An investigation of the thermal comfort and climate change resilience of bioclimatic design strategies for free running social housing in San Luis Potosi City, Mexico

Edgar Hilario Piña Hernandez

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Faculty of Humanities and Social Sciences, School of the Arts

Department of Architecture

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Declaration

I hereby certify that this thesis constitutes my own work and investigation. Where other sources of information have been used, they have been acknowledged, as it should be.

I declare that this thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Signed: Edgar Hilario Piña Hernandez

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Abstract

Rising temperatures due to global warming will impact on thermal comfort conditions in the social housing sector throughout the XXI century. Social housing represents the majority of the new build stock in the forthcoming decades in low and mid income countries such as Mexico due to demographic trends. Those families in social housing are particularly vulnerable to thermal discomfort because of the high initial and operating costs of HVAC systems that represent an economic burden that many of them will not be able to afford in order to achieve thermal comfort. Complementarily, the indiscriminate adoption of HVAC systems will add pressure to the national energy network and will further exacerbate global warming by increasing the amount of energy consumed by households. On the other hand, cities such as San Luis Potosi, Mexico have a relatively mild climate year-round which make it particularly suitable for the implementation of passive design as a low-cost strategy in order to achieve thermal comfort.

This research explores the potential of bioclimatic design strategies and locally available construction materials to generate thermal comfort and climate change resilience for free running social housing in San Luis Potosi up to 2080. To do so, a social housing prototype was designed in a contextually responsive way that incorporates several aspects of sustainability and translates them into architectural design guidelines. Then, the prototype was used for building energy simulations with DesignBuilder software in order to test the climate change resilience of the bioclimatic design strategies and locally available construction materials. Complementarily, parametric optimization simulations were done in order to find out the best windows sizes that would provide a balance between solar heat gains during the cold season while preventing over heating discomfort during the hot season. Simulation results demonstrated that it is possible to design free running social housing by the use of bioclimatic design, local construction materials, and natural ventilation. They also allowed to provide general design guidelines for the implementation of those parameters for the wider residential sector in San Luis Potosi City, Mexico. It was also found that the adaptive model of thermal comfort (AMTC) as developed by the ASHRAE 55-2013 standard is a suitable and locally appropriate first approach to thermal comfort for the social housing sector because it can incorporate people's thermal acceptancy with a more flexible thermal comfort temperature band than the one traditionally used when designing with the static model of thermal comfort. In that sense, the AMTC opens research possibilities for the development of locally appropriate energy saving standards and policy making.

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Table of Contents

List of figures

List of tables

Terms, definitions and acronyms

AC – Air conditioning

Ach/hr – air changes per hour

AMTC – Adaptive model of thermal comfort and preference

AVG - Average

CCS – Carbon capture and storage

CFL – Compact fluorescent lightbulbs

CMY – Climate model year

CONAPO – National population council by its Spanish initials

DEEVi – Energy efficiency design tool

epw – energy plus weather format

GHG – Greenhouse gas

HVAC – Heating, ventilation and air conditioning

IDG – Global performance index

INFONAVIT – National workers' housing fund institute by its Spanish initials

IPCC – Intergovernmental Panel on Climate Change

LED – Light emitting diode

MYA – Model year analysis

NGP – National gross product

OECD – Organisation for Economic Co-operation and Development

PHPP – Passive House Planning Package

PMV – Predictive mean vote

PMV ET – Predictive mean vote effective temperature

PVP – Photo Voltaic Panel

RUV – Unique housing registry by its Spanish initials

SAAVi – Water house saving simulator

SEDATU – Ministry of agrarian, territorial and urban development by its Spanish initials

SEN – National electric system by its Spanish initials

SHF – Federal mortgage society by its Spanish initials

SiE – Sisevive Ecocasa programme

SLP – San Luis Potosi

TM – Thermal mass

TMY – Typical meteorological year

VSM – Number of minimum wages by its Spanish initials

Chapter 1. The research problem

1.1 Introduction

It is now widely acknowledged by the scientific community that global temperatures are rising due to human-induced climate change. Along with warmer winters and hotter summers, it is expected that throughout the XXI century extreme weather events will become more frequent such as droughts, heat waves, hurricanes, flash flooding, etc. (World Wide fund for Nature, 2010). During the same time period Mexico will experience an important urban expansion (up to year 2050) propelled by demographic growth, especially in medium sized cities such as San Luis Potosi (Tovilla, 2015). Due to the generalized low-income levels of Mexican families (almost 50% of its population living in poverty), it is expected that most of the housing demand will concentrate in the informal[1] and in the social housing sectors (SNIIV2.0, 2017).

In 2013 the Mexican government introduced a controversial Energy Reform that, through constitutional amendments, allowed private investment in the electric and petroleum sectors (strategic sectors historically managed by the State). Soon after, gas and oil prices began to fall globally (H.K. Vietor & Sheldahl-Thomason, 2017). However, the reduction in subsidies and the liberalization of the sector has brought about constant increases in energy prices for the end consumers (households and industry). One of the main challenges for the social housing sector in Mexico is not only to provide affordable housing, but also to provide housing that will be able to withstand the expected rises in temperatures that are likely to be experienced through their life cycle while providing thermal comfort in an energy and cost-effective manner. This research explores the potential of bioclimatic design and natural ventilation (passive design) in providing thermal comfort climate change resilience up to year 2080 for the social housing sector in San Luis Potosi City, Mexico. One of the main advantages of this approach is that it does not rely on mechanical heating/cooling systems, whose operating costs can be an economic burden for low income families. Also, the indiscriminate adoption of AC systems adds pressure to the national energy system which ultimately further exacerbates global warming.

Although some research has been done exploring the potential of bioclimatic design in providing thermal comfort in different climatic regions of Mexico (Fernandez Melchor & Garcia Chavez, 2014) (Gutierrez, et al., 2014), very few have also explored its capacity to withstand the projected increases in temperature expected in the forthcoming decades due

[1] The informal sector accounts for nearly 50% of the urban growth in Mexico and it involves occupying land illegally, situation that further segregate that specific population sector. The phenomenon is quite complex with strong political implications; therefore, it is not considered as a target for this research.

to climate change. Also, little local research is available regarding the adaptive model of thermal comfort (Alpuche, et al., 2009). In consequence, this research explores the climate change resilience of locally appropriate bioclimatic design strategies and natural ventilation through the adaptive model of thermal comfort. To do so, building energy simulations and parametric optimisation are proposed as a cost-effective method.

It follows, from the building energy simulation approach, that a digital social housing prototype could be developed in a responsive way to its context, with the underlying assumption that sustainability is a local phenomenon that needs to be addressed locally. As a consequence, the research began by exploring, from a more general perspective, the role of social housing in its urban context, with a focus on sustainability, looking at demographic trends and social effects. Three case studies were examined that helped to better understand social housing in Mexico from an architectural perspective. Then, after the contextual, the research moves its focus towards San Luis Potosi City, by exploring local demographic trends, local weather and future scenarios of climate change. This was then followed by an evaluation of the future performance of bioclimatic design strategies. The construction materials selection was filtered through a multi-criteria analysis that allowed a match to those materials that have the largest impact in terms of energy and cost-effectiveness. This was done in response to the price sensitivity of the social housing sector. The next step consisted of validating the simulation parameters and this was done using data loggers that allowed the performance between a physical and a digital model of the same building to be compared. This process also allowed fine tuning of the general simulation parameters through a feed-back process. Finally, with all the parameters established, the digital prototype was tested with a series of parametric simulations that allowed the establishment of optimized windows sizes, construction materials and their performance for future weather scenarios chiefly.

The general results point towards the possibility to design and build thermally comfortable climate change resilient social housing up to year 2080 in San Luis Potosi City, Mexico employing locally available construction materials with natural ventilation. This means that the traditionally used construction materials and methods can be re-arranged through bioclimatic approaches chiefly, to design and build energy efficient social housing. Results also showed the appropriateness of the use of the adaptive model of thermal comfort as this is more suitable for and responsive to the naturally ventilated buildings which constitute the vast majority of the building stock in San Luis Potosi City and in Mexico generally.

1.2 Research Topic

Free running social housing resilient to climate change up to year 2080 through the use of locally appropriate bioclimatic design strategies in San Luis Potosi City, Mexico. An approximation through the implementation of the adaptive model of thermal comfort.

1.3 Research Questions

How to design free running social housing that will be comfortable year-round at present time and during an estimated 50 years life cycle, taking into consideration the expected rise in temperatures that the planet will experience due to climate change during the same time period for San Luis Potosi City, Mexico?

- Given San Luis Potosi City's weather conditions and geographical location, what are the most effective bioclimatic design strategies that can be implemented in the social housing sector in order to optimize thermal comfort?
- Which bioclimatic design strategies will still be effective in providing thermal comfort under future weather scenarios of climate change in the social housing sector?
- What locally available construction materials will be the most effective in providing thermal comfort at present time and also under future weather scenarios (climate change resilience) in tune with the locally appropriate bioclimatic design strategies?
- How and why can the AMTC be employed as a locally appropriate index for thermal acceptancy in the residential sector?
- How can building energy simulations be employed to test the effectiveness of locally appropriate bioclimatic design strategies, construction materials and windows sizes?
- How can simulation parameters be validated to more accurately represent reality and provide more certainty about the expected thermal comfort simulated outputs?
- How can research results be used to improve thermal comfort and climate change resilience in the residential sector and the construction sector in general in San Luis Potosi City?

1.4 Aims and objectives

The main goal of the research is to explore the climate change resilience and the potential of providing thermal comfort of locally appropriate bioclimatic design strategies at the present time and for future weather scenarios (years 2010, 2020, 2050 & 2080) for the residential sector, in particular for social housing in San Luis Potosi City, Mexico. To do so, a 3 stories high social housing prototype was designed in compliance with local construction normativity and regulations with the following objectives:

- To assess the capacity of different bioclimatic design strategies to provide thermal comfort for San Luis Potosi City, Mexico and to determine the most effective ones.
- To assess and compare the capacity to provide thermal comfort for future climate change scenarios (climate change resilience) of the most effective bioclimatic design strategies for San Luis Potosi City, Mexico.
- To assess and compare the thermal performance of the most commonly used and locally available construction materials in tune with the most effective bioclimatic design strategies that will provide thermal comfort climate change resilience for San Luis Potosi City, Mexico.
- To perform parametric optimization of the prototype in order to find out the best set of design solutions at present time and for future weather scenarios.

Research the effectiveness and appropriateness of employing locally available construction materials. Also, the outcomes will inform about how and whether the construction materials will be able to provide thermal comfort at present time but also in future weather scenarios of climate change in tune with a 50 years house life span (up to year 2080).

Results can potentially be used as locally appropriate bioclimatic design guidelines not only for the social housing sector, but also for the residential sector and for the construction industry in general. This will aid the development of a more energy efficient industry capable of providing thermal comfort in a natural way by minimizing the use of mechanical heating/cooling systems in the residential sector in San Luis Potosi City, Mexico.

1.5 General methodology and thesis outline

This chapter begins with a brief description of the methodology employed throughout the research process. This is followed up by the thesis outline since the research structure is responsive and, therefore, reflects as much as possible the research methods (process) employed.

It is important to begin by looking at the main research question, because the research methodology represents how the question is conceptualized and the strategy followed to find an answer to it:

- How to design free running social housing that will be comfortable year-round at present time and during an estimated 50 years life cycle, taking into consideration the expected rise in temperatures that the planet will experience due to climate change during the same time period for San Luis Potosi City, Mexico?

According to Nigel Cross, cited in (Groat & Wang, 2013), research design is an abductive thinking design process "…*The more useful concept…used by design researchers is abductive: a type of reasoning…which is the necessary logic of design. It…provides the means to shift and transfer thought between the required purpose and function and appropriate forms for an object to satisfy that purpose*" (Groat & Wang, 2013, p. 35). This reasoning leads to what the author describes to be the role of abduction in design when creating value is an inherent goal of research, they formulate the following equation:

WHAT (thing) + HOW (working principle) leads to VALUE (aspired)

or,

WHAT (climate change resilient social housing) + HOW (?) = VALUE (environmental benefits, costs and energy savings, thermal comfort)

Following this logic, since the early research stages there was an underlying assumption (abductive thinking) that it is possible indeed to achieve the objective (WHAT?) design/build free running social housing resilient to climate change.' Also, the VALUE is understood as the potential benefits in terms of energy savings, thermal comfort, and economic savings for low income families in Mexico, which leads to the following equation restatement:

HOW? = VALUE – WHAT

It is important to keep in mind that the equation presented is of a conceptual nature, thus, the sign (+/-) is only indicative of a correlation between the value that we want to obtain and its relationship with the object through which we might achieve it. Complementarily, to answering the research question HOW, aligns with what Jay Farbstein and Min Knatrowitz, cited in (Groat & Wang, 2013, p. 44), consider as *design-decision research* in which the researcher plays a designer role and his/her decisions are supported by research findings. This means that the decisions taken in relationship to the research/design process will be supported by research findings, avoiding assumptions and/or impositions to generate a research process grounded in reality as much as possible.

On the other hand, *simulation research* is a fundamental aspect of the project because building energy simulations, through DesignBuilder software (chiefly), were the main tools that allowed the performance and the behaviour of the different elements represented in the software to be assessed and compared. That representation is the model or prototype whose design process itself is a very important part of the research methodology in which it is acknowledged that the quality and accuracy of the model relies on the quality and accuracy of the information in which it feeds on.

Consequently, the research methodology was divided in to three parts: the first one consisted in studying the general context of social housing in Mexico, its characteristics and challenges, this was done through literature review and the findings were used as general design guidelines for research itself as much as for the prototype design. The second part follows the contextual analysis at a more local level (San Luis Potosi City). Again, literature review provided more specific design parameters (research design) and the technical aspects that were employed throughout the final research stage which is the simulation and results analysis (simulation research).

One of the main risks of simulation-based research is that it can easily fall into highly speculative grounds, especially when part of the research process involves the design of a prototype in which simulations will be run to test construction materials capacity to provide thermal comfort, natural ventilation, windows sizing, etc. The third part of the methodology tried to overcome the pitfalls of a highly speculative prototype by undertaking a two part contextual analysis, beginning from a national perspective down to the local context of San Luis Potosi City. This approach follows the logic of sustainability as a local phenomenon for which solutions are better met by studying the context in which the very phenomenon is happening. In the first section of the research the following general contextual aspects were explored:

- Chapter 2.1 & 2.1.1 urban development and sustainable urban development. Both terms represent the ultimate goal of the national development plan 2012-2018 for urban settlements in Mexico. Although the plan does not provide a clear definition of either term, it was necessary to explore them to better understand the role of social housing within those.

- Chapter 2.1.2 deep decarbonisation pathways in Mexico. The deep decarbonisation pathways are the overarching transitioning energy policies ratified by the Mexican government in the Paris agreement (December 2015) in which the country committed to reduce its CO_2 emissions through the decarbonisation its economy. The impact of such policies on social housing was explored.
- Chapters 2.2 & 2.3 Urban sprawl and segregation. Were studied as they are the most pressing unintended consequences of the current expansive urban and social housing growth model, characterized by a highly deregulated market driven by land speculation.
- Chapter 2.4 demographic trends in Mexico. By studying the national demographic projections up to year 2050, it was possible to identify growth trends in the forthcoming decades in tune with climate change projections.
- Chapter 2.5 housing segmentation. Allowed to understand the size of the social housing market and the relevance of the research project due to the potential benefits for the studied housing segment(s).
- Chapter 2.6 social housing. It was necessary to provide a brief description of what is social housing in the Mexican context, its main institutional stake holders, as well as the recent initiatives towards a sustainable social housing sector in Mexico.

Although not exhaustive due to time limitations, and because the main research goals are oriented towards thermal comfort (energy efficiency) in the social housing sector; the general contextual analysis allowed a better understanding of the different aspects that shape social housing in Mexico from a sustainable perspective, taking in to consideration, energy, social, policy, demographic, and economic elements. All the aforementioned aspects were considered as design driving forces as is further explained whenever the case at the end of each relevant chapter and/or sub-chapter.

Chapter 2.7 consisted in providing the research’s stance on bioclimatic design and a brief technical description on the weather files generated and employed throughout the building energy simulations.

Chapter 2.8 three case studies are presented in order to provide a better understanding of: a) a typical social housing unit that exemplifies the general characteristics and spatial distribution, and how, the same typology is reproduced all over the country regardless of local weather conditions; b) an example of a bioclimatically designed social housing prototype in a similar region to San Luis Potosi city, although just a project, it exemplifies recent attempts of developing locally appropriate responses to SH; however, it lacks supporting energy simulations and a more technical, measurable, and replicable methodology. Finally, c) shows a commercially available (built) mid/social housing neighbourhood designed with urban sustainable principles as well as bioclimatically designed housing units with the option of integrating AC systems latter on by the homebuyers. Although the case studies are not directly comparable, they show the diversity of approaches to social housing in Mexico from the regular practice (a), to conceptual design (b), and commercially available (c).

The second part of the analysis explores more in depth the local context of San Luis Potosi City. The study feeds upon and builds on the previous sections in an iterative manner that allowed research inform itself as briefly described next:

- Chapter 3.1 briefly describes the general geographic and climatologic characteristics of San Luis Potosi City, Mexico.
- Chapter 3.2 explores the local demographic projections and the social housing market size (housing segmentation) in San Luis Potosi City.
- Chapters 3.3 and 3.4 study the local weather as the stepping stone for the climate change projection analysis for years 2010, 2020, 2050 and 2080. The climate change scenarios were generated with Meteonorm software which incorporates up to date IPCC algorithms for climate change projections as is further explained in Chapter 3.4.
- Chapters 3.5 and 3.6 assessed the effectiveness of locally appropriate bioclimatic design strategies at present time and for the future weather scenarios of climate change. The analysis was done with ClimateConsultant software and it was found that the most resilient, thus, effective bioclimatic design strategy for San Luis Potosi City is high thermal mass.
- Chapter 3.7 consisted in a general construction cost analysis. Based on appraisers/contractors professional expertise, it was possible to select the construction elements that have the largest economic impact in the social housing sector by the use of a Pareto analysis. Although the analysis is not exhaustive, it supported and justified decision making about construction materials selection for the thermal comfort simulations.
- Chapter 3.8 once high thermal mass was found to be quite effective as bioclimatic design strategy, and with the general construction cost analysis, it was possible to choose the locally available construction materials that provided a balance between high thermal mass and costs.
- Chapter 3.9 consisted in studying Mexican norms to find out the thermal conductivity values of the construction materials to be represented in the simulations. This way, it

was possible to provide values representative of the national market that can also be easily replicated regardless of quality variations due to manufacturing processes.

Chapter 4 explores thermal comfort in naturally ventilated buildings. This chapter is the product of a part of the research that is not shown on the dissertation and consisted in a series of simulations that allowed to become familiar and proficient with DesignBuilder software. The simulations were run for a first prototype design that was dismissed when filtered through the cost analysis study which showed that the initially proposed build surface would be too expensive for the social housing segment in Mexico. Besides its invaluable use as a learning tool, the first prototype shed light on some technical limitations of DB.

The first series of thermal comfort simulations showed a large number of discomfort hours when employing the Pierce PMV ET index (found to be appropriate for naturally ventilated buildings). Through several thermal comfort simulations analysis, it was concluded that although air temperatures inside the prototype were slightly above or below the software thermal comfort band (20-25°C), the magnitude of that discomfort was negligible for most of the simulated time. This meant that the software thermal comfort sensitivity is locked-in with the static model of thermal comfort originally developed for buildings with HVAC systems, but not appropriate for naturally ventilated buildings. Further research on the subject led to conclude that the adaptive model of thermal comfort would be a more sensitive metric for thermal comfort (discomfort hours) for naturally ventilated housing and thus, it was adopted as is further explained in Chapter 4.

Chapter 5 is the end of the second part of the research and consisted in validating the general simulation parameters prior to their implementation into the final social housing prototype design. The validation consisted in placing data loggers in a bioclimatically designed house in San Luis Potosi. The house was simulated with DesignBuilder and the simulated air temperatures were compared with those measured as is further explained in Chapter 5.

The third part of the research incorporated all the knowledge from the previous two sections and synthesized them into the social housing prototype proposal. Although design itself was not meant to be a research objective, it was considered as a very important part of the process, therefore, especial attention was put so that it would reflect the local conditions of San Luis Potosi, City in a responsive way with its context. More details on the prototype can be found in Chapter 6

Chapter 7 consisted in thermal comfort simulations comparing the performance of red brick, hollow concrete block, and extruded brick in their capacity to provide thermal comfort at present time and for future weather scenarios of climate chage. The simulation results were processed with the adaptive model of thermal comfort temperature band, and a discomfort hours comparison was done with the static model of thermal comfort.

Chapter 8 employed the *shoe box* simplified simulation method for windows size parametric optimisation using the same three wall construction materials, during the same time period but focusing on the AMTC. Complementarily, the impact on thermal comfort when varying slab thickness was also studied as this would affect the amount of thermal mass, thus comfort conditions.

Chapter 9 allowed a better understanding of the energy exchange during the summer and winter design days by studying the energy balance of the prototype by hour and by floor, shedding light on the building and construction materials performance during the studied time period. This finer analysis was the culmination of the research process and the results obtained could not be possible without following the methodology presented. Furthermore, the methods are part of the robust research/learning process that led to the discussion and conclusions presented in Chapters 10 & 11 (Conclusion and Discussion respectively).

Finally, it is important to acknowledge the fact that although simulation based research is a time and cost-effective way to test design options and construction materials, the currently available simulation tools fall short in their capacity to incorporate and represent the multiple variables that conform our complex reality. This means that the results found, and the metrics employed might lack quantitative accuracy – instead, they are used to support the decisions than lead to the expected research outcome in a reasonably and verifiable manner.

Section 1. General contextual analysis

Chapter 2. Literature review

The literature review for this research begins with the broad perspective of the sustainable urban development and is slowly sized down to building level with an emphasis on the Mexican context. Firstly, the concept of urban sustainability is explored along with the influence that the deep decarbonisation pathways of Mexico's economy will have in the housing sector. Secondly, urban sprawl, segregation, demographic growth and housing segmentation were explored in the Mexican context providing some contextual design guide for the social housing prototype design. Thirdly, the social housing sector and its key players were explored in the context of the recent shift into a more sustainable social housing sector led by the Mexican government, in connection with climate change and the construction industry. Then, complementary basic information on the concept of bioclimatic design, weather, and energy simulations are presented in order to round up a general understanding of such concepts and their relationship with the building industry. Finally, three case studies are presented to better understand how social housing has been done in Mexico as well as to exemplify more recent approaches to bioclimatic design and sustainability in the social housing sector, followed by a brief discussion highlighting the main findings. It is important to note that the literature review had two functions for this research: explore the general context of and inform the prototype's design.

2.1 Sustainable Urban Development and Urban Sustainability

Sustainability and sustainable development are terms that became widespread at the end of the decade of 1980s after the United Nations (UN) published the influential report *Our Common Future* (also known as the Brundtland report) in which sustainable development goal was defined as that which '*seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future*' (United Nations, 1987, p. point 49). Beyond the rhetorical over use of the term in the last decades, its core goal has permeated diverse knowledge fields, from politics, marketing, sciences, etc. This is in part due to the increasing awareness about the unsustainability of our prevalent production-consumption models that has led to global warming as the most pressing environmental crisis induced by human activities, and that has highlighted the need of new models of production and consumption as well as social agreements that can guarantee a sustained environmental, political, economic, cultural, and social development. Models that can also grant life quality for humans in the present and in the future while respecting ecosystem's charge capacity and capable of granting the prevalence of life for non-human species in the planet.

The two main precedents of sustainability in the urban realm can be found firstly, on the 1992 Rio de Janeiro *Curitiva Declaration* and secondly, in the 1994 *European Cities Chart*. One of the main outcomes from those was that from then on, land was considered to be a non-renewable resource; it cannot be produced, replaced, nor replicated, because each land parcel is unique due to its intrinsic characteristic such as orientation, relative position, adjacencies, etc. Such conceptualization was also influenced by thermodynamics and ecological principles: '*This implies, among many other things, a maximum internationalization of all productive costs, including those related to the transformation and development of cities and territory*' (UPC, 2002, p. 8). This had a deep impact on territorial management because it acknowledged that excessive land consumption would eventually lead to its exhaustion in a foreseeable future. Therefore, its management requires strategies for demand containment, increased efficiency on its use (e.g. verticality in the construction sector), and its re-use and recycle.

On the other hand, the European Chart for Sustainable Cities proposed local action as the foundation for urban sustainable management, making especial emphasis on the sustainable management of natural resources such as energy, waste, sustainable urban mobility, spatial planning and urban planning but especially by acknowledging the global impacts and therefore interconnectedness of urban settlements.

It is also important to mention that this perspective is based on a conceptualization of urban systems as open ecosystems, analogue to living organisms. This means that to thrive, they require a permanent supply of matter, energy and information. However, cities, due to their size and complexity, surpass their immediate natural surrounding capacity to supply such inputs. Hence, they require to import some of them from other ecosystems. Furthermore, as any living organism, cities produce outputs (waste) which unlike those produced by biological organisms, will hardly reintegrate into the ecological cycle, surpassing by much the charge capabilities of its immediate natural surroundings. This relates us to the global interdependency and impacts of urban systems.

Therefore, the objective of sustainable urban management is to close the urban ecosystem as much as possible, with the following implications:

- Minimize natural resources consumption, especially the non-renewable ones or those with slow renovation rates
- Minimize waste production by reusing and recycling whenever possible
- Minimize air, water and land pollution
- Increase the proportion of natural spaces and biodiversity in cities (UPC, 2002, p. 20)

With such precedents, the Third European Summit on sustainable towns and cities, also known as Hannover 2000, identified six key aspects towards local urban sustainability:

1. Integrated urban planning
2. Compact urban development
3. Redevelopment of deprived urban areas
4. Less and more efficient consumption of land as well as other natural resources
5. Local energy and transport management
6. Fight against social exclusion, unemployment and poverty

These six points constitute action guidelines for design and implementation of specific urban planning and management tools and policies. They also provide some awareness about the role of housing within urban sustainability from an ecological perspective. If cities are conceptualized as living organisms, then build artefacts can be considered as the cells that constitute a larger body i.e. the city. From this perspective, housing is the minimum urban unit in which individuals develop (physically and psycho-affectively); it also constitutes the space in which urban dwellers, rest, leisure, feed and nurture, and also is the space in which people produce residues and consumes products and energy to meet their needs (this include but it is not limited to thermal comfort and wellbeing). Hence the importance of understanding the effect that urban forces excerpt over the social housing sector and vice versa.

2.1.1 Urban environment and Urban Sustainability

Cities are human artefacts and as such they are deeply connected to their natural environment. Vernacular architecture synthesizes a long historical trial and error adaptation of the build environment to the local climate (Sayigh & Zuhairy, 1993). However, due to the accelerated urbanization processes all over the world and cheap energy prices throughout most of the XX century, cities have experienced unprecedented growth, leaving aside traditional architectural knowledge and creating an acute separation between the urban environment and the natural (Nguyen & Reiter, 2017). It is within this context that it is necessary to distinguish between *urban environment* and *urban sustainability*.

Urban environment as a concept considers the city as the habitat in which humans interact and develop their daily activities. Cities exist in a specific geographic location with particular natural conditions (weather, vegetal cover, temperature, humidity, etc.). From this point of view, demographic, hence urban growth is not considered negative *per se* for the local or global environment; however, the complex interactions derived from demographic growth that impact on the urban sustainability of cities can be negative.

There are at least five physical tangible intersection areas between city dwellers and the urban environment:

1. Water
2. Air
3. Land
4. Waste
5. Transportation

Urban sustainability is deeply intertwined with these five elements; for instance, water is scarce in many Mexican regions and its availability is already a challenge for urban sustainability. On the other hand, water supply from other ecosystems can cause irreparable damage to the supplying hydric regions. This resource transference is also known as *sustainability importation*, and this can be either detrimental or positive depending upon the management of such processes.

Air is another sustainability challenge since its pollution has a direct negative effect on urban dwellers; producing affectations of the respiratory system for which the youngest and the elderly are particularly sensitive. Suspended particles on the air can come from cars, coal burn, industrial, and productive processes as well as extractive activities. Depending on the geography and weather, air currents can transport the urban pollution into far away regions, or when mixed with atmospheric water vapour it can produce acidic rain. Therefore, the impacts of urban pollution can even reach global scale.

When it comes about land, some of the most negative impacts of urban growth occur when agricultural land is used for urban development; or through the drainage of basins for the same purpose; or when occupying high risk areas which are prone to natural disasters (usually by low income families). This is a particularly complex phenomenon given that politics, economics, and planning capabilities usually have a more relevant role when decision making than the environment and long term sustainability. This is especially true for the Mexican context which is characterized by the prevalence of an open land market driven by speculation, and the lack of long term effective urban planning.

Waste management is another issue, a low percentage of waste water is treated, and instead it is just discharged on rivers and/or the sea. For solid waste management, landfill is still a common practice, whereas waste separation, reuse and recycle are still in seminal stages due to the lack of public awareness and the accompanying regulatory framework.

As for urban transport, the general problem is co-related to the lack of long term planning prevalent in Mexico. The rapid and almost anarchic urban growth experienced in the past 50 years did not take in to account mobility, and this situation has perpetuated itself until the present day. The speculative nature of land markets has had a negative impact on urban planning and in San Luis Potosi City private businesses (real estate) have created a dispersed, poorly connected, and poorly planned urban landscape, exacerbating inequity and a number of challenges that still need to be addressed.

In the last decade sustainability in the urban environment has become even more complex by integrating political and socio-cultural perspectives of those who inhabit them, thus, going a step further from the 'traditional' place-based approach and opening up the analysis/discussion on the temporal-spatial interactions of urbanization as a socio-ecological process and its interactions with other biophysical systems. Knowledge that leads to a better understanding of such interactions has the potential for achieving urban sustainability from a global (planetary) perspective. As better explained: *Any hope of achieving global sustainability in holistic terms requires that we understand the connections between urban processes, natural resources, land change, human migration, financial flows, and technology transfers and innovation with environmental change in this broader context* (Griffith, et al., 2018, p. 152). Furthermore, the integration of IT and big data in the urban analysis is opening up alternate ways of understanding and managing urban complexity such as is the case of the so called *Smart Cities.*

On the other hand, and of especial relevance for low and middle income countries such as Mexico, is the emergence of adaptation and mitigation strategies for sustainability and resilience in the urban context. This is because developing countries hold the fastest urban growing populations in the planet, in a poorly urban planned context, with high rates of poverty, irregular settlements in high risk areas, lack or substandard infrastructure and weak social and political institutions that will have to cope with the foreseeable and also the unexpected challenges posed by climate change (Griffith, et al., 2018). One of the ways to deal with this scenario is the adoption of mitigation actions that seek to reduce greenhouse gas (GHG) emissions. In Mexico this strategy has been adopted by the social housing sector in recent years through the development and implementation of the Mexican housing NAMA (Nationally Appropriate Mitigation Actions) that seeks to improve energy efficiency in the social housing sector while reducing greenhouse gas (GHG) emissions. The general idea is to produce a large impact through the aggregated benefits that the construction of new energy efficient houses and (in the mid-term) the retrofitting of the existing stock will have on GHG emissions reduction. All of this within the larger overarching Decarbonisation Pathways of the Mexican economy agenda (currently underway) that will be further explained in the following section.

There is still a long way to go to achieve urban sustainability in Mexican cities; however, first steps have been given with the national sustainable housing policy implemented by the Mexican government in recent years. Among the benefits, there is the creation of housing energy standards and a labelling system (still in the development and early implementation stages). Also, the fact that, even though slowly, there is increasingly a better understanding of the urban phenomenon as a complex one, and about the different issues that need to be addressed in order to improve urban life quality from a more holistic and sustainable perspective. The outlined urban scenario is commonplace for most Mexican cities and it is important to note that this research will address sustainability from the building perspective (social housing sector). However, as part of the contextual analysis it is important to understand the main challenges and driving forces around social housing as an integral part of its urban context. Finally, from this chapter it can be concluded that effective policymaking and planning are the overarching strategies that can enable the transitioning towards more sustainable cities in which the housing sector and especially the social housing sector concentrate resource consumption by individuals (see Fig. 2.1).

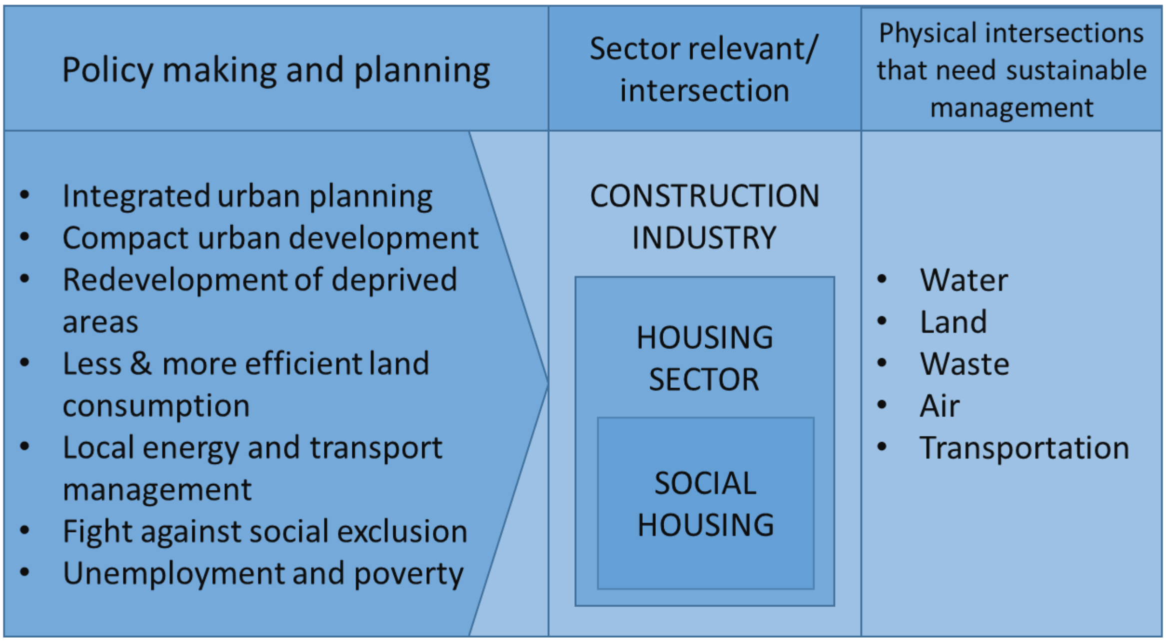

Figure 2.1 Sustainable urban environment from the housing sector perspective

2.1.2 Deep Decarbonisation Pathways in Mexico

As mentioned in the previous section, policy making can be considered as the general planning blueprint for achieving sustainability in our urban systems, and in Mexico the Deep Decarbonisation Pathways Project aims to outline how Mexico can transform its energy system by 2050 in order to achieve a low-carbon economy that in turn will aid in the global effort of reducing the risks of catastrophic global warming (>2°C by year 2100). The project is part of a multinational effort comprised by 16 countries with different stages of development and that altogether represent 70% of global greenhouse gas (GHG) emissions (Tovilla, 2015). The 16 countries are: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom and the United States.

The decarbonisation strategy relies on three ´pillars' or general strategies:

1. Energy efficiency. By improving the efficiency of end-use equipment like buildings, appliances, light bulbs, computers, vehicles, etc., we can expect a reduced intensity in the use of energy which can be translated in less household expenditure. However, this increased efficiency depends on technological improvements that can be levered or not by national norms and regulations.
2. Electrification and fuel switching. Relies on an aggressive implementation of carbon-neutral energy sources towards 2050 and the massive electrification across sectors. This means that clean electricity will become the main energy source nationwide displacing, coal, petrol and gas. To do so, new infrastructure will be required for production, distribution and storage of energy e.g. energy network for electric vehicles, smart meters, etc.
3. Low carbon electricity. When switching to renewables is not feasible, the implementation of low-carbon energy sources will be implemented. This strategy takes into account technologies such as carbon capture and storage (CCS) technologies which are still under development before feasible commercial applications. Therefore, there is still uncertainty about feasibility of widespread and implementation.

