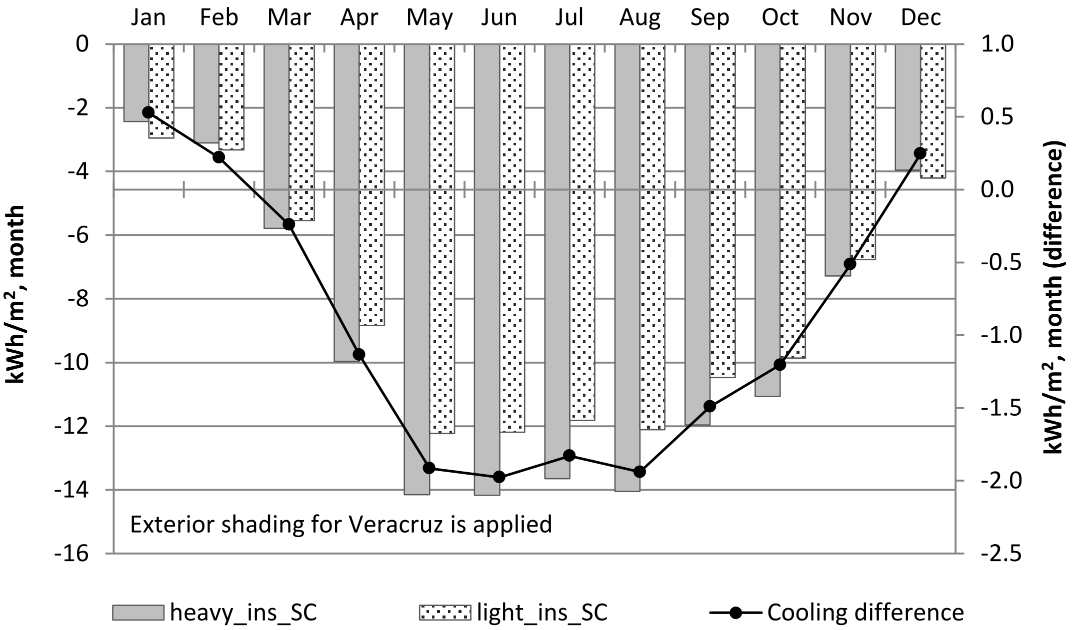


Figure 3.29 Monthly energy demand in the heavy weight insulated and the light weight insulated building with solar control glass. Exterior shading is applied, and floor slab is not insulated. Air temperature control set points: 20-25 °C, Veracruz.

As it can be observed from Figure 3.30, natural ventilation is not enough in order to lower down the indoor temperature to comfort limits in a typical summer day, therefore cooling will be needed. Nevertheless winter climate in Veracruz is similar to summer in Mexico city, therefore natural ventilation will manage to cool down the building in winter season and also during some part of the autumn and spring.

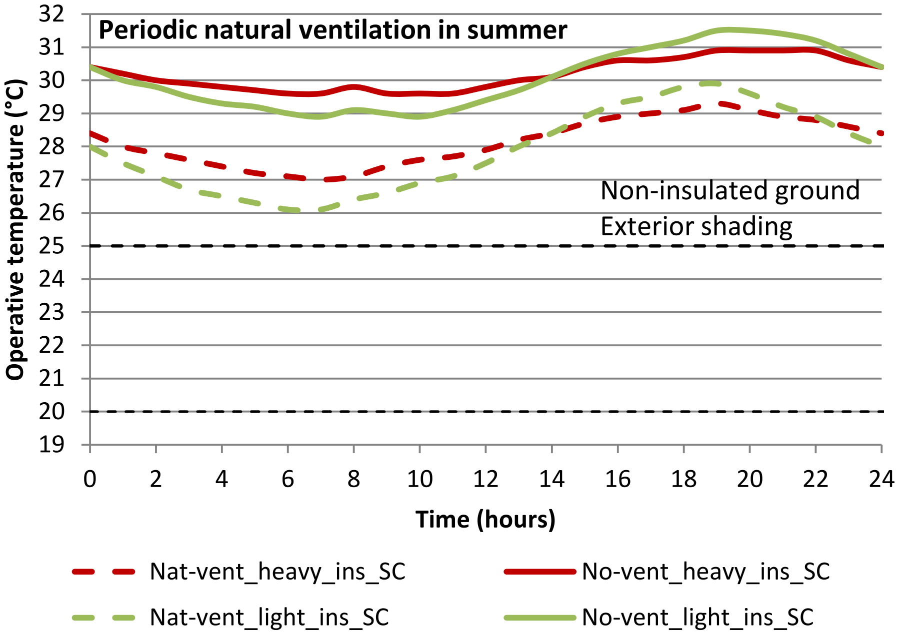


Figure 3.30 Operative temperature in a heavy and light weight insulated building with exterior shading and without ground insulation. Typical summer day with and without natural ventilation from 0:00 to 8:00 hr. and from 18:00 to 24:00 hr. Veracruz.

3.3.3 Summary tropical climate

Indoor temperatures in Veracruz are above the upper comfort limit most of the year, and as it was discussed before, thermal mass is useful as soon as temperatures are around the comfort limits. Thermal mass will be detrimental since more cooling will be needed in order to cool down the thermal mass.

A light weight building with low thermal mass is preferable. This type of construction store less heat so it has a faster temperature response, consequently less cooling will be needed.

Exterior shading is important in order to reduce the solar heat gains. Natural ventilation in combination with a non-insulated floor slab can be used to cool down the building in winter and during some time in the middle seasons of spring and autumn.

A single tinted glass is considered to be adequate for this climate. The cooling energy demand would be lower with a double unit glass with solar control, but the energy savings are not large enough to justify for the extra cost of this glass.

4 Implementation on the Typical House

The parametric study in the previous chapter was done in order to understand how the selected parameters affect the performance of thermal mass and predict if thermal mass will be beneficial or not in the analysed climates. The outcome from the parametric study in Sections 3.2.7 and 3.3.3 is to be applied in the typical house. It should be noticed that although the shoebox model was proposed in such a way that it would resemble the characteristics of the house as much as possible, still they are not exactly the same, and slight different results could be expected. The shoebox model was a simplification of a house with multiple rooms; therefore, in order to obtain more accurate results, simulations are to be performed in the real house.

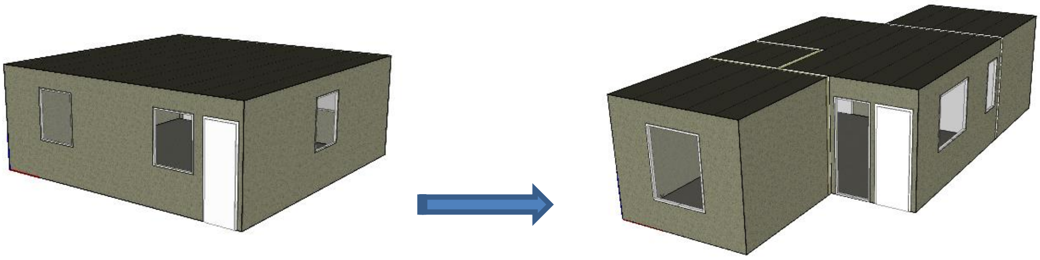


Figure 4.1 Implementation of the results from the shoebox into the house model.

4.1 Temperate climate, Mexico city

From the parametric study in the shoebox was concluded that thermal mass is useful in a temperate climate, and that thermal mass is more effective when temperature variations are larger. In order to confirm the conclusions from the shoebox, three different model configurations were analysed for the house, as follows:

1. The three base constructions described in Section 2.5. Floor slab is non-insulated.
2. Reduced temperature variations; Low-e glass is used and exterior solar shading is applied. Floor slab is non-insulated.
3. Increased temperature variations; the window-wall-ratio of the base constructions is increased from 11% to 20%. Floor slab is non-insulated.

An illustration of the three different model configurations is shown in Figure 4.2.

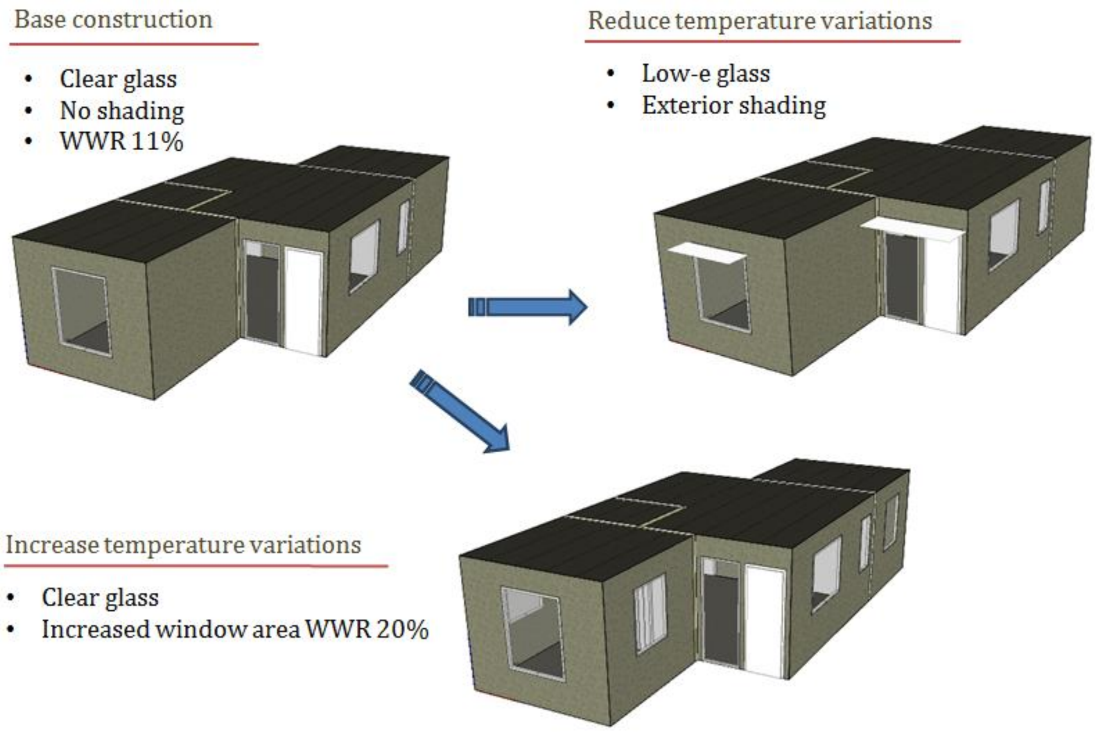


Figure 4.2 House model configurations, Mexico city.

Annual energy demand for the three different configurations are shown in Figure 4.3. In the vertical axis on the right side it is shown the energy difference in percentage comparing with the reference building (heavy weight non-insulated). So for example, the heavy weight insulated building with 20% WWR will get 86% heating demand reduction in comparison with the reference building, but it will have an increase of 43% in cooling demand.