Overall, it is expected that by 2050 around 40% of the energy in Mexico will be produced through renewable sources such as photovoltaics (PVPs) and solar thermal (Bataille, et al., 2016). Every policy decision will imply relying on specific technologies (mix of) compromising on others. However, there is high uncertainty about the cost-effectiveness and timely dissemination of some technologies such as CCS, electric vehicles, or the efficiency and affordability of PV's; therefore, one of the main challenges will be to define a clear policy pathway that would generate market certainty while providing enough room for adjustments (as necessary) for the decarbonisation pathways (Criqui, et al., 2016). The main areas of innovation in the forthcoming years for which policy will have to innovate in order to set an enabling framework for decarbonisation are:

- Technology. Depending upon chosen technologic mix for energy generation, storage and distribution there is the potential for market creation and innovation in R&D, this need to be enabled through appropriate set of policies

- Behavioural patterns. Changes in people's behaviour are very important, especially in key areas such as consumption, transportation, waste disposal and energy use.
- Policy instruments. Adequate policy instruments can enable the creation of new markets, stimulate investment, promote interinstitutional communication, learning, etc.
- Institutional settings. The decarbonisation effort will require strong institutional cooperation and knowledge exchange

Decarbonisation of Mexico's economy is a complex, non-linear, but achievable task. Authors such as Criqui et al (2016) propose Uncertainty Management and Dynamic Adjustment of the deep decarbonisation pathways to create policies that can cope and adjust in a timely and cost-effective way to changes on the pathways due to uncertainty. This will require pathways as sequences of policy actions designed to avoid lock-ins through the identification of 'tipping points' as conditions at which policies begin to perform unacceptably and therefore, will require new actions in order to achieve the main objectives (Criqui, et al., 2016, p. S48). This approach enables flexibility over time on de condition of having clear policy goals e.g. achieving 40% of national energy through solar technologies. On the other hand, monitoring through key indicators is proposed as a way to identify in due time whenever adjustments are necessary.

In the building sector, deep decarbonisation refers to the adoption and implementation of *best practices* in energy efficiency (1^{th} pillar) such as low carbon architecture (bioclimatic and passive design) plus the integration of highly efficient technologies (lighting, water, gas, etc.); electrification of end uses (2^{nd} pillar) e.g. electric cars, electric heating, switching to electricity for cooking, etc. From an economic perspective (which is the leverage for technological market penetration and widespread) household and commercial equipment is cheaper than industrial ones with shorter life cycles that in turn open up the opportunities for replacement by increasingly more efficient appliances (e.g. washing machines, T.V., microwave, fridge, heating, cooling, etc.). It is acknowledged that 'fast tracking energy efficiency progress in all energy end uses in buildings has direct immediate positive impacts on families' cash flow, and it is useful to promote energy and economic security' (Tovilla, 2015, pp. 9-10), furthermore, penetration of energy efficient technologies can be levered by energy efficiency regulations on the offer side (producers) and by substitution programmes for e.g. more efficient air conditioner units. Research on the effectiveness of bioclimatic design strategies in providing thermal comfort can help improving the overall energy efficiency in the residential sector as part of the decarbonisation of the Mexican economy within the 'energy efficiency' strategy (see Fig. 2.2).

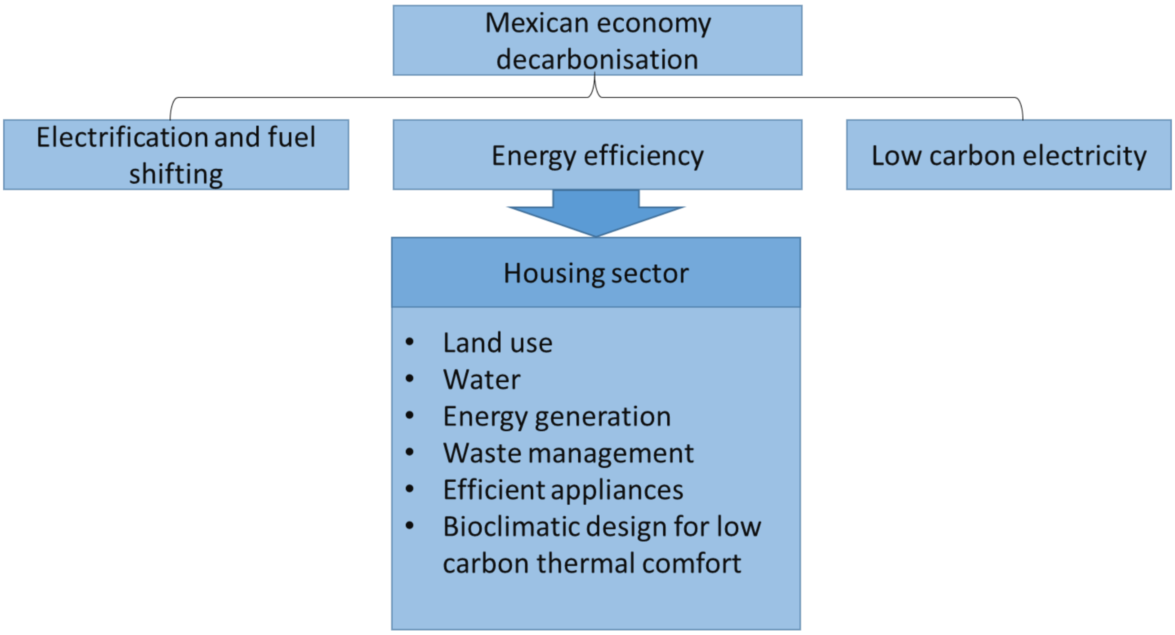

Figure 2 2 Deep decarbonisation pathways and the housing sector.

Decarbonisation of the Mexican economy is already underway in different economic sectors, and one of the most prominent is the social housing in which the Mexican Housing Nationally Appropriate Mitigation Actions (Mexican NAMA) are considered to be some of the most innovative worldwide.

2.2 Urban Sprawl in Mexico.

Urban sprawl will be understood for this research as “*the process in which the spread of development across the landscape far outpaces population growth*” (Don, et al., 2002). This phenomenon is particularly acute in developing-fast urbanizing countries such as Mexico, in which from 1980 to 2010 the population doubled, while its urban foot print grew seven times (Herbert, et al., 2012, p. 3).

Figure 2 3 Social housing neighbourhood in San Luis Potosi City, Mexico (Google, 2017).

Fig. 2.3 shows various house clusters developed by different construction companies, at first glance it is easy to note the lack of urban planning, especially on the streets with a ‘broken’ layout; also evident is the large amount of brown fields subject to urban speculation. This is just an example that repeats itself not only all over San Luis Potosi but all over Mexico.

In Mexico, urban sprawl is fostered by multiple causes such as the expansion of formal and informal settlements as well as the type of housing. Cities with a large share of formal employment sprawled chiefly due to formal housing developments on cheap far-flung land, with low built densities (single family row houses); while cities with a large share of informal employment sprawled due to informal settlements development (OECD, 2015, p. 66), characterized by the lack of basic infrastructure and services. A Mix of both types of sprawling shape the urban landscape of Mexican cities, and the prevalence of either type should be taken into account for urban policy design.

Urban sprawl was also made possible due to the lack of effective urban policies and weak local urban institutions in a housing market driven by the construction industry and land speculators (Cenecorta, 2006, p. 18). This situation has led to dispersed urban settlements with abundant urban voids (brown fields), poor public transport connections, low quality in the provision of urban services that in turn fail to fully capture agglomeration benefits associated with urbanization (productivity, innovation, agglomeration markets, access to amenities etc.). As a consequence, Mexican cities underperform their OECD (Organisation for Economic Co-operation and Development) peers, with a labour productivity stagnated over the past decades (OECD, 2015, p. 18). And even though urban sprawl cannot be regarded as the only cause for the loss of competitiveness, it is an important factor due to long trajectories from home-work-study-health centres, poor air quality, and the high costs associated with such phenomenon that negatively impact urban dwellers but especially low income families.

Regarding urban planning, in 2013, the Ministry of Agrarian, Territorial and Urban Development (Secretaria de Desarrollo Agrario, Territorial y Urbano, SEDATU by its Spanish initials) was created by consolidating in to a single ministry, housing, urban and rural policies (OECD, 2015, p. 106) and therefore, it is expected that this institution will more effectively help in reshaping urban policies in order to achieve the objectives set by the Mexican government in the National Housing Programme 2014-2018 (Progama Nacional de Vivienda 2014-2018) towards a more sustainable urban development model. However, it will take several years for design and implementation of the aforementioned urban policies given the diversity, complexity, and particularities of urban settlements in Mexico.

One of the main challenges for urban policy design that SEDATU will have to face is the avoidance of the ‘one fits all’ approach that is common practice when centralized planning is implemented in detriment of the diversity and particularities of the different urban settlements in Mexico (around 5 different weather patterns nation-wide from dessert to jungle, not to mention prevalent industrial/commercial activities, local history, etc.). Also, equally important will be to overcome local planning implementation barriers given that state planning institutions are subjected to short term political views and in many cases are co-opted by land speculators and corrupt politicians.

At the local level, in San Luis Potosi City, Mexico, one of the main challenges will be to define clear objectives and a locally appropriate strategic plan(s) towards urban sustainability. It is widely recognized the lack of knowledge and training of local institutions regarding urban design; their lack of long term strategic thinking/planning not to mention sustainability.

Urban sprawl is a multi-causal phenomenon and as such is a very complex one. If addressed, it would require large inter-institutional efforts in terms of resources and coordination. Such approach surpasses the scope of this research project. However, since it is widely acknowledged that vertical housing can potentially work as a counter measure against urban sprawl by making a more rational and efficient use of resources such as, land, services and urban infrastructure, it follows that verticality is highly desirable within the social housing context and therefore it is considered as a more efficient typology when compared with the single family row housing prevalent in the Mexican social housing market and in San Luis Potosi City.

2.3 Urban Segregation

Urban sprawl and urban segregation are closely bound, and the effects of the latter are in part due to the nature of the former; in that sense, irregular peripheral urban settlements are inhabited by low income families that earn their life in the informal economy and thus are left with few housing choices but the informal market (nearly 50% of the urban population in Mexico). On the other hand, the proliferation of huge low income housing clusters in urban peripheries, built and sold in the formal housing market by construction companies that are profit oriented and without proper urban planning schemes, have also led to urban segregation by geographically isolating huge pockets of low income families.

The term ‘segregation’ refers to the separation of one thing or group from another; while urban segregation is the way in which the different elements of the urban totality are separated. Following with this logic, socio-spatial segregation is the urban separation (and/or isolation) of social groups by income level in specific geographical areas within the city (Aymercih, 2004, p. 118). This separation is also reflected on the quality and provision of infrastructure and services where the higher income areas usually concentrate better quality of education and provision of infrastructure and services.

According to Monkkonen (2009, pp. 80-81) '*high-income groups are clustered in one zone of the city usually with an apex in the city centre and moving outward in one direction*' (this is true for San Luis Potosi City where high income families have historically moved from the centre to the west); while the poor occupy low density, peripheral and poorly-served areas; note that the latter areas are more homogenous in terms of income than 'affluent areas' are.

The main pervasive effects of socio-spatial segregation are:

- Inequity in the provision of infrastructure and services.
- The so called Neighbourhood effect also known in Spanish as '*efecto barrio*' (barrio effect). The Barrio Effect is characteristic of low income neighbourhoods and it can be understood as a socio-spatial phenomenon in which, low rates of social mobility due to poor social interactions, plus low quality education, plus little exposure to positive role models generate a pervasive sociological cycle that condemns poor people to remain poor throughout their lives.
- High rates of criminality in low income neighbourhoods.
- High rates of adolescent pregnancy in low income neighbourhoods.
- High school dropout rates in low income neighbourhoods.
- Fragmented and polarized societies due to lack of interactions between their members.
- Little diversity and little innovation leading to low competitiveness rates (Monkkonen, 2009) (Ortega & Rodriguez, 2017) (Caudillo Cos, et al., 2018).

Even though the phenomenon and its consequences are non-linear and non mono-causal, they do account for the side effects of rapid urban expansion in a poorly urban planned environment, such as is the case of San Luis Potosi City; all in all, these are just some of the challenges that need to be faced in order to achieve more sustainability and competitiveness in Mexican cities. It will be necessary to improve life conditions in already existing urban peripheries while at the same time trying and taking advantage of urban voids, as well as from prone to regeneration areas to increase urban densities whenever possible. Such an approach would require specific urban interventions supported by adequate research, policies, taxation incentives, and a long term urban planning perspective.

From a conceptual design perspective, verticality in the social housing sector mixed with diversified locations that prioritize social housing development (construction) in brownfields over peripheral expansion can potentially help alleviating some of the pervasive effects of urban segregation by in theory, enabling a richer socio-economic mixture over the existing urban network. Such an approach opens up hypothetical yet plausible design guidelines for the construction over brownfields with the following advantages and disadvantages:

Advantages:

- By using urban voids which are randomly distributed all over the city, a vertical social housing project can increase densities without risking saturation of urban services and infrastructure (CONAVI-SEDESOL, 2010, pp. 26-31) (Fracasso & Vakarelov, 2015) .
- This approach would not necessarily require the implementation of a complex and costly master plan, provided that building allocation respects local normativity and regulations.
- It can potentially increase social mixture by bringing closer low and mid income families as a counter measure to urban segregation.
- By building vertically the land price of centrally located plots can be distributed between the different flats (home buyers) making accessible urban land that otherwise would not be affordable by low and mid income families.

Disadvantages:

- The price of land depends upon urban location, and in Mexico this can account for up to 50-60% of housing final price tag (Estrada Diaz, et al., 2017) (Sánchez Corral, 2012).
- The façade and general building orientation would depend on the random allocation of urban voids which could deter bioclimatic design effectiveness.
- In an unregulated land market, new buildings could deter the effectiveness of bioclimatic design by blocking sun availability (tall new constructions).
- Risk of infrastructure saturation, especially in areas where it is old or deteriorated.
- Increased vehicle traffic due to more densities and therefore, more air pollutants.
- Oversaturation of rubbish recollection services, unless adequate measures are placed such as separation, recycling, and/or specific allocated areas and scheduled recollection.
- Without comprehensive studies there is also the risk of deteriorating neighbourhoods by saturating local services such as schools, or the lack of open spaces in areas where those are already missing; similarly, with health care and public transport.

Even though the aforementioned considerations were taken into account for the general conceptualization and design of the studied prototype, it is very important to make an emphasis on the architectural nature of the present research, therefore, urban implications will not be thoroughly studied. However, urban phenomena such as urban sprawl and urban segregation were considered as conceptual driving forces for the prototype design (small scale and verticality) under the assumption that sustainability is a local phenomenon that needs to be understood within its context at different tiers. This decision is because, even though the aforementioned phenomena conform to the day-to-day urban landscape in Mexican cities, addressing them surpasses the scope and nature of this research project that is focused on bioclimatic design, climate change resilience, and thermal comfort for San Luis Potosi City, Mexico through building energy simulations.

2.4 Demographic Trends in Mexico

All the data in this section were taken from the document titled: *Mexico's Population Projections 2010-2050* (CONAPO, 2012) published by the National Population Council (Consejo Nacional de Poblacion, CONAPO by its Spanish initials), which is the Mexican authority regarding demographic projections and whose information is used by national and local governments for policy design and decision making.

In 2012 the Mexican population reached 116.9 million inhabitants with an annual growth rate of 1.35%. Fecundity rates have decreased from 6.1 children in 1960 to 2.24 in 2012 and it is expected to go down as much as 2.08 by 2030. Currently, Mexico is in the last stages of the demographic transition towards lower levels of mortality, fecundity and growth

From a demographic perspective, Mexico is a young country and in the next three decades there will be a lower proportion of under 15 year olds in the population with a high proportion moving in between the 15 and 64 years range; this phenomenon constitutes the so called 'demographic bond'. The demographic bond means that most of the country's population will be at a productive (working) age at the same time; this will be a unique opportunity to promote internal growth, investments in health, education, and to promote the creation of job opportunities. It is estimated that by 2020 there will be 82.6 million people of working age and by 2050 the country will reach a peak of 85.5 million. During this process, the average age will go from 29 years in 2010 to 31 in 2020 and 38 in 2050. Fifteen years old and younger population will decrease from 33.9 million in 2010 to 32.7 million in 2020 and to 28.9 in 2050. Finally, 65 years and older population will increase from 7.1 million in 2010 to 9.8 million in 2020 and 23.1 million by 2050. Aging population is expected to triplicate from 2010-2050.

While family composition will remain stable (around 2 children per family unit), the fact that most of the population will be at a productive age will also have an impact on housing demand, which is expected to keep growing until 2050 but at a lower rate than in past decades and with an increase in unipersonal homes. In consequence, it is also expected that the urban foot print of Mexican cities will keep growing, hence the relevance of research in the housing sector to align the urban sustainability objectives of the Mexican government with its urban growth projections, and the construction industry.

2.5 Housing Segmentation in Mexico

During decades, the official Minimum Wage in Mexico was the national index for establishing, all sorts of penalty fees, housing mortages, financial transaccions and general banking in Mexico. While this measure granted a nation-wide taxation, penalty and mortgage base line, it also negatively impacted purchaisng power of the minimum wage for workers (Anon., 2015). This is because every single increment in workers' income was diminished by an equaly proportional increment on interest rates and prices from different transactions all over the country; e.g. a mortgage with a value of 118 VSM (Minimum Wages or Veces el Salario Minimo[2], VSM by its Spanish initials) would change its amount in pesos (currency in Mexico) with the yearly actualization of the minimum wage instead of being actualized accordingly with national inflation which is a more appropriate refference.

On January 27th 2016 it was published in the Official Federation Daily, the constitutional reform to change the index-link of the minimum wage. With this reform, from January 28th 2016, the minimum wage can NO longer be used as an index, unit, base, measure, or reference for matters extraneous to its nature (Abogados, 2016).

The minimum wage as index has been substituted by the UMA (Unit of Measure and Actualization); this UMA is now used as an account unit, index, base, measure or reference to determine the amount of payments, liabilities and all transactions foreseen by Federal laws, as well as local laws. Because of the change in metrics, UMAs are the new measurement unit from 2017 onwards. However, in this research, all official data regarding house value and segmentation will be shown in VSM since historical data up to year 2016 was measured employing such metric, thus, providing more consistency in the metrics employed.

[2] According to the Federal Work Law in Mexico a Minimum Wage is the minimum amount of money that a worker must receive for his services during a working day (CONASAMI, 2014). From January 1th 2018 the minimum wage in Mexico was 88.36 Mexican pesos (CONASAMI, 2018) equivalent to £3.32, according to currency rates from 14th of May 2018, when £1=26.54 Mexican pesos (recovered from: https://www.banamex.com/)

The National Institute of Statistics and Geography (INEGI by its Spanish initials) became the institute in charge of calculating the UMA's value. The daily UMA value is an equivalent to $73.04 MX (Mexican Pesos) and its initial monthly value was equivalent to $2,2020.42 MX (January 2016). By doing this, the UMA value is updated according to changes in national consumption prices instead of being tied to the minimum wage which was detrimental of the purchasing power of the Mexican working class. However, the positive impacts of this reform on family economics will be felt only in the mid-long term.

Mandatory nationwide implementation of the new index was January 2017, however from 2016 onwards, mortgages, financing, banking, credits, and all sorts of financial schemes have as 'ceiling' for their annual increments the annual national inflation. As for housing, the segmentation based on VSM will remain as a reference nationwide, however, old and new mortgages are actualized using the UMA index since 2016 onwards. One of the advantages of the desindexation from the minimum wage is that it allows to know since the early acquisition of a mortgage the exact amount of money to be paid in Mexican pesos by the end of it.

As mentioned before, housing segmentation in Mexico is based on the Number of VSM that a specific house-type cost, hence, there are six classifications (SEDATU, n.d.) used by housing institutions in Mexico and the equivalent income in UMAs that a housold should earn in orther to be able to purchase a house, as shown in Table 2.1.

Table 2.1 Housing segmentation and income level in Mexico

Housing segmentation and income level in Mexico		
Housing segment	**Value in VSM**	**Family income UMA**
Social	118	2.6
Affordable	118.1-200	2.6-4
Traditional	200.1-350	4.1-5
Intermediate	350.1-750	5.1-10
Residential	750.1-1,500	>10
Residential Plus	>1,500	>10

Affordable and Traditional housing will be the housing segments targeted by the present research, given that those families are the ones that can actually purchase a housing mortgage in the formal sector due to their income levels. Also, in practical terms, those families are still considered to belong into the social housing sector in Mexico.

2.6 Social Housing

The demographic growth experienced in Mexico in the last decades has led to a rapid urban growth in a poorly urban planed environment. Although the Mexican government has made important progress in the provision of social housing in quantitative terms, there is still a lot to do from a qualitative perspective, energy efficiency, urban context, accessibility, financial mechanisms etc. In this section, a brief history of the major players in the Mexican social housing sector is presented followed up by the more recent development of sustainable social housing in Mexico and the Mexican social housing Nationally Appropriate Mitigation Actions (NAMA), then a brief review of the whole building approach from the Passivhaus technical perspective is done for the Mexican context closing with a brief discussion focused on identifying potential research implications.

2.6.1 What is INFONAVIT?

Social housing in Mexico cannot be understood without examining the role of the National Workers' Housing Fund Institute (Instituto del Fondo Nacional de la Vivienda para los Trabajadores, INFONAVIT by its Spanish initials). INFONAVT was created in 1972 by presidential decree and, in consequence, constitutional amendments were made in order to make access to *adequate housing* a right for all Mexicans. Hence, by modifying the Labour Law, employers had to pay from then on 5% of the workers' wages to INFONAVIT to contribute the necessary funding for the Institute to be able to provide worker's housing (Diaz Ramirez, 2012).

Since its creation, INFONAVIT has enjoyed a high degree of institutional autonomy and it can be considered as a government-sponsored mortgage bank specialized in granting loans chiefly for the purchase of social housing with low interest rates (lower than commercial banks). In recent years its products range has diversified to reach a wider population and now it offers loans not only to buy new homes (which remains as its main goal) but also for home improvement, and self-construction (but at a lesser level). INFONAVIT finances about 70% of social housing in Mexico and from years 2005-2010 it provided 2,671,400 mortgages (BBVA Research, 1th Semester 2015, p. 46), equivalent to the financing of about the same number of new social houses in Mexico during the same period.

Although INFONAVIT has succeeded in reducing housing shortage in Mexico, it has been done chiefly from a quantitative perspective for which the number of mortgages provided (new houses) was the main institutional goal, leaving aside urban context, services, infrastructure, and the environment in an unregulated market as the Mexican, which manifest the economic inequalities in the country, in consequence, urban sprawl and urban segregation has been just some of the most pervasive unintended by-products of this housing policy (Medina Ortega & Rodriguez, 2017).

As counter measure and, in line with the National Development Plan objectives, INFONAVIT began moving in to a more comprehensive and holistic housing approach since the mid-2000s by setting up three strategic planning goals:

- Transitioning towards a model of smart sustainable urban development enabling dignified housing for Mexican families.
- To reduce in a responsible manner the housing shortage through improvement and expansion of existing housing as well as through the acquisition of new housing.
- To achieve a better interinstitutional coordination between government tiers for sustainable territory ordinance, as well as stimulating regional, urban metropolitan and housing development (Building and Social Housing Foundation bhsf, 2014).

The most tangible product of such strategies can be found in the Green House Mortgage programme and the housing NAMA. It is important to acknowledge the political/institutional willingness to move into a more holistic view of the social housing sector that understands it as a part of a larger and more complex urban system for which the government and its institutions play a very important regulatory role.

2.6.2 Sustainable Housing in Mexico

Sustainable housing initiatives in Mexico are amongst the first and most ambitious in Latin America because "*they have put sustainability on the low-cost housing agenda during a boom in housing construction*" (Jung 2008, 16). The pathway has been incremental, beginning in the 1990s and early 2000s with pilot projects on energy and water efficiency that generated a market for low energy fluorescent bulbs and highly efficient water fixtures that later were made mandatory (from 2011 onward) on new built social houses though the Green Mortgage programme first implemented in 2009 (INFONATIV 5 March 2014). The GM is a complementary subsidy that allows low income families to buy houses with a number of eco-technologies: solar water heater, efficient toilet, low consumption water fixtures, efficient light bulbs (CFL and/or LED), insulation materials, PVPs, energy efficient appliances (air-conditioning and fridges), solar water heater, etc. depending upon income level. Additionally, the green mortgage also provides a point rating system depending upon energy efficiency and the eco-technologies implemented. Such a system measures the energy savings achieved through the mortgage. The green mortgage amount is dependent upon family income and thus, the eco-technologies that can be financed and implemented through it.

Currently, the National Strategy for Sustainable Housing incorporates all major players of the social housing sector in Mexico, such as public institutions, academia and the private sector. According to their estimations, there is an existing potential to generate savings between

30% to 70% in electricity and gas consumption and greenhouse gas emissions reduction of about 1 up to 1.5 tonnes of CO_2 per house per year (IDEA Foundation 2013, 48).

Even though important measures are being taken to create a sustainable social housing sector in Mexico, prevalent SH and residential design in general does not take in to account bioclimatic principles nor thermally efficient construction materials as leading design departure, therefore, reproduction of the same construction typologies with little variation all over the country regardless of local weather conditions (Chan 2010) is common practice in the Mexican social housing sector and in the residential sector in general. Furthermore, barriers identified, such as the lack of consumer awareness, increased first costs to developers, non-enabling regulatory environment, lack of coordination (both institutional and in the private sector), lack of technical knowledge in sustainable design, construction, and technologies, low technology availability, and highly subsidized energy prices (Jung 2008; IDEA Foundation 2013; Ebel et al. 2012, 55) still need to be overcome in the short and mid-term.

2.6.3 Mexico's housing NAMA

NAMA stands for Nationally Appropriate Mitigation Actions and they are strategies targeting developing economies to aid enabling sustainable development with national economic priorities. The 2012 Mexican Sustainable Housing NAMA was the first of its kind worldwide and its objective is to mitigate residential GHG emissions by providing supplemental financing to '*improve electrical, fossil fuel and water efficiency through the implementation of eco-technologies, architectural design improvements and the use of efficient construction materials*' (CONAVI, 2012).

The Sustainable Housing NAMA builds up on the green mortgage based on the implementation of eco-technologies and addresses energy efficiency in the housing sector through a 'whole building' approach based on and supported by the German Passivhaus Institute. Technical aid was also provided by Environment Canada, the United Kingdom, GIZ (Deutsche Gesellshaftfur Internationale Zusammenarbeit) and GMbH (German Development Cooperation) to develop energy efficiency improvements in typical Mexican social housing in different bioclimatic locations. The improvements were implemented in pilot projects that were monitored and the data acquired was used to fine tune the Passivhaus simulation software for local conditions. Although different metrics are employed, one of the main targets of the programme is to demonstrate energy and its equivalent CO_2 emissions reductions.

The Mexican NAMA is designed in such a way that its deployment and targets can be further improved in incremental stages based upon previous experiences. In the mid and long term it aims to include the urban context and the whole residential sector (currently its focussed on the social housing sector alone) and has been successful in beginning the transition into a more sustainable construction industry in Mexico by creating a flexible social house design approach and fostering the development and market penetration of energy efficient technologies firstly deployed through the green mortgage programme. The NAMA programme is based on three specific energy efficiency targets: Eco Casa 1 which represents conventional architectural design but with the implementation of eco-technologies such as solar water heater, efficient lighting fixtures and water saving fixtures chiefly. Followed by Eco Casa 2 which builds up on the previous by adding roof insulation, walls insulation, better windows and highly efficient appliances but with increased costs. Finally, Eco Casa Max which optimises all measures including architectural design and extensive insulation and is the most expensive of the three.

Preliminary monitoring results from pilot projects in Mexican cities (CONAVI, 2012, p. 96) showed that houses in harsher climates (Hermosillo City hot and dry, and Cancun City hot and humid) benefited the most from higher efficiency levels like the Eco Casa Max. In such scenarios the highest investment required to achieve the standard is justified by energy consumption and its equivalent CO_2 emissions reductions. In contrast, in the milder climates of Mexican cities, such as Guadalajara and Puebla, the proportion in the energy and CO_2 reductions seems to be more modest. Given the more intense capital investment required to achieve the Eco Casa Max, and the low income levels of the families targeted for the programme, it would be beneficial to look for alternatives that are capable of providing thermal comfort in mild climatic regions. Doing so would prevent over specification and the associated higher capital cost required, making energy efficient social housing accessible for more low and mid income families.

Overall, by 2017 the Mexican NAMA had proved to be rather successful at several tiers:

- It has fostered interinstitutional coordination between the main social housing institutions nationwide and with the private sector.
- It has laid the foundation for national energy and efficiency standards in the social housing sector.
- In June 2017 surpassed the 2020, 400,000 tCO_2e (tonnes of CO_2 equivalent) reduction target with reductions exceeding 1,090,000 tCO2e (NAMA Facility, 2017).
- By implementing energy and water saving measures it has helped reducing the resource intensity of the social housing sector.

There are still many challenges for full market penetration and adoption of energy efficiency standards, especially in the residential sector given that the NAMA focuses on social housing alone. Also, for energy efficiency in the residential sector in general there is still lack of knowledge and awareness from homeowners, developers, planners and local administrations. On the technical side some technologies are still imported and expensive and there is a lack of expertise on their installation and operation. From a regulatory and institutional perspective codes and norms are not mandatory and are not standardized and tailored for every geographic and bioclimatic location in Mexico (CONAVI, 2012, pp. 16-17). On the other hand, in recent years the liberalization of fuel and energy prices (which used to be highly subsidized) is stimulating market penetration of energy efficient technologies in all sectors given the increasing energy prices. Table 2. 2 shows constant increases in the residential electricity price from year 2002-2015 and a reduction from years 2016-2017, the variation reflects the liberalization of prices and the gradual reduction in subsidies.

Table 2.2 Annual average residential electricity price in Mexico

Annual average electricity price in Mexico in cents per kilowatt-hour (Mexican pesos)																
Sector	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Residential	77.50	85.21	88.90	92.80	99.27	102.57	107.13	107.86	113.27	118.32	118.61	116.02	119.85	119.58	118.73	109.44

Energy information system with data from CFE and LyFC (SENER, 2018)

Recent research on energy efficiency in newly built houses under the NAMA developed standards showed that the benefits in the implementation of energy efficient technologies is deterred by the lack of awareness and education of the end users in some cases diminishing the CO_2 emission reductions by 50% over the projected savings (Calderon-Irazoque, et al., 2017). Moreover, energy efficient social housing in Mexico, when contextually evaluated employing international standards, falls short in its relationship with the urban network (Arredondo-Rea, et al., 2018) which opens improvement opportunities from a more holistic perspective.

One of the main risks of the implementation of a nation-wide standard such as the Passivhaus whole building approach is whether it is appropriate for every geographical and bioclimatic location in Mexico. Some regions have mild weather most of the year and might require a less technologically and, therefore, less costly intensive approach to achieve energy efficiency for thermal comfort. This is particularly relevant because of the long term uncertainty of the full effects of climate change, thus, the sort of energy efficiency provided by passive/bioclimatic design is also considered to provide *climate change resilience* and can be considered as a *climate change adaptation strategy* for the housing sector because its main goal is to provide thermal comfort at present time but also under future weather scenarios, thus, minimising energy consumption fort thermal comfort during the building lifespan.

In consequence, developing locally appropriate research on the effectiveness and climate change resilience of bioclimatic design strategies becomes topical, since bioclimatic design is considered as a first tier approach in architectural sustainable design (Colley & Connell, 2007) (Fathy, 1986) (Foruzanmehr, 2018) (Hyde, 2000) (Lechner, 2009), and is also a low-cost strategy for thermal comfort pertinent for low and mid income countries such as is the case of Mexico.

2.6.4 Climate Change and the construction industry

Human induced climate change is a widely acknowledged phenomenon whose future impacts are not yet fully understood, given the complexity and unpredictability of the global climate system and our interdependency with it. Due to the scope and potential implications of climate change, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC does not conduct research itself but, instead, '*it assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change*' (Intergovernmental Panel on Climate Change, n.d.).

The scientific nature of the work reviewed by the IPCC and the methods employed for that revision are meant to provide a neutral perspective on the challenges and opportunities posed by climate change. However, the IPCC work is meant to create an impact in decision making as its reports are policy-relevant while avoiding a prescriptive approach/narrative. The body of work produced by the IPCC in the last 30 years has been the foundation for countries to develop their own strategies and supporting policies to better deal with climate change in harmony with their unique conditions (environmental, geographic, demographic, cultural, economic, etc.) and development targets.

The prevailing climate change scenarios point to toward rising global temperatures leading to warmer winters, hotter summers, generalized reduction of fresh water supplies due to the melting of mountain ice caps which feed rivers, and variations in rainfall patterns. It is also expected an increase in the frequency and intensity of extreme weather phenomenon such as flash flooding, hurricanes, tornados, etc. However, the impacts of those phenomenon will be uneven all over the planet and thus it is necessary for each country to develop its own strategies for climate change adaptation.

The building industry is a very particular business because buildings are part of larger urban socioeconomic, cultural and political systems embedded in geographic regions with unique climate and weather patterns. Also, most of the existing build stock was designed for the climate that existed when they were built (best case scenarios) and in most cases are not apt to cope with current and future climates. Hence, it is important for the construction sector to develop locally appropriate adaptation strategies given that buildings have a long life span (30-50 years minimum) which means that new build stock will have to cope with future weather scenarios of climate change. It is important to make a distinction between new buildings and existing ones (retrofitting) since each would require different type of interventions. A finer sub-division is also necessary depending upon build typology and end use because energy requirements, occupancy patterns, and the intensity of resources consumption vary as a function of those; e.g. vertical or horizontal housing (single family, multi family, detached housing, row housing), commercial buildings, factories, hotels, offices, etc. this sub classification is especially relevant for sectorial policy making.

As mentioned before, current efforts in sustainable construction in Mexico have focussed on GHG emissions reductions in the social housing sector through the Green Mortgage programme (introduction and dissemination of eco-technologies for the social housing sector) and, most recently, through the housing NAMA, incorporating energy efficiency, thermal comfort, and water consumption with a technical approach supported by the Passivhaus Institute through the whole building approach.

On the other hand, international experience shows that countries such as the UK (Gething, 2010), and Australia (Australian Sustainable Built Environment Council, 2012) have developed general adaptation strategies focused on three main aspects:

- Designing for comfort. Building design, open and urban design, thermal comfort (heating and cooling)
- Construction. Structural stability above and below ground, weather proofing, detailing and construction materials
- Water managing. Water conservation (efficiency), drainage and flooding prevention/management

From an architectural perspective, design for comfort, and construction are closely intertwined given that both aspects are interdependent since architectural design and construction materials selection will impact on thermal comfort and the overall energy efficiency of a building (orientation, window sizing, materials specification, etc.). Water management on the other hand, is quite complex and strongly depends on local water supply, distribution, and management at regional and urban level and all the way down to building level in which efficiency can be achieved through the implementation of water saving/efficient fixtures (toilet, shower, zinc, etc.). Alternatively, strategies such as rain water harvesting, are strongly dependent on rain availability, which varies by region.

From an economic perspective it is also widely acknowledged that the implementation of mechanisms that increase resilience are more cost-effective when implemented early (through planning, design, or policy) than through subsequent retrofit interventions (Australian Sustainable Built Environment Council, 2012, p. 16). This is particularly relevant for the Mexican context with a growing population that is expected not to stabilize until 2050. With increasing urbanization rates that are expected to reach 83% of the population by 2030 with almost 50% of that population living in poverty. Hence, the relevance of developing low-cost energy efficient and climate change resilient design alternatives for the Mexican low income social housing.

Recent research in different geographic locations such as Mexicali City, Mexico (Gutierrez, et al., 2014), San Juan City, Argentina (Alvarez, et al., 2017) and from an evolutionary perspective of bioclimatism (Nguyen & Reiter, 2017) had focussed on testing the present and future effectiveness of bioclimatic design strategies as a cost-effective and locally appropriate climate change adaptation strategy for the construction sector (Beccali, et al., 2018). This is particularly relevant for naturally ventilated buildings whose thermal comfort parameters are closely related to outdoor temperatures and for which a closer look at present weather conditions as wells as future weather scenarios can provide with general strategies that might generate thermal comfort climate change resilience for the housing sector.

2.6.5 Whole building approach

The whole building approach has been mentioned as the conceptual basis for the development of the social housing energy efficiency standard/rating in Mexico, therefore it is important to better understand it in the context of this research. From a broader perspective the ‘holism’ concept was coined in 1926 by the South African Prime Minister Jan Christian Smuts; his innovative approach was a shift in perspective leaping from an atomist and reductive conception of nature to a perception that made no distinction of individual parts in nature but patterns and arrangements that contributed to a whole. Furthermore, in 1969 Buckminster Fuller, when working for the USA space programme, and when faced with large complex systems, came to the realization that “*Synergy is the only word in our language that means behaviour of whole systems, unpredicted by the separately observed behaviours of the system’s parts or any subassembly of the system’s parts*” (Prowler, n.d.). Such ideas are the conceptual framework that gave birth to the whole building design approach which feeds on interconnectedness and synergy concepts and translates them into *integrated design* and *integrated team process* which involves an objective based collaborative approach between all stake holders. The successful implementation requires a balance between the multi-criteria objectives of: accessibility, aesthetics, cost-effectiveness, functionality (programme, systems & operation), historic preservation, productivity (occupant's well-being), safety, and sustainability (environmental performance). This way buildings are conceptualized beyond the narrow boundary of the building 'skin' and are understood as part of a complex and larger 'whole' which can be understood all the way up to urban sustainability (Section 2.1).

As mentioned earlier, the Mexican social housing NAMA *whole building approach* was developed with technical aid from the Passivhaus Institute. Hence, it feeds on the Passivhaus standard which, in a nutshell, is a building standard for energy efficiency first developed in Germany in the early 1990s by Professors Bo Adamson and Wolfgang Feist (PASSIVHAUS, n.d.). According to the Passivhaus Institute, it can provide energy savings up to 90% compared with typical building stock in northern Europe by making use of a highly insulated envelope (walls, roof and floor) and energy efficient windows (double or triple glazing) coupled with a highly efficient ventilation system with heat recovery. By doing so, small energy sources such as those from appliances and body heat are enough to provide thermally comfortable conditions with little or no extra energy inputs even in a harsh winter. The mechanical ventilation system with heat recovery is a key element because a tightly sealed building envelope (0.6ach/hr) requires mechanical air movement to provide enough fresh air inside the building (Cotterell & Dadeby, 2012).

Furthermore, the technical capacity of the contractor is essential to deliver construction quality as specified. In other words, it requires a comprehensive holistic approach throughout the design and construction processes. During the early design stages in which environmental and climatic analysis are carried out to identify the best orientation capable of providing heat during winter and devising efficient mechanisms to block sun's radiation during summertime to prevent over-heating. The process also requires from the design team to be knowledgeable enough to be able to specify appropriate construction systems/materials and technical detailing. On the other hand, the construction team (contractors) should also be technically capable of delivering the appropriate quality with especial attention into detailing joints, air sealing, and thermal bridging avoidance. Finally, it is also important to make sure that the end user understands how the building/systems works to avoid unnecessary energy consumption by misusing the building components/systems (Keeffe, et al., 2017). Generally speaking, the integration of all the above is considered to be a whole building approach within the Passivhaus framework with the following pros and cons for the Mexican context:

- A highly insulated building needs to be airtight to perform at its best - both targets are complimentary and expensive, given the extensive use of insulation, high end windows and doors and the technical expertise required for their proper execution.
- The Passivhaus standard has proven successful, especially when implemented in extreme weather conditions both in cold (Jacobson, 2013) (Technology Strategy Board, 2010) and hot regions (Consoli, et al., 2017) (Killough, n.d.); however, for mild climatic regions, such as San Luis Potosi, Mexico, building to such a tight standard might be a case of over-specification which, *per se,* is energy and resource intensive and, thus, an expensive decision, especially for the social housing sector.
- Although some research in Northern countries highlight the risks of over-heating in housing built to meet the Passivhaus standard (Hopfe, et al., 2013) (Ahmed, et al., 2015) (Fletcher, et al., 1017), in most cases, overheating is either the result of design faults (lack of windows shading, poor attention to orientation), failure in the implementation of mechanical systems especially the heat recovery ventilation system and due to the lack of understanding of the building and its systems by end users and managers.
- The yardstick for the Mexican social housing NAMA is that of the amount of energy and its equivalent in CO_2 emissions avoided by the hours reduction in the use of HVAC systems due to the buildings' energy efficient design (CONAVI, 2012). However, HVAC penetration in the social housing sector in Mexico is very low even in regions with extreme weather conditions such as the *hot and dry* areas which account for 20.5% of national AC use (Beele & Gonzalez Osorio, 2016). This is due to the high costs of buying and operating an AC system for low income families that in the other hand has made people more tolerant to naturally occurring exterior temperatures. Without assuming that such a situation represents actual peoples' preference, this scenario is an opportunity for the use of natural ventilation whenever feasible as a first tier approach in opposition to the assumption of every homeowner employing mechanical ventilation systems particularly in regions with mild weather such as San Luis Potosi City (temperate and dry) in which AC penetration accounts for 2.3% of the national AC use in the social housing sector (Beele & Gonzalez Osorio, 2016, p. 46).

In the 2016 *Study on the characterization of air conditioning in social housing in Mexico* (Beele & Gonzalez Osorio, 2016) concluded that the penetration of AC systems is strongly influenced by energy prices, given the low income levels of most of the Mexican population, and suggested a shift in policies towards energy efficiency and reduced energy consumption which supported the idea of exploring the potential of natural ventilation and bioclimatic design to provide thermal comfort in regions such as San Luis Potosi City. While social housing in quantitative terms concentrates the largest number of AC and fans as shown above, a closer look as the percentage of the total penetration by income level and climatic region (Table 2.3) shows a high contrast in AC penetration by climatic region in which the t*emperate and dry* (which includes San Luis Potosi City) shows a very low penetration rate even in the higher income level (>11 VSMM). In contrast, Table 2.4 shows a larger penetration of fans similar to that of AC in the *hot and dry* regions.

Table 2.3 Percentage of homes with AC system by income level and climatic region

% OF HOMES WITH AC SYSTEM BY INCOME AND CLIMATIC REGION				
CLIMATIC ZONE	4 VSMM	7 VSMM	11 VSM	>11 VSMM
HOT & DRY	24.30	32.68	39.02	56.80
TEMPERATE & DRY	3.55	6.63	10.37	27.33

Elaborated with data from (Beele & Gonzalez Osorio, 2016, p. 46)

Table 2.4 Percentage of homes with FANS by income level and climatic region

% OF HOMES WITH FANS BY INCOME AND CLIMATIC REGION				
CLIMATIC ZONE	4 VSMM	7 VSMM	11 VSM	>11 VSMM
HOT & DRY	66.55	74.00	79.37	88.56
TEMPERATE & DRY	29.50	37.61	45.43	63.42

Elaborated with data from (Beele & Gonzalez Osorio, 2016, p. 51)

The study shows that due to the high initial and operating costs in contrast to income levels, AC penetration is relatively low even in extreme hot and dry conditions. In the case of San Luis Potosi City there is a larger penetration of fans, this can also be because the milder climatic conditions make increased air speed an effective and cheap (affordable) way of improving thermal comfort conditions for households. Note that fan forced ventilation is also a complementary strategy for a natural ventilation regime. Given that San Luis Potosi City is in what is considered as a temperate and dry climatic region[3], and the low penetration rates of AC and the more widespread use of fans for cooling due to the low income levels of the social housing sector, it is important to explore the potential of natural ventilation through bioclimatic design in providing thermal comfort as a means of improving energy efficiency in the social housing sector.

[3] The study uses a finer climatic sub division for San Luis Potosi City and therefore, considers the local weather as 'temperate and dry' where as other sources might consider it 'hot and dry'.

2.7 Bioclimatic design, climate and weather

This section aims to provide a better understanding of the concepts and some of the methodological tools employed during the research process, particularly those related with weather simulation, which is the stepping stone for building energy simulation. It is also meant to provide an introductory understanding of bioclimatic design in architecture, which will be further explained in forthcoming chapters.

Although the close relationship between the build and local weather (environment) has been acknowledged in vernacular architecture since hundreds of years ago, it was not until the mid XXth century that the concept of '*Modern Bioclimatic Architecture*' became part of the architectural thought. The establishment of the International Society of Biometeorology by UNESCO in 1956 was a breakthrough in the understanding and widespread of the relationship between weather and human wellbeing. Also, in 1953 the Olgay brothers published their classic book *Design with Climate, Bioclimatic Approach to Architectural Regionalism,* which is considered as the culmination of the introduction of the bioclimatic design concept to the modern architectural profession (Sayigh, et al., 1993, p. 522). In their book, the Olgay brothers introduced the Bioclimatic Chart, which manages to plot (define) '*thermal comfort*' parameters specific for a given climatic location.

The bioclimatic chart manages to correlate several climatic parameters such as: wind speed, relative humidity, dry bulb temperature; the effect of air movement on vapour pressure; the effect of added moisture on high temperatures; and the correlation of radiation and dry bulb temperature. Further developments led to the '*Building Bioclimatic Chart*' introduced by Givoni in 1969 which, in turn, manages to differentiate between external conditions and internal building conditions; it also correlates relevant passive heating/cooling strategies appropriate for any given studied location. Ever since, the building bioclimatic chart has been a very useful tool during the first stages of the architectural design process to select the most pertinent bioclimatic design strategies.

Nowadays, several software, such as *Climate Consultant*[4]*,* manages to plot the building bioclimatic chart for a selected location provided the input of the relevant weather file is available. By the simplification of such a process, architects can focus on devising the best way to pull together bioclimatic design strategies instead of spending a large amount of time plotting and charting. Therefore, it can be thought of as a pre-design analysis tool meant to be used at the sketch design stage. Figure 2.4 shows the building bioclimatic chart for San

[4] Climate Consultant is a software developed by Robin Liggett and Murray Mine for the UCLA energy Design Tools Group. The building generates Building Bioclimatic Charts using climatic files on 'epw.' format. It also shows in a user friendly and graphic way the most relevant climate parameters for architectural design correlating them with comfort models such as the California energy Code Comfort Model and ASHRAE.

Luis Potosi, which was generated with Climate Consultant software and an 'epw' file which uses weather data up to year 2010.

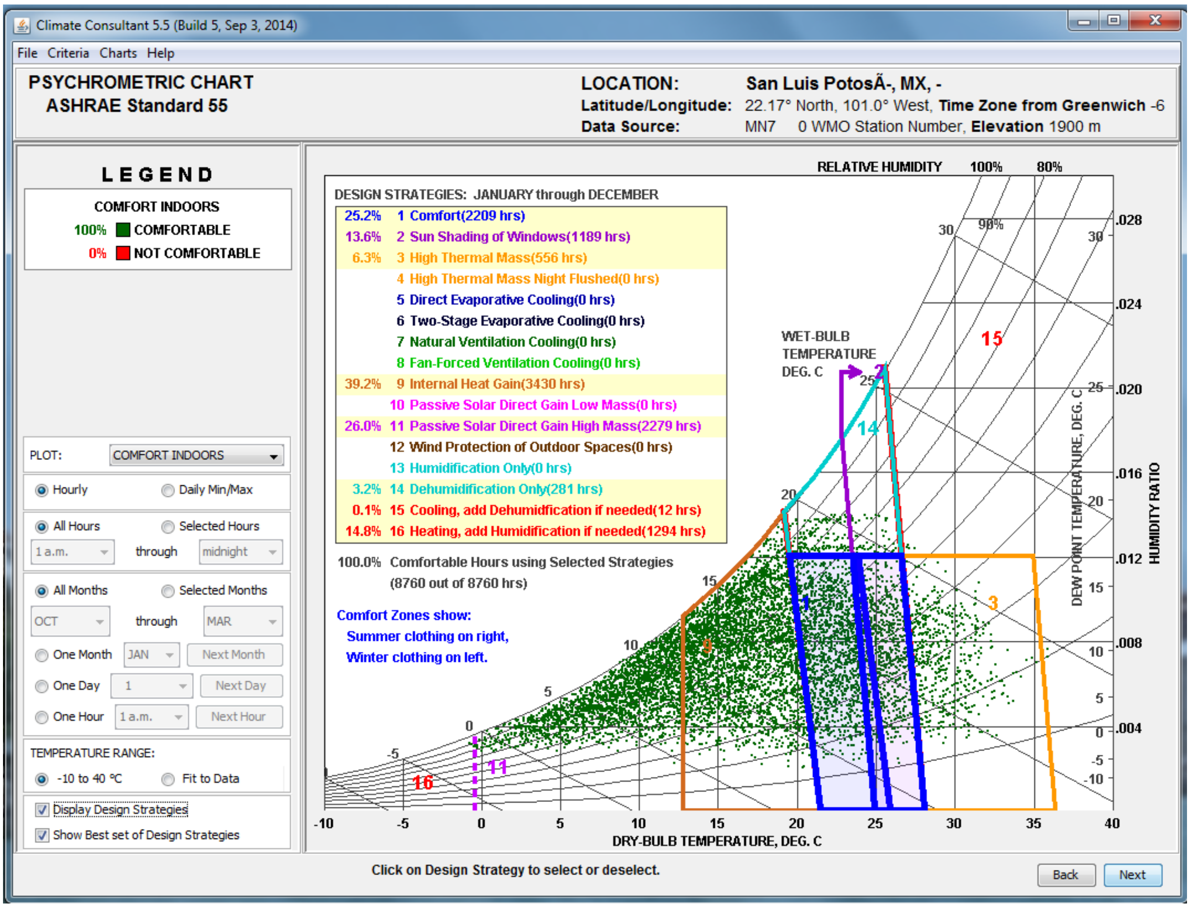

Figure 2.4 Building Bioclimatic Chart for San Luis Potosi City, generated by the author with Climate Consultant 5.5 software

The building bioclimatic chart plots the comfort zone and shows the different passive design strategies to achieve it as well as their effectiveness in doing so. This is the first step in the general architectural design process. It is not meant to be used as a 'cake recipe'; instead, it is a tool that can help improve building energy performance and climate responsiveness in an energy efficient way through different alternatives/mixes of passive design strategies.

In the chart, the most effective passive design strategies for San Luis Potosi are: sun shading of windows, high thermal mass, internal heat gains, passive solar direct gain high mass. It also shows that heating might be needed; and that a building will provide thermal comfort 25% of the time without the implementation of any passive design strategy. However, this analysis level can only be considered as general design guidelines and more complex energy simulations of buildings are necessary to assess their effectiveness. Finally, it is important to bear in mind that some of the strategies shown in the building bioclimatic chart might not be compatible between themselves – instead, they represent a range of 'design opportunities'.

2.7.1 Weather files and energy simulation

As an introduction, it is important to make a distinction between the most commonly used concepts in relation to weather and climate. Firstly, weather comprises the day-to-day changes in meteorological conditions, including temperature, rainfall, snow etc. Secondly, climate relates to average weather conditions based on, typically, 30 years of observations for any given location. Thirdly, microclimate is the term used to designate the climatic conditions directly surrounding the living organism (Sayigh, et al., 1993, p. 530). Finally, there is usually a big difference between the general climate of a region and the specific microclimates within the very same region (due to geographical factors etc.).

During the 1980s decade, the Model Year Analysis (MYA) was introduced and consisted of a modelling technique to obtain the best model that reflects the amount of solar radiation and the sunshine duration for specified locations. The technique is applied because climate in any specific location varies from one year to the next and, actually, will not repeat itself in the same location until 30 years (12 years in some cases).

Based on the cyclic nature of weather and having at least 10 years of observations on weather data, it is possible to produce a Climate Model Year (CMY). This model year is not an average year but a more sophisticated representation of climate in a specific location. One of the main advantages of this CMY is that it eventually allowed the simplification of climate computer modelling as well as the effects of climate on buildings. The CMY includes dry bulb temperature, wet bulb temperature, global (or direct) solar radiation, wind speed, wind direction and atmospheric pressure.

If sufficient locations in a region (or the world) are mapped using the model year technique, then it is possible to produce Model Year Climate Mapping (MYCM); this is relevant since climate has a very interactive nature with its surroundings. Therefore, it is possible to obtain the CMY for a location for which we do not have enough weather data (Sayigh, et al., 1993, p. 530). Such is the principle underlying weather generation software such as *Meteonorm* (which also uses more complicated algorithms included those from the IPCC).

In this research the weather file type used for simulations is the EnergyPlus weather format (epw) which is a standard format for weather simulation and is widely used by energy simulation software in the build environment and it was generated with Meteonorm as no robust weather files were available for San Luis Potosí City[5]. The epw format draws from around 20 different sources from all over the world and includes the TMY and its further

[5] Meteonorm employs datasets from years 1991-2010 for radiation and from years 2000-2009 for temperature to generate user defined weather files such as was the case for San Luis Potosi City, Mexico.

developments (TMY2 and TMY3). Therefore, it is one of the most reliable standards for weather simulation and is the one used on this research.

2.8 Case studies

The following case studies show, firstly, a typical social housing unit in Mexico, followed by what can be considered as good examples of recent institutional and private sector led approaches for achieving more sustainable social housing. The second case study was designed for a temperate and dry region in Mexico and for future modifications accordingly with family growth and income (departing from a single room house). The third case study is a commercial development in a hot and humid region that incorporates bioclimatic design principles departing from the typical social housing unit and demonstrates what can be aspired to in social housing. Case studies two and three show striking similarities in build area and plan layout due to economic restrictions that in turn lead to similar design responses. Differences can be found mainly on the construction materials and the incorporation of bioclimatic design strategies. Note that the case studies show what, architecturally, is considered to be social housing; however, location and land price can make the same build typology expensive enough to be classified as mid income housing, such as is the case of the third case study, which also has a larger built area. Still, the examples shown are meant to be regarded from the architectural typology. Additionally, all of them where designed for a standard social housing plot of 6 by 15 metres.

2.8.1 Case study one: Typical social housing unit

In the past decade Mexican cities have experienced significate growth rates with an urban expansion that can be considered rather chaotic, as has been described in Sections 2.2 and 2.3. One of the main driving forces of urban expansion has been social housing, which itself has been shaped by the predominant market role of INFONAVIT, resulting in the implementation of what can be considered as a typical or standard social housing prototype that with slight variations has been replicated all over Mexico, from the northern hot and dry regions to the hot and humid south. Such standardization has allowed social housing mass production, providing housing for families in Mexico. However, in recent years, and especially with the changes in the social housing policy that seeks to transform the sector into a sustainable one, it has become evident that the standardized approach has been detrimental in some cases for Mexican families' life quality.

Figure 2.5 shows the typical social housing unit on a 6m front by15m deep plot (90m^2), which is the standard social housing plot. The average built surface is of 45m^2 and incorporates an open plan living/dining, kitchen, two bedrooms, and a bathroom with parking for one car and a small garden area in the frontal side of the plot and a service courtyard on the back side of the plot. The spaces are designed for a couple with 1-2 children, which is the average Mexican family composition (Chapter 2.4).

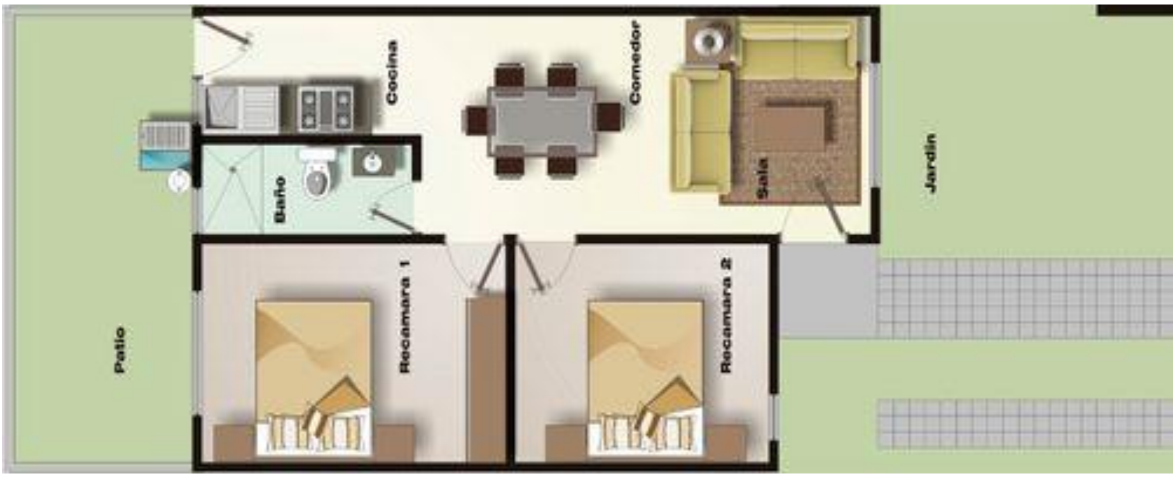

Figure 2.5 Typical social housing plan

Figure 2.6 shows the façade repetition of a typical social housing block that can easily be found in every Mexican city. No attention is given to building orientation nor local climatic conditions, and little attention is paid to the integration of the social housing clusters with the existing urban network. This includes basic infrastructure, public transport, medical and education services etc. This conceptualization of social housing as a commodity isolated from its context in a poorly urban planed context in which real state profit is the main driver has exacerbated urban segregation and urban sprawl in Mexico.

Figure 2.6 Row house social housing facade

In addition, the housing units are not designed to accommodate future changes, and these are done as family income levels increase and/or family composition grows. As a result, expansions to the original layout are done without a proper plan and, in many cases, they are detrimental to inhabitants' life quality due to the lack of architectural design in the intervention which in turn can lead to reduced natural light and ventilation and a reduction in overall thermal comfort performance.

Figure 2.7 shows the unplanned and non-regulated changes in a social housing neighbourhood in which every home owner modifies its house according to their changing needs and economic possibilities. Little consideration is given to sustainability but the addition of echo technologies such as those supported by the green mortgage programme (Chapter 2.6.2) such as efficient light bulbs (CFL or LED), water saving showers, faucets and toilet and in some cases a solar water heater whose efficiency can be easily deterred by neighbouring housing modifications.

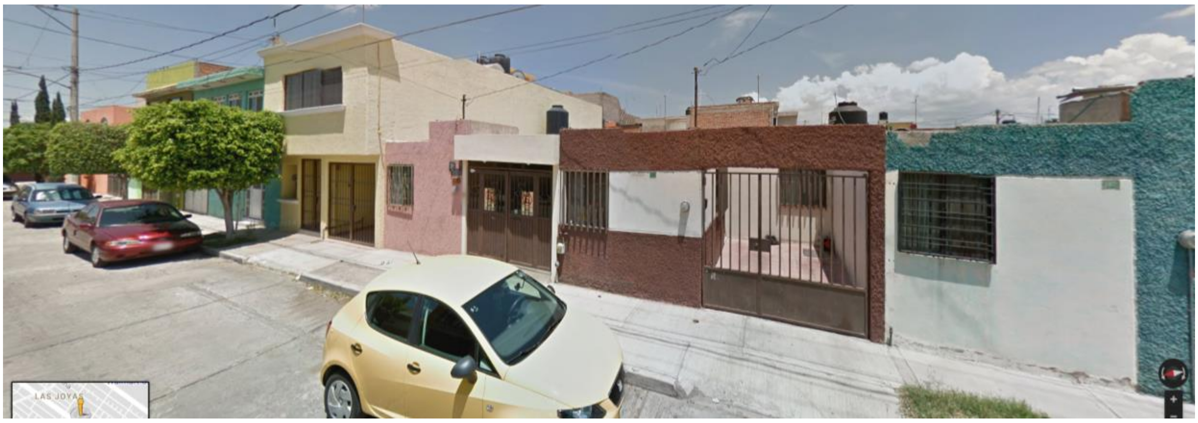

Figure 2.7 Consolidated social housing neighbourhood in San Luis Potosi City, Mexico (Google, 2018)

The typical social housing unit shown as a case study exemplifies the social housing situation in Mexico. The sustainability housing NAMA strategy implemented by the Mexican government in recent years seeks to improve new social housing and eventually will incorporate retrofitting guidelines (Section 2.6.3). However, it is still necessary to develop locally appropriate research that can help improve social housing in a responsive way to its environment. The following case studies show some examples of innovative approaches to sustainability in the social housing sector in Mexico, both depart from the typical unit shown here.

2.8.2 Case study two: Guanajuato, Mexico by SURarquitectura

In recent years INFONAVIT created the Sustainable Development Research Centre (CIDS by its Spanish initials). With the title 'From territory to inhabitant' the institute developed an architectural design exercise in which by invitation, selected Mexican architectural workshops were challenged to develop an alternative locally appropriate social housing design that responds to cultural, social, environmental, spatial and functional solutions differentiated by locality, taking into account local weather conditions, and with a focus on assisted self-produced housing. The main goal is to find out conceptual and architectural normative processes that can be employed for this type of housing (see Fig. 2.8 to Fig. 2.11).

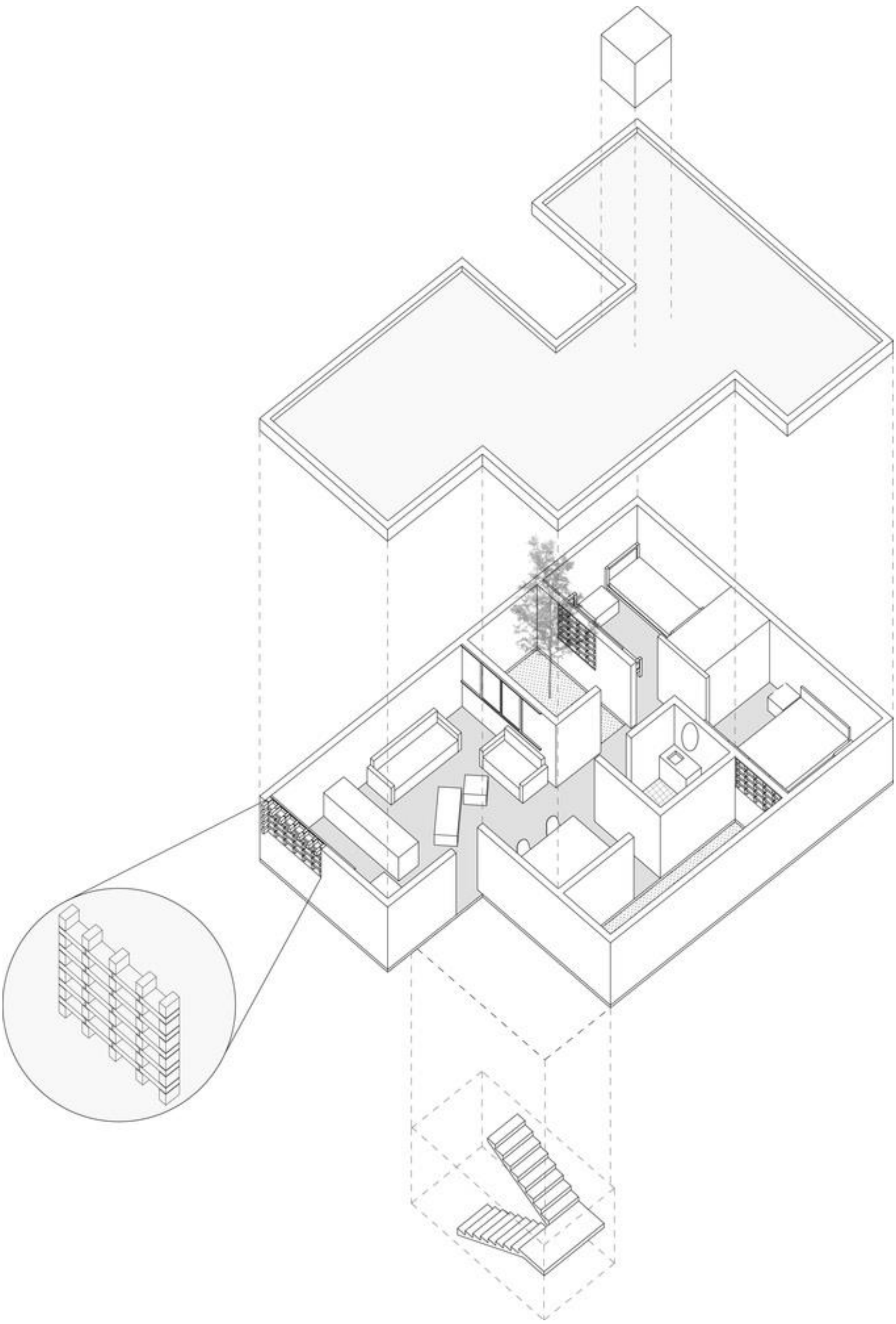

Figure 2.8 Prototype isometric perspective (Zatarain, 2017)

The case study project was designed by the Mexican architectural workshop SURarquitectura for the municipality of Cortazar in Guanajuato State, which is located at 21°01’08”N and 101°15’46”W and 2,072m above sea level, with a very similar temperate-dry climate than that of San Luis Potosi City. The proposal was developed through on-site analysis, questionnaires, direct interviews, meteorological and geographic data as well as historical research on local architectural typologies.

Figure 2.9 Main façade of the single floor prototype (left) and with the second floor addition (right) (Zatarain, 2017)

The proposal incorporates internal courtyards as means to provide natural lighting and ventilation while allowing a better control over the exposed envelope area to the elements, thus, allowing for more flexibility regarding the building's orientation. A red brick lattice on the windows is proposed to better control direct sun exposure enhancing visual privacy and safety.

The project has four different growing options, with a minimum built surface of 39.44m^2 that incorporates kitchen, living/dining in an open floor plan plus one bedroom and bathroom. On a successive stage, the floor plan can grow to accommodate a total of two bedrooms and an inner courtyard for a build area of 69.28m^2 (Figure 2.8) The next growing stage duplicates the floor plan on the second floor for an inhabitable area of 144.14m^2, while still leaving enough room for a vertical circulation and the incorporation of further changes that might include a small commerce area that can alternatively be used for animal keeping. Finally, in a last growing stage, the first and second floor plan layout is repeated on a third floor.

Figure 2.10 Interior courtyards view (Zatarain, 2017)

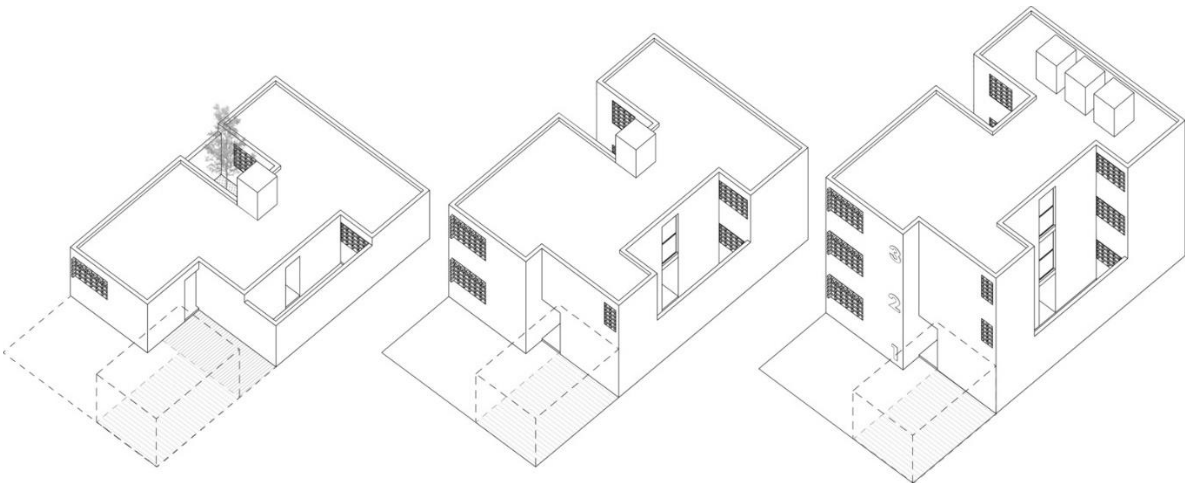

Figure 2.11 Incremental growth isometric perspective (Zatarain, 2017)

Although not enough information about the project is provided regarding thermal comfort, it represents an interesting bioclimatic approach that incorporates the courtyard concept at a small scale for social housing as a locally appropriate cultural and bioclimatic response. The project relies on natural ventilation for thermal comfort and the construction system employs concrete and redbrick which are construction materials with high thermal mass appropriate to the local climate.

No information is provided about the implementation or not of parametric simulations that could have helped in *testing* and improving the overall design. However, the inclusion of questionnaires and interviews with local people is an example of good practice from the social and cultural dimensions of sustainability.

Adaptability to future changes is addressed in the SURarquitectura project by designing in such a way that more build area can be added to accommodate demographic and family composition changes (Figs. 2.10 & 2.11); however, it does not explore the capacity of the house to adapt itself or to face the increasing temperatures that the building will have to cope with, through its life span due to climate change. In fact, very little research is currently done in Mexico from such perspective.

2.8.3 Case study three: Alika by ARA Arquitectos

Alika is a social housing cluster developed by ARA Arquitectos in the southern Mexican State of Veracruz, which is located at 19°11'25"N and 96°09'12" W at an altitude of 10m above sea level. It has a hot and humid tropical weather and an average temperature of 25.3°C with humidity levels above 74% year round. For the project, sustainability principles were employed at urban level prioritising the creation of green areas over high density housing clustering since the finished project will accommodate 2,400 houses in a plot of land that would traditionally accommodate up to 4,000 housing units (Figure 2.12).

Figure 2.12 shows the stark contrast between the traditional densely packed social housing neighbourhoods (right) with the open areas and wide streets from ALIKA (left). (Anon., 2017)

The difference in land was employed for open green spaces like a park, BBQ area, children's outdoor games, large streets that give priority to pedestrians (as stated by the developer). The project is well located in relationship to the urban network and has easy access for bicycle, public, and private transport. Native trees found in the plot were relocated as a preservation strategy. Efficient LED street lights and 3 wind turbines for electricity generation are also part of the project.

The case study is the two floor duplex housing design (three different prototypes were developed on-site). This means that two houses share a common wall that separates them with a built area of 72.82m^2 per house (Figures 2.13 and 2.14), and an inner height of 2.70m for improved natural ventilation and lighting; sun shading is provided with louvres, and also 50mm (two inches) of sprayed polyurethane provided rooftop insulation.

.

Figure 2.13 Main façade and street view (Anon., 2017)

Internet and electricity installations are integral part of the design and a dedicated area for air conditioning unit is also provided. Although air conditioning is necessary for thermal comfort in the region due to the high temperatures and moisture levels that prevail year round, there is a lack of information about specific studies regarding how and to what extent thermal comfort conditions can be achieved naturally by design alone means (natural ventilation), which in turn could be used to optimize the cooling system. Social housing in the region is sold without AC systems and those are latter added by the home owners which means that their energy efficiency varies per house unit, also, in many cases, low income households might not be able to purchase and afford to operate those which makes even more relevant to know at what extent does natural ventilation is capable of providing thermal comfort. Especially because the Mexican southern states with tropical weather (hot and humid) are the poorest and least developed and for the social housing sector have a very low AC penetration which represents about 4% of the national AC use (Beele & Gonzalez Osorio, 2016, p. 46).

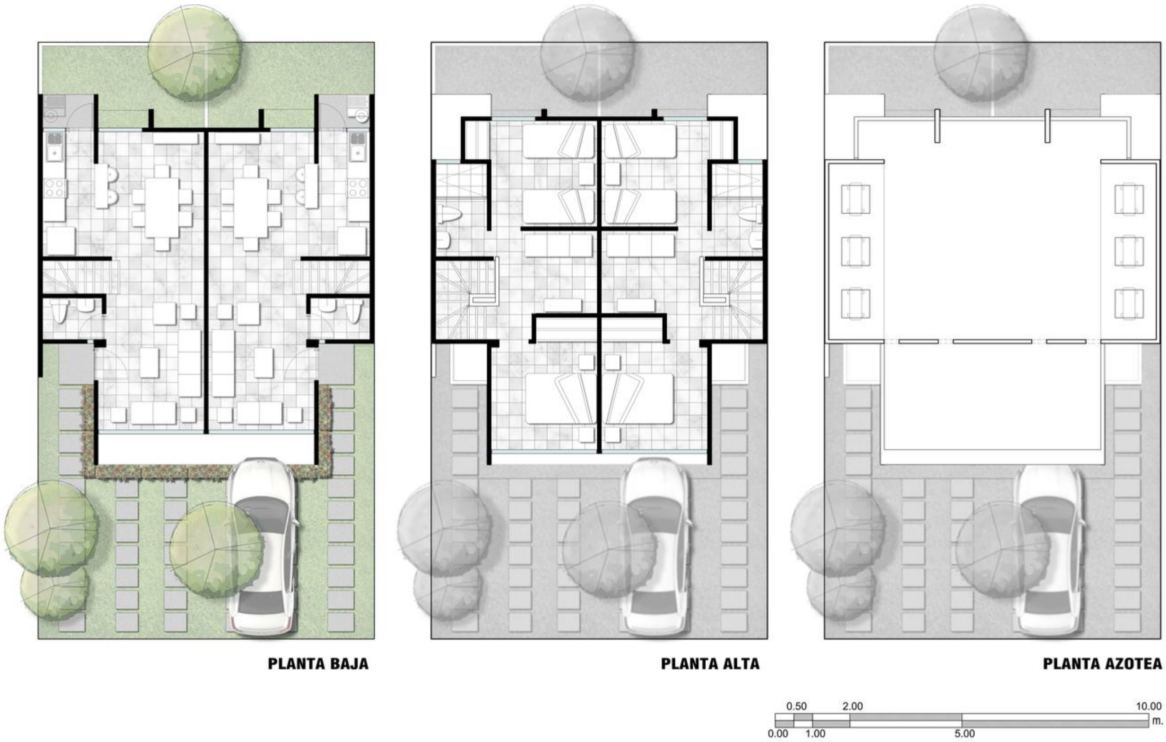

Figure 2.14 Duplex housing from left to right: first floor, second floor, and roof top plan. (Anon., 2017)

Both projects show the growing interest in exploring bioclimatic design as a cost-effective way to produce locally appropriate sustainable social housing. However, none of the examples measures the effectiveness of the bioclimatic design strategies and natural ventilation in providing thermal comfort. This means that the design approach is closer to vernacular architecture in the sense that it feeds on traditional knowledge but lacks a more technical/scientific approach that can actually quantify or provide a proxy on the effectiveness of the bioclimatic design strategies highlighting the technical void in knowledge that can be the foundation for the development of locally appropriate norms and regulations for natural ventilation and bioclimatic design.