From the results in Figure 4.3 it can be confirmed that thermal mass can compensate for temperature variations. So a heavy weight insulated building with a base construction will demand nearly the same energy as a light weight insulated building with reduced temperature variations. In a similar way, when window area is increased and as consequence temperature variations increase as well, the energy demand increment will be much larger in a light weight insulated building than in a heavy weight insulated with a higher thermal mass.

It can also be corroborated that thermal mass becomes less effective when temperature variations decrease. By comparing the heavy weight insulated and the light weight insulated buildings it can be observed that the energy savings obtained from a heavy weight building are lower when temperature variations are reduced. So for example, the cooling energy savings in the light weight building are 23% while in the heavy weight building are 59%, this is a considerable difference of 36%; when temperature variations are reduced this difference is just 15% (77% - 62%), this means that the heavy weight construction became less effective when a low-e glass and solar shading was included.

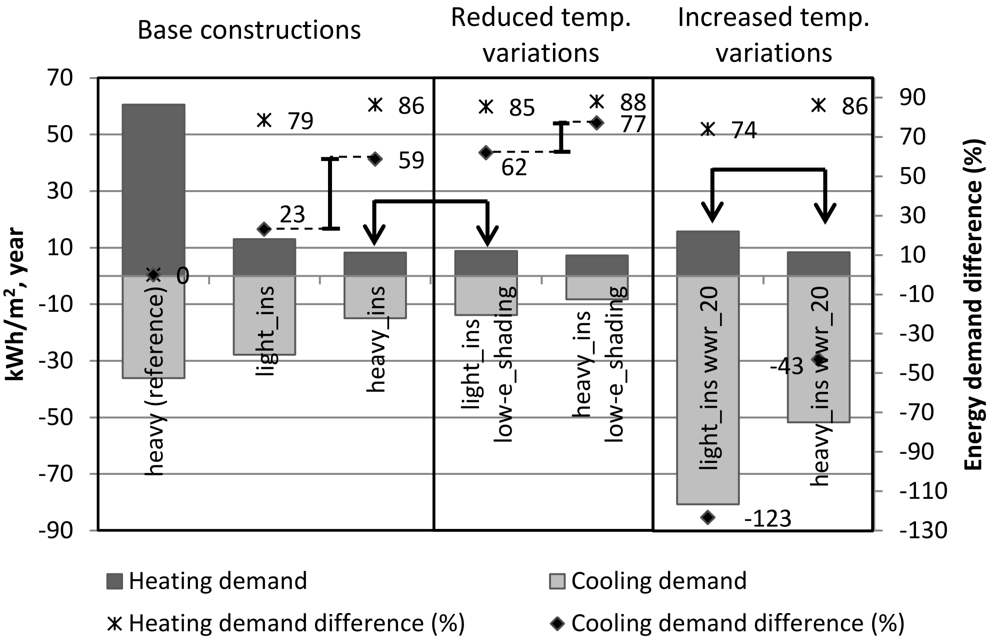


Figure 4.3 *Annual energy demand from the three house model configurations (left vertical axis). Energy demand difference compared with the reference building (right vertical axis), Mexico city.*

4.2 Tropical climate, Veracruz

In a tropical climate such as Veracruz, it was concluded from the shoebox, that thermal mass would be detrimental and a light weight construction with low thermal mass would demand less energy. The same parameters implemented on the shoebox in Section 3.3.2 were applied on the house model. In Figure 4.4 it is shown the comparison between the reference building and the constructions with the added improvements. On the right vertical axis can be read the percentage of energy savings compared with the reference building. A light weight insulated construction with exterior shading and tinted glass will reduce in 55% the energy demand comparing with the reference building. It is confirmed that a house with a light weight construction will demand less energy.

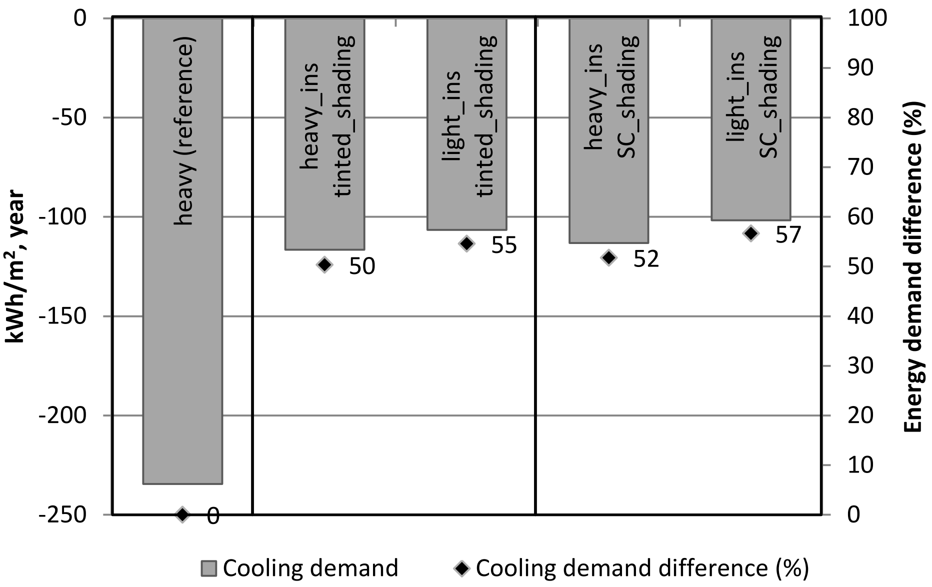


Figure 4.4 *Annual cooling demand from the house model in selected constructions (left vertical axis). Energy savings compared with the reference building (right vertical axis). Exterior shading is applied to the windows with tinted and solar control glass. Floor slab is not insulated. Air temperature control set points: 20 – 25 °C, Veracruz.*

5 Thermal mass discussion

Some thoughts and reasoning about thermal mass that arose along the project are mentioned in this section. These issues were not further analysed since they were out of the scope of this thesis, but it was considered worth to mention as ideas for future work analysis.

Right amount of thermal mass should be used

If walls are too massive, only some part of the thickness of the wall is useful since heat will penetrate into the wall just to a certain depth depending on the material properties and the temperature driving potential. On the other hand, if walls are too thin then thermal mass will reach equilibrium very fast and will stop absorbing heat. In climates with small temperature variations, thin walls should be enough to keep temperatures stable. But, in climates where temperature variations are large like in a desert, then thicker walls would be desirable.

When heating and cooling is used, the effect of thermal mass is reduced

In summer, when mechanical cooling is used, thermal mass will absorb heat until the control set point temperature of 25 °C is reached. Cooling will switch on to keep temperature lower than 25 °C. Thermal mass will reach equilibrium and stop absorbing heat when cooling is working since temperature will be maintained in 25 °C. If no cooling is used, temperatures will go above 25 °C so thermal mass will continue absorbing heat until outdoor temperature drops down or until it reaches equilibrium. Therefore, thermal mass is more effective in free running temperature.

Position of thermal mass

The effect of thermal mass can be positive or negative depending on where it is located. So the performance of thermal mass can vary if it is a wall, ceiling or floor, or if it is close to a window or far away in the middle of the room were no solar radiation is received.

When temperature variations are reduced, less thermal mass is needed

When temperature variations are reduced thermal mass becomes less effective, so the amount of thermal mass can be reduced without affecting the thermal environment. This implies that by adding exterior solar shading, the temperatures in the room will be reduced, and in consequence the temperature driving potential will be smaller. This will result in less penetration depth into the thermal mass so part of the thickness of the construction is not useful. Therefore, the thickness of the construction or the area of the thermal mass could be reduced.

6 Conclusion

Thermal mass is beneficial as soon as indoor temperatures fall within the set comfort limits, otherwise a light weight construction with low thermal mass would be preferable.

In a temperate climate such as in Mexico city, a heavy weight construction with high thermal mass is desirable. Temperatures are kept more stable, more time inside the comfort zone is achieved and energy demand is reduced.

In a tropical climate such as in Veracruz, indoor temperatures are above the upper comfort limit most the year. A light weight construction is more adequate for this clime, since it has a faster temperature response, so less energy is needed to cool down the building.

The effect of thermal mass is greater when temperature variations are larger, so by adding high performance windows and exterior shading, temperatures are maintained more stable, so the benefit of thermal mass is reduced. On the other hand, this improvements might be needed in order to reduce the heat loads and bring indoor temperatures within the comfort limits so thermal mass becomes useful.

Thermal mass has the ability to compensate for increased temperature variations due to larger windows or high transmittance of single pane glasses. This means that energy demand in a high glass façade building will be less with a heavy weight contruction than with a light weight.

7 References

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8 Appendix

8.1 Climate data

The climate files used for this study are typical year weather files IWEC which stands for ‘International Weather for Energy Calculations’. The ‘American Society of Heating, Refrigeration and Air-Conditioning Engineers’ (ASHRAE) developed this weather files from hourly data collected by the U.S. National Climatic Data Center within a period of up to 18 years (ASHRAE, 2001).

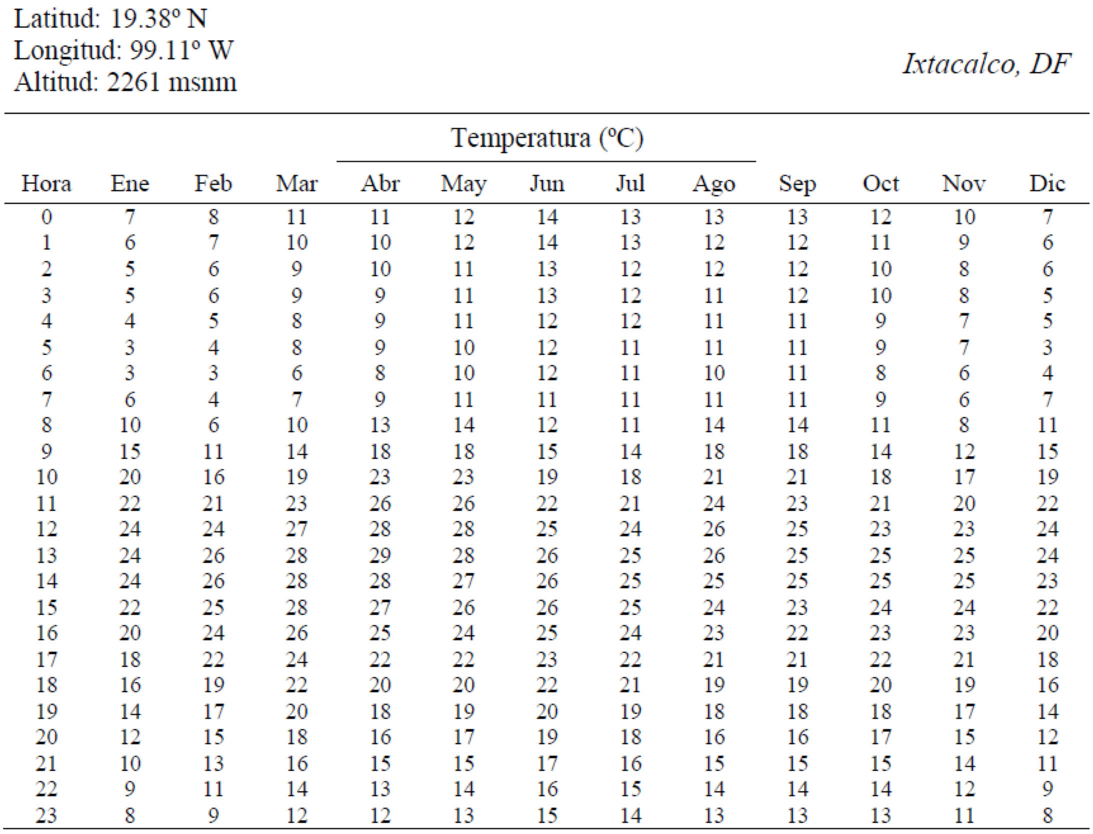
The hourly data from the IWEC files is processed by IDA ICE 4.5.1, and monthly climate values are obtained for Mexico city and Veracruz like shown in the Table below.

Table 8.1 Monthly climate data for Mexico city and Veracruz (ASHRAE, 2001).

Month	Mexico city			Veracruz		
	Dry bulb temp	Direct normal radiation	Diffuse rad on horizontal surface	Dry bulb temp	Direct normal radiation	Diffuse rad on horizontal surface
	(°C)	(W/m^2)	(W/m^2)	(°C)	(W/m^2)	(W/m^2)
January	14.9	154.6	86.1	21.1	113.1	78.4
February	15.6	157.8	95.7	22.1	87.9	100
March	17.6	154.7	114.4	23.3	111.3	105
April	18.6	135.7	130.3	25.8	115.5	121.5
May	19.1	121.5	137.7	27.6	104.4	137.3
June	18.6	122.3	135.6	27.5	141.1	122.4
July	17.6	110.3	137	27.1	111.3	131.1
August	17.4	132.7	124.8	27.2	155.6	120.5
September	17.5	118.2	125.4	26.6	98.6	125.2
October	16.3	123.6	104.7	25.8	127.8	98.3
November	15.6	120.1	90.7	23.6	137.8	84
December	13.6	105.8	88.6	22.5	72.4	92.1
Annual mean	16.9	129.6	114.3	25.0	114.9	109.7

In Table 8.2 and Table 8.3 it is shown the hourly mean temperature for Mexico city and Veracruz according to (Morillón Gálvez, 2004). These temperature data was not used for the simulations in this study, but they were useful to visualize the temperature variations along the year.

Table 8.2 Hourly mean temperature for Mexico city (Morillón Gálvez, 2004).

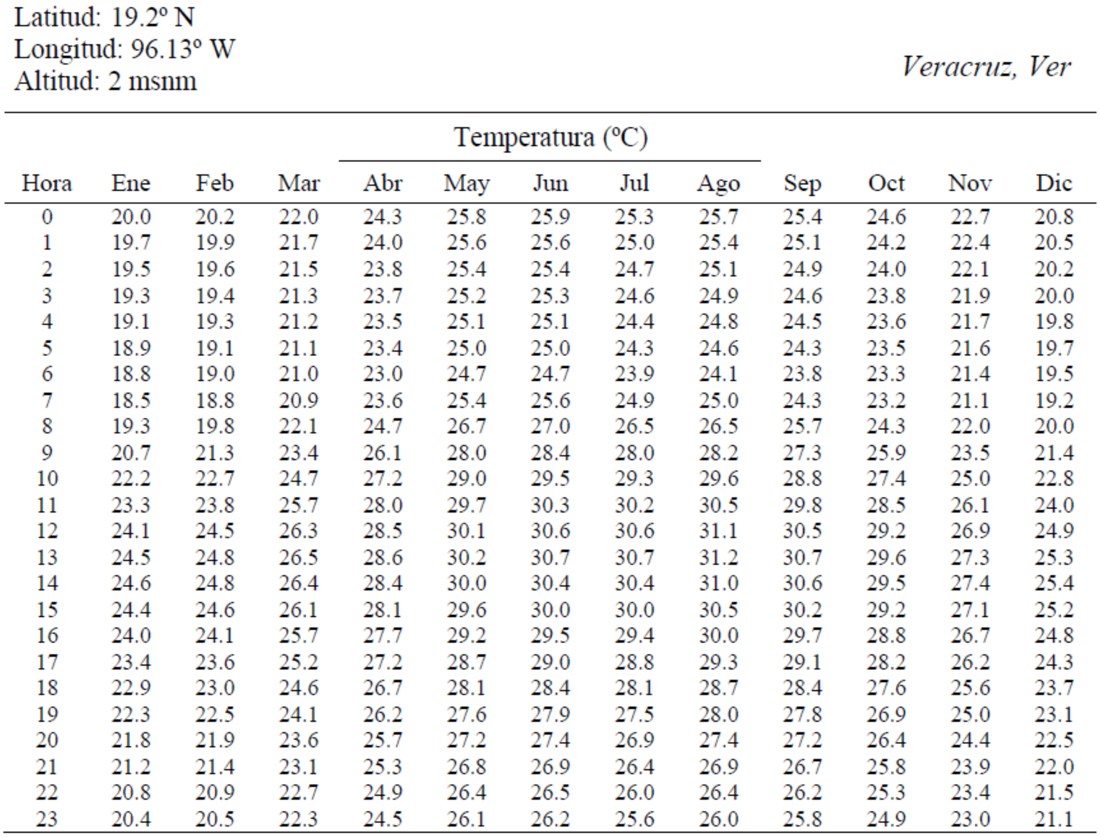


Latitud: 19.38° N
Longitud: 99.11° W
Altitud: 2261 msnm

Ixtacalco, DF

				Temperatura (ºC)								
Hora	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic
0	7	8	11	11	12	14	13	13	13	12	10	7
1	6	7	10	10	12	14	13	12	12	11	9	6
2	5	6	9	10	11	13	12	12	12	10	8	6
3	5	6	9	9	11	13	12	11	12	10	8	5
4	4	5	8	9	11	12	12	11	11	9	7	5
5	3	4	8	9	10	12	11	11	11	9	7	3
6	3	3	6	8	10	12	11	10	11	8	6	4
7	6	4	7	9	11	11	11	11	11	9	6	7
8	10	6	10	13	14	12	11	14	14	11	8	11
9	15	11	14	18	18	15	14	18	18	14	12	15
10	20	16	19	23	23	19	18	21	21	18	17	19
11	22	21	23	26	26	22	21	24	23	21	20	22
12	24	24	27	28	28	25	24	26	25	23	23	24
13	24	26	28	29	28	26	25	26	25	25	25	24
14	24	26	28	28	27	26	25	25	25	25	25	23
15	22	25	28	27	26	26	25	24	23	24	24	22
16	20	24	26	25	24	25	24	23	22	23	23	20
17	18	22	24	22	22	23	22	21	21	22	21	18
18	16	19	22	20	20	22	21	19	19	20	19	16
19	14	17	20	18	19	20	19	18	18	18	17	14
20	12	15	18	16	17	19	18	16	16	17	15	12
21	10	13	16	15	15	17	16	15	15	15	14	11
22	9	11	14	13	14	16	15	14	14	14	12	9
23	8	9	12	12	13	15	14	13	13	13	11	8

Table 8.3 Hourly mean temperature for Veracruz (Morillón Gálvez, 2004).



Latitud: 19.2° N
Longitud: 96.13° W
Altitud: 2 msnm

Veracruz, Ver

				Temperatura (ºC)								
Hora	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic
0	20.0	20.2	22.0	24.3	25.8	25.9	25.3	25.7	25.4	24.6	22.7	20.8
1	19.7	19.9	21.7	24.0	25.6	25.6	25.0	25.4	25.1	24.2	22.4	20.5
2	19.5	19.6	21.5	23.8	25.4	25.4	24.7	25.1	24.9	24.0	22.1	20.2
3	19.3	19.4	21.3	23.7	25.2	25.3	24.6	24.9	24.6	23.8	21.9	20.0
4	19.1	19.3	21.2	23.5	25.1	25.1	24.4	24.8	24.5	23.6	21.7	19.8
5	18.9	19.1	21.1	23.4	25.0	25.0	24.3	24.6	24.3	23.5	21.6	19.7
6	18.8	19.0	21.0	23.0	24.7	24.7	23.9	24.1	23.8	23.3	21.4	19.5
7	18.5	18.8	20.9	23.6	25.4	25.6	24.9	25.0	24.3	23.2	21.1	19.2
8	19.3	19.8	22.1	24.7	26.7	27.0	26.5	26.5	25.7	24.3	22.0	20.0
9	20.7	21.3	23.4	26.1	28.0	28.4	28.0	28.2	27.3	25.9	23.5	21.4
10	22.2	22.7	24.7	27.2	29.0	29.5	29.3	29.6	28.8	27.4	25.0	22.8
11	23.3	23.8	25.7	28.0	29.7	30.3	30.2	30.5	29.8	28.5	26.1	24.0
12	24.1	24.5	26.3	28.5	30.1	30.6	30.6	31.1	30.5	29.2	26.9	24.9
13	24.5	24.8	26.5	28.6	30.2	30.7	30.7	31.2	30.7	29.6	27.3	25.3
14	24.6	24.8	26.4	28.4	30.0	30.4	30.4	31.0	30.6	29.5	27.4	25.4
15	24.4	24.6	26.1	28.1	29.6	30.0	30.0	30.5	30.2	29.2	27.1	25.2
16	24.0	24.1	25.7	27.7	29.2	29.5	29.4	30.0	29.7	28.8	26.7	24.8
17	23.4	23.6	25.2	27.2	28.7	29.0	28.8	29.3	29.1	28.2	26.2	24.3
18	22.9	23.0	24.6	26.7	28.1	28.4	28.1	28.7	28.4	27.6	25.6	23.7
19	22.3	22.5	24.1	26.2	27.6	27.9	27.5	28.0	27.8	26.9	25.0	23.1
20	21.8	21.9	23.6	25.7	27.2	27.4	26.9	27.4	27.2	26.4	24.4	22.5
21	21.2	21.4	23.1	25.3	26.8	26.9	26.4	26.9	26.7	25.8	23.9	22.0
22	20.8	20.9	22.7	24.9	26.4	26.5	26.0	26.4	26.2	25.3	23.4	21.5
23	20.4	20.5	22.3	24.5	26.1	26.2	25.6	26.0	25.8	24.9	23.0	21.1

8.2 Selection of typical climate days

The typical days for day simulations are shown in the Table below. The process how these days were chosen is explained in this Appendix.

Table 8.4 Typical climate days for selected locations.