2.9 Conclusion

The concept of urban sustainability as discussed in Section 2.1 is the overarching target for policy making and the ultimate sustainability goal if a catastrophic rise in global temperature is to be avoided. Currently, the largest global economies, including Mexico, have committed to the decarbonisation of their economies by phasing out carbon based fuels and technologies in favour of electrification along with increasing energy and resource efficiency in all of economy sectors, while minimizing the carbon based energy production

(Section 2.1.2). Such processes will have deep impacts in our energy production, distribution and consumption systems and might as well be considered as the beginning of the post-petrol era. The process is very relevant not only because it is already underway, but also because as mentioned above, it will impact all economic and productive sectors including the construction industry. From an architectural perspective and the housing sector in particular, it is widely acknowledged that early design decisions that lead to low energy consumption for thermal comfort are very important because they incorporate manifold objectives that can contribute with varying intensity and at different tiers to urban sustainability:

- A well planned and executed bioclimatic/passive design extends the time that thermal comfort happens naturally in a building without relying on HVAC systems and the energy required for operation. This in turn impact positively on people’s wellbeing while reducing energy consumption which also relieves peak demand for heating/cooling on the energy network.
- Promotes the efficient use of natural and locally available resources and if coupled with tailored educational programmes, it can also aid in making people more aware of their relationship within nature.
- Can potentially provide or be part of focalized design and construction strategies and guidelines for climate change resilience and adaptation measures with extended benefits throughout the building’s life cycle for its inhabitants.
- If complemented with eco-technologies can promote a more efficient end user energy and resource consumption such as that from water (e.g. implementation of efficient fixtures, solar water heater, rainwater harvesting whenever suitable); land (e.g. by the efficient use of urban land through verticality); waste (e.g. implementing waste water treatment at building level whenever feasible); energy (e.g. efficient light fixtures, efficient household appliances, on-site generation).
- Energy savings can also be considered as a socio-economic benefit, especially for low income families from whom energy expenditure represents an important percentage of their income.
- Potential benefits of sustainable architecture can be as broad and as deep (social, cultural, economic, urban, political, environmental, and health, etc.) as the objectives and the execution of the integrated design approach, e.g. regenerative architecture.

The construction industry in Mexico is faced with a decarbonisation scenario in which the country’s government has set up the target of generating 40% of the national energy production from renewable sources by year 2050. During the same time period housing demand will be stimulated by demographic growth (Section 2.4), with a high concentration of that demand for the lower income population. With the increasing rise in fuels and electricity prices due to the liberalization of the energy sector in Mexico it is not only desirable but necessary to improve energy efficiency in the housing sector so that more people can have better life standards while containing the environmental damage of such improvements in an affordable manner.

On the other hand, it is important to keep in mind that the full impacts of climate change are not yet fully understood and therefore, adaptation actions like thermal comfort climate change resilience are considered to be particularly relevant for urban sustainability and resilience. This is because this type of measure does not rely on supplementary energy sources and, therefore, is less vulnerable to energy price variations or shortages. Complementarily, given the low income levels of social housing dwellers in Mexico and the low AC penetration in the sector, there is an opportunity window for the research of alternatives that will allow extending thermal comfort naturally, especially in regions with relatively mild climatic conditions such as is the case of San Luis Potosi City.

The following chapters explore with more detail San Luis Potosi City as the local context of sustainability. Beginning with a closer look at local demographic trends, the local weather and its future climate projections, etc. Then after, the information is used as the foundation in which the research project builds up to the creation of a locally appropriate social housing digital prototype in which energy building simulations and parametric optimisation are performed in order to test the climate change resilience of bioclimatic design strategies and the most commonly used construction materials in proving thermal comfort with a natural ventilation regime.

Section 2 Local contextual analysis

Chapter 3. The local context of San Luis Potosi City, Mexico

As mentioned before, sustainability is a local phenomenon, thus, it is necessary to better understand San Luis Potosi City as the local context for this research. To do so, this chapter explores the city's geographic location, the local trends in population growth and how they affect housing demand. This is followed by a description of the housing segmentation in San Luis Potosi City which, in turn, allows an understanding of for whom social housing is built. Then, the local weather is studied for present time as well as the expected temperature changes due to human induced climate change up to the year 2080. Such analysis is the stepping stone for analysing locally appropriate bioclimatic design strategies and their effectiveness at present time and under future weather scenarios.

Building up on the most effective bioclimatic design strategies for San Luis Potosi City, locally available construction materials are studied so that they can be chosen based on their capability to provide thermal comfort. A multi-criteria analysis is done based on general cost structure for social housing in order to find out the construction elements that impact the most on the final cost, this way it was possible to match general bioclimatic design strategies resilient to climate change with locally available and appropriate construction materials in a cost-effective way. Such analysis was also used to find out the thermal conductivity values of the construction materials based on Mexican norms that in turn were employed for the thermal comfort simulations on DesignBuilder software.

3.1 San Luis Potosi, Mexico

San Luis Potosi City is the capital city of the homonymous Mexican state; it is located at 22°,36'12'' North and 100°,25'47'' West with a surface area of 63,068 km^2. It is considered to be part of the central region along with other 13 States (Aguascalientes, Colima, Ciudad de México, Guanajuato, Hidalgo, Jalisco, Michoacán, Morelos, Nayarit, Queretaro, Tlaxcala and Zacatecas). The 14 states that form Mexico's 'central region' account for 49.50% of the Mexican population and 20.70% of the country's surface (SEDATU, 2014, p. 17). The classification of the aforementioned Mexican states in a region denominated as 'Centre' responds to geographical, economic, and functional relationships, and it is considered that this particular region articulates, the industrial and more developed North region of the country and the Southern least developed region; the central region also articulates commerce and exchange between the Mexican Gulf and the Pacific Ocean region (East and West respectively). Fig. 3.1 shows the location of San Luis Potosi State

Figure 3.1 San Luis Potosi State

In 2011 San Luis Potosi contributed 1.9% of the National Gross Product (NGP) and, according to SEDATU (2014, p. 84), the construction industry, along with real estate services, were two of the main activities in the region with high levels of specialization.

3.2 Population Growth and Housing demand

Housing is considered as a basic human need; hence, its demand is intrinsic to population growth. In Mexico, CONAPO estimates housing *potential demand*"[6] based on the estimated formation rate of *new homes*. A new home is defined as "*a unit made up of one or more people united or not by kinship that inhabit the same residence and share feeding expenses*" (Partida, 2008). Mexican Housing Institutions consider that each new home will require a house unit which is what from now on we will call potential demand.

CONAPO'S Housing demand projections for San Luis Potosi State up to year 2030, estimate that from years 2015-2030 house stock will grow from 674,373 units to 812,318 units, this means that around 137,945 new houses will need to be built to satisfy demand due to population growth in SLP (Ibid., p. 52).

By normativity, the minimum lot size for social housing under the current single detached unit prevalent construction scheme is of 90m^2 (6m front, 15m depth lots); this implies that it will be necessary to add 12,415,050 m^2 of housing area (without taking in to account

[6] Potential Demand is made up by all new homes that will be formed according to demographic trends; this estimation does not take in to account home owners income levels, house prices nor house affordability.

urbanization areas such as streets, walkways, parking and additional infrastructure) to satisfy demand until year 2030; therefore, vertical social housing becomes relevant as an alternative to foster a more compact urban growth. It is also estimated that the average number of inhabitants per house in SLP will decrease from 3.9 inhabitants in 2015 to 3.3 in 2030 (Ibid., p. 58).

From a demographic perspective, one of the most important trends will be the increasing number of *unipersonal homes* (made up of one person) which will rise 55% from 58,220 in 2015 to 90,130 in 2030. It is important to notice that the aforementioned projections were estimated for the whole of San Luis Potosi State and its 28 municipalities, whilst, the Metropolitan area of SLP-SGS[7] concentrate around 42% of the State's housing stock (and housing demand) according to INEGI (2014).

3.2.1 Housing Segmentation

From years 2011-2014 INFONVIT granted 125,185 mortgages for new house acquisition in San Luis Potosi State; popular housing was the biggest segment with 67.5% of lent mortgages, followed by traditional housing with 18.2%, and Intermediate housing with 11.1% (Table 3.1).

Table 3.1 Housing Mortgages granted by INFONAVIT in San Luis Potosi State by housing segment, years 2011-2014

HOUSING MORTGAGES GRANTED BY INFONAVIT IN SAN LUIS POTOSI STATE BY HOUSING SEGMENT, YEARS 2011-2014							
	ECONOMIC	POPULAR	TRADITIONAL	INTERMEDIATE	RESIDENTIAL	RESIDENTIAL PLUS	TOTAL
TOTAL	1,511	84,540	22,787	13,979	2,184	184	125,185
AVERAGE	378	21,135	5,697	3,495	546	39	30,466
%	1.21	67.53	18.20	11.17	1.74	0.15	100

Elaborated by the author with data from INFONAVIT

As can be observed in Table 3.1, most of the mortgages granted for new built houses in San Luis Potosi in the studied period were for the popular and traditional segments, while the economic segment only acounted for 1.21%.This trend will continue since no significant changes in income levels that would improve the purchasing power of Mexican families are expected in the forthcoming years.

Table 3.2 shows the potential demand in SLP and Soledad de Graciano Sanchez (SGS) municipalities from years 2011-2015 (both municipalities conform a metropolitan area); it can

[7] SLP-SGS stands for the metropolitan area of the San Luis Potosi and Soledad de Graciano Sanchez municipalities

be observed that 47.2% of the potential demand in SLP was concentrated in the two lower income strata (2 VSM and 2.0-2.6 VSM highlighted in grey colour); while in SGS the very same income segments acounted for 68.3% of the demand. This difference in the demand tells us that: a) SGS population has a larger proportion of low income families and, b) this population segments are left out of the formal housing sector because their income level is not enogh for them to be granted with a houisng mortgage (and actually pay for it) under current local market conditions, and therefore, it is very likely that they will satisfy their housing needs on the irregular market.

Table 3.2 San Luis Potosi-Soledad de Graciano Sanchez housing demand by income range (VSM), years 2011-2014

SAN LUIS POTOSI-SOLEDAD DE GRACIANO SANCEZ HOUSING DEMAND BY INCOME RANGE (VSM), YEARS 2011-2015									
MUNICIPALITY		Income Segmentation by Number of Minimum Wages (VSM)							
		2	2.0-2.6	2.61-3.99	4.0-6.99	7.0-10.99	>11	TOTAL
SAN LUIS POTOSI	AVERAGE	19,568	7,566	13,109	9,915	3,698	3,667	**57,522**
	%	34.0	13.2	22.8	17.2	6.4	6.4	**100.0**
SOLEDAD DE GRACIANO SANCHEZ	AVERAGE	1,645	512	554	294	103	50	**3,158**
	%	52.1	16.2	17.5	9.3	3.3	1.6	**100.0**

Elaborated by the author with data from INFONAVIT

The situation is very similar all over the country; however, it is out of the scope of this research to explore further into this matter given that it can be considered as an structural problem that involves, national income levels and its distribution, as well as housing and land policies, e.g. the lack of an urban land market for low income families complemented by selfconstruction technical aid.

Focusing on San Luis Potosi City alone, and with up to date statistics from the National System of Housing Information and Indexes or SNIIV2.0 by its Spanish initials (SNIIV2.0, 2017) which became publicly available in 2017, the potential housing demand for San Luis Potosi City (municipality) for 2017 is shown in Table 3.3.

Table 3.3 Potential housing demand in San Luis Potosi city year 2017

POTENTIAL HOUSING DEMAND IN SAN LUIS POTOSI CITY YEAR 2017						
YEAR	UP TO 2.6 UMA	2.61-4.0 UMA	4.1-5.0 UMA	5.1-10 UMA	>10 UMA	TOTAL
2017	86,456	14,220	26,758	8,411	6,601	**142,446**
%	60.69	9.98	18.78	5.90	4.63	**100.00**

Elaborated with data from SNIIV2.0

It is important to know this information in order to be able to place in perspective market type and market size that will be targeted through this research, which is that of families with income levels in ranges from 2.61-3.99 VSM and 4.0-6.99 VSM (2.61-4.0 UMA & 4.1-5.0 UMA rspectiveley). This represents 40% of the housing demand in SLP and 26.8% in SGS

(Table 3.2) up to year 2014 and 28.76% of the demand for year 2017. Note that the variation in percentage between Tables 3.2 and 3.3 is partially due to the change in metrics from VSM to UMA (Chapter 2.5) and also due to the fact that table 3.3 does not represent a historical statistic but rather a section in time for year 2017. The main reasons for chosing this particular housing segment are:

- Houses built for this segement account for the vast majority of the formal housing sector in the country.
- Houses are built within a regular (legal) framework, which involves, land tenancy, infrastructure, services and property rights.
- Improvements in energy efficiency for this housing segments can potentially benefit the construction industry in terms of competitivity (know how); it also benefits families, by saving them money in energy bills and by providing them with a better life quality; it benefits the urban system by making a more efficient use of the available resources and lowering preassure on supporting systems (land, energy, water, drainage, etc.).
- Construction in this segment will continue in the forthcoming decades which is both an opportunity and a challenge for the local construction industry and the local urban system.
- There is a political will to shift towards more sustainable urban systems in Mexico especially in the social housing sector, therefore, this research aims to add knowledge for that pourpose at local level.

From a research perspective, even though the chosen housing segment might not be the biggest in quantitative terms, it is the one that drives the country’s housing industry because it represents the majority of the new built house mortgages granted in Mexico within a legal and formal framework in terms of employment, land use and tenure. In consequence, these housing segments also hold a high transformative potential in terms of innovation and implementation of new knowledge and technologies for the construction industry, locally in San Luis Potosi City as nationwide.

3.3 San Luis Potosi City Weather

San Luis Potosi City (SLP) is located 1,864 m above sea level with a latitude of 22°09'02" N and 100°58'3' W; it is located on the central region of Mexico which is flanked by the 'Sierra Madre Oriental' or eastern mountain range on the east and by the 'Sierra Madre Occidental' or western mountain range on the west. This particular topography creates a semi-arid weather since both mountain ranges retain most of the moisture coming from the Mexican gulf and the Atlantic Ocean (East) and from the Pacific Ocean (West) respectively. The region is drought prone and its high altitude above sea level causes important shifts in temperature during night time throughout most of the year. In consequence, low temperatures can be a cause of discomfort especially during winter time. Overall, SLP's weather can be considered as mild.

Table 3.4 show average, maximum and minimum monthly temperatures as well as the difference between the latter. It is particularly interesting to notice that the difference between the maximum and minimum temperatures varies from 19.40°C-27.30° on an average. This is very beneficial for high thermal mass as bioclimatic design strategy since it performs better with daily temperature fluctuations ≥ 6°C.

Table 3.4 Monthly average temperature in San Luis Potosi

TEMPERATURE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
AVERAGE	12.30	14.60	17.30	19.30	21.10	20.50	19.90	19.70	18.50	16.90	14.40	12.20
MAXIMUM	26.70	26.00	29.50	32.30	33.90	30.50	29.60	28.60	31.10[8]	28.80	26.20	26.80
MINIMUM	0.30	1.90	3.10	5.00	9.00	11.10	10.10	9.30	9.80	6.10	0.90	0.00
DIFFERENCE	26.40	24.10	26.40	27.30	24.90	19.40	19.50	19.30	21.30	22.70	25.30	26.80

Elaborated by the author with data from CONAGUA

Although local weather in SLP is relatively mild, there is a void in research/knowledge regarding locally appropriate bioclimatic design strategies as well as their effectiveness for future weather scenarios of climate change. This is true not only for SLP's architecture schools, but also for most of the other Mexican universities. There is also a lack of knowledge and awareness about the potential effects of climate change for the built environment. Hence, the relevance of developing locally appropriate research which can potential help to fill in that void in local knowledge is important.

On the other hand, given the relatively mild air temperatures due to local weather, it might be somewhat easy from a technical and cost-effective perspective to have an energy efficient and climate change resilient local housing construction industry. In consequence finding

[8] All climatological charts with statistical data from the national meteorological service show higher temperatures in September, this includes when looking at them from monthly average, maximum monthly average and minimum monthly average.

locally appropriate bioclimatic design strategies that can also provide resilience to climate change (future weather scenarios) is a fundamental objective of this research. Especially for the social housing sector which can better rip-off the benefits of an energy efficient construction industry.

3.4 Climate Change Projections

The baseline and future weather projections for San Luis Potosi City were created using Meteonorm software[9]. In order to better understand the potential impacts of global warming and climate change at local level, a set of three different future weather scenarios were analysed for years 2020, 2050 and 2080. The climate change projections are based on the Intergovernmental Panel on Climate Change (IPCC) scenarios from the 2007 Fourth Assessment Report. Although there are several IPCC future scenarios only those used for future weather files generation will be described (IPCC AR4 B1, A1B and A2). Chiefly, because those are the ones available in weather generation software such as Meteonorm. It is also important to note that currently, the representative concentration pathways (RCP) are considered the most up to date basis for climate modelling in the scientific community, however, the weather simulation software used for this research did not incorporated those scenarios during the research project.

The RCP incorporates integrated assessment modelling; land use historical data and future projections; atmospheric pollutant emissions and concentrations (particles' atmospheric life cycle); but most importantly, it represents harmonization of models and accessible information for researchers (van Vuuren, et al., 2011). As mentioned, the advances brought by the RCP are not yet fully available for weather generator software. Thus, their inclusion here is just to acknowledge that more advanced simulations will be available in the near future.

Next, only a brief description of the AR4 scenarios available for future weather modelling through software and therefore, the ones used for this research are presented. Note that more scenarios are available from the IPCC AR4.

The A1B scenarios represent a more integrated world with a balanced emphasis on all energy sources. The A1B scenarios is characterized by:

- Rapid economic growth.
- A global population that reaches 9 billion in 2950 and then gradually declines.

[9] Meteonorm Software is a database for solar applications and system design for any location in the world; it contains historic meteorological data sets from local weather stations and can interpolate that information for any given location in the world. The software is also capable of creating climate change projections for future weather scenarios as it incorporates the latest climate change simulation algorithms ratified by the IPCC.

- The quick spread of new and efficient technologies.
- A convergent world -income and way of life converge between regions.
- Extensive social and cultural interactions worldwide.
- A balanced emphasis on all energy sources

The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterized by:

- Rapid economic growth as in A1, but with rapid changes towards a service and information economy.
- Population rising to 9 billion in 2050 and then declining as in A1.
- Reductions in material intensity and the introduction of clean and resource efficient technologies.
- An emphasis on global solutions to economic, social and environmental stability.

Finally, the A2 scenarios represent a more divided world. The A2 scenarios are characterized by:

- A world of independently operating, self-reliant nations.
- Continuously increasing population.
- Regionally oriented economic development.
- Slower and more fragmented technological changes and improvements to per capita income. (National Oceanic and Atmospheric Administration, Earth System Research Laboratory, s.f.)

The Scenarios B1 (low atmospheric emissions), A1B (mid atmospheric emissions) and A2 (high atmospheric emissions) were used for the projections (Cattin, et al., 2018, p. 45). According to the IPCC (Meehl, et al., 2007), '*there is close agreement of globally averaged surface air temperature multi-model mean warming for the early 21st century for the three non-mitigated IPCC special reports on emission scenarios including only anthropogenic forcing*' (scenarios B1, A1B, and A2). This means that although there is always uncertainty when simulating complex systems such as global temperatures, the three aforementioned scenarios managed to reduce such uncertainty and therefore, they are generally accepted for future weather scenarios of climate change.

In the first instance, the B1 scenario for climate change with low temperature changes due to global warming was studied (Table 3.5). In a second instance, the A1B moderate climate change scenario was studied (Table 3.6); and, finally, the A2 scenario with the highest expected changes in temperature was also studied (Table 4.7). Note that year 2010 is the base line for comparison for all the scenarios.

Looking only at the average temperature between Tables 3.5-3.7, the changes do not seem to be very dramatic throughout the different scenarios. However, giving a closer look to design temperatures (maximum and minimum), which are the ones that need to be taken into consideration for architectural design, the picture is quite different. For instance, even in the best-case scenario an increase of at least 3°C is expected during the April and May (hottest months) from 34 to 37°C between years 2010 to 2080; and up to 5°C in the A2 (high) scenario with an increase from 34 to 39°C between years 2010 to 2080.

Table 3.5 SLP-SGS Average and design maximum and minimum temperatures (°C) B1 (low) scenario[10]

SLP-SGS Average and design maximum and minimum temperatures °C B1 (low) Scenario													
Year	**Temp.**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2010	**max**	27	29	32	34	34	32	32	31	28	29	28	27
	avg	13	15	18	20	21	20	20	20	19	17	15	13
	min	-1	2	2	6	9	11	11	10	9	6	2	0
2020	**max**	31	33	34	35	37	33	33	31	30	30	30	31
	avg	16	16	20	22	23	22	21	21	20	19	18	17
	min	4	1	5	7	11	12	11	11	11	8	5	6
2050	**max**	32	32	34	36	35	35	33	32	31	33	32	32
	avg	17	18	20	23	24	23	22	22	21	20	18	17
	min	4	5	6	8	11	12	12	12	12	8	5	4
2080	**max**	32	34	35	37	37	34	34	32	31	33	31	32
	avg	17	18	21	23	25	23	22	22	21	20	19	17
	min	4	3	7	10	12	13	13	12	2	8	6	5

Elaborated by the author with Meteonorm7 software and ClimateConsultant6 software

[10] The baseline year 2010 weather file was generated using Meteonorm software climate data due to the lack of enough local weather stations that could provide with robust historical data. The 'period temperature' employed was 2000-2009; the radiation period employed was 1991-2010. No further modifications were done to the 'epw' file generated. Any significate changes in temperatures between time periods might be attributable to baseline weather file generation process

Table 3.6 SLP-SGS Average and design maximum and minimum temperatures (°C) A1B (medium) scenario

SLP-SGS Average and design maximum and minimum temperatures °C A1B (medium) Scenario													
Year	**Temp.**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2010	**max**	27	29	32	34	34	32	32	31	28	29	28	27
	avg	13	15	18	20	21	20	20	20	19	17	15	13
	min	-1	2	2	6	9	11	11	10	9	6	2	0
2020	**max**	31	32	34	36	37	34	33	32	30	32	31	31
	avg	16	16	20	22	23	22	21	21	20	19	18	16
	min	2	1	7	7	11	12	11	11	11	8	5	3
2050	**max**	32	33	36	37	37	35	34	33	31	34	33	32
	avg	17	18	21	23	24	23	22	22	21	20	19	17
	min	4	4	8	10	13	13	13	13	13	8	5	4
2080	**max**	33	35	36	39	39	36	34	34	33	34	32	33
	avg	18	19	22	25	26	24	23	23	22	21	20	18
	min	5	4	7	11	13	14	13	13	13	10	7	5

Elaborated by the author with Meteonorm7 software and ClimateConsultant6 software

Table 3.7 SLP-SGS Average and design maximum and minimum temperatures (°C), A2 (high) scenario

SLP-SGS Average and design maximum and minimum temperatures °C A2 (high) Scenario													
Year	**Temp.**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2010	**max**	27	29	32	34	34	32	32	31	28	29	28	27
	avg	13	15	18	20	21	20	20	20	19	17	15	13
	min	-1	2	2	6	9	11	11	10	9	6	2	0
2020	**max**	31	32	34	35	36	34	33	31	31	32	32	30
	avg	16	16	20	22	23	22	21	21	20	19	18	16
	min	4	1	5	8	11	12	11	11	11	8	5	4
2050	**max**	31	33	35	38	37	34	33	32	32	32	33	32
	avg	17	18	21	23	24	23	22	22	21	20	19	17
	min	3	6	4	10	13	13	12	12	12	12	5	4
2080	**max**	32	34	37	39	39	36	35	34	34	35	33	33
	avg	18	19	23	25	26	25	24	24	23	22	20	19
	min	4	4	8	12	14	15	15	14	13	12	7	6

Elaborated by the author with Meteonorm7 software and ClimateConsultant6 software

There is still a lack of consensus in the scientific world about a specific scenario for the increase in temperatures due to global warming derived of human induced climate change, and so it is useful to adhere to the *Precautionary Principle* which states that:

> '*The emergence of increasingly unpredictable, uncertain, and unquantifiable but possibly catastrophic risks such as those associated with Genetically Modified*

Organisms, climate Change etc., has confronted societies with the need to develop a third anticipatory model to protect humans and the environment against uncertain risks of human action: the Precautionary Principle (PP). The emergence of the PP has marked a shift from post-damage control (civil liability as a curative tool to the level of a pre-damage control anticipatory measures of risks.' ((COMEST), 2005, p. 7)

In tune with the PP, this research aims to anticipate changes derived from increasing temperatures and their impact on thermal comfort due to human induced climate change in the social housing sector in SLP City, Mexico.

Consequently, the A1B (medium) scenario was chosen for analysis and simulation purposes given that it provides parameters for design that will ensure building energy efficiency without risking under-specification (associated with the B1 low scenario) nor over-specification (associated with the A2 high scenario). This is particularly relevant for the social housing sector for which over-specification would necessarily imply higher construction costs; whilst on the other hand, under specification might lead to under-performance in terms of thermal comfort levels.

3.5 Locally appropriate bioclimatic design strategies and climate change projections for San Luis Potosi City, years 2010, 2020, 2050 and 2080

Bioclimatic design strategies can be considered as design directions to solve particular problems posed by the design brief with tangible (measurable) and intangible benefits (subjective). The key relies in evaluating, selecting and integrating alternative strategies appropriate for build typology and local weather (Hyde, 2000). For this research, bioclimatic design strategies will be prioritized not only because of their appropriateness and effectiveness regarding local weather but also because of their thermal comfort and climate change resilience potential (future weather scenarios). According to Hyde (2000), when studying a building as a *climate filter*, the three main factors that affect its performance are:

- Microclimate and topography.
- Building form and fabric. In this case, the building bioclimatic chart relates us to locally specific bioclimatic design strategies for which the fabric will play a major role in terms of thermal performance. As for the building form, the low-rise vertical prototype, is proposed to provide compact flats in order to minimize exposed surfaces and therefore improve the overall building energy performance.
- Plant and equipment. One of the main objectives of this research is to achieve a full passive design for which no plant or equipment would be necessary by means of bioclimatic and parametric design optimisation as well as construction materials selection.

Through the consideration or not of these factors, and according to the same author, it is necessary to make a distinction between passive, active, and mixed models of climate modification in architectural design.

a. A passive building is considered to be that which does not employ plant or equipment to modify its internal climate (temperature and humidity chiefly). Instead the internal temperature is closely related to the local climate providing the same shade temperature of the exterior inside the building. This means that the building's thermal performance will vary accordingly to seasonal changes, and therefore, it is necessary to assess the number of days throughout the year when the internal conditions will be out of the comfort zone (as few as possible) and if simple user behaviour modifications can compensate and minimize thermal discomfort (changes such as wearing an extra layer of clothing during winter or wearing light clothing during summer time or opening/closing windows, etc.).
b. An active building is that which relies in plant and equipment to modify internal conditions to maintain thermal comfort though the year. In practice, over-reliance on such technologies has led to architectural design that does not take into account local weather; architecture that is highly energy intensive with the associated environmental and economic burdens. In addition, there are some potential issues related to poorly designed buildings which heavily depend on mechanical systems for thermal comfort, such as the sick building syndrome, mould growth, poor air quality, just to name a few.
c. A hybrid building is that which was designed to take advantage of passive design to maximize natural thermal comfort as well as of mechanical systems to compensate for periods of time when it is not possible to achieve thermal comfort 'naturally'. This approach is the most complex in terms of management since it requires a close monitoring of the internal and external climatic conditions in order to automate the operation of the mechanical systems, otherwise it would require a more active involvement and understanding of the systems by the users (less efficient)

Now that the distinction between the three design approaches is clear, it is important to emphasise that one of the main objectives of this research is to produce a passive building through the combination of construction materials, solar orientation and locally appropriate passive design strategies.

As mentioned in the previous section, and based on the Precautionary Principle, a moderate climate change scenario was chosen for resilience analysis of the bioclimatic design strategies in San Luis Potosi up to year 2080. Note that all the strategies analysed constitute excellent alternatives for energy efficiency and thermal comfort performance for San Luis Potosi City.

In Table 3.8 it can be observed how, as temperatures rise from 2020 and 2050, buildings will become slightly more naturally comfortable until 2080 when, due to overheating, there will be a 2% drop in the amount of naturally comfortable time; however, it is very important to bear in mind that predictability of complex systems such as climate change becomes less accurate and therefore less reliable the further in time the projections. Although this consideration applies for all of the bioclimatic design strategies, it is also important to emphasize that in any case, projections for 2080 still depict a plausible scenario (although less accurate), and therefore it will be part of the set of simulations of this research.

Table 3.8 Bioclimatic design strategies performance in percentage of comfort time, years 2010, 2020, 2050 & 2080

Bioclimatic design strategies performance in Percentage of comfort time, years 2010, 2020, 2050 & 2080				
Design Strategy	**2010**	**2020**	**2050**	**2080**
1. Naturally Comfortable	27.00	28.00	28.00	26.00
2. Sun shaded Windows	15.00	21.00	23.00	25.00
3. High Thermal Mass	8.00	14.00	17.00	20.00
4. High Thermal Mass night F	8.00	14.00	19.00	21.00
5. Direct Evaporative Cooling	8.00	13.00	16.00	17.00
6. Two stage Evap. Cooling	8.00	14.00	17.00	19.00
7. Internal Heat Gain	39.00	37.00	35.00	30.00
8. Passive Solar gain high mass	25.00	23.00	21.00	20.00
9. Cooling add Dehumidify if needed	-	1.00	2.00	5.00
10. Heating add humid. If needed	12.00	8.00	5.00	4.00
11. Fan-Forced Ventilation Cooling	3.00	5.00	5.00	5.00
12. Nat. Vent cooling	5.00	7.00	8.00	8.00

Elaborated by the author with Meteonorm7 software and ClimateConsultant6 software

Table 3.8 also shows the percentage of comfort time that can be achieved by the implementation of different bioclimatic design strategies in San Luis Potosi City and was created with future weather scenarios generated through Meteonorm software and analysed with ClimateConsultant software. The idea is to be able to choose among the different strategies those that are more suitable for a specific building design and typology since the early design stages.

Note that some of the strategies are not compatible between them (e.g. 5 & 10). This is because the table represents a ‘menu’ of possibilities rather than a design ‘recipe’. That being said, lets proceed with the description of the main strategies (those that are and will be most effective) and their performance under climate change scenarios.

A well designed south oriented building in San Luis Potosi performs Naturally Comfortable (Design Strategy 1 in Table 3.8) 27% of the time when taking as reference the temperatures for 2010. As soon as year 2020, and until 2050, that percentage will increase to 28%. By 2080, due to increasing temperatures, the majority of the discomfort experienced locally will shift from predominantly due to low temperatures to predominantly due to high temperatures and buildings will be naturally comfortable 26% of the time.

High Thermal Mass (3) and High Thermal Mass with Night Flush (4) will perform increasingly better, almost doubling their effectiveness as soon as 2020 and doubling it by 2050. Internal Heat Gains (7) as bioclimatic design strategies will become increasingly less effective; however, it will still be very efficient in aiding to achieve thermal comfort during the cold season.

Where applicable, Direct Evaporative Cooling (5) and Two Stage Evaporative cooling (6) will become increasingly more efficient. However, their implementation will not be considered viable bioclimatic design strategies for this research due to the fact that they would require either a less compact layout design approach or reliance on mechanical equipment to provide and distribute humidity inside the building.

Passive solar gain high mass (8) will become slightly less effective, with a reduction of 5% on its performance from year 2010-2080 (from 25% to 20%); however, it will still be a very efficient bioclimatic design strategies.

Fan-Forced Ventilation (11) and Natural Ventilation Cooling (12) can also play important roles for thermal comfort, especially during summer time and on very hot days. It is important to take into consideration that fan forced ventilation is only effective with air temperatures below 37°C (Kishore Khambadkone & Jain, 2017, p. 476). According with climate change projections (Table 3.6 average scenario) monthly average external air temperatures during the months of April and May will rise up to 39°C by year 2080.

As for heating (10), the rise of temperatures due to climate change, will make it increasingly less efficient. Also, due to the fact that it would require mechanical systems, it will not be considered as a viable strategy for this research.

Finally, Sun Shaded south Windows (2) will not be considered as a viable bioclimatic design strategy, since previous research by the author, found out that it is not only not effective for San Luis Potosi City, but it is counter-productive as will be further explained in the next section.

From this general analysis we can conclude that four bioclimatic design strategies are viable for providing thermal comfort through passive design in the social housing sector:

- High thermal mass (3)
- High thermal mass with night flushing (4)
- Internal heat gains (7)
- Passive solar gain high mass (8)

High thermal mass is the common characteristic of the four complementary strategies, however, the implementation of night flushing would require a different design approach due to the ventilation regime necessary for such a strategy to be effective along with its necessary supplementary systems if automated. Such an approach would lead to a 'hybrid' building design more suitable for other construction typologies (e.g. offices)

Finally, two design strategies can extend thermal comfort period during the hot season (summer time):

- Fan forced ventilation (11)
- Natural ventilation cooling (12)

A natural ventilation regime will be studied and simulated with DesignBuilder software since one of the primary objectives of this research is to find out the different sets of characteristics necessary for a locally appropriate passive building design which inherently rely on natural ventilation. Finally, fan forced ventilation will also be considered for its potential in providing thermal comfort conditions.

As a conclusion to this section, it is necessary to emphasize that, although thermal mass (3) is the main bioclimatic design strategy to be employed in the prototype proposal, due to its effectiveness in providing thermal comfort throughout the studied time period (years 2010-2080); it will still be necessary to determine the most efficient way to implement it in order to provide thermal comfort climate change resilience in the social housing sector.

3.6 Sun shaded windows as bioclimatic design strategy.

This section is based on the design and 3D modelling of a vertical social housing prototype for San Luis Potosi, Mexico which was used to test thermal comfort performance resilience to climate change up to year 2080 (Appendix 1) as part of the requirements for the fulfilment of the degree of Master in Sciences in Sustainable Environmental Design in Architecture by the University of Liverpool 2013-2014. The software employed was Autodesk AutoCAD for 2D design; ArchiCAD for 3D modelling in a compatible format with Ecotect for sun study analysis, and finally, DesignBuilder software for 3D modelling and thermal performance evaluation. Also, the results shown here were published by the author in the journal INVI, in May 2018 with the title: Prototype for sustainable social high-rise housing, an approach to climate change resilience (Pina Hernandez, 2018).

The comparison between both prototypes was possible because both were designed as compact flats buildings of small scale (four and three floors). High thermal mass was employed as the main bioclimatic design strategy and an 'optimal' south orientation was also a key design feature for both prototypes. Also, similar construction materials were employed such as redbrick and hollow concrete block. For the prototype in this chapter, the flats layout is larger that for the PhD prototype, because accessibility was considered as an important design generator. The south façade faces the street and provides access to the flats, also, the bedrooms and living/dinning area are south facing. The kitchen, laundry area, and bathroom are north facing as those areas requires less direct sunlight. East and west facades do not have windows as those are considered problematic orientations, especially the west sun exposed areas which overheat in the evenings generating discomfort.

For the thermal comfort analysis in this section the Pierce PMV was employed because, at the time of the research, it was found to be suitable for naturally ventilated buildings, although it is acknowledged that it has a tendency to under predict thermal sensation in naturally ventilated buildings (Bizaee, et al., 2012; Humphreys et. al, 2016). However, the Pierce PMV index allowed comparison of the building performance with and without window shading devices, showing more comfortable conditions when windows were unshaded (Tables 3.10 & 3.11) in San Luis Potosi City. Note that the accuracy of the magnitude of the discomfort shown should be considered just as indicative for this particular chapter as other methods for measuring discomfort in naturally ventilated buildings, such as the adaptive model of thermal comfort, are better predictors.

Also, it was decided to only test the south façade because it represents the 'best' orientation and therefore, studying it will show at what extent thermal comfort can be achieved when combined with bioclimatic design strategies (best case scenario). In that sense it is assumed that other façade orientations would diminish the thermal comfort performance of the building. Also, simulating all façade orientations (north, south, east, and west) would greatly increase the number of simulations to be performed diverting time from the south façade orientation optimization process.

The Predicted Mean Vote or PMV is an index that predicts the mean value of the thermal sensation votes of a large group of persons on a sensation scale expressed from -3 to +3 corresponding to the categories: cold (-3), cool (-2), slightly cool (-1), neutral (0), lightly warm (+1), warm, (+2) and hot (+3) according to ASHRAE 55 (2013, p. 3). According with PMV, thermal comfort is considered in the range between -0,5 and +0.5 PMV. The index is a function of six variables: air temperature, mean radiant temperature, air velocity, air humidity, clothing resistance and activity level (Bánhidi & Frohner, 2007)

On the other hand, the Pierce two-node model was developed at the John B. Pierce Foundation at Yale University and has been continuously developed ever since. The pierce model thermally lumps the human body as two isothermal, concentric compartments, one representing the internal section or core where all the metabolic heat is assumed to be generated and the second compartment is the skin, allowing passive heat conduction from the core to the skin to be accounted for. It is in its capacity to account for the heat exchange between a person and its environment that it was considered compatible with natural ventilation conditions, however, with the availability and analysis of the ASHRAE RP-884 database it was possible to uncover biases on the PMV index (Humphreys, et al., 2016, p. 109). Such as the reliance in clothing and metabolic rate that tends to overestimate subjective warmth if operative temperature, water vapour, or clothing insulation are high (Humphreys, et al., 2016, p. 104), also when outdoor temperatures are above 25°C and below minus 10°C.

In 2001, Fanger and Toftum introduced an adaptive component into the PMV equation (Humphreys, et al., 2016, p. 108) for non-air-conditioned buildings in warm climates such as is the case of San Luis Potosí City and is still part of the ASHRAE. This situation led to the adoption of the index for simulation analysis as shown in Tables 3.10 and 3.11, however, values should be considered just as a reference for this chapter alone as further research showed that the adaptive model of thermal comfort is a more appropriate index for naturally ventilated buildings leaving PMV as a better predictor for HVAC buildings.

A similar analysis to the one shown in Table 3.8 was done in order to select the most efficient bioclimatic design strategies that would also provide resilience to climate change. As Table 3.9 shows, one of the most efficient strategies for San Luis Potosi City is ‘sun shaded windows’. According to the literature review (Hyde, 2000, p. 32) (Lechner, 2009, pp.

122-128) (mpa The Concrete Centre, 2012, p. 5) and software review (ClimateConsultant 6.0), sun shaded windows would provide increasingly better thermal comfort inside the building. However, when running some preliminary thermal comfort simulations in order to test DesignBuilder's sensibility to variations such as the implementation or not of sun shading devices and the sensibility to the modelling (or not) of the external stairs in the building (Table 3.9), it turned out that the prototype without 'sun shaded windows' had a better thermal comfort performance in a consistently manner as shown in the total number of discomfort hours at the bottom of Table 3.9. Less discomfort hours means a better performance.

Table 3.9 Comfort hours' general sensitivity test

Comfort Hours General Software Sensitivity Test												
Month	Ground Floor Flat A			First Floor Flat B			Second Floor Flat C			Third Floor Flat D		
	Shading devices		Without	Shading devices		Without	Shading devices		Without	Shading		Without
	with	without	Stairs	with	without	Stairs	with	without	Stairs	with	without	Stairs
JAN	238	222	218	222	195	191	271	234	229	219	200	197
FEB	188	164	161	169	131	128	192	157	152	160	125	124
MAR	178	151	147	142	107	106	162	110	103	124	99	97
APR	135	126	125	96	82	82	74	64	62	80	77	79
MAY	97	95	97	94	94	98	93	91	95	115	116	119
JUN	128	126	123	108	106	106	114	112	114	118	120	124
JUL	163	161	157	127	127	126	146	146	146	133	135	138
AUG	184	181	177	136	134	127	138	138	138	121	123	130
SEP	196	181	177	143	124	120	149	138	137	128	124	124
OCT	200	181	180	171	139	136	184	141	136	161	141	137
NOV	208	181	176	175	132	128	214	152	143	175	133	132
DEC	240	223	220	226	197	194	288	256	252	231	207	204
TOTAL	2155	1992	1959	1809	1568	1543	2024	1739	1707	1765	1601	1606

Elaborated by the author with DesignBuilder software data

This fortuitous finding led to more simulations in order to better understand why such a discrepancy was found and weather it would perform in a similar way under future weather scenarios. Tables 3.10 and 3.11 show a Pierce PMV Index comparison by floor and year (2002, 2020, 2050 and 2080) of two identical prototypes but with the implementation or not of sun shading devices.

Table 3.10 Pierce MPV Index, prototype WITHOUT shading devices, reference year 2002.

Month	Pierce PMV Index, Prototype Without Shading															
	Ground floor Flat A				First floor Flat B				Second floor Flat C				Third floor Flat D			
	2002	2020	2050	2080	2002	2020	2050	2080	2002	2020	2050	2080	2002	2020	2050	2080
JAN	-1.13	-0.93	-0.73	-0.45	-1.02	-0.77	-0.53	-0.21	-1.12	-0.82	-0.54	-0.17	-1.15	-0.81	-0.55	-0.22
FEB	-0.91	-0.72	-0.49	-0.19	-0.76	-0.52	-0.25	0.11	-0.81	-0.52	-0.20	0.21	-0.81	-0.50	-0.20	0.17
MAR	-0.70	-0.43	-0.16	0.14	-0.49	-0.16	0.16	0.52	-0.47	-0.08	0.29	0.68	-0.44	-0.01	0.34	0.71
APR	-0.26	0.01	0.22	0.54	-0.01	0.32	0.56	0.95	0.02	0.44	0.73	1.17	0.17	0.59	0.84	1.25
MAY	-0.10	0.21	0.41	0.78	0.16	0.52	0.76	1.24	0.22	0.67	0.95	1.50	0.38	0.84	1.09	1.61
JUN	-0.09	0.21	0.43	0.75	0.16	0.51	0.78	1.20	0.21	0.66	0.97	1.45	0.37	0.82	1.12	1.60
JULY	-0.15	0.15	0.37	0.69	0.08	0.42	0.68	1.10	0.10	0.54	0.85	1.33	0.27	0.69	0.98	1.45
AUG	-0.18	0.13	0.35	0.64	0.05	0.41	0.67	1.05	0.06	0.53	0.83	1.26	0.24	0.67	0.97	1.39
SEP	-0.20	0.12	0.35	0.64	0.01	0.40	0.67	1.03	0.01	0.50	0.81	1.23	0.14	0.61	0.92	1.33
OCT	-0.48	-0.16	0.05	0.50	-0.26	0.14	0.40	0.94	-0.22	0.24	0.53	1.12	-0.22	0.27	0.56	1.14
NOV	-0.83	-0.59	-0.33	-0.08	-0.66	-0.37	-0.06	0.24	-0.69	-0.33	0.01	0.34	-0.75	-0.37	-0.03	0.29
DEC	-1.11	-0.88	-0.70	-0.43	-1.01	-0.73	-0.50	-0.19	-1.13	-0.76	-0.50	-0.14	-1.16	-0.77	-0.53	-0.20

Elaborated by the author with DesignBuilder software data

Table 3.11 Pierce PMV Index, prototype WITH shading devices

Month	Pierce PMV Index, Prototype With Shading															
	Ground floor Flat A				First floor Flat B				Second floor Flat C				Third floor Flat D			
	2002	2020	2050	2080	2002	2020	2050	2080	2002	2020	2050	2080	2002	2020	2050	2080
JAN	-1.27	-1.07	-0.87	-0.60	-1.23	-0.98	-0.74	-0.41	-1.37	-1.07	-0.78	-0.41	-1.32	-0.99	-0.72	-0.38
FEB	-1.10	-0.91	-0.69	-0.39	-1.02	-0.79	-0.51	-0.16	-1.12	-0.84	-0.52	-0.10	-1.03	-0.72	-0.41	-0.04
MAR	-0.90	-0.63	-0.37	-0.08	-0.76	-0.43	-0.11	0.25	-0.80	-0.38	-0.01	0.38	-0.65	-0.22	0.13	0.51
APR	-0.36	-0.09	0.12	0.44	-0.14	0.19	0.44	0.82	-0.13	0.29	0.59	1.04	0.07	0.50	0.75	1.16
MAY	-0.12	0.18	0.38	0.76	0.13	0.49	0.73	1.21	0.19	0.64	0.92	1.47	0.36	0.82	1.07	1.59
JUN	-0.11	0.19	0.41	0.74	0.13	0.49	0.75	1.18	0.18	0.64	0.94	1.42	0.35	0.80	1.10	1.58
JULY	-0.17	0.13	0.35	0.67	0.05	0.40	0.66	1.07	0.07	0.51	0.82	1.30	0.25	0.67	0.96	1.43
AUG	-0.22	0.09	0.30	0.59	-0.01	0.35	0.61	0.98	-0.01	0.47	0.77	1.19	0.19	0.63	0.92	1.35
SEP	-0.33	-0.01	0.22	0.50	-0.15	0.24	0.51	0.85	-0.19	0.32	0.64	1.04	0.02	0.50	0.80	1.20
OCT	-0.67	-0.37	-0.16	0.27	-0.52	-0.14	0.12	0.65	-0.52	-0.07	0.22	0.79	-0.43	0.05	0.34	0.92
NOV	-1.00	-0.75	-0.49	-0.24	-0.89	-0.60	-0.28	0.02	-0.99	-0.60	-0.24	0.09	-0.94	-0.56	-0.21	0.11
DEC	-1.25	-1.02	-0.83	-0.57	-1.21	-0.92	-0.70	-0.38	-1.37	-1.00	-0.73	-0.36	-1.32	-0.93	-0.69	-0.35

Elaborated by the author with DesignBuilder software data

The cells highlighted in blue colour show the discomfort due to low temperatures, while the cells highlighted with orange colour show the discomfort due to high temperatures. This particular analysis demonstrated that sun shading of windows would generate discomfort due to increasing low temperatures inside the building as a direct consequence of less sun entering the building.

Additional sun-shade analysis (Appendix 1) on the façade of the building during the equinoxes and solstices helped further to understand that San Luis Potosi City's latitude naturally produces a self-shading south façade through the early and late hours during the hot season (note that this is true only for a south oriented façade). Also, for the study, only north and south façades were studied as they are the ones with the potential to provide the best thermal comfort performance, which was one of the research goals, as opposed to measuring discomfort due to east or west orientations.

On the one hand, this self-shading reduces excessive solar gain during the hot season, thereby reducing the overheating risk. Conversely, during wintertime the building greatly benefits from solar gain (due to naturally lower sun light angles) which, in turn, help to create warmer internal conditions. This is true only for a south oriented façade and the study/design of shading devices for other orientations was not part of the research goals.

This unexpected early outcome, based on previous research, highlighted the relevance of conducting locally appropriate research on sustainability in architecture, and provided evidence to discourage the use of 'sun shaded windows' as part of a bioclimatic design strategy for San Luis Potosi City on a south oriented facade. Therefore, such a strategy was not taken into consideration for this research even though general literature and software review do recommend it. Finally, more on this bioclimatic design strategy will be discussed at the end of the research as new findings shed light under which design conditions it might actually be suitable and beneficial.

3.7 Construction costs

In Mexico, cost engineering is a specialization field whose main objective are to estimate a project's cost, understanding that such a cost will be the one registered at its completion, after accountability of each expenditure, supply steam or immputable charges, both directly and indirectly, as well as the contractor's profit (Varela, 2009, p. 14). According to the same author, the cost engineering task is one of a conjectural nature, since the process is knowledge-based on expertise, observations, reasoning and consultation. Thus, it implies the application of scientific and empiric knowledge in order to make conjecturing (guesswork) as realistic as possible to estimate construction costs and then being able to control them during the construction process.

One of the main principles applied for cost estimations in the construction industry in the Mexican context is the *Pareto criteria*, which was developed by the economist Wilfrido Pareto (1848-1923). The Pareto criteria states that around 80% of the effort is employed in 20% of the work and is widely implemented in management (Borjas & Manuel, 2005). Extrapolating, this means that usually 20% of the construction work concepts account for nearly 80% of the construction costs (effort); whilst the other 80% of the concepts can be considered as 'trivial' since they only account for 20% of the construction costs. This criterion helps to pay attention to what is actually relevant and can be extrapolated to many different fields; therefore, it will be of particular use for this research when selecting the construction concepts/materials that impact the most on the final cost in the social housing sector. By doing so, it will be possible to identify which construction materials if changed would have the largest economic impact but also the largest benefit in providing thermal comfort.

3.7.1 Cost estimation methods in construction

Cost estimations in construction are defined by their level of reliability, quickness, and information availability. Table 3.12 shows the type of estimations classification most frequently used in the Mexican context. As for the estimation method employed for this research, it will be *by assemblies* (elements of construction pieces), with an estimated accuracy of +/- 20%.

Table 3.12 Cost estimation, type and precision

	Estimation type	Precision	Time	Information
A	Magnitude order (or approximation)	+/- 35%	1-60 min	Very little
B	Parametric (or by m2)	+/- 30%	1-4 hrs	Conceptual (area)
C	By components (constructive phases whole systems)	+/- 25%	1-2 days	Conceptual (area)
D	**By assemblies (elements or construction pieces)**	**+/- 20%**	**1-7 days**	**Conceptual/preliminary design**
E	Unitary price	+/- 10%	3-4 weeks	Whole project

Elaborated with information from (Varela, 2009, p. 27)

It is also important to bear in mind that cost estimations are not an absolute, and they are hardly repeated given that conditions change from one construction work to the next; however, if estimations are done by people with experience both on-site as well as in office and also relying in previous works databases, then estimations can provide a good deal of accuracy.

Such is the case of the following cost estimations *by assemblies* (shown in percentage by concept) which were kindly provided by *GC Contractors*, a small San Luis Potosi City construction company with more than 15 years expertise in the social and mid-income housing sectors. Note that the company's manager, the Arch. Francisco Salas Monsivais, holds a master's degree as Independent Appraiser and is registered with the State's Public Works department in SLP. Therefore, his professional profile supports his expertise and methods.

The cost estimations shown in Figure 3.2 were calculated for a construction system based on confined brick walls, using locally produced red bricks jointed with cement-sand mixture; cast in situ colonnades or 'castillos', cast in situ perimeter stemwall and cast in situ top ring beams similar to those from Figure 3.3. Cast in situ concrete floor slabs (150 mm thick, plus finishes) and flat concrete roof (150-200 mm thick, plus finishes).

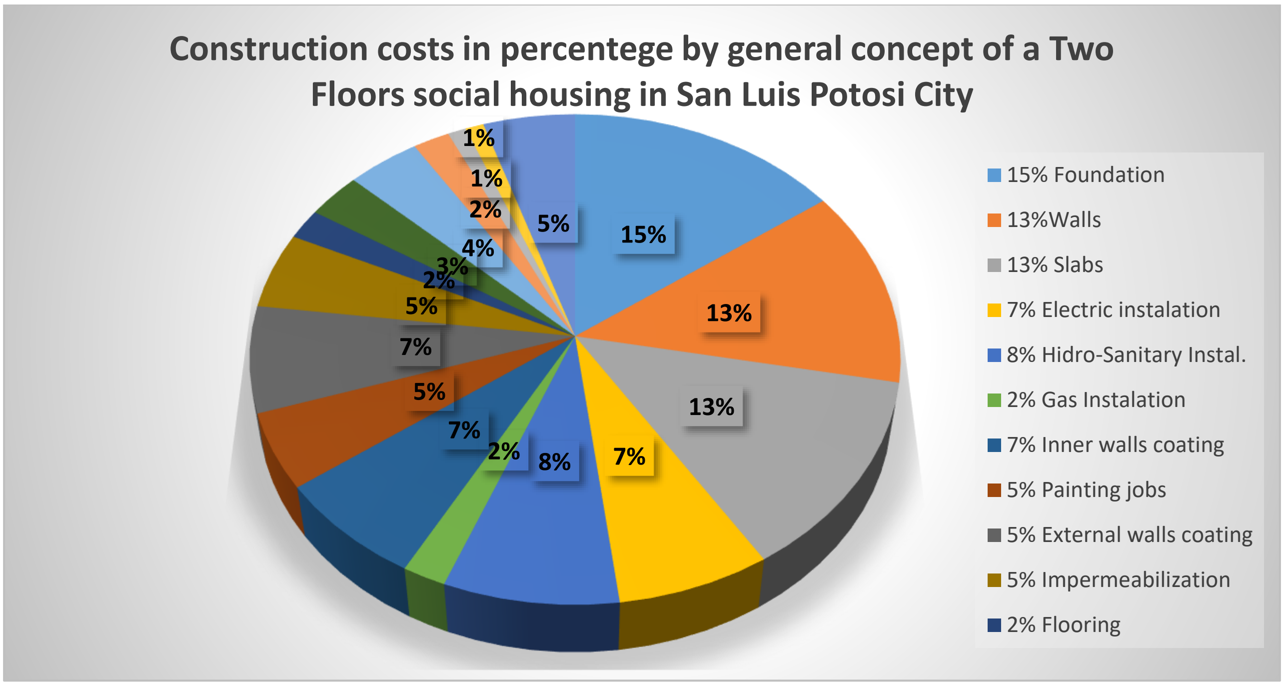

Figure 3.2 Construction costs in percentage, in San Luis Potosi City, Mexico. Elaborated by the author with data from GC Contractors, Feb. 2016

Figure 3.3 Traditional construction system.

On the other hand, big construction companies who specialize in social housing do use more technological advanced prefab construction systems since those are more in tune with the high construction volumes of repetitive housing units. However, they still rely on intensive hand labour especially for wall construction which in this sector changes red brick for hollow concrete blocks; leaving prefabrication primarily for the concrete slabs and in-wall colonnades as well as doors and windows lintels; with few exceptions where the whole house system is prefab, as shown in Figure 3.4.

Figure 3.4 Installation of a prefab roof slab (Grupo GIC, 2016).

This research will not prioritize one construction system over the other in economic terms; instead, it will give priority to their capacity in providing thermal comfort. This is because it has been acknowledged by the World Bank (The World Bank, 1993), in a cross-country comparative study about the housing construction sector, that the economic savings due to the implementation of innovation in construction materials, systems and technologies are not reflected in the final price of the house. This is partially explained by the fact that innovation and practices that are part of a company’s culture constitute competitive advantages. On the other hand, the general structure of the housing sector makes it a non-conventional market which does not respond to commonly accepted conventions and regularities. For instance, in the housing sector, the demand is made up by families with different income levels where ample social sectors living in poverty are unable to afford a house (purchase a mortgage) while competing with high income families for land (location) and housing.

On the side of the offer, in very exceptional cases, this surpasses the demand. Therefore, construction and real estate companies have no stimulus to lower house prices. Under these circumstances, technologies and processes become competitive advantages which are unique for each company, thus any improvement in such aspects improves profit instead of bringing house prices down and actually benefiting low income families. That being said, the most relevant construction concepts derived from Figure 3.2 are:

- Foundation
- Walls
- Slabs
- Inner walls coating

From these four concepts which account for 48% of the construction costs, only the walls, slabs, and inner walls coating are directly related to the buildings thermal comfort performance, therefore these will be the basis for construction materials selection and parametric simulations with DesignBuilder software. The foundations will not be simulated since their impact on the building's thermal comfort is almost irrelevant, provided that thermal bridging is correctly implemented between this element and the building's walls.

3.8 Construction materials selection and bioclimatic design strategies

As mentioned earlier, the main criteria for construction materials selection should always be in tune with the locally appropriate bioclimatic design strategies. As concluded in Section 3.5, the most effective bioclimatic design strategies for SLP up to year 2080 are:

- High thermal mass (3)
- High thermal mass with night flushing for summer season (4)
- Internal heat gains for winter season (7)
- Passive solar gain high mass for winter season (8)

From the bioclimatic design strategies above high thermal mass with night flushing (4) will not be considered for this research. However, high thermal mass (3) is and will be (for future weather scenarios) the most effective bioclimatic design strategy in providing natural thermal comfort for San Luis Potosi City. Therefore, it will be considered as a main design criterion. As for passive solar gain high mass (8), this relies on high thermal mass (3) with an appropriate orientation and sun exposure due to windows sizing. In consequence, construction materials selection will be based on this criterion.

3.8.1 Thermal mass as a bioclimatic design strategy

Generally speaking, thermal mass is considered as the ability of a material to absorb and store heat (CCAA, 2010). However, for a construction material to be useful in the build environment (thermal comfort), it is required to have a combination of three basic properties. Firstly, a high specific heat capacity; secondly, high density since the heavier the material, the more heat it can store; thirdly, a moderate thermal conductivity, so that the rate of heat flow in and out of the material is slow enough to take advantage of the diurnal temperature shift (mpa The Concrete Centre, 2012, p. 4).

Heavyweight construction materials such as brick, stone and concrete share the aforementioned properties; all of them combine a high thermal storage capacity with moderate thermal conductivity (heat will be absorbed and released slowly).

When designing with thermal mass (TM) it is important to understand concepts such as diurnal temperature variation, which stands for the daily temperature shift that occurs from daytime to night-time (24hours cycle). In order for TM to properly work, a minimum of 6°C daily temperature variation is needed. As shown in Section 2.7, in SLP the average daily temperature variation is of at least 12°C, condition that makes it very suitable for the implementation of TM as a bioclimatic design strategy.

This daily temperature shift is important since it is closely related to the heat flow to and from a building over the course of 24 hours also, the temperature shift occurs slower inside the building than outside. This is due to time lag (measured in hours) which is the time for heat to pass through a material or construction element. It is also the delay between the peak outer and inner surface temperature of a wall or roof (mpa The Concrete Centre, 2012, p. 2).

During summer time buildings with high-medium TM slowly absorb excessive heat during the day, generating cooler inner temperatures (it is necessary to keep windows closed to take advantage of the difference in temperature from the exterior). At night, when external temperatures drop down, the construction materials slowly release the stored heat generating warmer internal temperatures. This is particularly advantageous during winter time.

In summer, during night time, it is necessary to get rid of the stored heat through ventilation; by doing so, the construction materials discharge the absorbed heat and get ready to be charged again. This discharged heat process that occurs during night time will leave the TM ready to begin a new 24hr cycle. One of the main advantages of this process, is that it provides stable inner temperatures due to the material's lag time and this is translated in naturally more comfortable conditions inside the building.

During winter time, the ventilation strategy consists in leaving windows closed and allowing sun light in; this way, the buildings TM will be heated (slowly) through the day. At night, when exterior temperatures drop sharply, the stored heat will be slowly released, providing naturally comfortable temperatures. During the cold season some discomfort is expected through the early morning hours when the building's TM is depleted until it is charged again, chiefly by the sun and/or by the residual heat of human activities/appliances.

For TM to work properly, the main energy source is the sun, therefore, orientation plays a key role. The biggest windows need to face south with a ±30° East-West tolerance to make the most out of winter sun's low angles while avoiding over heating during summer time.

According to The Concrete Centre (2012), as a general rule, windows should be at least 15% of a room's floor area to provide adequate daylight, and no more than 40% of the façade area in order to prevent excessive heat gains/losses. Proportions can change depending on the type of crystal and if using single, double or triple glazing. However, according to research conducted in Mexico by Mora Juarez (2014), thermal mass was shown to be more effective in combination with single glass when daily temperature variations are large (such as is the case for SLP), note that the aforementioned research was done for Mexico City climate on a heavy weight and thermally insulated prototype.

3.8.2 Construction materials selection by concept

In Section 3.8 it was concluded that high thermal mass is the most appropriate bioclimatic design strategy for San Luis Potosi, while in Section 3.8.2 it was concluded that the most relevant construction elements regarding their impact in thermal comfort are:

- Walls
- Slabs, and
- Inner walls coating

Further steps consist in matching each construction concept with high thermal mass construction materials that are locally available and accordingly with common construction practice in the social housing sector in San Luis Potosi.

3.9 Locally available construction materials' thermal conductivity

In the last decade in Mexico there has been an increasing tendency for standardization in the construction industry, especially on the quality and properties of the most commonly used construction materials as well as in the establishment of National Official Norms for energy efficiency and insulation. The later were the main sources for the thermal conductivity values of the construction materials simulated with DesignBuilder software. On the one hand, the NOM-020-ENER-2011 (Pedraza Hinojosa, 2011) about energy efficiency in residential buildings besides providing a list of thermal values for construction materials, also provides building's orientation criteria.

On the other hand, the National Organism of Normalization and Certifiacation of Construction and Edification (ONNCCE by its Spanish initials) published the APROY-NMX-C-460-ONNCCE-2007 (ONNCCE, S.C., 2007) in which a method was determined for the calculation of the insulation 'R' value for the housing envelope by thermal zone in Mexico seting up specific target values to be achieved depending upon general location of the building (house), however, no insulation was considered during the research/simulations. The document also contains a list of construction materials thermal values representative of the Mexican market which partially helped building Table 3.13.

Complementarily, the same norm also establishes that San Luis Potosi is located in a thermal zone classified as 3B for dry, arid and semiarid climate patterns; characterized by annual precipitations lower than annual evaporation rates and with 2,076.6 cooling degree days for SLP.

Table 3.14 shows the recommended design "R" values by component and bioclimatic zone and as mentioned earlier, SLP City is on the thermal zone number 3B highlighted in green colour. It is important to note that compliance with the norm is not mandatory, it is meant to be used as a reference; also, the fact that it is not a prescriptive norm allows for design flexibility and construction materials selection.

Finally, the construction materials' thermal conductivities in Table 3.13 will be used for simulations on DesignBuilder, whereas the recommended thermal resistance "R" values from Table 3.14 will only be used as reference to compare with the performance achieved through the 'R' values obtained by the use of the locally appropriate construction materials.

Table 3.13 Construction materials thermal conductivity

Construction materials thermal conductivity				
	Size	Conductivity	Density	
Material		W/m K	kg/m3	Source
Crafted common red brick	7x13x20cm	0.872	2,000	NOM-020-ENER-2011
Extruded hollow red brick		0.998	2,050	APROY-NMX-C-460-ONNCCE-2008
Hollow concrete block	15x20x40cm	0.698	1,700	NOM-020-ENER-2011
Gypsum plaster	1cm	0.372	800	NOM-020-ENER-2011
Mortar cement:sand	1cm	0.630	2,000	APROY-NMX-C-460-ONNCCE-2008
Reinforced concrete	10cm	1.740	2,300	NOM-020-ENER-2011
Glass	4mm	0.930	2,200	NOM-020-ENER-2011
Glass	6mm	1.160	2,700	NOM-020-ENER-2011

Elaborated by the author with information form (Pedraza Hinojosa, 2011) & (ONNCCE, S.C., 2007)

Table 3.14 Recommended thermal resistance "R" values by component and thermal zone

Thermal Zone number	Roofs m2 k/W			Walls m2 k/W			Ventilated internal floor m2 k/W		
	Minimum	Habitability	Energy Sav.	Minimum	Habitability	Energy Sav.	Minimum	Habitability	Energy Sav.
1	1.40	2.10	2.65	1.00	1.20	1.40	NA	NA	NA
2	1.40	2.10	2.65	1.00	1.20	1.40	0.70	1.10	1.20
3A, 3B & 3C	1.40	2.30	2.80	1.00	1.80	1.90	0.90	1.40	1.60
4A, 4B & 4C	1.40	2.65	3.20	1.00	2.10	2.30	1.10	1.80	1.90

Taken from APROY-NMX-C4601-ONNCCE-2007 (ONNCCE, S.C., 2007, p. 5)

3.10 Conclusion

From years 2015 to 2030 a minimum of 12,415,050 m^2 of housing floor area will be required in San Luis Potosi to meet housing demand due to demographic growth. This figure does not consider complementary spaces such as streets, sidewalks, public spaces, etc., making vertical construction particularly relevant in terms of efficient land use.

Formal housing demand will concentrate in the *traditional* and *intermediate* segments - for families that earn 3.99-6.61 VSM. Even though this segment is not the largest, it is the one that, due to an existing regulatory framework (urban, legal, financial, and industrial), holds a strong potential for innovation and energy savings.

Given the relatively mild climate in San Luis Potosi City, Mexico, bioclimatic design strategies hold a strong potential for achieving thermal comfort year round without the need of HVAC systems. Such is the central thesis of this research which seeks to understand if, and how, this could be achieved at the present time, and also for future weather scenarios.

As for climate change, the A1B medium scenario was chosen given its plausibility of occurrence over the B1 (low) and A2 (high) ones. These last two scenarios also risk under or over specification of buildings and their components respectively and therefore, will not be considered for thermal comfort simulations.

After the A1B climate change scenario was chosen, the effectiveness of locally appropriate bioclimatic design strategies for San Luis Potosi City, from years 2010-2080 were also studied; with the following being the better performing in terms of providing thermal comfort:

- High thermal mass
- Internal heat gains
- Passive solar gains

On a complementary note, sun-shaded windows (2) with a south orientation as a bioclimatic design strategy proved to be counter-productive. As was explained in Section 3.6, San Luis Potosi City's latitude, being relatively close to the Equator, prevents excessive heat gains during summer due to the high sun altitude while providing useful solar gain during winter time naturally. The use of sun shading devices on the south facing façades exacerbates low temperatures during winter time, and the benefit it provides during summer is small, hence, its implementation is not justified and it is advisable not to use window shading devices on the south facing facades in San Luis Potosi City, Mexico.

As result of the construction costs analysis it was concluded that the construction elements with the larger impact on the building's budget and thermal comfort are:

- Walls (external)
- Slabs (including roof)
- Inner walls coating (also external coating)

These elements are the ones that will be simulated using locally available construction materials with high thermal mass in order to evaluate which of them (or mix of them) provides better thermal comfort and climate change resilience in a passive building design. Note that thermal conductivities by Mexican national norms were employed in order to provide consistency to the simulations and for the sake of replicability of the method employed for the construction materials selection.

Chapter 4. Thermal comfort in naturally ventilated buildings (free running buildings)

As described in Section 3.5, a free running building is one that which relies on passive design strategies and natural ventilation to provide thermal comfort to its occupants without the use of mechanical ventilation for heating or cooling. However, indices employed for thermal comfort measurement were originally developed for the design of heating, cooling and air conditioning (HVAC) systems, when this new technology promised to bring year-round comfort conditions. HVAC systems have now reached housing in developed countries. This happened against a scenario in which energy prices were low and there was little to no concern about the global effects of anthropogenic activities. Those conditions led to the decoupling between architecture and its natural environment as the advent of HVAC systems allowed to create a constant artificial environment regardless of architectural design features.

Nevertheless, at the end of the XX century it became clear that human activities have a planetary impact that is driving global warming while at the same time fossil fuels and energy in general have become increasingly expensive, allowing a turn of the wheel in the architectural and engineering practice. It is now increasingly acknowledged that it is more efficient to design in such a way that buildings can make the most of their natural environment to provide thermal comfort and only then, if necessary, implement heating or cooling just when they are actually needed. This approach relies on natural ventilation and hence creates a building environment that changes in a symmetric way with its natural surroundings, thus, providing a more dynamic building environment in terms of the variations in temperature, ventilation, and comfort. Also allowing for more opportunities for occupants to adapt themselves and the building in order to get thermal comfort. It follows that in order to better understand and predict at what extent thermal comfort can be achieved in such conditions that the adaptive model of thermal comfort (AMTC) was developed.

Before going into more depth with the AMTC it is necessary to provide a definition for thermal comfort which is based on the ANSI/ASHRAE 55-2013 followed up by a brief description of the PMV index widely employed to predict and measure thermal satisfaction (thermal comfort) in mechanically ventilated buildings. Finally, the general principles of the adaptive model of thermal comfort are introduced followed by their implementation in order get a thermal comfort temperature band suitable for free running residential buildings San Luis Potosi City, Mexico.

The ASHRAE 55-2013 was chosen over other standards, such as the European EN15251 or the ISO 7730, because unlike these, the ASHRAE standard does not rely on a building classification associated with a comfort index that inherently assumes that all buildings will have an HVAC system. Also, ASHRAE offers a specifically developed adaptive model of thermal comfort (AMTC) which makes its adoption for San Luis Potosi City more straightforward. It follows that according to the ANSI/ASHRAE Standard 55-2013 (ASHRAE, 2013), an acceptable thermal environment depends on the interaction of six factors:

a. Metabolic rate: measured in 'Met Units'; it represents the human body heat or power production when performing a given activity and it is associated with the place (type of space) in which that activity is performed.
b. Clothing insulation: measured in 'Clo' represents the insulation level due to clothing type and it is closely related with the building/space activity (e.g. office, house, school).
c. Air temperature
d. Radiant temperature: is the uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure. The calculations complexity is automated by energy plus in DesignBuilder.
e. Air speed
f. Humidity

The thermal acceptability of an environment is also known as thermal comfort, which is '*that condition of mind that expresses satisfaction with the thermal environment*' (ASHRAE, 2013, p. 19). Due to the subjective nature of the definition, which relies on individual perception, extensive laboratory and field surveys were studied to provide statistical data that is representative of a large percentage of population feeling thermally comfortable. Furthermore, results of such studies have been the foundation for HVAC standardization world-wide.

In buildings with HVAC systems, it is considered that the majority of people will experience comfort when in a temperature range between 20-25°C, thus, heating and cooling systems are designed to provide those temperatures year round. One of the main criticisms to such standard, is that it does not takes into consideration external temperatures, people's preferences and adaptability, nor building typologies (home, offices, schools) leading to build environments isolated from their natural surroundings (temperature, humidity, air speed, etc.).

In this context, it is common to find buildings in a tropical country or in northern latitudes with HVAC systems set up into this temperature range (20-25°C) leading to high energy consuming buildings. On the other hand, it is undeniable that under extreme or consistently low/high temperatures for prolonged time periods, it would be necessary for the implementation of heating/cooling to provide thermal comfort. It is also important to note that the thermal comfort standard was developed for northern countries with cold winters and mild summers. The standard development also considered building occupants as static (sitting in an office) and incapable of adapting their clothing or the opening/closing of windows behaviour. Therefore, it hardly reflects the geographical and cultural context of milder climates such as is the case of San Luis Potosi City, Mexico nor the residential sector.

Probably the best known model for thermal comfort is the Predicted Mean Vote (PMV) index, which predicts the percentage of people that will feel comfort/discomfort in a building. It was first developed by Fanger in 1970 (Humphreys, et al., 2012, p. 44), and its relevance relies on the fact that it has been the basis for the development of most national and international thermal comfort standards. The seven point Fanger index, which is the index developed and adopted by the ASHRAE Standard 55 (ASHRAE, 2013, p. 9.12), classifies users' thermal response to environmental conditions inside a building as follows:

- 3 = hot
- 2 = warm
- 1 = slightly warm
- 0 = neutral
- -1 = slightly cool
- -2 = cool
- -3 = cold

Note that PMV was developed from laboratory based experiments in which the comfort variables were manipulated, and participants were limited to record their thermal sensation while performing specific activities. Although, a large number of participants took part on the experiments, the main focus was still on finding out the best set of conditions/temperatures for HVAC systems operation assuming little to no control of building occupants over their environment.

In contrast, research works such as those from Chou & Nanyang (2010), Nicol & Pagliano (2007) and Shajahan & Nasreen (2016), suggested that the upper and lower limit temperatures for free running buildings should be closely related to outside air temperatures. The same authors developed methodologies based on ASHRAE Standard-55 to calculate locally appropriate thermal comfort indexes which they applied in specific geographical locations respectively. Their methodologies are based on extensive field measurements (internal and external temperature and humidity measurements taken 2-3 times a day) and thermal sensation questionnaires, also applied 2-3 times a day to the building occupants. Although this type of research method is the most accurate way to estimate an adaptive local comfort temperature band, it surpasses the time, economic and technical scope of this research. Instead, the adaptive model of thermal comfort for occupant-controlled naturally conditioned spaces will be used which is also known as *adaptive model of thermal comfort and preference (AMTC)*.

The AMTC was the culmination of decades of debate between those who supported a fixed or *static* model of thermal comfort which is particularly good for setting parameters in HVAC buildings, against those who considered a more flexible approach in terms of adaptation and preferences from users, especially in unconditioned buildings like in naturally ventilated and bioclimatic design based architecture (de Dear, et al., 1997, pp. 2-3) such as is the case of this research.