Typical days	Mexico city	Veracruz
Winter	30-December	15-January
Summer	18-May	07-May
Shoulder season	06-October	08-November

Three representative days are chosen for each location. Two of them are taken from the months with minimum and maximum mean temperatures in a year; the third day comes from a month with an intermediate temperature. In Table 8.5 it is shown the mean dry-bulb temperatures for Mexico city and Veracruz. Highlighted in blue colour is the coldest month, in orange the warmest and in green it is the month which temperature is closer to the intermediate temperature between the coldest and warmest months.

Table 8.5 Mean dry-bulb temperatures for Mexico city and Veracruz (ASHRAE, 2001).

Monthly Mean Temperatures	Mexico city (°C)	Veracruz (°C)
January	14.9	21.1
February	15.6	22.1
March	17.6	23.3
April	18.6	25.8
May	19.1	27.6
June	18.6	27.5
July	17.6	27.1
August	17.4	27.2
September	17.5	26.6
October	16.3	25.8
November	15.6	23.6
December	13.6	22.5
Annual mean	16.9	25.0

The next step is to look for a typical day in these months. The selection of the typical winter day is explained for the city of Veracruz; the process was exactly the same for other months.

A typical day will be defined by the mean daily temperature range which is shown in Figure 8.1. The upper limit of 26.1 °C is obtained by averaging the maximum hourly temperatures of every day, while the lower limit of 17.2 °C comes from the average of the minimum hourly temperatures. The hourly temperature data was taken from the climate file from ASHRAE.

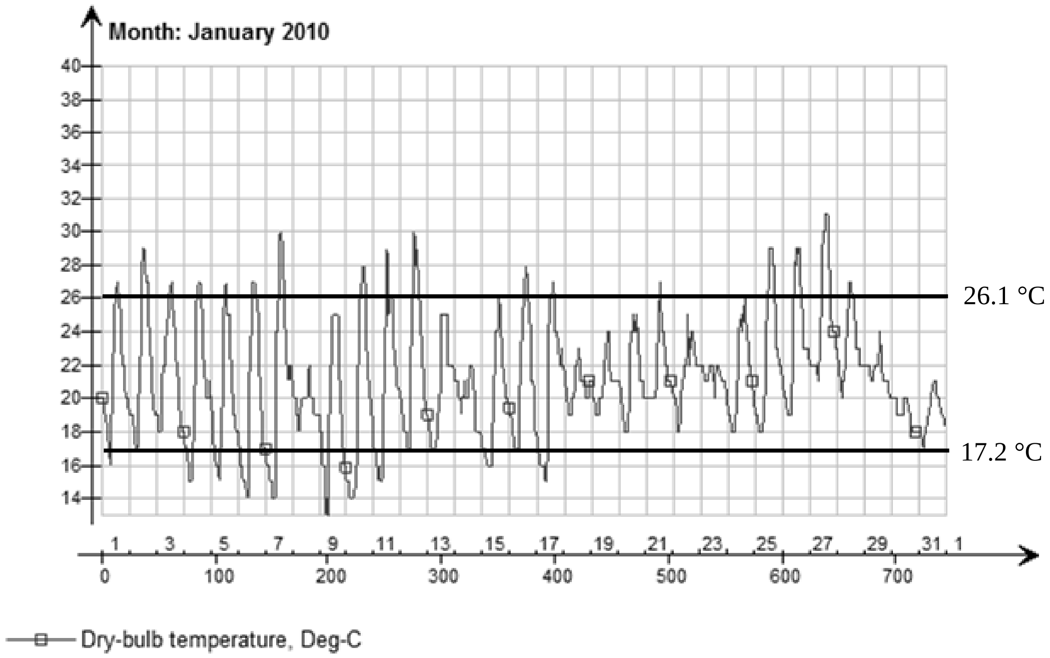


Figure 8.1 Daily dry-bulb temperatures in January, Veracruz.

The 1st, 3rd, 13th, 15th, and 24th of January fit quite good within the mean daily temperature range. To choose among one of these days, the solar radiation is considered. In Table 8.6 it is shown the summation of the direct and diffuse solar radiation of every day, the mean value is 191.5 W/m^2. The sum of the radiation on the 15th of January is the closest to the mean value, so this day is selected as a representative typical day.

Table 8.6 Temperatures and solar radiation in January, Veracruz.

Date	Max. Daily temperature (°C)	Min. Daily temperature (°C)	Mean direct normal rad, W/m^2	Mean diffuse rad on hor surf, W/m^2	Sum radiation, W/m^2
1-Jan	27.0	16.0	248.2	47.3	295.5
2-Jan	29.0	17.0	246.8	47.9	294.7
3-Jan	27.0	18.0	60.2	106.0	166.2
4-Jan	27.0	15.0	246.7	49.7	296.4
5-Jan	27.0	15.0	196.7	68.0	264.7
6-Jan	27.0	14.0	249.0	48.5	297.5
7-Jan	30.0	14.0	159.7	57.3	217.0
8-Jan	22.0	18.0	70.4	101.2	171.6
9-Jan	25.0	13.0	241.5	54.6	296.1
10-Jan	28.0	14.0	234.5	54.0	288.5
11-Jan	29.0	15.0	8.8	89.5	98.3
12-Jan	30.0	17.0	176.2	57.2	233.4
13-Jan	25.0	17.0	51.5	89.8	141.3
14-Jan	22.0	17.0	4.2	89.7	93.9
15-Jan	26.0	16.0	113.3	89.3	202.6
16-Jan	28.0	17.0	252.9	51.3	304.2
17-Jan	27.0	15.0	209.2	53.0	262.2
18-Jan	23.0	19.0	12.3	92.5	104.8
19-Jan	24.0	19.0	97.3	94.7	192.0
20-Jan	25.0	18.0	29.4	100.3	129.7
21-Jan	27.0	20.0	32.0	88.1	120.1
22-Jan	25.0	18.0	5.8	91.0	96.8
23-Jan	22.0	19.0	5.8	91.5	97.3
24-Jan	26.0	18.0	20.3	95.1	115.4
25-Jan	29.0	18.0	196.5	68.3	264.8
26-Jan	29.0	19.0	80.0	118.0	198.0
27-Jan	31.0	21.0	219.3	54.5	273.8
28-Jan	27.0	20.0	18.1	95.8	113.9
29-Jan	24.0	20.0	6.8	93.9	100.7
30-Jan	20.0	18.0	4.9	96.5	101.4
31-Jan	21.0	17.0	7.1	95.3	102.4
Mean	26.1	17.2	113.1	78.4	191.5

The hourly mean outdoor temperature and solar radiation in the selected typical days is shown in Figure 8.2 and Figure 8.3.

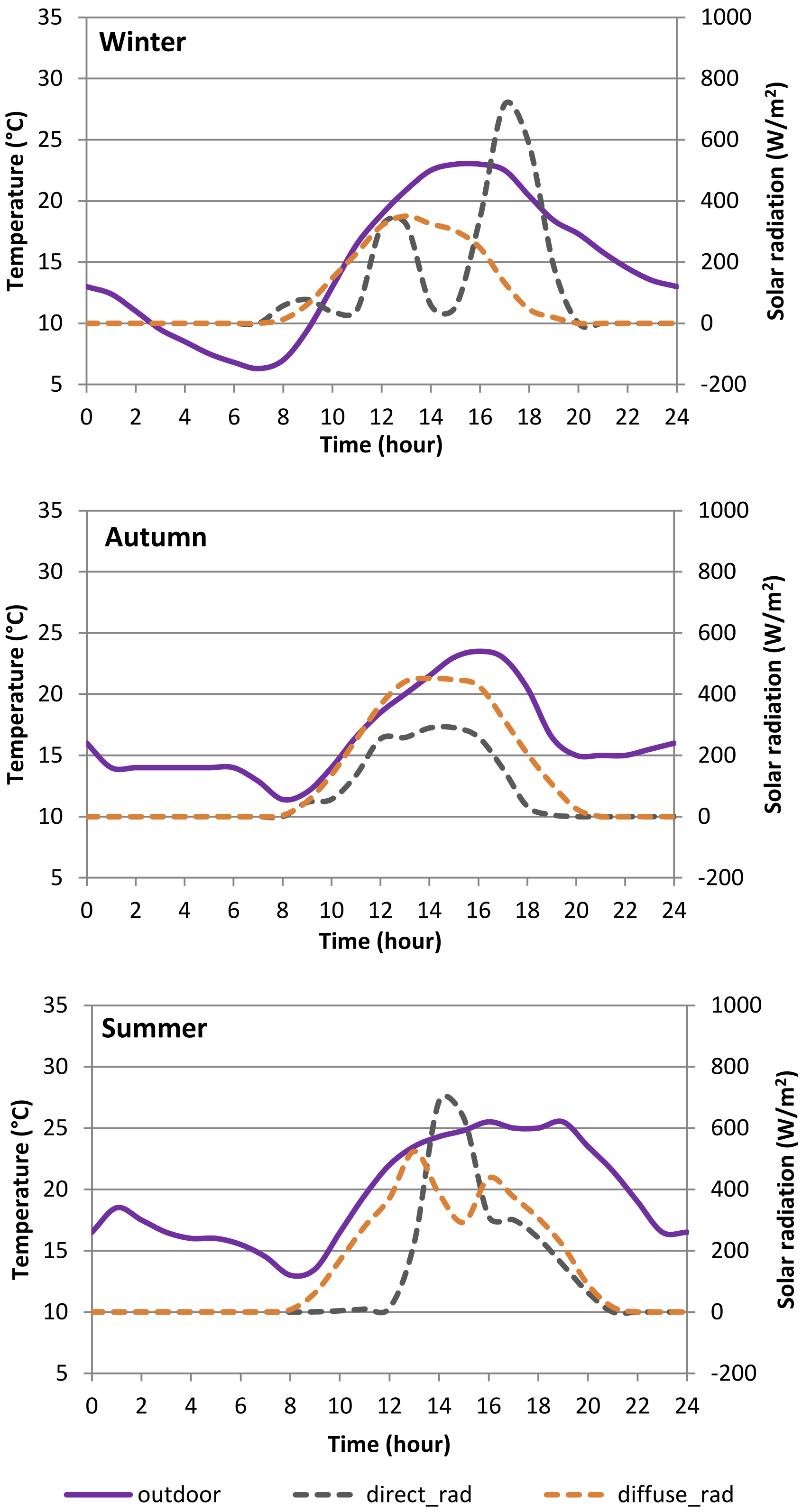


Figure 8.2 *Mean air outdoor temperature, direct normal solar radiation and diffuse solar radiation on horizontal surface. Mexico city.*