The main assumption underlying the AMTC is that users are actively involved in adapting themselves and their environment(s), that they hold thermal preferences influenced by contextual factors, and their past thermal history. In other words: "*satisfaction with an indoor climate results from matching actual thermal conditions in a given context and one's thermal expectations of what the indoor climate should be like in that same context*" (de Dear & Shiller Brager, 2001, p. 101), this means that satisfaction occurs through appropriate adaptation to the indoor climatic environment. In the analysis to the RP-884 conducted by de Dear et.al. (1997), they found that the preferred temperature in a naturally ventilated building increased approximately one degree for every three-degree increase in the mean monthly outdoor temperature. Their research led to the development of the linear equations that allow to determine an optimum comfort model and its acceptability temperature limits, also known as the adaptive comfort standard which was adopted by ASHRAE 55-2013 and can be written as follows:

- Comfort temperature (°C) = 0.31 (mean outdoor monthly air temperature) + 17.8
- Upper 80% acceptable limit (°C) = 0.31 (outdoor air temperature) + 21.3
- Upper 90% acceptable limit (°C) = 0.31 (outdoor air temperature) + 20.3
- Lower 80% acceptable limit (°C) = 0.31 (outdoor air temperature) + 14.3
- Lower 90% acceptable limit (°C) = 0.31 (outdoor air temperature) + 15.3

When it comes about the applicability of the adaptive comfort standard in occupant controlled naturally ventilated buildings, the ASHRAE standard 55-2013 (ASHRAE, 2013) clearly defines four criteria that need to be met:

1. The building/space has no mechanical cooling system nor heating systems in operation.
2. Representative occupants have metabolic rates ranging from 1.0 to 1.3 met which fall in the ‘resting’ range which makes them suitable for residential and most office activities (ASHRAE, 2013, p. 5)
3. Representative occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5 to 1.0 clo., as is the case in residential environments.
4. The prevailing monthly mean outdoor temperature is greater than 10°C and less than 33.5°C such as is the case for San Luis Potosi, City at present time and up to year 2080 according to climate change projections (Sections 3.3 & 3.4).

The ASHRAE 55 (2013, p. 12) also advices using the 80% acceptable upper and lower limit for calculations, leaving the 90% limit for information only. Finally, de Dear (2001, p. 105) states that when implementing the AMTC, it already accounts for local and whole-body thermal discomfort effects in typical buildings; it also takes in to consideration people’s clothing adaptation in naturally conditioned spaces so it is not necessary to estimate insulation from garment, nor other behavioural adaptations, neither humidity, or air speed limits. As can be noted, the use of the AMTC in naturally ventilated buildings in compliance with ASHRAE 55-2013 is an acceptable method to set up a locally appropriate thermal band to measure comfort with the results for San Luis Potosi City Mexico.

The comfort band for year 2010 (climatic reference year) is 18-28°C. As soon as 2020 and up to year 2080 the temperature comfort band changes slightly as global temperatures rise from 19-28°C (Tables 4.1-4.4). These temperatures will be used for thermal comfort analysis in forthcoming chapters and when explicitly indicated.

Table 4.1 Year 2010 AMTC, 80% acceptability

YEAR 2010 AMTC, 80% ACCEPTABILITY, °C													
MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TEMP
MEAN TEMP.	13	15	18	20	21	20	20	20	19	17	15	13	BAND
UPPER 80%	25.33	25.95	26.88	27.5	27.81	27.5	27.5	27.5	27.19	26.57	25.95	25.33	28 °C
OPTIMUM	21.83	22.45	23.38	24.00	24.31	24.00	24.00	24.00	23.69	23.07	22.45	21.83	24 °C
LOWER 80%	18.33	18.95	19.88	20.5	20.81	20.5	20.5	20.5	20.19	19.57	18.95	18.33	18 °C

Elaborated by the author

Table 4.2 Year 2020 AMTC, 80% acceptability

YEAR 2020 AMTC, 80% ACCEPTABILITY, °C													
MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TEMP
MEAN TEMP.	16	16	20	22	23	22	21	21	20	19	18	16	BAND
UPPER 80%	26.26	26.26	27.5	28.12	28.43	28.12	27.81	27.81	27.5	27.19	26.88	26.26	28 °C
OPTIMUM	22.76	22.76	24.00	24.62	24.93	24.62	24.31	24.31	24.00	23.69	23.38	22.76	24 °C
LOWER 80%	19.26	19.26	20.5	21.12	21.43	21.12	20.81	20.81	20.5	20.19	19.88	19.26	19 °C

Elaborated by the author

Table 4.3 Year 2050 AMTC, 80% acceptability

YEAR 2050 AMTC, 80% ACCEPTABILITY, °C													
MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TEMP
MEAN TEMP.	17	18	21	23	24	23	22	22	21	20	19	17	BAND
UPPER 80%	26.57	26.88	27.81	28.43	28.74	28.43	28.12	28.12	27.81	27.5	27.19	26.57	28 °C
OPTIMUM	23.07	23.38	24.31	24.93	25.24	24.93	24.62	24.62	24.31	24.00	23.69	23.07	24 °C
LOWER 80%	19.57	19.88	20.81	21.43	21.74	21.43	21.12	21.12	20.81	20.5	20.19	19.57	19 °C

Elaborated by the author

Table 4.4 Year 2080 AMTC, 80% acceptability

YEAR 2080 AMTC, 80% ACCEPTABILITY, °C													
MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TEMP
MEAN TEMP.	18	19	22	25	26	24	23	23	22	21	20	18	BAND
UPPER 80%	26.88	27.19	28.12	29.05	29.36	28.74	28.43	28.43	28.12	27.81	27.5	26.88	28 °C
OPTIMUM	23.38	23.69	24.62	25.55	25.86	25.24	24.93	24.93	24.62	24.31	24.00	23.38	24 °C
LOWER 80%	19.88	20.19	21.12	22.05	22.36	21.74	21.43	21.43	21.12	20.81	20.5	19.88	19 °C

Elaborated by the author

Note that DesignBuilder automatically works with the 20-25 °C temperature band for thermal comfort calculations of discomfort hours in buildings. Even though the software allows to set up and simulate natural ventilation conditions, it does not allow the discomfort hours to be calculated using the AMTC. From an analytical perspective, this situation will allow the number of discomfort hours to be found if the prototype under study was a conventional building with HVAC systems through the static thermal comfort model. A more detailed analysis and data processing (using the very same output data set from DesignBuilder) was used to determine the number of discomfort hours through the implementation of the ATMC. Presumably, the difference between both discomfort hours will account for an equivalent amount of energy to be saved by shifting from one thermal comfort model and its comfort temperature band to another.

4.1 Conclusion

Comfort is considered as a climate and culture-specific phenomenon for which countries and regions within countries are beginning to develop their own approaches to energy savings and comfort standards (Humphreys, et al., 2012, p. 58). It is acknowledged that the expectations and aspirations for comfort vary between people who live in naturally ventilated buildings from those who live in air conditioned ones. It follows that allowing an indiscriminate adoption of air conditioning in mild climate regions such as San Luis Potosi might lead to what is called the '*ratchet effect*', meaning that once AC is adopted, it is very difficult to reverse peoples' thermal preference for naturally ventilated buildings. The fact that currently there is a low adoption rate of AC systems in regions similar to San Luis Potosi City, Mexico (Section 2.7.1) which accounts for nearly 59% of the national population, can be seen as an opportunity for developing locally appropriate energy saving and comfort criteria based on the AMTC.

It can be expected that due to increasing temperatures from climate change, the adoption rate of AC systems will increase in forthcoming years, particularly in poorly designed buildings. This need not to be the case for new nor retrofitted buildings if bioclimatic design and natural ventilation turn out to be enough for providing thermal comfort at present time and under future weathers projections of climate change. Even in the worst case scenario in which AC would be needed in the future, it is still necessary to develop recommended set up temperatures for such systems that reflect local conditions in a wider temperature band than the narrow 20-25°C from the static model of thermal comfort.

In consequence, thermal comfort for this research is based on the ASHRAE-55 AMTC as was described and defined for San Luis Potosi City, Mexico. This is considered as a sensible and generally accepted thermal comfort index for free running buildings. The comfort thermal band was calculated considering the recommended minimum thermal acceptancy of 80%, which means that more than 80% of occupants will find the building thermally acceptable (ASHRAE, 2013, p. 5). With that information, the calculated thermal band for year 2010 is of 18-28°C and of 19-28°C for years 2020-2080. It follows that less than 10% of discomfort time due to high temperatures during the hot season (summer time) and 10% of discomfort time due to low temperatures during the cold season (winter time) are considered to be acceptable. In other words, if less than 876 hours of discomfort time is achieved then there is no need for mechanical heating nor cooling. Complementarily, the static model of thermal comfort with a 20-25°C thermal band will also be employed for the sake of comparison since this will allow to better understand the difference in discomfort time when employing either model.

Having a thermal comfort model that reflects local weather conditions opens the possibility of developing locally appropriate criteria for energy savings and thermal comfort in free running buildings. A good deal of research and education is necessary to integrate the cultural and behavioural components of thermal acceptancy. For example, the hypothetical case of a worker who spends most of his/her working time (8 hours or more) in a fully conditioned environment with a static model of thermal comfort temperature band year round, just to go back to his/her free running house. How will such a contrast in a person's daily exposure to different operative temperatures affect his/her thermal perception and preference for free running buildings? In this case, will this influence the desirability of owning HVAC systems in the person's own house? How can those correlations, if proven, be managed at local level through heating/cooling regulations/recommendations? These and other contextually relevant questions are for future field research work that currently surpass the extent of this project. Still, the answer to those questions might play a key role in how and if the AMTC will ever be successfully implemented in the residential sector in San Luis Potosi City, Mexico and similar climatic regions in such a way that would allow for energy efficiency in the building sector since the early design stages.

Note that it is well understood that the full development of a locally appropriate AMTC standard or index requires a methodology based on surveys, questionnaires and measurements that would provide statistical significance. However, these surpass the scope and limitations of this research. Instead, the ASHRAE-55 AMTC is employed as a proxy that will allow to test the effectiveness of bioclimatic design and natural ventilation in providing thermal comfort and hopefully will set up a precedent in the region for further and deeper research that might lead to locally appropriate energy saving standards that reflect people's adaptability and interactions with their built environment in Mexico.

Chapter 5. Validation of general simulation parameters

In previous chapters basic simulation parameters were stablished, chiefly thermal conductivity values of construction materials representative of the Mexican market such as concrete, glass, aluminium, red brick, hollow concrete block, extruded red brick to name a few (Chapter 3.9). Generation of '.epw' weather files for San Luis Potosi City (Chapter 3.4) to be used for the building energy simulations. Next step consisted in providing some level of validity for such parameters. To do so, temperature and humidity were measured with dataloggers during a small time period (one month during winter-time December-January 2015-2016) in a built house in San Luis Potosi City (inside and outside). Then, the house was digitally modelled with DesignBuilder software and the outside recorded temperatures were used to modify the baseline '.epw' weather file (for year 2010) to perform building energy simulations that in turn allowed to compare the digital building temperatures versus the recorded ones.

It is very important to note that the house was designed by the author employing bioclimatic design principles, chiefly high thermal mass. Also, especial attention was given to the two-floor single-family house orientation to take advantage of the north and south facades (front and rear facades respectively). Complementarily, the house was designed and built in a row-house plot; therefore, east and west sides of the house are adjacent to neighbouring houses reducing envelope exposure to the elements. This characteristic was simulated with the use of adiabatic blocks (DesignBuilder software) that in turn allowed to represent the thermal effect of the adjacent constructions over MALI house (Architectural plans, perspectives, photos, and simulation parameters can be found in Appendix 2).

The traditional construction system of cast in situ concrete colonnades, red brick walls, single glazing windows with aluminium frames with 50% of maximum operability for natural ventilation, and concrete slabs/roofs were used for the two floors MALI house construction and then simulated in a digital model.

It is also due to the small scale of the vertical social housing prototype (three floors), that the same construction system of MaLi house was proposed and simulated for the former. Thus, allowing for the extrapolation of MaLi simulation results for the validation and fine-tuning process of the building energy simulations of the vertical social housing prototype.

In MaLi house the master bedroom and the living room were placed in the ground floor, both with a south orientation. On the first floor, 2 bedrooms and a studio are also south facing, this way, all habitable areas overlook the back garden taking advantage of the south orientation for natural light, ventilation, views and heat gains (wintertime), while retaining privacy.

North facing, the stairs volume (double height), a guest's toilet, the kitchen, and laundry area can be found on the ground floor. On the first floor also north facing, a circulation, a reading area and a bathroom are located. This way all service areas are north oriented while facing the street and providing a noise buffer between the busier street and the more secluded living and resting areas which overlooks the garden area. A very similar north-south strategy for the service and habitable areas was used on the flats' prototype design (Chapter 6).

The general characteristics shared by MALI house and the vertical social housing prototype studied in this research are:

- Bioclimatic design with high thermal mass as the main design strategy.
- North-South (service-habitable areas respectively) design strategy to provide the best orientation to the habitable areas while using the north service areas as buffer to the noisy and busy street.
- Same construction materials in MALI house and the red brick flats' prototype. Which allowed to extrapolate and finetune the simulation parameters of MALI house to the prototype. Although quantitate accuracy cannot be achieved chiefly due to the small amount of measured time period, still the data gathered physically when contrasted with the simulations allowed to 'fine tune' the general simulation parameters for the research through a feedback process.
- Single glass pane in windows with aluminium frame and 50% operability were used in MALI house as in the simulated prototype.

It is acknowledged that a simulation-based research/prototype inherently hold many pitfalls especially when it comes about the more or less accurate representation of real-life conditions. Especially, the complexity of simulating the multidimensional interactions that generate thermal comfort (behavioural, climatic, energy transference, etc.). In consequence, it was considered as an advantage to have the opportunity to measure through dataloggers at least temperature and humidity in a built house that then was simulated with DesignBuilder software. The main goal was to observe the differences and similitudes between measurements and simulations and in doing so traying to close the gap (as much as possible with the limited time and sensors) between the digital and real-life house.

MaLi house construction began at the end of year 2014 and was completed in early 2015. The close relationship with the contractor and homeowners facilitated the installation of the environmental data loggers. A set of four HOBO data loggers were set up from December

10th 2015 to January 13th 2016 in the two storey house built and then simulated with the same construction materials thermal properties (Section 3.9) Note that the short amount of time (little more than one month) for the measurements reflects the impossibility of a longer stay in Mexico due to technical and economic restrictions.

The data loggers recorded temperature and humidity with an hourly frequency and were placed as follows (refer to Appendix 2 for more details on the house layout and size):

- One data logger was placed outside the house, protected from direct sun light and wind in the service courtyard in order to get external air temperatures (Figure 5.1). and recorded temperature and humidity from December 11th to January 12th
- A second data logger was placed in the living/dining area with an open plan design and recorded temperature from Dec. 18th- Jan 10th (Figure 5.2).
- A third data logger was placed in the ground level bedroom from Dec. 11th-Jan. 12th. (Figure 5.3).
- The fourth data logger was placed in the 1st floor bedroom from Dec. 11th-Jan. 12th (Figure 5.4).

For temperature comparison the information from the outside datalogger was used to substitute the same data sets (temperature and humidity) in the reference 'epw.' weather file for San Luis Potosi City (year 2010) with an hourly frequency from December 11th, 2015 to January 12th, 2016 using EnergyPlus[11] software weather statistics and conversions tools. Then, the DesignBuidler digital model of MaLi house was simulated with the modified weather file and the resulting temperatures were contrasted with their on-site measured counterparts.

Note that although all data loggers were set up on the same date, there was some data loss during the transference to the PC which explains the discrepancies in the recorded dates in the Living/dining area which only recorded from December 18th, 2015 to January 10th of 2016 (Figure 5.2). Ground floor and first floor bedroom dataloggers (Figures 5.3 and 5.4 respectively) recorded temperatures from December 11th, 2015 until January 12th, 2016.

[11] EnergyPlus software was developed by the U.S. Department of Energy Building Technologies Office and manged by the National Renewable Energy Laboratory. It is considered as one of the best simulation engines and can be found as the main energy simulation engine in DesignBuilder, Autodesk Green Building Studio, Ladybug, Sefaira Systems, and OpenStudio to name a few.

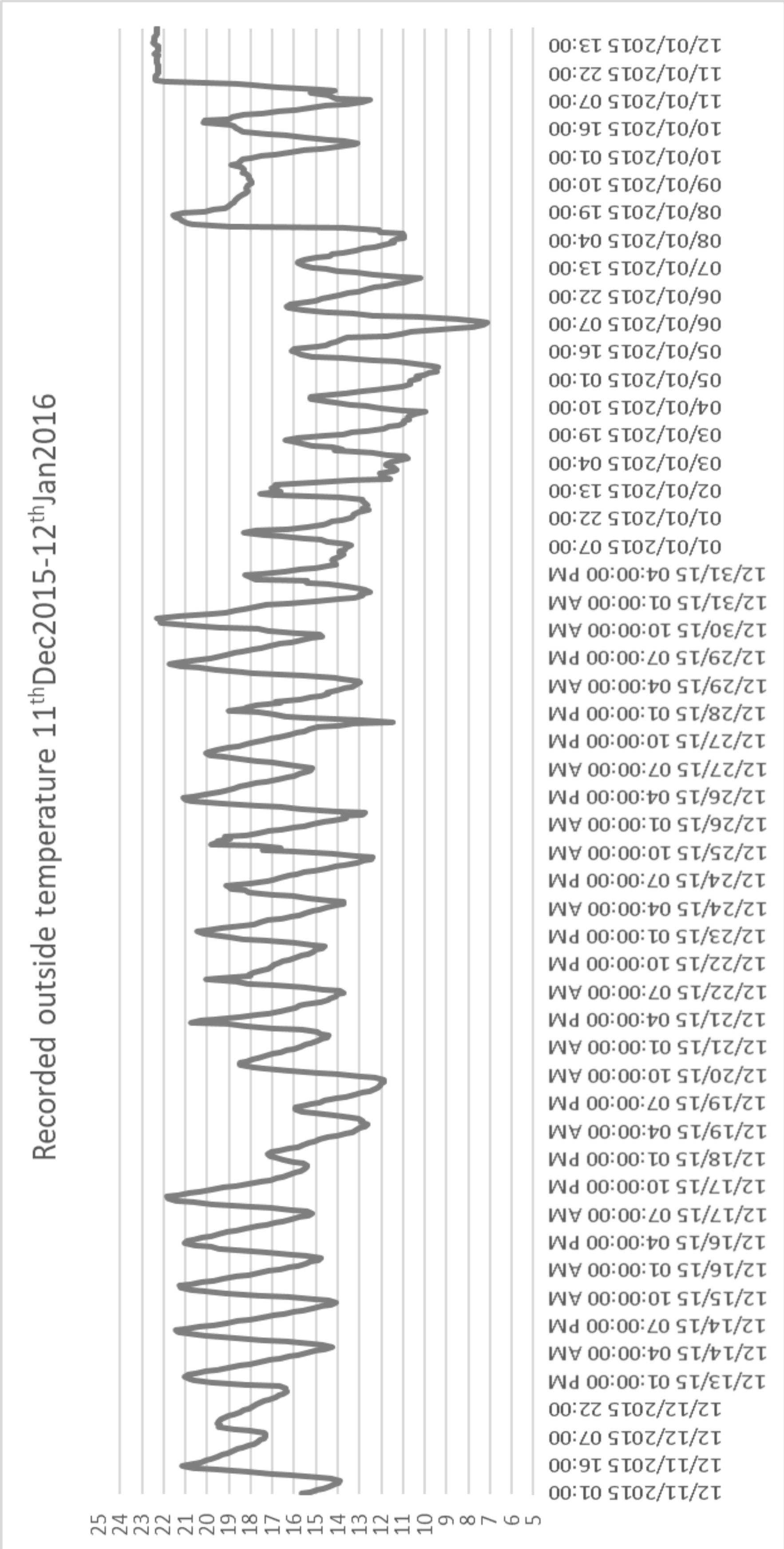

Figure 5. 1 Recorded outside temperature Dec. 11th2015 – Jan 12th2016

As already mentioned, the datalogger placed outside the house was set up in the service courtyard avoiding direct sun exposure, in a well-ventilated position, and protected from rainfall. Figure 5.1 shows the recorded outside temperatures with a maximum daily temperature fluctuation of 10°C. The lowest temperature recorded was 7°C and the maximum was 22°C. Note that winters in the studied region are sunny most of the time with an hourly average direct normal radiation of 441 Wh/sq.m in December and 450 Wh/sq.m in January[12]. Also, note that December and January are usually the coldest months in San Luis Potosi City.

The temperatures from Figure 5.1 were used to perform the building energy simulations because they are the recorded external temperatures and thus, should allow to test the temperature performance of the digital house during the same time. The main idea is that the closer and symmetric that the recorded temperatures in the internal areas of the house are to the corresponding simulated ones, then the more certainty and thus, validity of the simulation parameters. Especial attention was given not to modify thermal conductivity values of construction materials as part of the fine tuning process, as those remain the same throughout the research and are representative of the Mexican market.

There are some known sources of potential discrepancy between the built and simulated conditions. Firstly, as explained in Chapter 7.1, the walls' red bricks are produced in a crafty and labour-intensive manner that results in high heterogeneity in terms of quality. It should be expected that the red bricks employed in construction differ from the Mexican norm standard. This is chiefly because the soil used, and furnace technology employed for fabrication also widely vary between suppliers. however, it was decided to use the 'official' conductivity value from Mexican norms for simulations. Conducting laboratory tests would have been not only costly, but also impracticable due to the post-built testing scenario.

Secondly, although it was found that 12 arch/hr is a ventilation rate representative of the construction typology in the region (Trebilcock, 2014), when setting up automated natural ventilation in DesignBuilder, the infiltration is not taken into consideration for simulations. Instead, the windows operability percentage becomes the relevant parameter. Several infiltration rates were tested (simulated) with no impact in thermal comfort temperatures in order to reach this conclusion. Due to the large amount of generated data those simulations are not shown in this research as they were considered also as part of the software learning curve as well as of the fine-tuning process.

[12] Average hourly direct normal radiation obtained with Climate Consultant software from San Luis Potosi City '.epw' weather file.

Finally, another potential source of discrepancy between the building and the simulation is due to the lack of surveys or questionnaires for MaLi house family in order to better represent the real use of the spaces (occupants' behaviour). Instead, the respective residential area schedule from DesignBuilder software was set up.

At the time of the measurements no research sources were found that could provide information about representative 'average family schedules' for space use in the residential sector in Mexico. This situation narrows down the simulation results shown in this chapter only to building temperature responsiveness as opposed to the more complex thermal comfort.

Once the main potential sources of discrepancies between the building and its simulation are presented it is possible to proceed with the analysis. Figure 5.2, 5.3 and 5.4 show the temperatures comparison. The grey line shows the recorded outside temperatures (Figure 4.1) to provide a contrast with the simulated operative temperature (orange line) and data logger recorded temperature (blue line) from the respective area. Results vary by monitored space and the larger discrepancies will be explained as much as possible at certain extent by user's behaviours, as will be discussed later.

Figure 5.2 shows temperatures for the living/dining area with a good agreement between the recorded inside and outside air temperatures, with important temperature swings during the day. In an informal talk with the homeowners they stated that a strong and cold draught was felt inside the house and that they felt cold temperatures in the living/dining area. After a close look at the area, it was found that the staircase skylight was the source of the draught due to poor installation. It was recommended to seal off the gaps in the skylight which was done a few days later. This situation partially explains the closeness between the recorded inside and outside temperatures from December 18-23rd (note that due to some data loss, the data logger in this area only recorded usable data from December 18th to January 10th). In addition, the homeowners were reminded of the importance of keeping windows closed and unobstructed to allow for the sun to naturally heat the internal surfaces (high thermal mass). It was also mentioned at some point during the informal conversation that their teenage daughter left doors and windows open as she preferred lower temperatures. It is believed that such behaviour added discomfort due to low temperatures in the house as the double height in the staircase thermally links the living/dining area with the upper floor. Figure 5.2 also shows that after the sealing of the skylight the internal temperature increased even on the coldest recorded day (January 6th). Still, daily temperature variation was around 7ºC in the worst cases, and 2ºC on the best performing days.

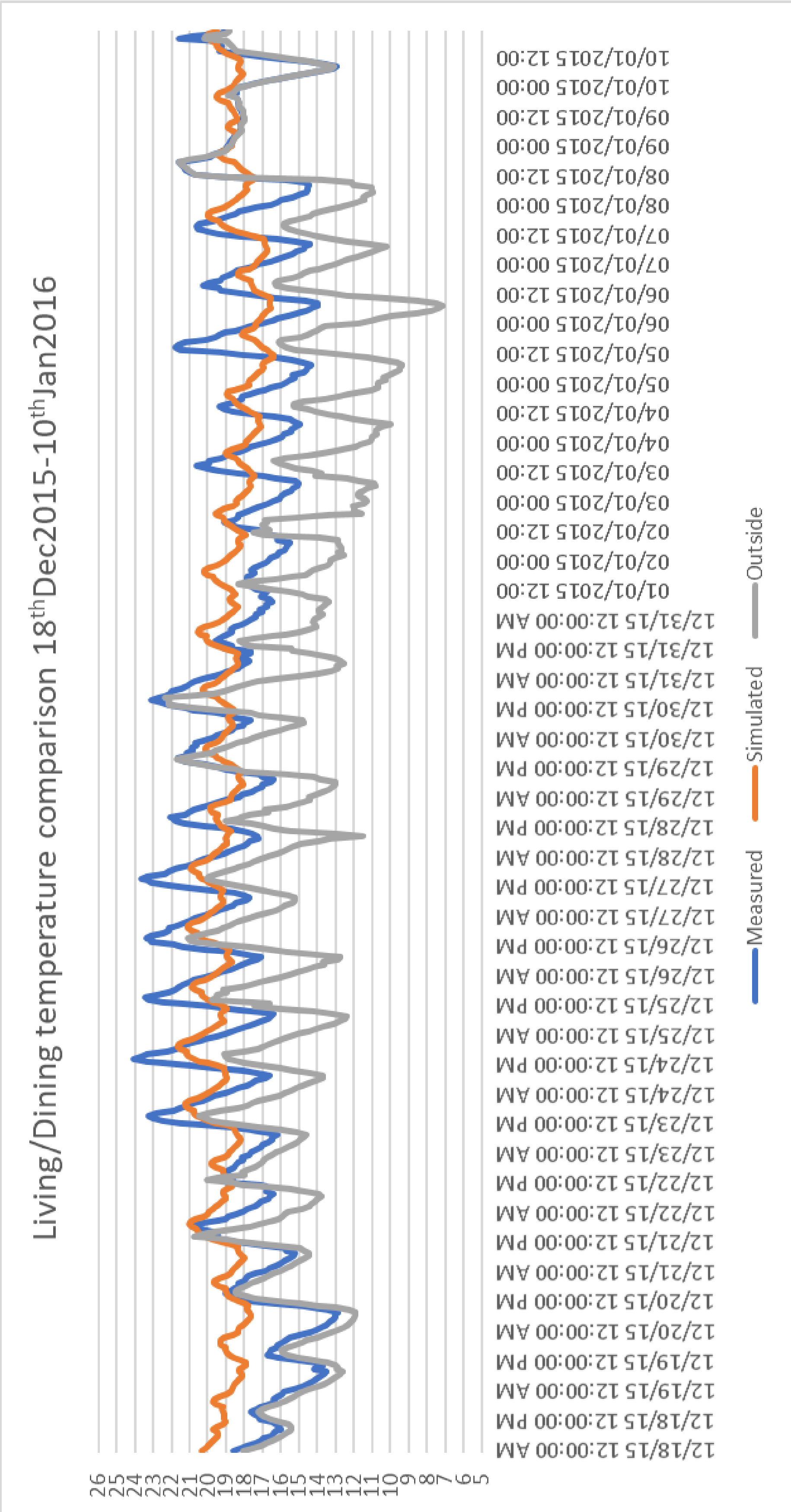

Figure 5. 1 Living/dining temperature comparison Dec. 18th2015 – Jan 10th2016

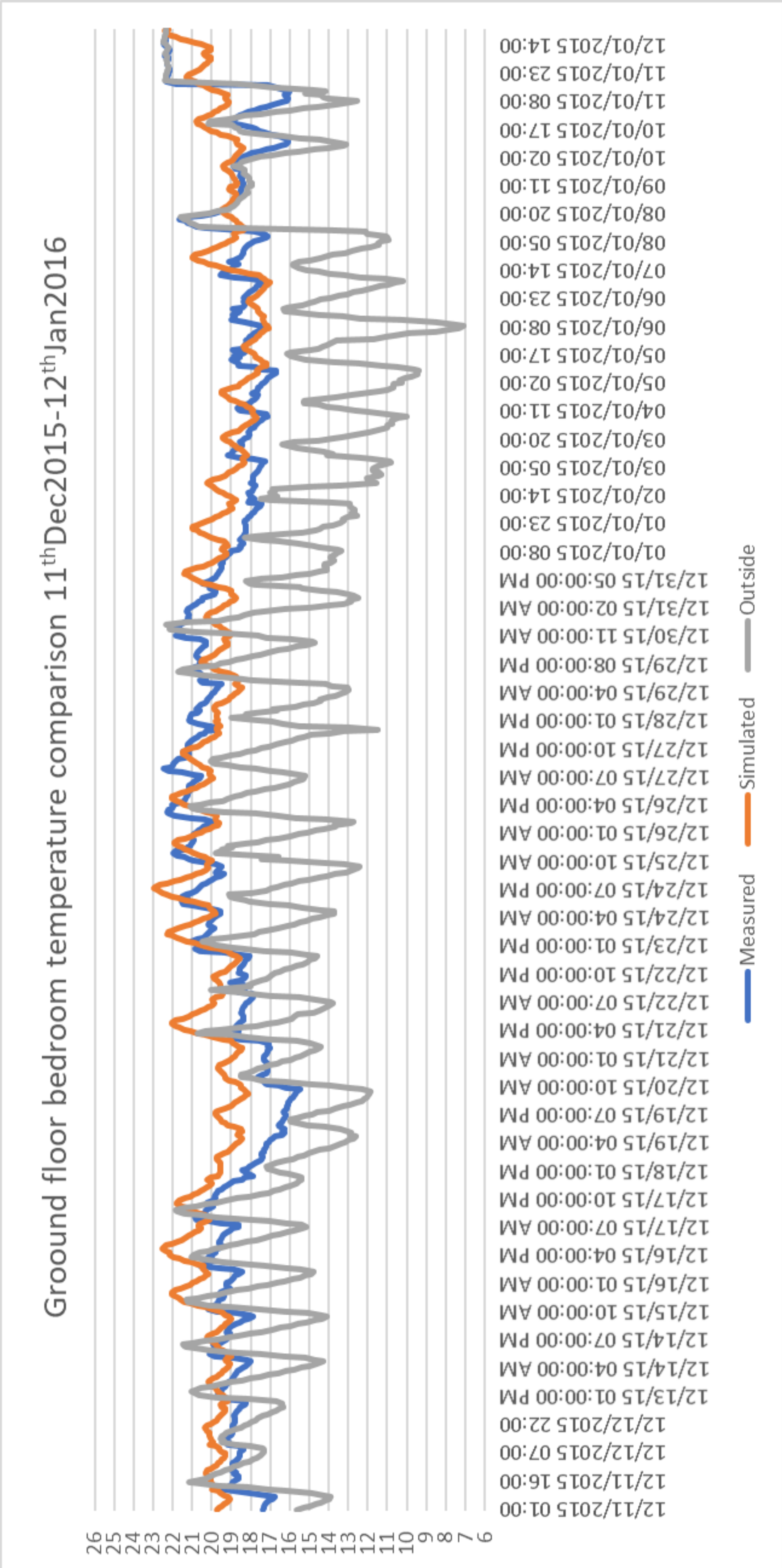

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Figure 5. 3 Ground floor bedroom temperature comparison Dec. 11th2015 - Jan. 12th2016.

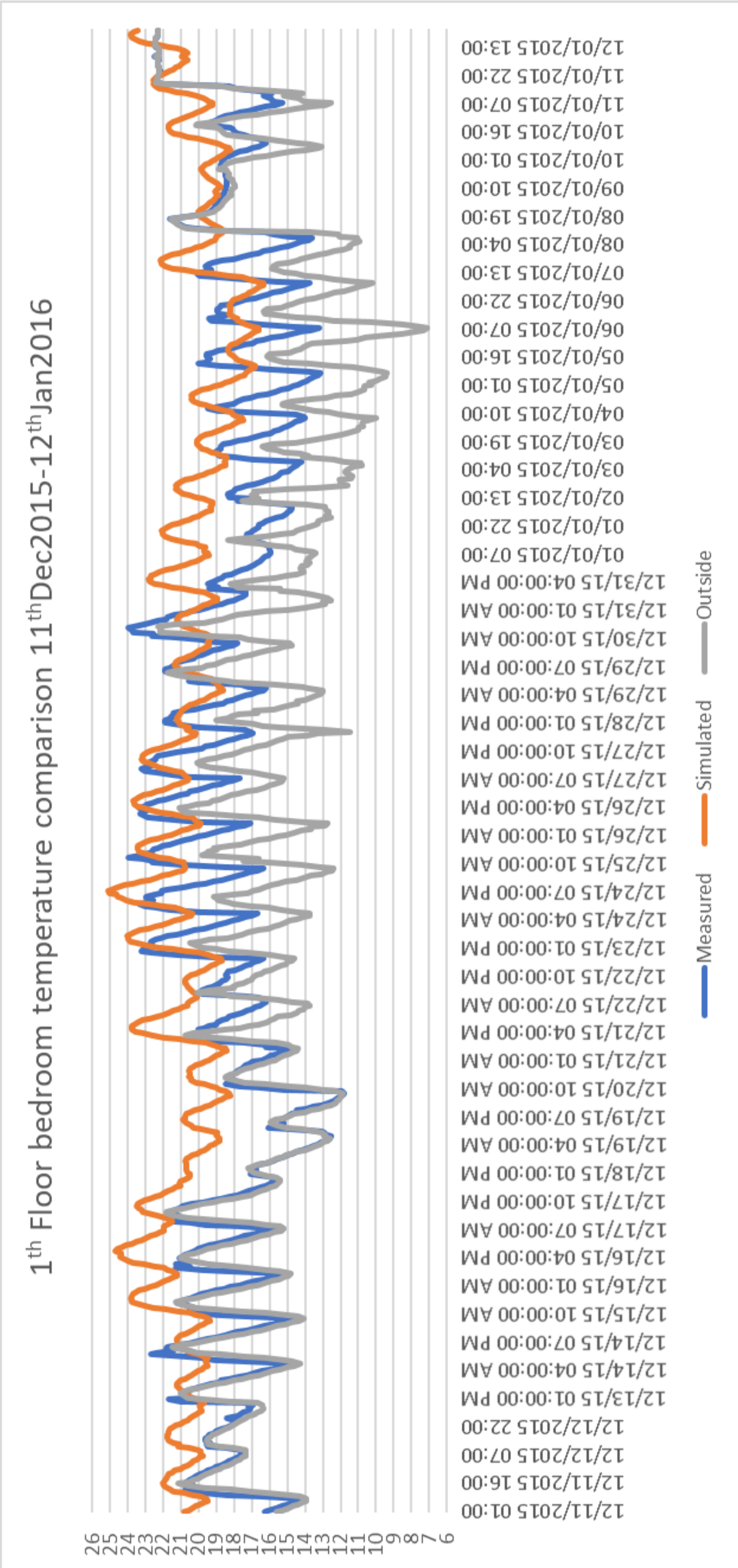

Figure 5. 4 1st floor bedroom temperature comparison Dec. 11th2015 – Jan. 12th2016.

Figure 5.3 shows a very similar performance between the simulated and the measured temperatures for the ground floor bedroom throughout the monitored days. The figure shows a larger asymmetry from December 18-20th but a good similarity for the rest of the recorded and simulated time. Overall, the recorded temperatures show a stable temperature behaviour with daily temperature swings between 2-3ºC. It is important to note that the recorded lowest temperatures inside the bedroom (December 20th) does not match with the recorded lowest outside air temperatures (January 5-6). This is attributable to windows operation as the occupants left the window open late evening (this was stated in an informal conversation) allowing for temperatures to drop inside the bedroom. The temperature drop was consistent with the described behaviour.

Overall, there was a very similar behaviour in terms of temperature magnitude and swings between the recorded and simulated data, with the larger difference of temperature around 3ºC. It is known that, for most of the time, the ground floor bedroom had closed windows, allowing solar radiation in and preventing large temperature drop at night. At the time of the measurements, the occupants shared the room with their 1-year old baby; also, the homeowners stated that no heating equipment was used during the monitoring period.

Figure 5.4, shows temperatures in the 1th floor bedroom (teenage daughter) with the worst performance. It was stated during the informal conversation that the daughter left windows open day and night. After the informal conversation with the homeowners we can see a slight improvement in temperature which also coincides with the sealing off the skylight (around the 21th of December similarly with Figure 5.3 living/dining area). Except for small periods of time 22-23 December and from December 31th to January 5th in which the simulated and recorded temperatures are very similar we can observe two main differences. Firstly, and as already mentioned, before December 21th, recorded inside and outside temperatures are almost identical. Secondly, after the sealing off the skylight the recorded internal temperature (blue line) still shows important daily temperature swings of around 6ºC but remains 3-4ºC higher than the external temperatures.

From the three monitored spaces only the ground floor bedroom showed stable recorded temperatures (small daily fluctuations), which was very similar and symmetric with the simulated temperatures. The other two spaces, the living/dining and 1st floor bedroom, behaved very differently to the ground floor bedroom. The large temperature swings recorded in the latter areas can be partially attributable to user's behaviour (upper floor windows opened during cold days and nights) and to the low quality skylight installations which can be contrasted with the recorded temperatures (before and after fixing the skylight).

Overall, the simulation and monitoring process allowed improvement in the general parameters that were applied latter on to the prototype in this research. Chiefly, the natural ventilation set up for which originally, an infiltration[13] rate of 12ach/hr was set up as it was considered to be representative of the construction typology (red brick walls, cast in situ concrete slabs and colonnades) in the region (Trebilcock, 2014). However, when setting up natural ventilation in DesignBuilder the software takes into consideration for the calculations the percentage of operable windows (50% in this case) and the predefined 'crack template' (Data tab in Model options) rendering any assigned infiltration rate useless for simulation purposes (at least up to version 4 of the software).

On the other hand, from a methodological perspective, it should have been more accurate to record external temperatures with a portable *in-situ* weather station, this could help improve accuracy of the external temperature records for future research/monitoring. Also, the implementation of windows sensors would allow monitoring their operation, thus, allowing to contrast fluctuations in internal temperatures and their potential correlation with more certainty (this was not economically feasible for this research). Finally, it is also very important to inform users about the bioclimatic strategies implemented and how to make the most out of them e.g., through day/night windows operation in the different seasons in order to improve the thermal performance of the house.

The default 'residential' template from DesignBuilder was used for occupancy as well as the ASHRAE building type and category for the sake of consistency with the bioclimatic analysis on Climate Consultant software and with the latter use of the adaptive model of thermal comfort from ASHRAE 55-2013.

The creation of a library with the main construction materials to be simulated as well as their thermal properties was another process that was improved with the simulation of MaLi house, the experience and know-how latter was carried on to the prototype simulated in this research.

With one monitored space in close agreement with measured and simulated temperatures, and the certainty that such a space had no unwanted infiltration, and that windows operation was kept in closed position, it can be argued that the simulation parameters employed can be carried into the research prototype reflecting reality at a reasonable extent. However, it is important to acknowledge that the fact that two out of three monitored spaces had a larger discrepancy between recorded and simulated temperatures, highlighting the pitfalls of the validation process and research itself. Chiefly, that simulation results represent 'ideal'

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[13] The infiltration is the unintentional introduction of air in to a building, typically through cracks in the building envelope, and through gaps in windows and doors (U.S. Department of Energy, 2011)

conditions which are not usually met in real life, such as the proper operation of windows and the good quality and installation of doors, windows, and skylights (no unwanted infiltration).

Also, the performance of a building is strongly influenced by its inhabitant's behaviour. In order to close the gap between the simulation and real-life extensive monitoring is necessary (including windows and doors sensors, complemented with behaviour and thermal sensation questionnaires). Such are the limitations of this research and, therefore, the results shown should be considered with care and just as a reasonable but flawed approximation to reality.

Section 3 Building energy simulations

Chapter 6. Prototype design

The prototypes' design began with the contextual analysis done in previous chapters in which local weather and the appropriateness of a small scale vertical social housing were studied. The prototype design is a means to test the climate change resilience of the chosen bioclimatic design strategies as well as construction materials. The whole design process was carried out taking in to consideration local construction regulations and restrictions as if it was meant to be built (H. Ayuntamiento de San Luis Potosi, S.L.P., 2012) (Comision Nacional de Vivienda CONAVI, 2010) (Secretaria de Economia, 2013). This way norms and regulations became design guidelines but were also restrictions that kept the prototype design more closely grounded to the realities of the local social housing market. In Figure 6.1 from left to right of the street façade can be seen the kitchen square window followed by a red brick lattice that provides natural light and ventilation to the laundry room. The vertical window does the same in the bathroom. Finally, is the staircase to the different flats and the corridor between the stair case and the border wall.

Figure 6.1 Street façade (North access façade)

The prototype is a three-family dwelling designed to fit in to two typical social housing lots with a 6-metre front by 15 metre depth each (90 m^2) for a total of 12 metre front and 15 metre depth lot (180 m^2). By merging two social housing commercial lots it is possible to accommodate 3 families in a plot of land that would normally accommodate only two families, reducing the consumption of 90m^2 of non-renewable urban land that otherwise would be needed for the third family.

Given that one of the main goals of the research was to test the performance of bioclimatic design, the prototype was designed with the two bedrooms and the open plan kitchen/dining/living south facing, as can be seen in Figure 6.2. The south of the plot faces the backyard to provide more intimacy to the resting areas. The north of the plot is street facing and accommodates the bathroom, the laundry room and the kitchen. This way the service areas work as a buffer between the busier street and the more secluded south facing resting areas. Figure 6.3 shows the hypothetical location of the prototype in a typical social housing block.

Figure 6.2 Back façade (South façade)

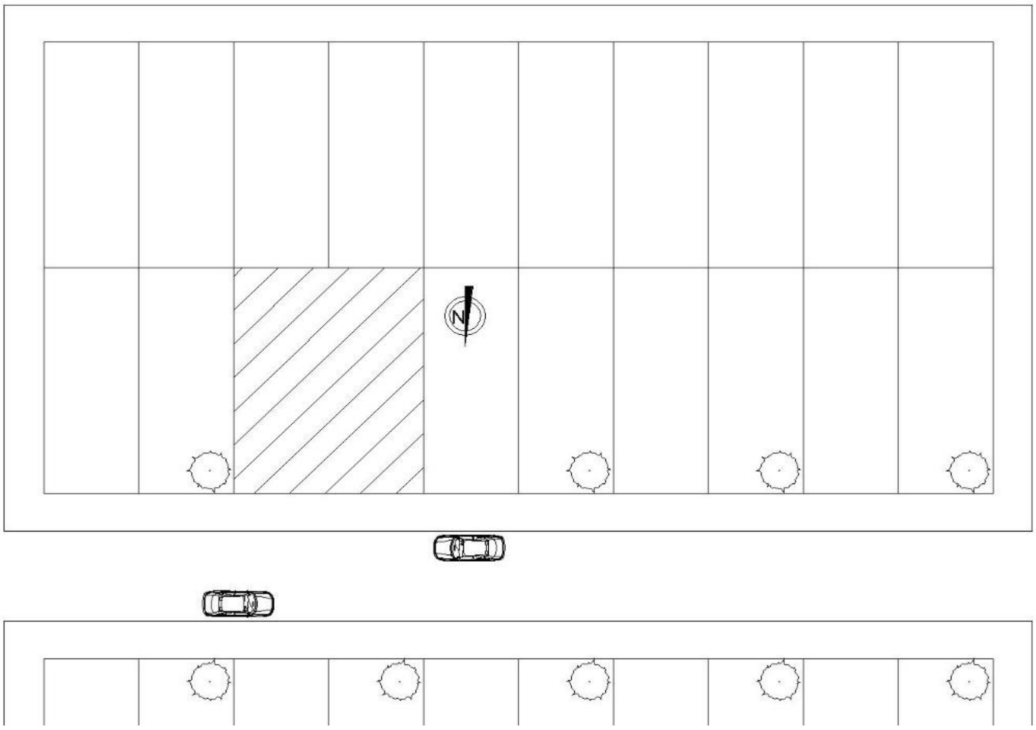

Figure 6.3 Site plan

Figure 6.4 Floor plan

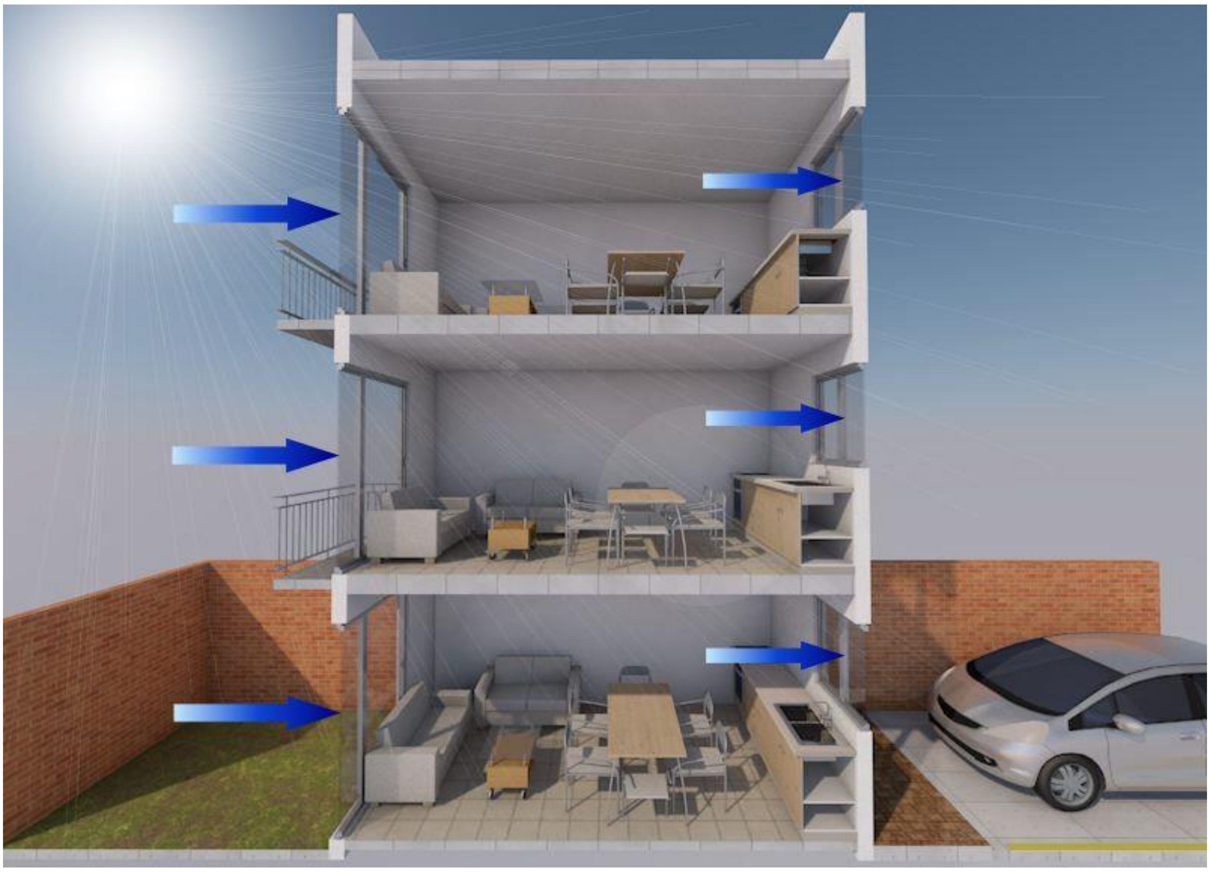

Figure 6.5 Section A-A

Figure 6.6 Section B-B

The flats' main door is west oriented, and it is protected by the staircase that grants access to the three building levels (flats) as can be seen in Figure 6.4, which also shows a top perspective of the flat. The main access is articulated from the neighbouring plot by a corridor that grants access to the backyard. Finally, the plots' east side is treated as an adjacency.

Sections A-A and B-B (Figures 6.5 and 6.6 respectively) show sun exposure through the south façade and the natural cross ventilation strategy in the open floor kitchen/dining/living areas. Section C-C (Figure 6.7) shows a view of the south oriented bedrooms and the living area facing towards the backyard, providing natural sun light year-round. Note that the images on this chapter reflect optimal windows sizes found through the parametric optimization process from Chapter 8. With a 2.20 x 2.20m window size in the living/dining area and 2.20 x 1.45m window size for the bedrooms.

Figure 6.7 Section C-C

Section D-D (Figure 6.8) shows a cut through the north facing service areas: bathroom, laundry room and kitchen as well as the staircase. By designing the kitchen/dining/living areas as a single open space the usability of such area can be maximized providing flexibility of use and furniture arrangement. Also, this type of space helps to create a natural cross ventilation from the south to the north façade. Perceptually an open floor set up provides a more spacious sensation. The large window on the south façade and the addition of a small balcony also helps to generate the sensation of a lager inner area. One parking lot is available for each flat in compliance with local regulations.

Figure 6.8 Section D-D

As discussed on Chapter 4, the choice of construction materials reflects local practice in the social housing sector in Mexico. For the envelope and internal partitions, 150 mm red brick, hollow concrete block or extruded hollow red brick were simulated in order to test which construction material would perform better in terms of thermal comfort. Slabs and floors are made of 200 mm thick cast in-situ concrete which aids in providing high thermal mass to the building as part of the main bioclimatic design strategy.

Natural ventilation, in tune with the adaptive model of thermal comfort (AMTC), was set up, given that one of the goals of this research is to demonstrate that a passive building without mechanical heating nor cooling can provide thermal comfort to its inhabitants year-round.

The build surface per flat is 51.85m^2 from which 41.79 m^2 are the internal habitable surface and 3.24m^2 are from the laundry room which is a semi exposed area. Note that the difference in surface reflects walls thickness. The internal height measured from floor to ceiling is 2.50m in compliance with the Mexican norm ONCCE (2007)

In Section 3.2 the target population for this research was defined as those families with income levels ranging from 2.61-6.99 VSM, which represents 40% of the housing demand in San Luis Potosi City for the studied period. Family composition in San Luis Potosi City is of four members on average, therefore, a 2 bedroom design was flexible enough to accommodate the needs of either a young couple, or a single person while the build surface is still within what can actually be purchased by the target population.

Some of the advantages of this small scale vertical approach that will not be explored in depth come with the more efficient use of the already existing urban infrastructure such as clean water, sewage, electricity, streets, sidewalks, etc. Also, the prototype is designed to take advantage of potentially existing urban voids which usually are found randomly all over the city and with sizes that comply with urban regulations and that can easily accommodate the prototype.

According to the IDEA Foundation (2014) and Cape Town (2012), small scale verticality provides higher urban densities which as mentioned above helps to make the most out of the existing urban infrastructure. Furthermore, on the social side, verticality can potentially aid in providing a more rich social mixture while preventing urban segregation when implemented as part of a larger more complex and multidisciplinary urban densification plan Cox (2012) and IDEA Foundation (2014).

6.1 Sun Study

As part of the design process and general analysis of the prototype, sun studies of the south façade were carried out. Figures 6.9, 6.10 & 6.11 show sun exposure during June 21th (summer solstice) at 09:00, 12:00 and 15:00 hours. Simulations demonstrate that during the longest day of the year, and chiefly throughout the hot season, the south façade with the largest window area will receive very little direct sun. This aids in providing naturally lower temperatures inside the building. Figures 6.12, 6.13 & 6.14 show sun exposure during December 21th (winter solstice) at 09:00, 12:00 and 15:00 hours respectively. As can be seen, during the shortest day of the year and throughout winter time due to the lower solar angle, the building will naturally benefit from sun penetration along the day. This is particularly beneficial during the cold season in which solar radiation can be stored by the building's high thermal mass to be slowly released after the sunset, thus aiding in providing higher and more comfortable temperatures inside the building.

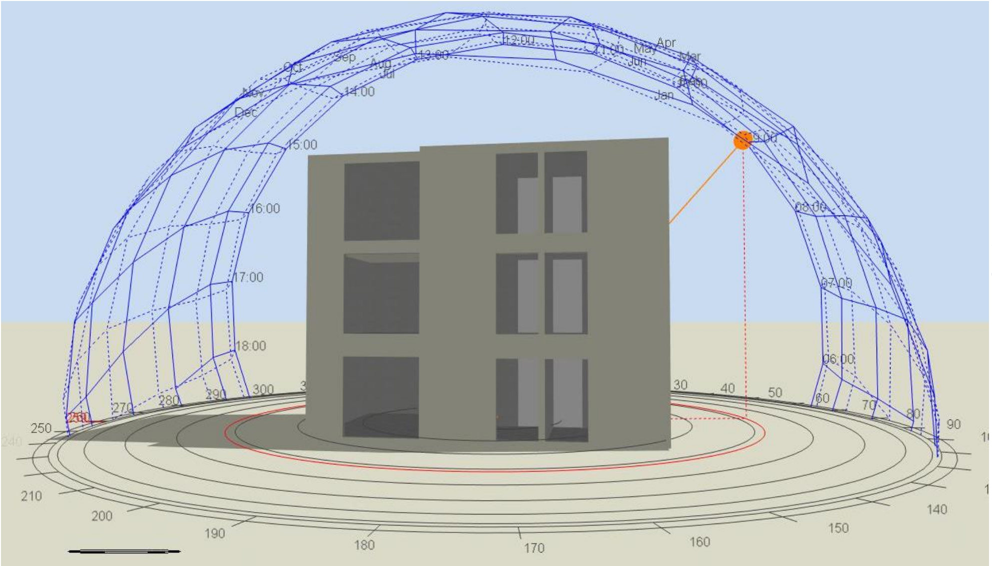

Figure 6.9 Sun study south façade, 21th of June 9:00 hours

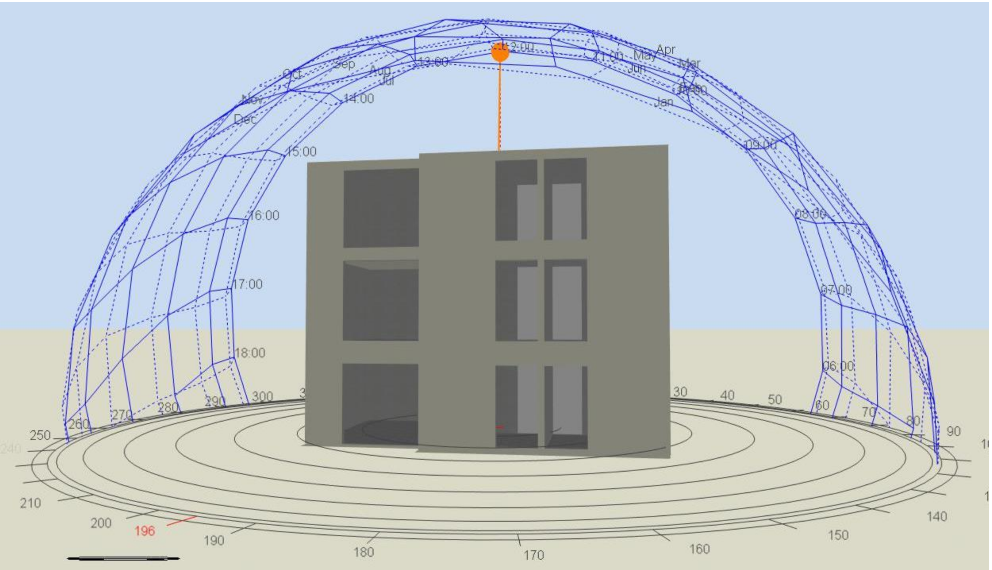

Figure 6.10 Sun study south façade, 21th of June 12:00 hours

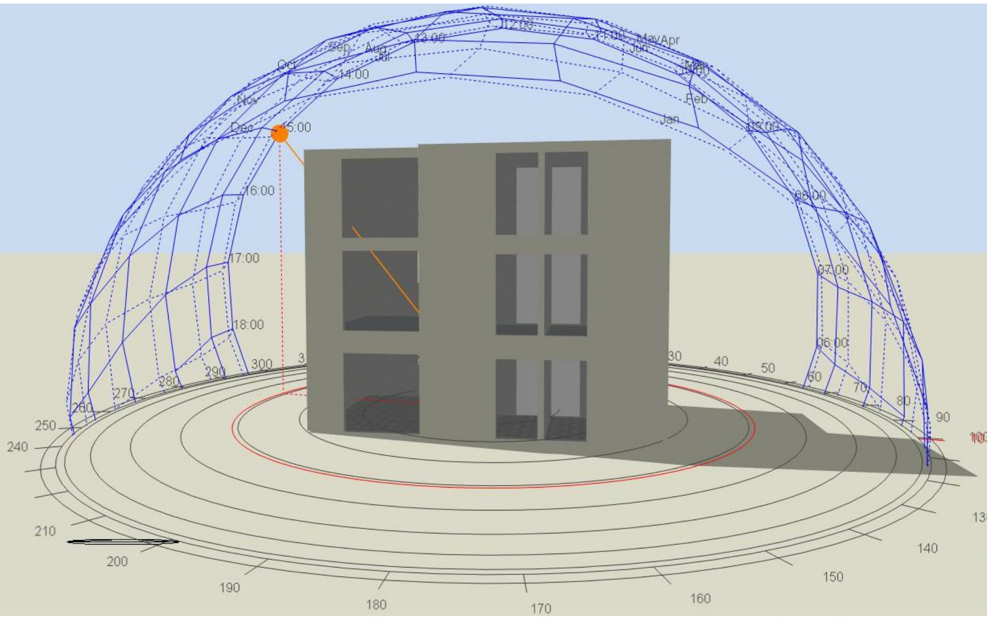

Figure 6.11 Sun study south façade, 21th of June 15:00 hours

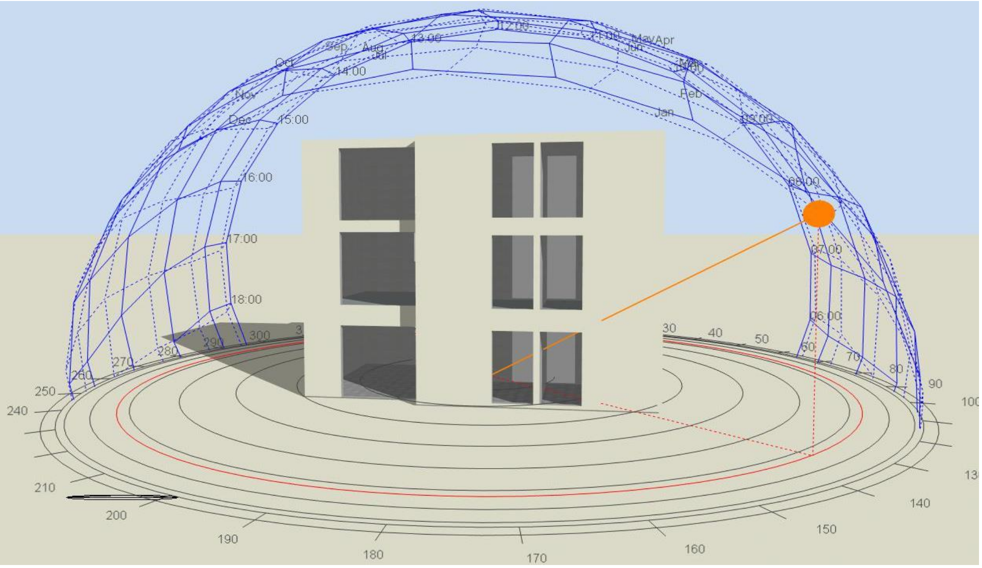

Figure 6.12 Sun study south façade 21th of December 9:00 hours

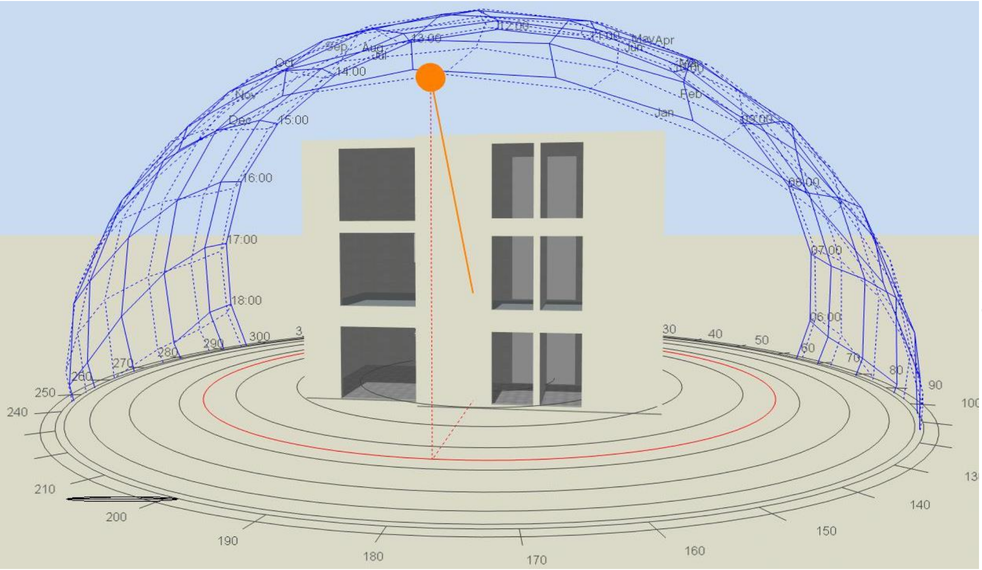

Figure 6.13 Sun study south façade, 21th of December 12:00 hours

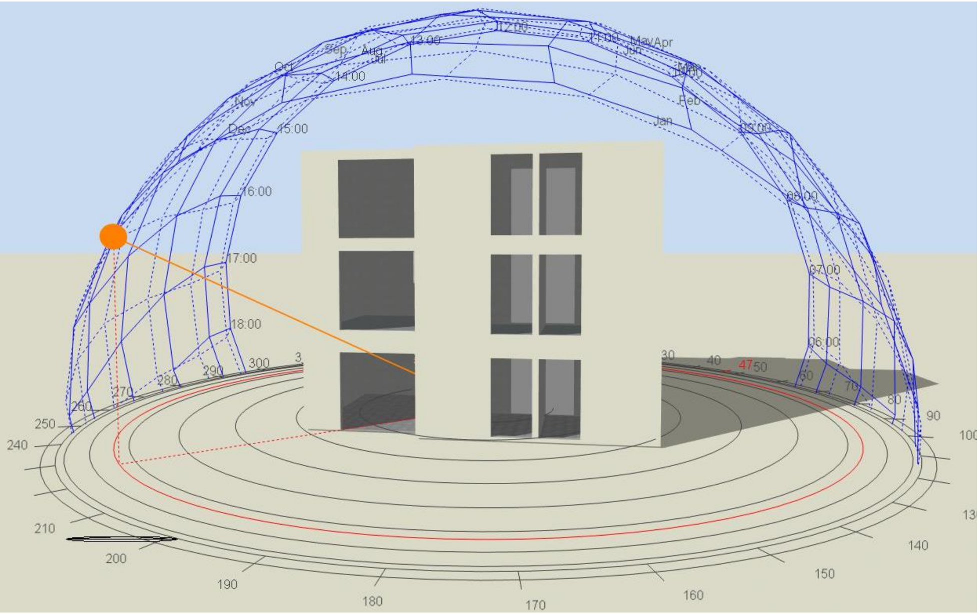

Figure 6.14 Sun study south façade, 21th of December 15:00 hours

It was found that the use of shading devices was not only not necessary but counterproductive during winter time given the geographical proximity of San Luis Potosi City to the Equator (Chapter 3) which naturally prevents sun over exposure during summer time on a south façade.

Note that in order to retain the efficiency of the high thermal mass it would be necessary to educate the users so that they would prevent blocking the sun coming inside the building by the furniture layout (keeping it away from the south facing windows) or by the use of carpets that would prevent direct floor sun exposure on the areas adjacent to south facing windows.

The sun study proved to be a great aid for better understanding the relationship between the building and the sun which is the main energy source in a passive solar design, and it is highly advisable to do so as part of the regular practice in architectural design.

It is important to note the fact that even though attention has been given in trying to simulate real life conditions for the prototype, there are a series of limitations in doing so. For instance, the potential impact of neighbouring buildings (mass and height). The wind conditions of a site that will vary daily and seasonally, also de variability in the amount of solar radiation available, etc. Therefore, simulations and results should be considered just as a plausible representation of reality, especially when quantitate values are shown as simulation results.

Finally, once the design was set up, the next step consisted in generating thermal comfort simulations and parametric optimization of the prototype which will be shown in the next chapter.

Chapter 7. Thermal comfort simulations

In this chapter results for thermal comfort based on DesignBuilder software simulations are shown for current and future climates. The simulations will focus on the effect of changing wall construction materials (Appendix 3) while keeping the rest of the parameters unchanged; this allows comparison in terms of thermal comfort performance of the three most commonly used wall construction materials in the Mexican social housing market which are:

- Red brick
- Hollow concrete block
- Extruded brick

Note that for the three sets of simulations, a natural ventilation regime was set up in DesignBuilder software. Calculated ventilation set up was chosen over scheduled ventilation because it is a simplified version that incorporates windows openings (maximum 50% and when outside temperatures falls below 15°C then the percentage is reduced to 5%), a crack template set up to *medium airtightness* (infiltration) in accordance with the construction system employed. The software also incorporates buoyancy and wind driven pressure differences.

By using calculated natural ventilation instead of scheduled means that the behaviour of occupants was not taken into consideration for windows operation because of the limited resources at the time of the research that could provide reasonably accurate templates grounded on surveys. On the other hand, the use of ASHRAE's adaptive model of thermal comfort provides a temperature band that allowed to set up a minimum of 18°C or 19°C (depending on the simulated year) in which windows are automatically set up as closed to avoid heat loss. 18°C and 19°C are the lower temperature limits for thermal comfort.

Other simulation parameters include external wall rendering of cement-sand mortar, internal rendering of gypsum plaster and single glazing 3-4mm clear crystal windows with aluminium frames. The first wall construction material simulated was red brick. Data interpretation will follow in a chronological order (years 2010, 2020, 2050 & 2080) to better understand the expected changes due to increasing temperatures by human induced climate change.

Before showing conclusions from this chapter, temperature analysis for January and May, the coldest and hottest month respectively are shown in order to provide a wider perspective about the magnitude of discomfort in length and in magnitude for years 2010, 2020, 2050 & 2080.

7.1 Red brick prototype

The first wall construction material simulated was red brick since it is regarded as a good quality construction material and preferred by homeowners over hollow concrete block because it is traditionally believed that it provides better thermal comfort conditions and overall construction quality.

In Mexico, the production of ‘common red brick’ is very labour intensive, with low technological inputs. According to Cardenas (2012) around 50% of the brick production in Mexico is crafted by ‘traditional’ producers, which in turn leads to high levels of heterogeneity on the quality and properties of the final product.

Another factor that impacts on the quality and thermal properties variability of red brick is the earth from which they are made. Physical and chemical soil compositions vary widely throughout the country; therefore, it is expected that locally available soil and the furnace technologies employed will have an impact on the physical, mechanical and thermal properties of the final product. However, for this research the thermal conductivity employed for software simulations is that from the Official Mexican Norm in Chapter 3 Table 3.13 because it is considered to be the recommended quality/performance standard with national validity.

Simulation results analysis begin by looking at the expected changes in monthly average (AVG) operative temperatures through years 2010, 2020, 2050 and 2080 (CCh scenarios in Table 7.1 and Figure 7.1).

Table 7.1 Red brick prototype monthly average (AVG) temperature (°C) comparison by year

Red brick prototype monthly average temperature (°C) comparison by year				
Month	Year			
	2010	2020	2050	2080
Jan	19.4	20.9	21.6	22.4
Feb	20.5	21.1	22.5	22.8
Mar	21.7	23.1	24.0	25.1
Apr	23.3	24.7	25.7	26.5
May	23.9	25.2	26.1	27.1
Jun	23.6	24.7	25.6	26.4
Jul	23.2	24.0	25.0	25.8
Aug	23.1	23.7	24.7	25.4
Sep	22.7	23.5	24.3	25.1
Oct	22.1	23.1	23.9	24.9
Nov	20.7	22.3	22.9	24.0
Dec	19.7	21.0	22.0	22.7

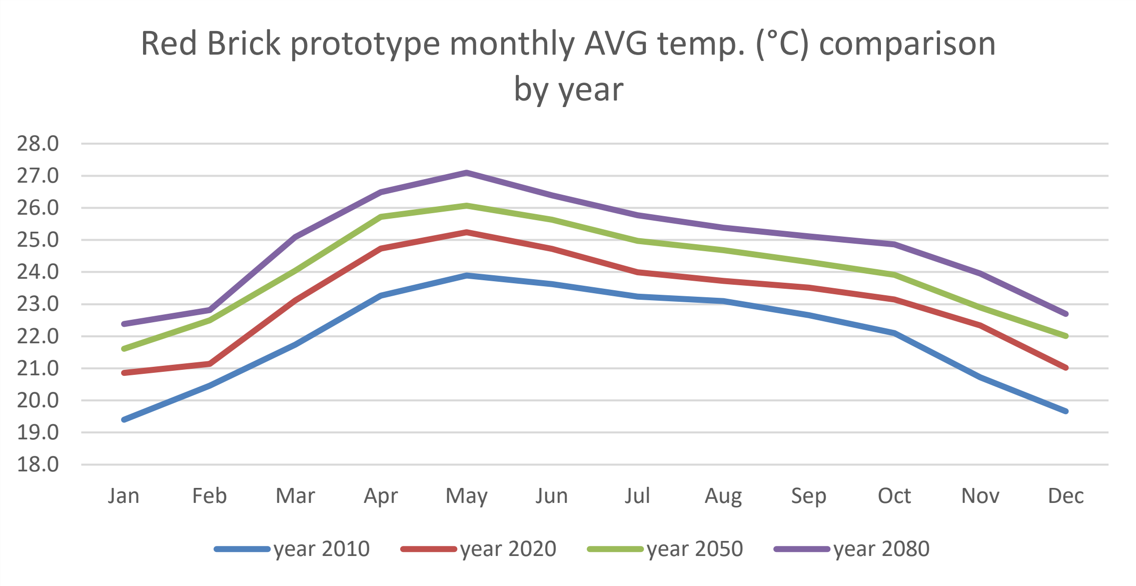

Figure 7.1 Red brick prototype monthly average (AVG) operative temp. (°C) comparison by year

As expected, operative temperatures will rise as the planet gets warmer due to climate change (Chapter 3.4). The symmetry in the monthly average temperature comparison by year is because temperature inside a naturally ventilated building is closely related to external temperature (chiefly outside dry bulb temperature).

Table 7.2 compares the total number of discomfort hours that the prototype would experience when employing the adaptive or the static model of thermal comfort and the difference in the number of discomfort hours between both thermal comfort approaches. It also shows whether the discomfort is due to high or low temperatures thus allowing to have a glimpse on coping strategies (heating or cooling).

Table 7.2 Red brick Adaptive/Static discomfort hours' comparison by year

Red brick Adaptive/Static discomfort hours comparison by year									
Year	Adaptive			Static			Difference		
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	High temp.	Low temp.	Total
2010	0	310	310	609	1640	2249	**609**	**1330**	**1939**
2020	56	412	468	1698	902	2600	**1642**	**490**	**2132**
2050	274	122	396	3044	433	3477	**2770**	**311**	**3081**
2080	585	74	659	4492	258	4750	**3907**	**184**	**4091**

Figure 7.2 shows the number of discomfort hours by year when employing the static model of thermal comfort with a comfort thermal band between 20-25°C. This means that operative temperatures below 20°C are considered as discomfort due to low temperatures. Similarly, temperatures above 25°C are considered to represent discomfort due to high temperatures.

The figure also shows that when employing the static model in 2010 (reference year) discomfort time was chiefly due to high temperatures with 2,114 hours below 20°C and only 545 hours above 25°C.