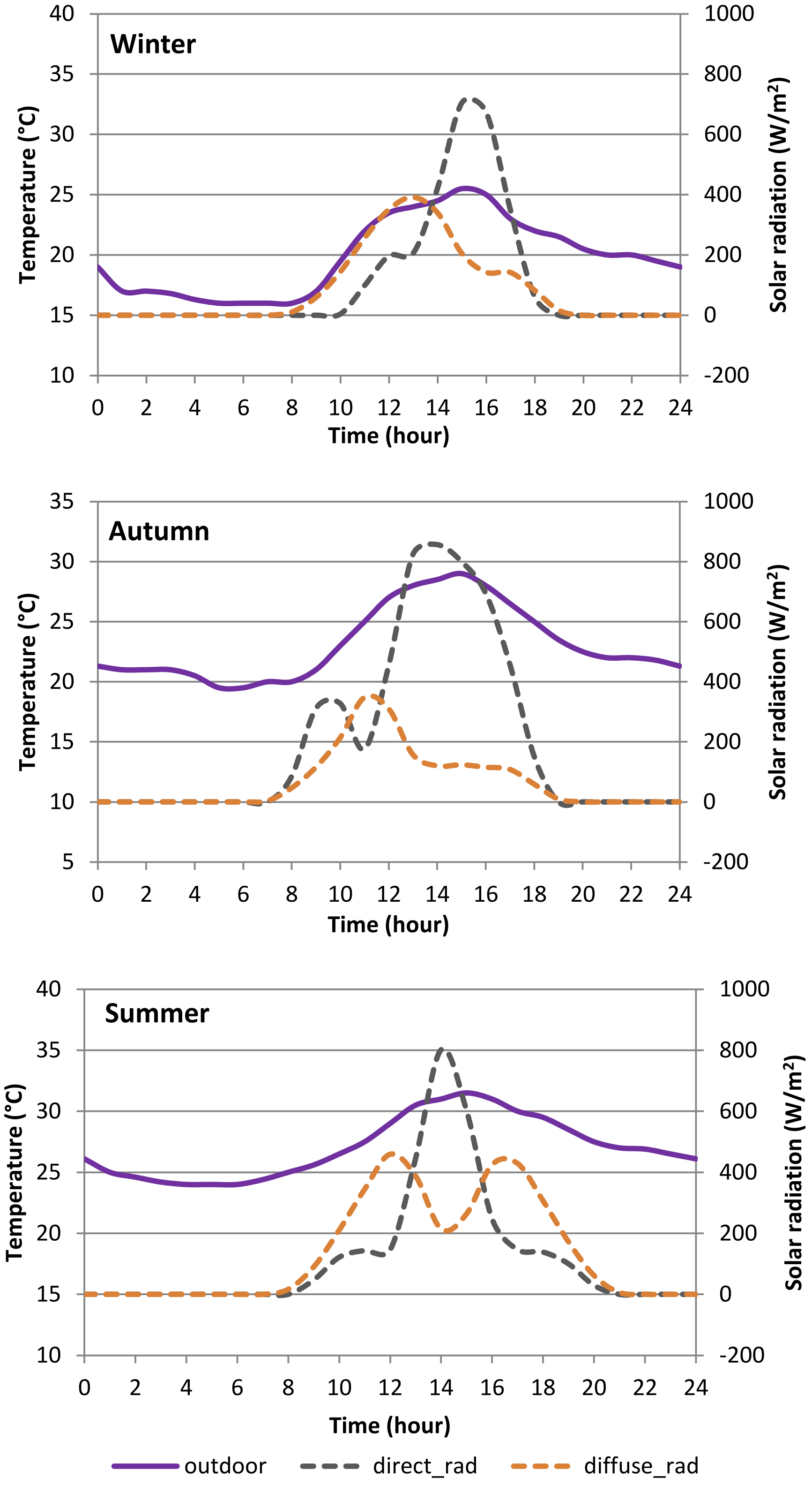


Figure 8.3 *Mean air outdoor temperature, direct normal solar radiation and diffuse solar radiation on horizontal surface. Veracruz.*

8.3 Original drawings of reference house

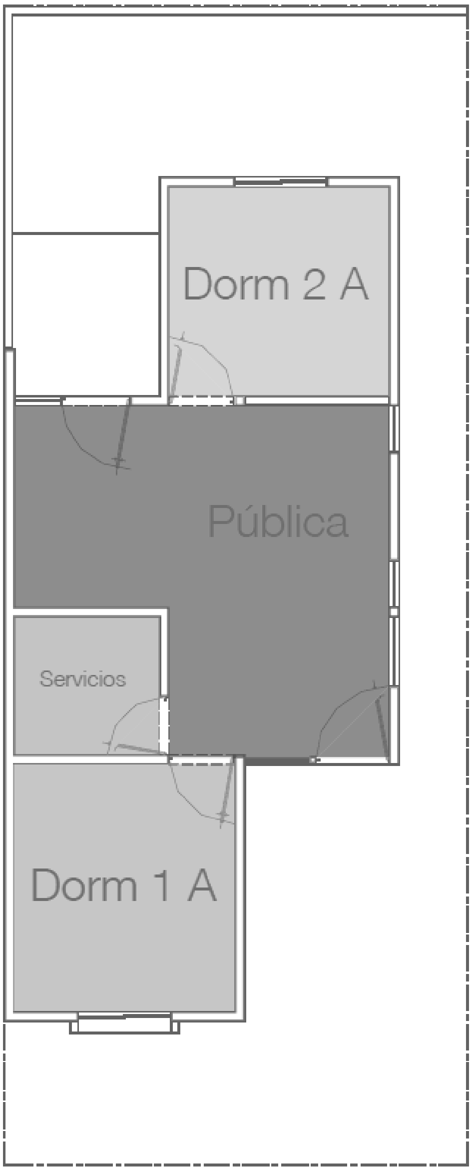


Figure 8.4 Plan view of a typical social house in Mexico (Campos Arriaga, 2011).

Figure 8.5 Three dimensional model of a typical house in Mexico (Campos Arriaga, 2011).

8.4 Materials thermal properties

The thermal properties of the materials used in the three base constructions are shown in the tables below. Materials properties were not available in the Mexican NAMA (GIZ, 2012) or in the energy efficiency study by (Campos Arriaga, 2011), therefore they were defined after other sources.

Table 8.7 Material properties of heavy weight construction non-insulated (reference building).

MATERIALS	Thickness	Density	Thermal Conductivity	Specific Heat C_p	Resistance R
Wall construction	Δx (m)	ρ (kg/m^3)	λ (W/m K)	(J/kg K)	(m^2 K/W)
Cement plaster with sand (ext) [1]	0.019	1860	0.72	840	0.026
Concrete block, medium weight [2]	0.100	1400	0.51	1000	0.196
Gypsum plaster with sand (int) [1]	0.013	1680	0.81	840	0.016
Roof construction					
Plasticool layer (1.2 mm) [3]	0.001	515	0.039	840	0.031
Reinforced concrete slab [4]	0.120	2300	1.7	880	0.071
Floor slab construction					
Tiles [2]	0.005	1900	0.84	800	0.006
Reinforced concrete slab [4]	0.100	2300	1.7	880	0.059

[1] (Cengel & Ghajar, 2011), [2] (Szokolay, 2004), [3] Plasticool technical sheet, [4] (EQUA, 2013)

Table 8.8 Properties of exterior EPS insulation for heavy weight insulated construction.

MATERIALS	Thickness	Density	Thermal Conductivity	Specific Heat C_p	Resistance R
	Δx (m)	ρ (kg/m^3)	λ (W/m K)	(J/kg K)	(m^2 K/W)
Expanded polystyrene (EPS) [1]	0.050	16	0.04	1200	1.250

[1] (Cengel & Ghajar, 2011)

Table 8.9 Material properties of light weight construction insulated.

MATERIALS	Thickness	Density	Thermal Conductivity	Specific Heat	Resistance
Wall construction	Δx (m)	ρ (kg/m^3)	λ (W/m K)	C_p (J/kg K)	R (m^2 K/W)
Cement plaster with sand (ext) [1]	0.019	1860	0.72	840	0.026
Plywood (16 mm) [1]	0.016	545	0.12	1210	0.133
Insulation & studs (walls) [5]	0.100	60	0.045	1270	2.22
Gypsum board (16 mm) [1]	0.016	800	0.17	1090	0.094
Roof construction					
Plasticool layer (1.2 mm) [3]	0.001	515	0.039	840	0.031
Plywood (16 mm) [1]	0.016	545	0.12	1210	0.133
Ins., rafters and air cavity (roof) [5]	0.150	80	0.06	1346	2.500
Gypsum board (16 mm) [1]	0.016	800	0.17	1090	0.094
Floor slab construction					
Tiles [2]	0.005	1900	0.84	800	0.006
Reinforced concrete slab [4]	0.100	2300	1.7	880	0.059

[1] (Cengel & Ghajar, 2011), [2] (Szokolay, 2004), [3] Plasticool technical sheet, [4] (EQUA, 2013), [5] Self calculated

The combined value of the insulation and the wooden frame structure was calculated according to the method described in Norma Oficial Mexicana NOM-020-ENER-2011 (Secretaría de Energía, 2011).

8.5 Type of glass

In the figure below it is shown the results from the free running temperature simulations with different types of glass, see results Section 3.2.2Type of glass.

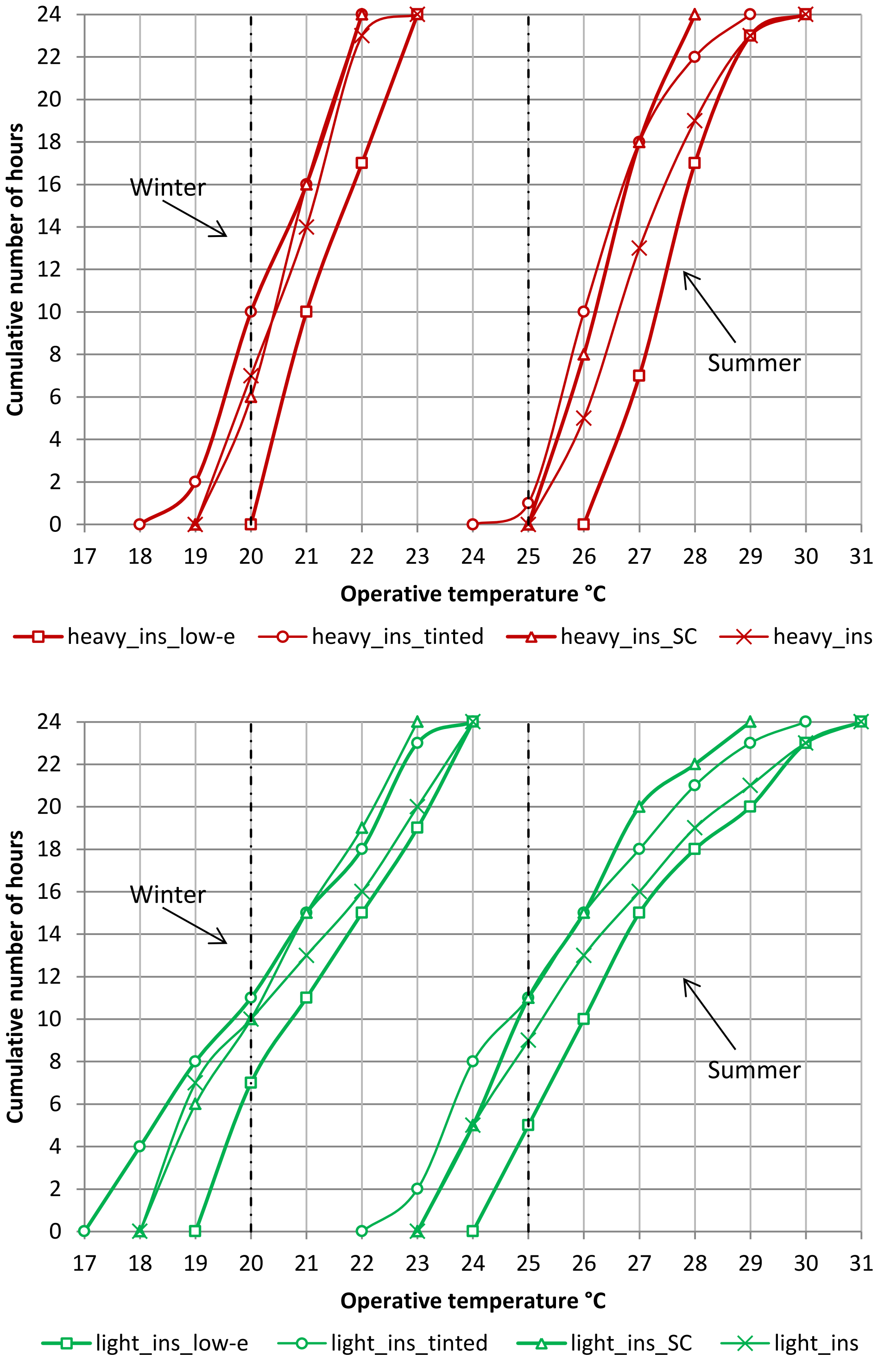


Figure 8.6 *Cumulative number of hours of operative temperatures with different types of glass. Free running temperature simulations in a typical winter and summer day, Mexico city.*

Table 8.10 Time in a typical winter and summer day when operative temperature is within an acceptable comfort range of 20 – 25 °C. Free running temperature simulations, Mexico city.

Type of building	Winter	Summer	Type of building	Winter	Summer
	%			%	
heavy_ins_low-e	100	0	light_ins_low-e	71	21
heavy_ins_tinted	58	4	light_ins_tinted	54	46
heavy_ins_SC	75	0	light_ins_SC	58	46
heavy_ins	71	0	light_ins	58	38

For the energy simulations, the mean air temperature in the room was given as the control set point in order to regulate the cooling and heating devices. The mean air temperature is maintained within the range of 20 – 25 °C as shown in Figure 8.7. The operative temperature is also affected by long wave radiation from surrounding surfaces therefore its amplitude is larger than the mean air temperature.

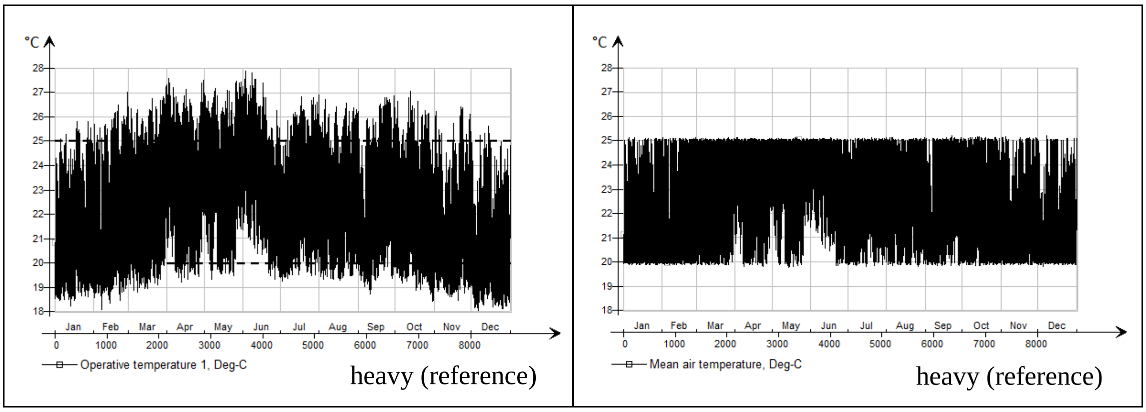
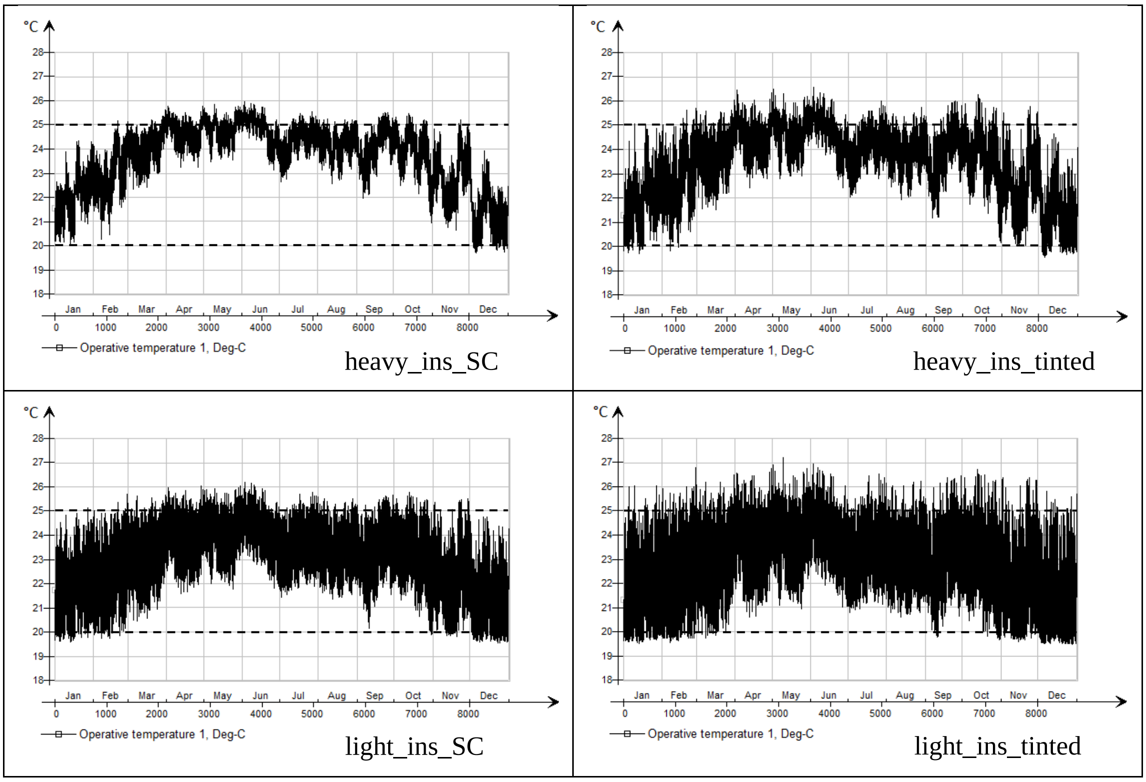


Figure 8.7 Annual operative and mean air temperature in the heavy weight non-insulated construction (reference building); control set points: 20 – 25 °C, Mexico city.

In order to visualize the influence of an insulated glass and a non-insulated glass in comfort along the year, annual energy simulations were performed using a double glass unit with solar control and a single tinted glass, see Figure 8.8 .

Daily operative temperature amplitude is smaller in the heavy weight insulated building. This more stable temperature is attributed to a higher heat capacity of the construction compared with the light weight building. The solar control glass achieves more stable temperatures than the tinted glass since it allows less solar radiation into the building and reduces the heat transmission with the outdoor environment thanks to the low-U value of the window.

If thermal comfort is priority then an insulated glass would be recommended, otherwise a single glass can be a more economical option.



heavy_ins_SC

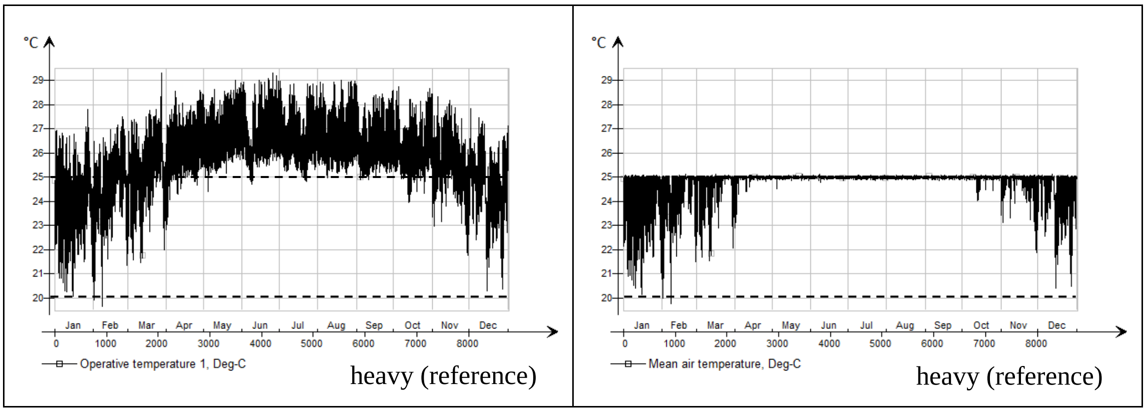
heavy_ins_tinted

light_ins_SC

light_ins_tinted

Figure 8.8 Annual operative temperatures in the heavy weight insulated and light weight insulated constructions with solar control and tinted glass; control set points: 20 – 25 °C, Mexico city.

The same simulations are performed for the city of Veracruz. The daily operative temperature amplitude is smaller in Veracruz than in Mexico city, this is because the daily outdoor temperature variations are also smaller. From the mean air temperature graph in Figure 8.9 it can be seen that cooling will be required along the whole year; cooling units will switch on and off from October to March, but from April to September temperatures are always higher than the control set point of 25 °C so cooling will be working constantly all the time.



heavy (reference)

heavy (reference)

Figure 8.9 Annual operative and mean air temperature in the heavy weight non-insulated construction (reference building); control set points: 20 – 25 °C, Veracruz.

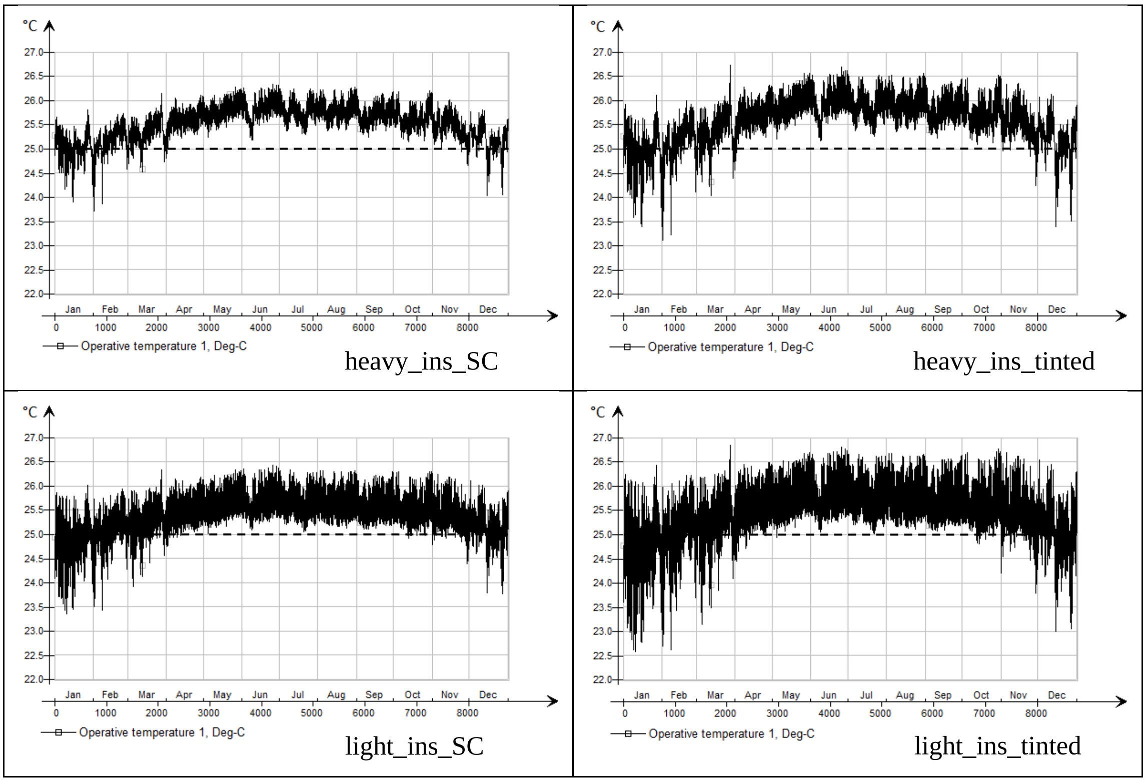


Figure 8.10 Annual operative temperatures in the heavy weight insulated and light weight insulated constructions with solar control and tinted glass; control set points: 20 – 25 °C, Veracruz.

8.6 Fixed shading

According to the passive design guidelines given by (Reardon, et al., 2010), building orientation and shading devices should aim to avoid the sun during the whole year round in warm climates where there is no need for winter heating, while in temperate climates it is desirable to let in the winter sun to heat the building by passive means.

The Stereographic diagram is one of the most accepted methods to describe the movement of the sun, so this will be used in order to propose the length of the shading elements. It should be noted that these diagrams give local times. The solar time can be obtained with a correction of -40 minutes for Mexico city and -28 min for Veracruz. This means that there is a difference of 12 minutes between the sun paths of Mexico and Veracruz. This is not a significant difference, so for simplification the same diagram will be used for both locations.

In Figure 8.11 it is shown a stereographic diagram for Mexico city. The equinox dates on March 21 and September 22 separate the winter from the summer months. The months below the equinox line are the winter months and the ones above are summer months. Given that Mexico city has a temperate climate, the solar radiation is to be shaded only during the summer months, these months are highlighted in red.

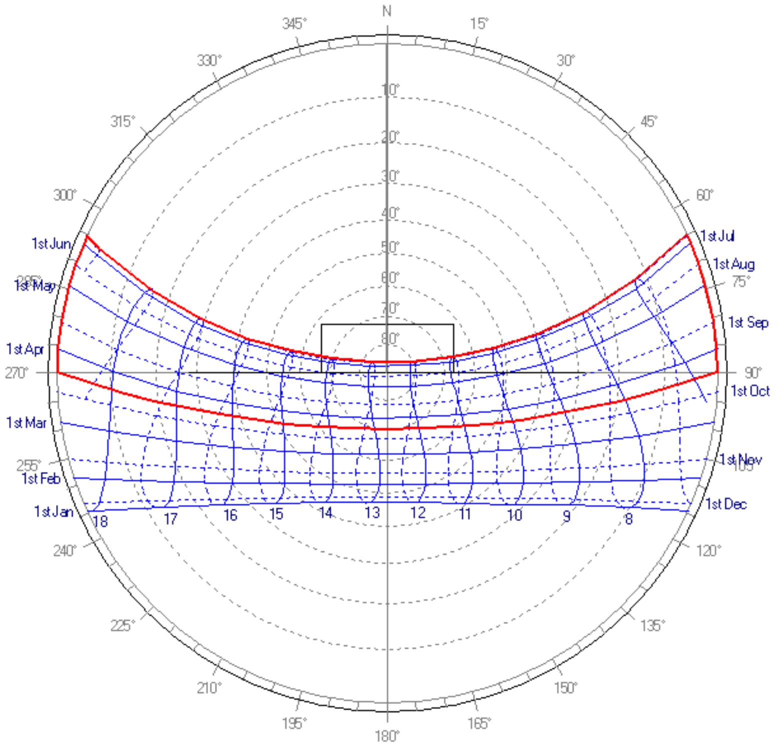


Figure 8.11 Sun path during the summer months, latitude 19°.

In order to shade the south and north facades during the summer months, fixed shading devices are proposed. A shading mask is drawn by using Vertical Shadow Angles (VSA) and Horizontal Shadow Angles (HSA). The method to draw the shading mask is explained in method sheet M.1.5 (Szokolay, 2004).

The vertical shadow angle to shade the south façade during the summer months can be found according to the following equation (Szokolay, 2004):

$$VSA = 90° - LAT \qquad (8.1)$$

For a latitude of 19° and using equation (8.1) it is found a VSA of 71°. This angle will shade the south façade during the summer months according to the figure below.

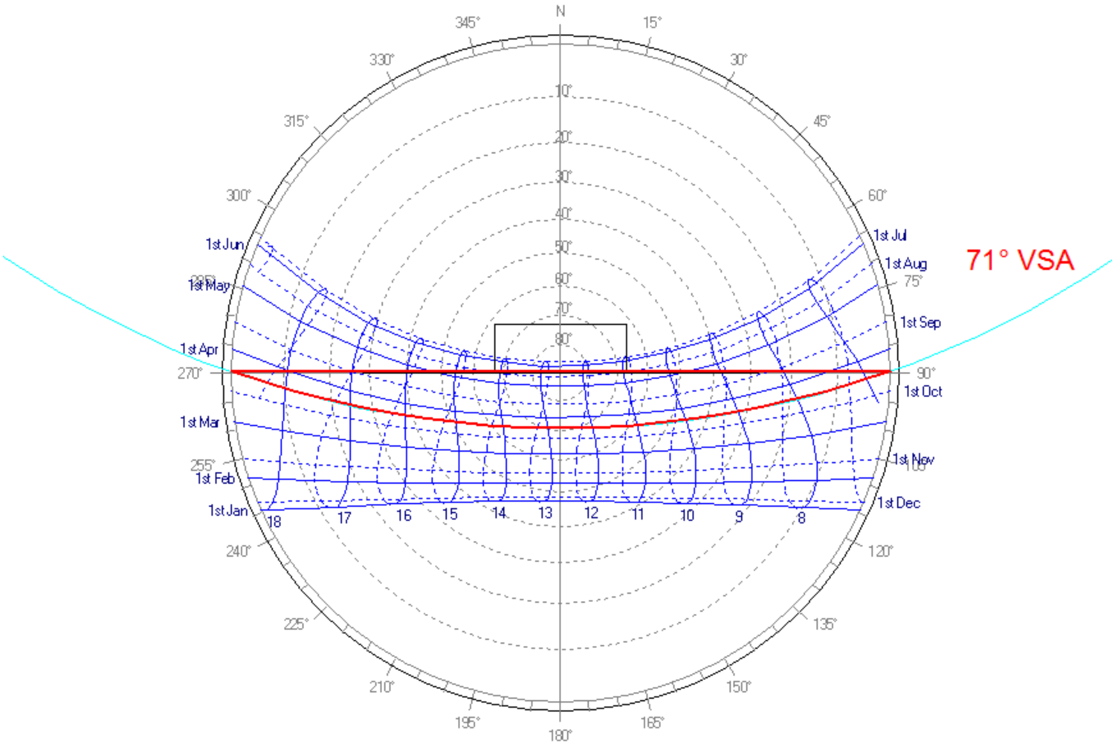


Figure 8.12 Shading mask with fixed horizontal element in south façade, Mexico city.

In the North façade, vertical shading elements are most effective. Most of the solar radiation can be shaded in summer with an HSA = -75° and +75°, see Figure 8.13.

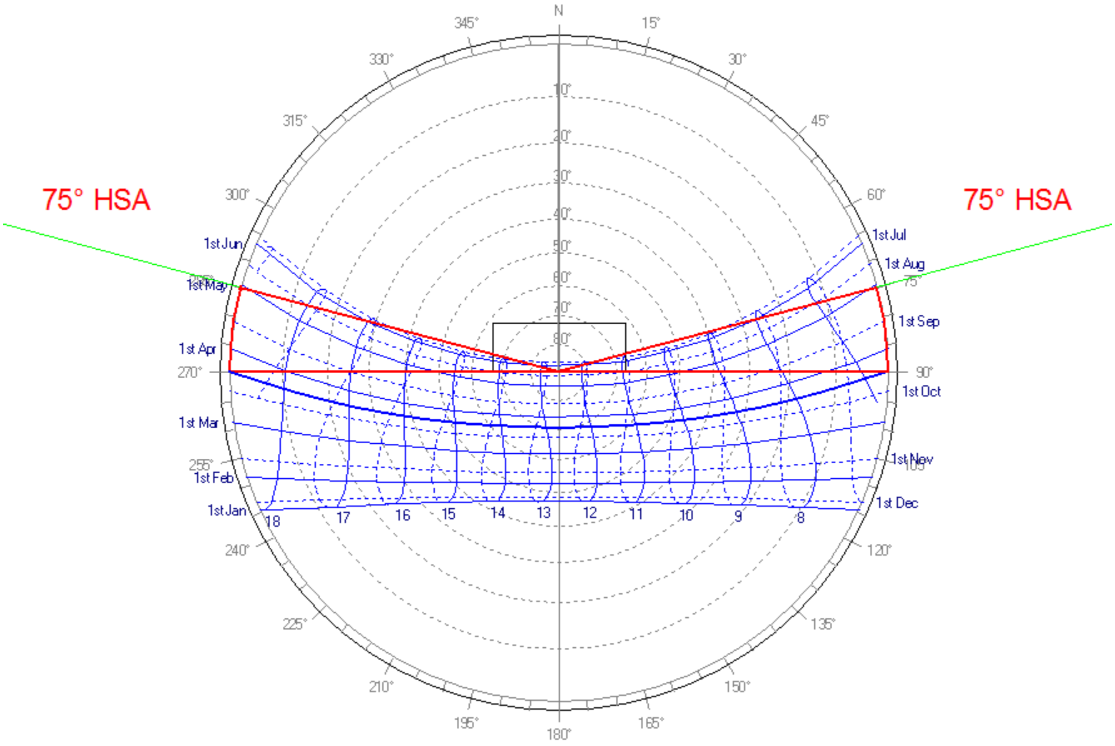


Figure 8.13 Shading mask with fixed vertical elements on the north façade, Mexico city.

The vertical and horizontal shadow angles are VSA = 71° (south façade) and HSA = -75° and +75° (north façade). The length of the shading elements is calculated for the corresponding shadow angles. In the south façade will be used an horizontal shading element of 41 cm, while in the north façade a vertical element of 27 cm will be needed, see Figure 8.14.

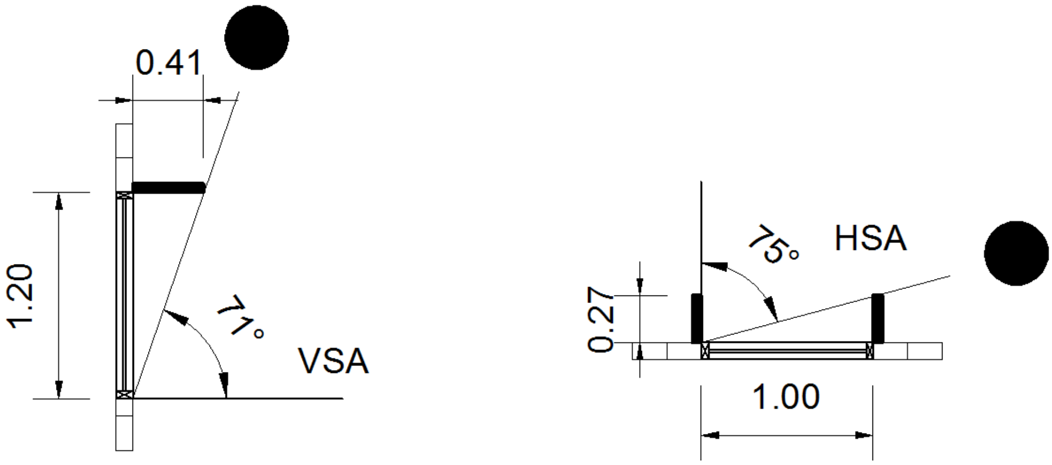


Figure 8.14 Shadow angles and their corresponding shading elements, Mexico city. Profile view of the south façade (left), View from above of the north façade (right).

It was decided not to shade the east and west façade in Mexico city since shading on these facades will also shade the winter solar radiation which is desirable to warm the building. A summary table showing the shadow angles and the length of the shading elements on every façade can be seen in Table 8.11.

Table 8.11 Shadow angles, window dimensions and length of shading devices for Mexico city and Veracruz.

		Facade Orientation			
		South	North	East	West
Mexico city	VSA (degrees)	71	-	-	-
	Window height (cm)	120	-	-	-
	Horizontal shading device length (cm)	41	-	-	-
	HSA (degrees)	-	75	-	-
	Window width (cm)	-	100	-	-
	Vertical shading device length (cm)	-	27	-	-
Veracruz	VSA (degrees)	56	-	56	56
	Window height (cm)	120	-	120	120
	Horizontal shading device length (cm)	80	-	80	80
	HSA (degrees)	-	75	-	-
	Window width (cm)	-	100	-	-
	Vertical shading device length (cm)	-	27	-	-

The shading strategy in the city of Veracruz should aim to block the direct solar radiation during the whole year. Nevertheless, in order to shade the sun all year round, the length of the shading elements would be unrealistically long. Therefore, reasonable lengths were proposed as in Table 8.11. Shading masks for the south, east and west facades in Veracruz are shown in Figure 8.15, Figure 8.16 and Figure 8.17. The shading on the north façade is the same for both climates.

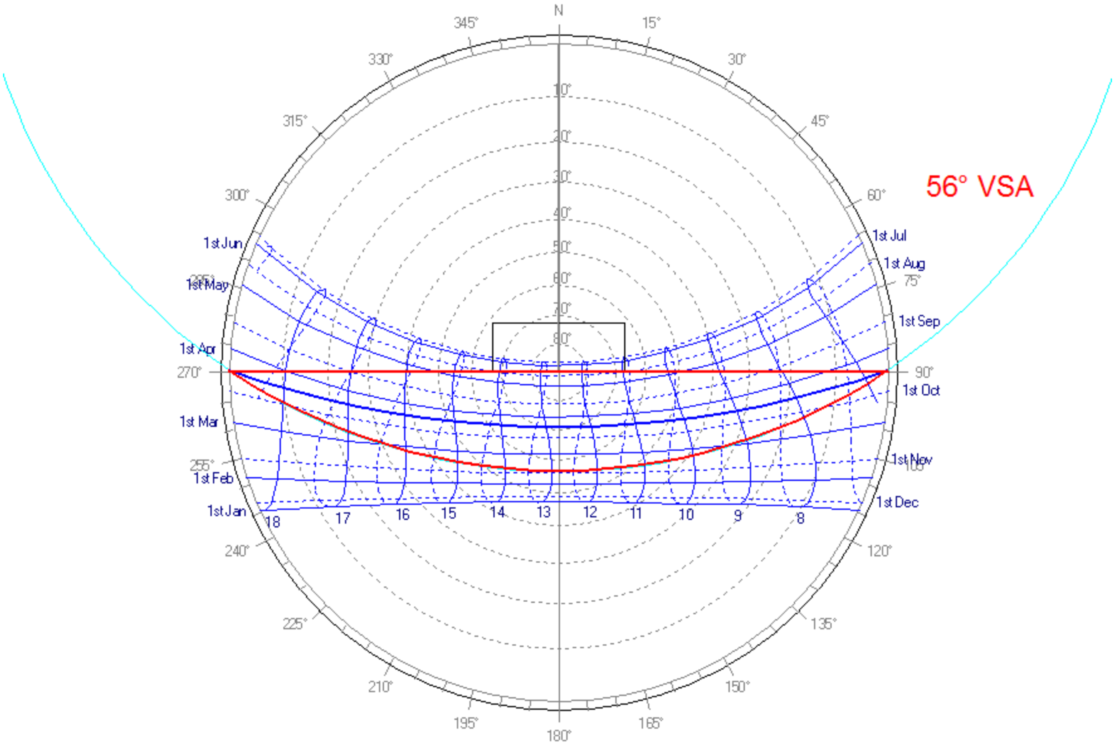


Figure 8.15 Shading mask with fixed horizontal element on the south façade, Veracruz.

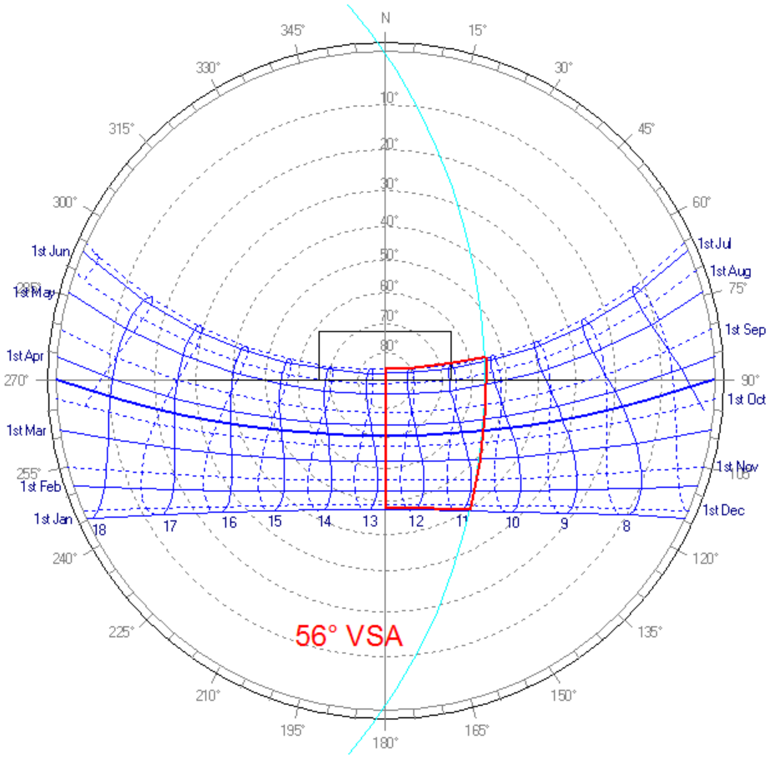


Figure 8.16 Shading mask with fixed horizontal element on the east façade, Veracruz.

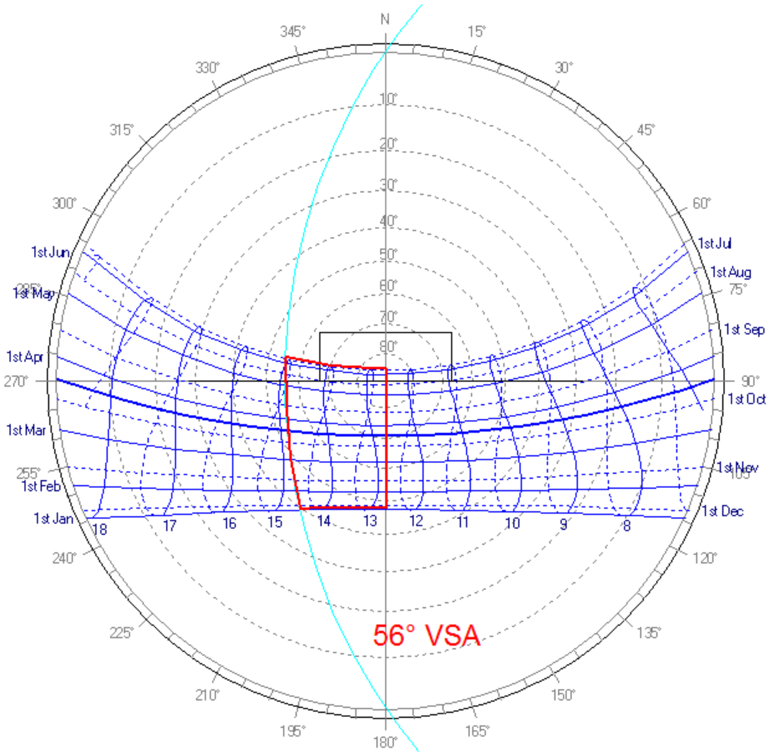


Figure 8.17 Shading mask with fixed horizontal element on the west façade, Veracruz.