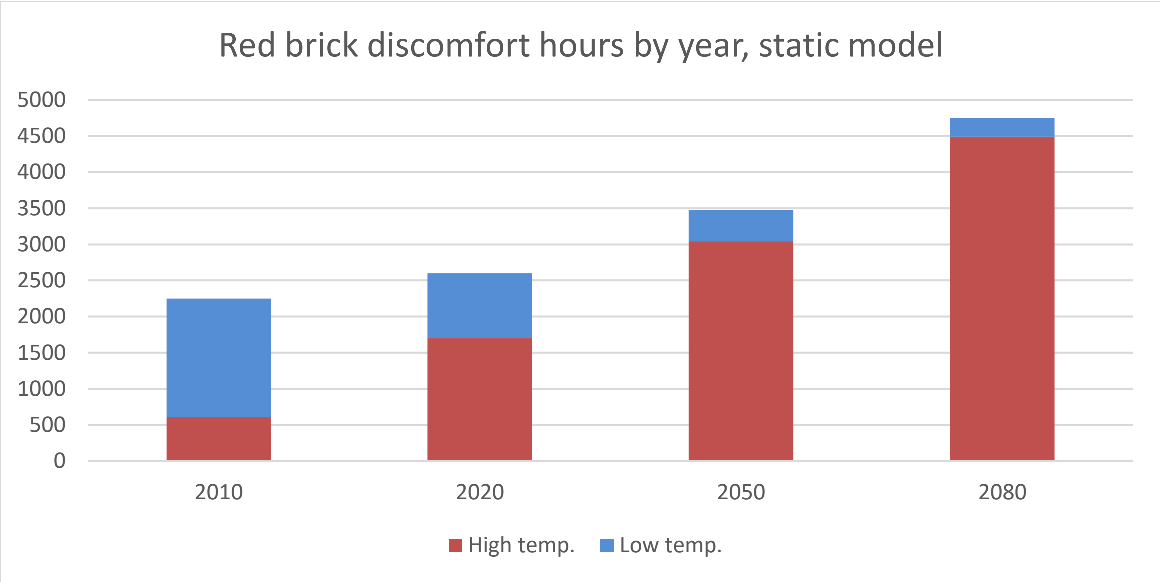

Figure 7.2 Red brick discomfort hour's comparison by year, static model

As soon as 2020 the nature of the discomfort time is shifted, and the majority of discomfort time is due to high temperatures, with 1,698 hours of discomfort time, and a reduction of discomfort time due to low temperatures to 902 hours. By 2050 discomfort time due to low temperatures is further reduced up to 433 hours while discomfort due to high temperatures almost doubles from the previous scenario and reaches 3,044 hours. For 2080 the scenario is very similar, with discomfort due to low temperatures reducing to 258 hours and discomfort due to high temperatures reaching 4,492 hours.

When employing the static model of thermal comfort, as soon as 2010 the majority of discomfort will have been due to high temperatures and the amount of time will increase by 1000+ hours over every analysed time period while discomfort due to low temperatures will be greatly reduced. Since the static model was developed for HVAC buildings, these figures represent the amount of time that heating/cooling would be necessary to generate comfort conditions within the building. Results also mean that from year 2020 and up to year 2080 cooling would be necessary to generate temperatures between 20-25°C inside a building. The static model would require an increasing demand for cooling which means that more energy will be required adding pressure to the local energy network and increasing operative costs and CO_2 emissions to the atmosphere. In contrast, when employing the AMTC, the number of discomfort hours drop dramatically below 700 for every studied year. Note that during the reference year (2010) there was no discomfort due to high temperatures, only due to low temperatures for 310 hours (see Figure 7.3).

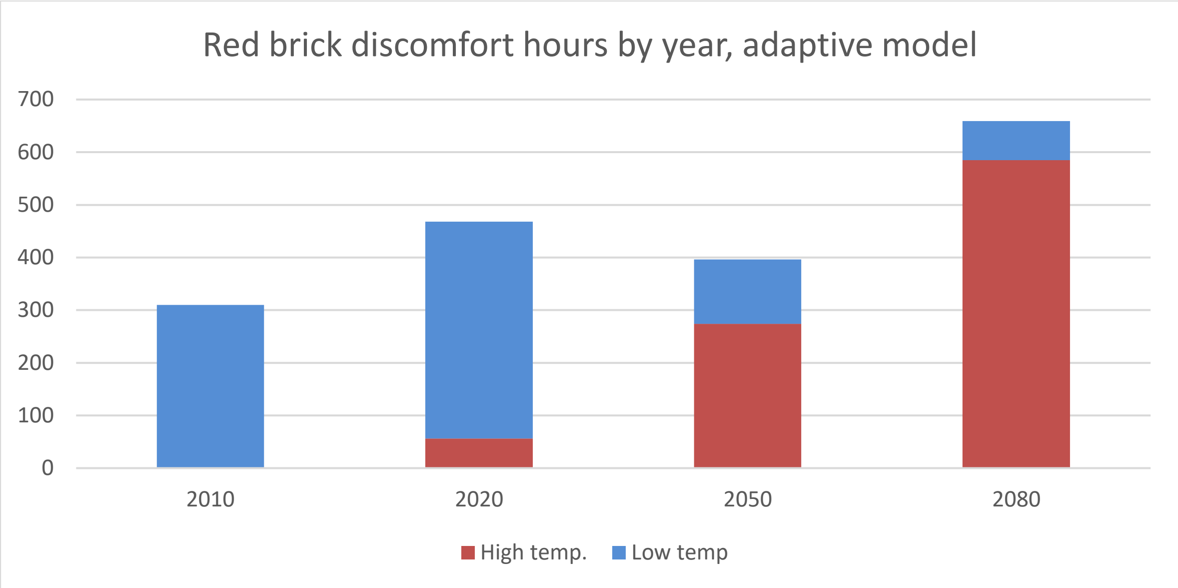

Figure 7.3 Red brick adaptive model discomfort hour's comparison by year

By 2020, discomfort due to low temperatures increases to 412 hours - this is because when employing the AMTC the thermal band changes; in 2010 it was between 18 and 28°C but by 2020 and up to 2080 it is 19 to 28°C to reflect the general increase in temperatures due to climate change (Chapter 4). Note that in 2020 discomfort due to high temperatures is felt for the first time and it is as low as 56 hours. After 2020 there will be a constant increase in the number of discomfort hours due to high temperatures, which is what can be expected by human induced global warming. Simultaneously, discomfort due to low temperatures will be constantly reduced until 2080

In 2050 the building will experience 274 hours of discomfort time due to high temperatures, which is rather a small amount of time. By this year discomfort due to low temperatures will drop down to 122 hours, which can also be considered as a small period of time. The number of discomfort hours due to high temperatures (585) in year 2080 will be double that in the previous simulated year (2050) but can still be considered as a small amount of time. On the other hand, discomfort due to low temperatures will be drastically reduced to only 74 hours.

Note that in all scenarios with the AMTC, discomfort time occurs for less than 10% of the year or less than 786 hours even when adding discomfort due to low and high temperatures. Overall there is a large difference in the number of discomfort hours when employing the adaptive or the static model of thermal comfort, being the adaptive model the one with the best performance in terms of providing less hours of discomfort.

Simulation results seem to reinforce the argument that given the geographical location of San Luis Potosi City, and its relatively mild weather, bioclimatic design alone might be sufficient to provide thermal comfort in the social housing sector at present time and also under future weather scenarios (up to 2080) during 80% of the year. However, buildings are particularly sensitive to discomfort due to low temperatures up to year 2050. Consequently, under such circumstances it can be said that the use of high thermal mass and particularly the traditional use of red brick as wall material can be used as part of a wider bioclimatic design strategy.

7.2 Hollow concrete block prototype

Hollow concrete block (HcB) is a widely used construction material in Mexico, and especially in the social housing sector. Its main advantages when compared to red brick are:

- Faster construction times due to the larger piece size which in turns provides savings on layout times and labour.
- Widely available all over the country.

The main disadvantages are:

- Even though it is produced industrially, there are no quality standards, therefore, quality (thermal properties) vary widely.
- Due to its hardness, nailing to HcB walls is particularly complicated and can cause damage to the whole piece. This generates a 'low' quality perception from users (home owners), and can create air leakage inside the building.
- There is a widespread perception that HcB constructions are of less quality and far more sensitive to external temperature variations than those made from red brick.
- DesignBuilder and the majority of the energy simulation software for the construction industry does not simulate the thermal effect of air trapped in the block-wall cavities (due to the complexity of the calculations); hence, thermal comfort simulations for this research employ the thermal conductivity and density values from the NOM-020-ENER-2011 (Pedraza Hinojosa, 2011).

Simulations were carried out for the proposed prototype changing only wall construction materials from red brick to hollow concrete block, with the rest of the simulation parameters remaining the same. As in the previous section, simulation results analysis began by looking at the expected changes in monthly average (AVG) operative temperatures through the years 2010, 2020, 2050 and 2080 (climate change scenarios in Table 7.3 and Figure 7.4).

Table 7.3 Hollow concrete block prototype monthly AVG temperature (°C) comparison by year

HCB prototype monthly AVG temperature (°C) comparison by year				
Month	year			
	2010	2020	2050	2080
Jan	22.0	23.5	24.3	25.3
Feb	23.1	23.7	25.2	25.5
Mar	23.7	25.0	25.9	27.1
Apr	24.3	26.0	26.9	27.6
May	24.7	26.0	26.9	27.9
Jun	24.4	25.6	26.5	27.2
Jul	24.0	24.7	25.8	26.6
Aug	23.9	24.5	25.5	26.2
Sep	23.9	24.7	25.5	26.3
Oct	24.0	25.0	25.9	26.9
Nov	23.5	25.1	25.6	26.8
Dec	22.4	23.7	24.9	25.7

Again, as expected, operative temperatures will rise as the planet gets warmer due to climate change (Table 7.3 and Figure 7.4). However, average operative temperatures for the hollow concrete block prototype will be slightly warmer than in the red brick one.

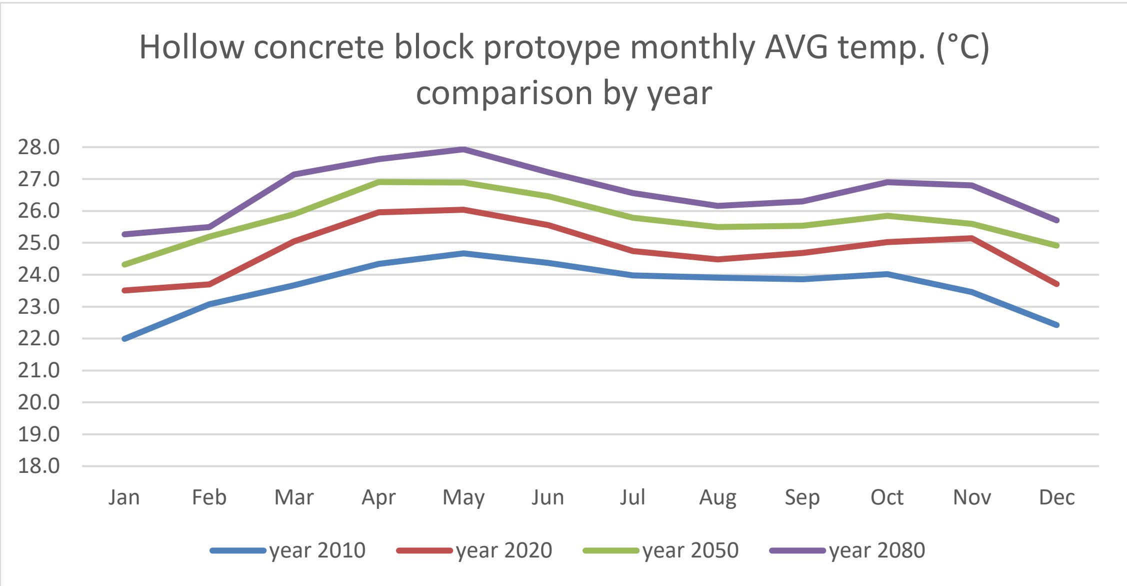

Figure 7.4 Hollow concrete block prototype monthly AVG operative temp. (°C) comparison by year

Table 7.4 compares the total number of discomfort hours that the prototype would experience when employing the adaptive or the static model of thermal comfort and the difference in the number of discomfort hours between both thermal comfort approaches. It also shows whether the discomfort is due to high or low temperatures, thus allowing a glimpse on coping strategies (heating or cooling).

Table 7.4 Hollow concrete block Adaptive/Static discomfort hours' comparison by year

Hollow concrete block Adaptive/Static discomfort hours comparison by year									
Year	Adaptive			Static			Difference		
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	High temp.	Low temp.	Total
2010	0	267	**267**	575	1584	**2159**	575	1317	**1892**
2020	46	367	**413**	1645	848	**2493**	1599	481	**2080**
2050	243	97	**340**	3049	364	**3413**	2806	267	**3073**
2080	528	64	**592**	4550	238	**4788**	4022	174	**4196**

For the prototype simulated with hollow concrete block walls, there will be discomfort due to low temperatures throughout the studied years, although the number of discomfort hours will decrease continuously overtime. Discomfort due to high temperatures will also be present throughout the studied years, but this will continuously increase as temperatures rise due to climate change.

Figure 7.5 clearly shows that when employing the static model of thermal comfort there will be a consistent incremental increase in the number of discomfort hours due to high temperatures whilst there is a continuous decrease in the number of discomfort hours due to low temperatures throughout the studied years.

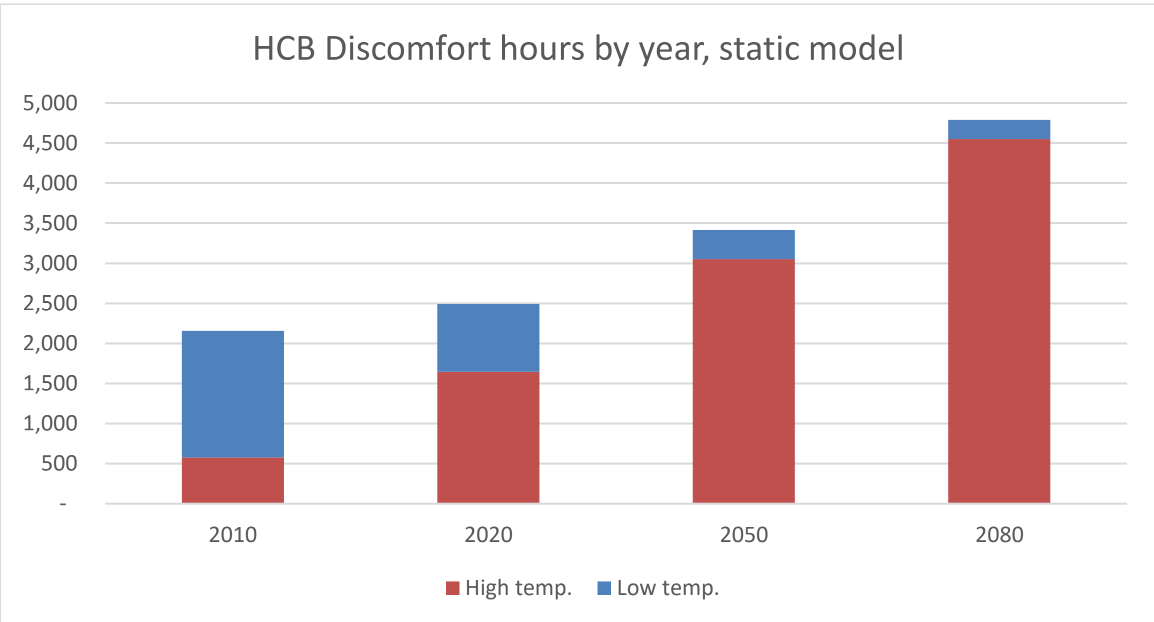

Figure 7.5 Hollow concrete block discomfort hour's comparison by year, static model

In 2010 (reference year) the majority of discomfort was due to low temperatures, with 1,584 hours; in contrast, little discomfort is experienced due to high temperatures, with only 575 hours. This means that the building would only require heating to compensate for discomfort due to low temperatures.

In 2020, the building will experience the majority of discomfort due to high temperatures with 1,645 hours, while discomfort by low temperatures will drop to only 848 hours. This means that as soon as 2020, the building will require cooling instead of heating to generate thermal comfort during most of the time.

By 2050 discomfort due to high temperatures will grow by as much as 3,049 hours, with discomfort due to low temperatures being as little as 364 hours.

Results for 2080 represent the larger amount of discomfort due to high temperatures through the studied years, reaching 4,550 hours. By then, discomfort due to low temperatures will drop to 238 hours. Like the previous set of simulations (red brick), when using the AMTC (Figure 7.6), the number of discomfort hours falls dramatically from thousands in the static model to just hundreds (bellow 600 hours). There will be no discomfort due to high temperatures during the reference year 2010, with only 267 hours of discomfort due to low temperatures.

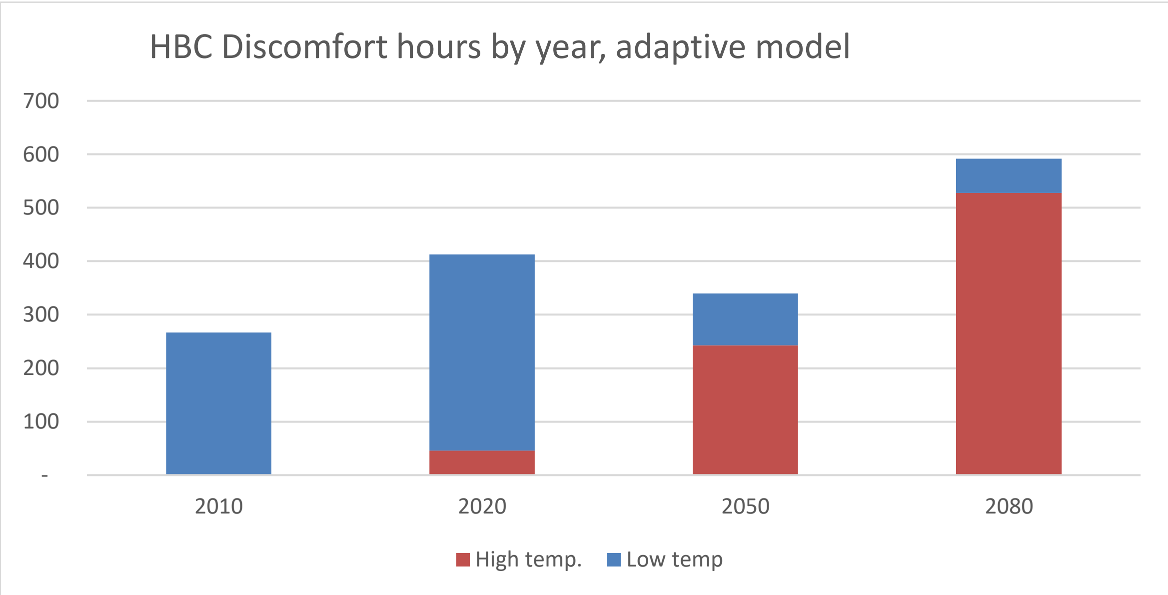

Figure 7.6 Hollow concrete block adaptive model discomfort hour's comparison by year

Results for 2020 show a peak in the number of discomfort hours due to low temperatures even larger than that from year 2010. This is explained by the change in the adaptive thermal comfort band. For year 2010 the comfort band employed for analysis is of 18-28°C. While due to increasing outdoor temperatures by climate change, from year 2020 and up to year 2080, the comfort band changes to 19-28°C.

In 2050 there will be a drastic reduction in the number of discomfort hours due to low temperatures when compared with the previous analysed year (2020); falling from 367 to 97 hours. 2050 is also the year in which the building will shift to a discomfort produced chiefly by high temperatures (243 hours).

By 2080 there will be a two-fold increase in the number of discomfort hours due to high temperatures when compared with year 2050, rising from 243 up to 528 hours. At the same time, discomfort by low temperatures will drop to only 64 hours.

When using the ATMC the prototype will experience discomfort most of the time due to low temperatures from 2010 up to 2020. Then it will shift to a discomfort predominantly due to high temperatures in 2050 and up to year 2080. Still, the number of discomfort hours is less than 10% of the time for all the studied years.

7.3 Extruded brick prototype

Extruded brick has better conductivity values than hollow concrete block and red brick. From the three wall construction materials it is the only one that is produced in a more industrialized and standardized manner; therefore, it provides more consistency in terms of quality and performance. On the other hand, out of the three construction materials, it is the only one that is not locally produced so it needs to be transported from other regions, which adds to its cost and carbon footprint. This disadvantage can be outweighed if the material manages to generate enough energy savings by providing higher levels of thermal comfort.

The thermal comfort simulation methodology is the same one that the employed for the red brick and the hollow concrete block prototypes, with all the parameters remaining the same, except for the wall construction material. Thermal comfort performance is studied for climate change scenarios for 2010, 2020, 2050 and 2080.

As in the previous sections, simulation results analysis begin by looking at the expected changes in monthly average (AVG) operative temperatures through years 2010, 2020, 2050 and 2080 (climate change scenarios in Table 7.5 and Figure 7.7).

Table 7.5 Extruded block prototype monthly AVG temperature (°C) comparison by year

Extruded prototype monthly AVG temperature (°C) comparison by year				
Month	year			
	2010	2020	2050	2080
Jan	19.4	20.9	21.6	22.4
Feb	20.4	21.1	22.5	22.8
Mar	21.7	23.1	24.0	25.1
Apr	23.3	24.7	25.7	26.5
May	23.9	25.2	26.1	27.1
Jun	23.6	24.7	25.6	26.4
Jul	23.2	24.0	25.0	25.8
Aug	23.1	23.7	24.7	25.4
Sep	22.7	23.5	24.3	25.1
Oct	22.1	23.1	23.9	24.9
Nov	20.7	22.3	22.9	24.0
Dec	19.7	21.0	22.0	22.7

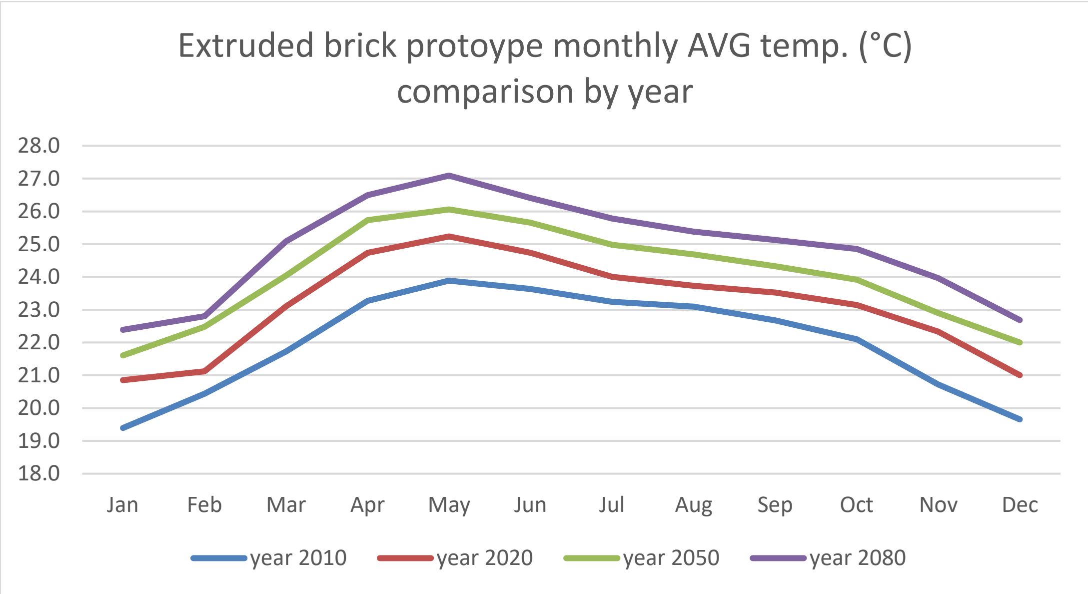

Figure 7.7 Extruded brick prototype monthly AVG operative temp. (°C) comparison by year

Table 7.6 allows comparison of the total number of discomfort hours that the prototype would experience when employing the adaptive or the static model of thermal comfort and the difference in the number of discomfort hours between both thermal comfort approaches. It also shows whether the discomfort is due to high or low temperatures.

Figure 7.8 shows that when employing the static model of thermal comfort during the reference year 2010, most of the discomfort is due to low temperatures (1,620 hours) with little discomfort due to high temperatures (572 hours).

Table 7 6 Extruded brick Adaptive/Static discomfort hours' comparison by year

Extruded brick Adaptive/Static discomfort hours comparison by year									
Year	Adaptive			Static			Difference		
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	High temp.	Low temp.	Total
2010	0	285	285	572	1620	2192	**572**	**1335**	**1907**
2020	46	380	426	1630	880	2510	**1584**	**500**	**2084**
2050	241	103	344	3030	382	3412	**2789**	**279**	**3068**
2080	531	66	597	4515	244	4759	**3984**	**178**	**4162**

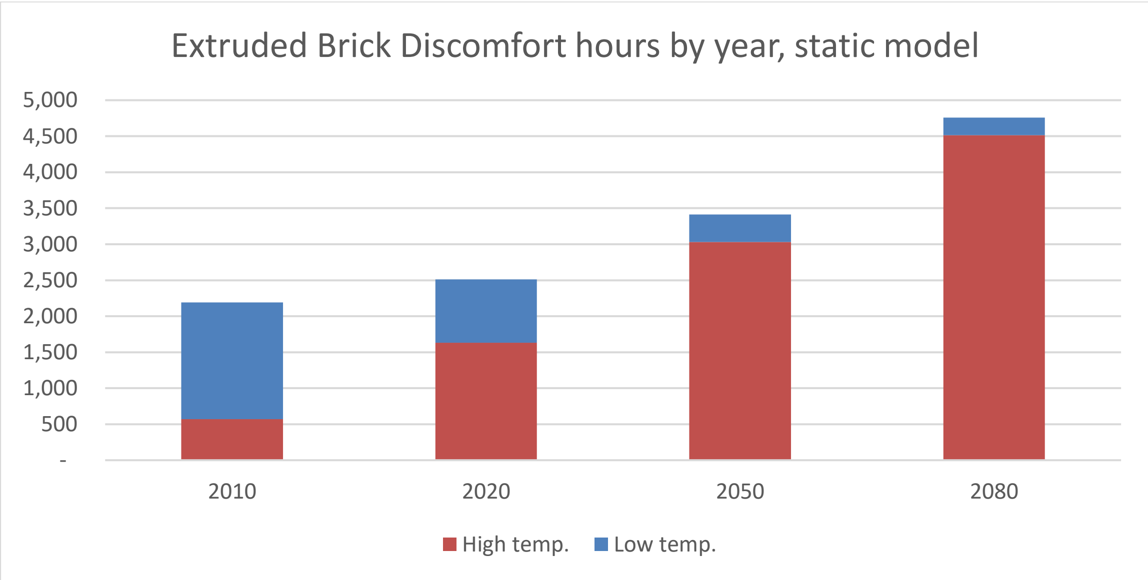

Figure 7.8 Extruded brick discomfort hour's comparison by year, static model

As soon as 2020 the scenario shifts towards one in which the majority of discomfort will be due to high temperatures, with 1630 hours, and only 880 hours of discomfort due to low temperatures. From this year onwards, discomfort will be predominantly due to high temperatures and the amount of discomfort time will continuously increase overtime. In 2050 discomfort due to high temperatures will rise to 3,030 hours, almost a two fold increase in the number of hours when compared with 2020. Discomfort by low temperatures will be experienced only 382 hours which is more than half of the discomfort time experienced in the previous time period. By 2080 discomfort due to high temperatures will rise up to 4,515 hours while discomfort due to low temperatures will be as low as 244 hours.

These results show that a building with HVAC system in San Luis Potosi city and built with extruded block will require cooling systems in order to provide thermal comfort to its occupants in a thermal band between 20-25°C. On the other hand, the small amount of time with discomfort due to low temperatures hardly justifies the implementation of heating systems, especially after year 2020.

Figure 7.9 shows discomfort hours when employing the AMTC. In year 2010 (reference year) there was only discomfort due to low temperatures with just 285 hours and no discomfort due to high temperatures.

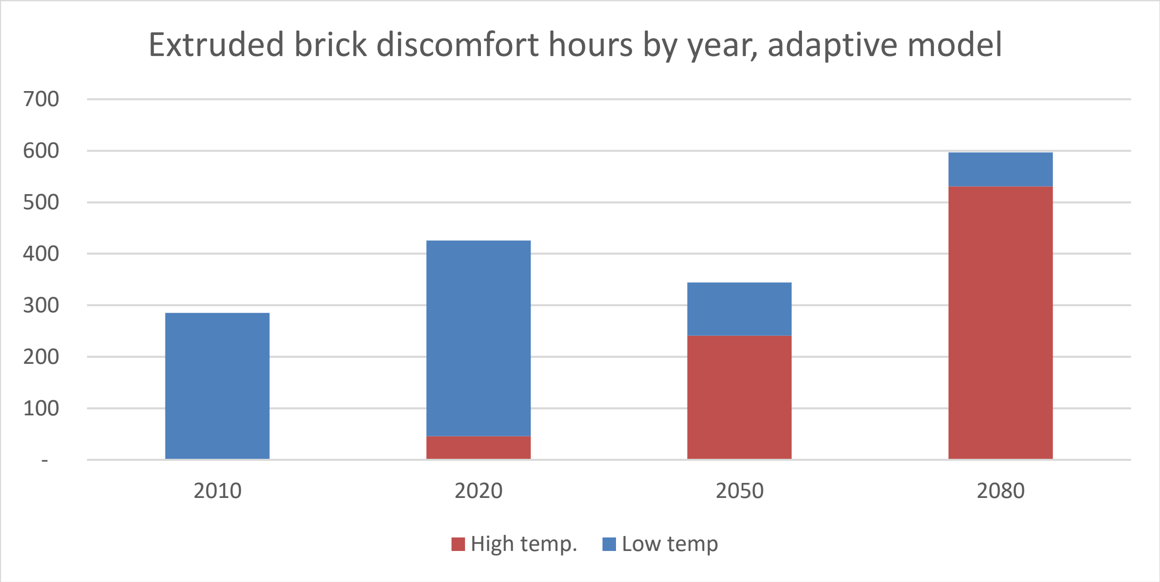

Figure 7.9 Extruded brick adaptive model discomfort hour's comparison by year

In 2020 very little discomfort due to high temperatures will be experienced, with only 46 hours. In contrast, there will be an increase in discomfort due to low temperatures to 380 hours. The increase in discomfort due to low temperatures is explained by the change in the comfort band temperature range. For 2010 it is between 18-28°C and from 2020 onwards it is 19-28°C to reflect climate change scenarios with higher temperatures. In 2050 the trend will shift, and most of the discomfort will be due to high temperatures, with 241 hours against 103 hours of discomfort due to low temperatures. In 2080 discomfort due to high temperatures will increase to 531 hours whilst discomfort due to low temperatures will be of only 66 hours.

The impact of the adoption of the AMTC can clearly be observed in the large drop in the total number of discomfort hours when compared with the static model. Equally important is the impact in the nature of discomfort in the building - from 2010 to 2020 it will be predominantly due to low temperatures and from year 2050-2080 it will be due to high temperatures.

Overall, when employing the AMTC the amount of discomfort time is rather small and supports the argument for the use of bioclimatic design and natural ventilation as climate change resilient strategies capable of providing thermal comfort year round.

7.4 Discomfort temperature analysis

The magnitude of discomfort time was also analysed for the red brick prototype because it is the worst performing in terms of temperatures and thermal comfort, therefore, it represents the worst-case scenario which makes it particularly fit for analysis because good practice in architectural design for thermal comfort takes into consideration the worst-case scenarios of high and low temperatures (summer and winter design weeks). Also, January and May (coldest and hottest months respectively) were chosen for analysis in order to provide sufficient data for a wider perspective that when using only design weeks.

For the sake of analysis, figures 7.10-7.17 show on the left side graph the overlapped operative and outside dry bulb temperature, while on the right side graph, the operative temperature is isolated with its corresponding AMTC temperature band highlighted in colour; this way it's possible to compare in a glance the outside air temperatures and the building temperature responsiveness to it. In figure 7.10, January 14th is the coldest day; when outside temperatures fall below 0^{o}C the building manages a lowest operative temperature of 15^{o}C which is only 3^{o}C below comfort temperatures. Discomfort time occurs from 0:00-16:000 hours and naturally comfortable temperatures only from 17:00-23:00 hours (7 hours). Note that the lowest 15^{o}C temperature was reached only during tree non-consecutive days from 4:00-11:00 hours approximately.

However, it can be argued that most of discomfort happened during the 8th-9th of January when temperatures never reached the comfort band, radiant temperatures (not shown) were particularly low which suggests two consecutive cloudy days; this also reinforces the importance of sun availability for thermal comfort during winter time.

Overall, during January 2010 discomfort hours were 222 which account for nearly 30% of the month and 71% of discomfort for year 2010 with a distribution during the late night and early day hours and a minimum operative temperature of 15^{o}C. With discomfort distributed during non-consecutive days and a trend for low temperatures reduction a centralized heating system might be excessive give a good architectural bioclimatic design.

On the other hand, figure 7.11 shows that no discomfort due to high temperatures was experienced during the studied time, year 2010 when employing the AMTC for analysis.

During year 2010 in both figures (7.10 &7.11), outside dry bulb temperature had a daily fluctuation of 10^{o}C or more (suitable for high thermal mass) while operative temperature varied no more than 5^{o}C in January as in May. This is relevant because discomfort is also associated with large temperature changes over a small time period in any given direction (hot or cold); while the prototype managed the daily 5^{o}C variation over a 24 hours' time period.

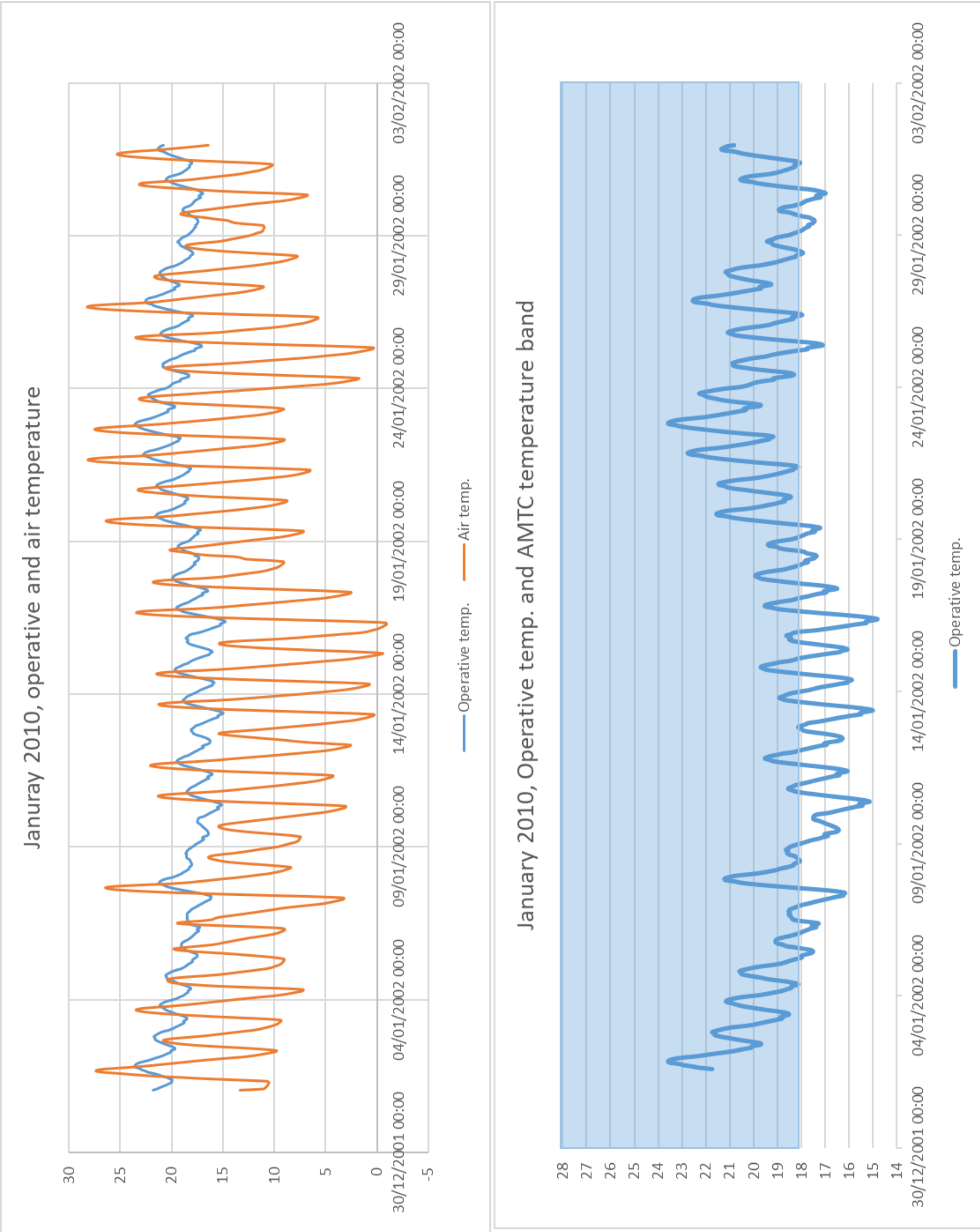

Figure 7.10 January 2010, operative, outside dry bulb, and AMTC temperature band.

Figure 7.11 May 2010, operative, outside dry bulb, and AMTC temperature band.

Figure 7.12 right side shows that by year 2020 the AMTC temperature band changes to 19-28^{o}C. In January, the lowest temperature is 16^{o}C (+1^{o}C than in January 2010, figure 7.10) which is 3^{o}C below comfort temperature. With two consecutive days below comfort, 18th-19th of January during which the maximum operative temperature is 18^{o}C which is below comfort.

The number of hours below comfort during January are 232, slightly higher than in 2010 which reflects the increase in discomfort time due to low temperatures from table 7.2.

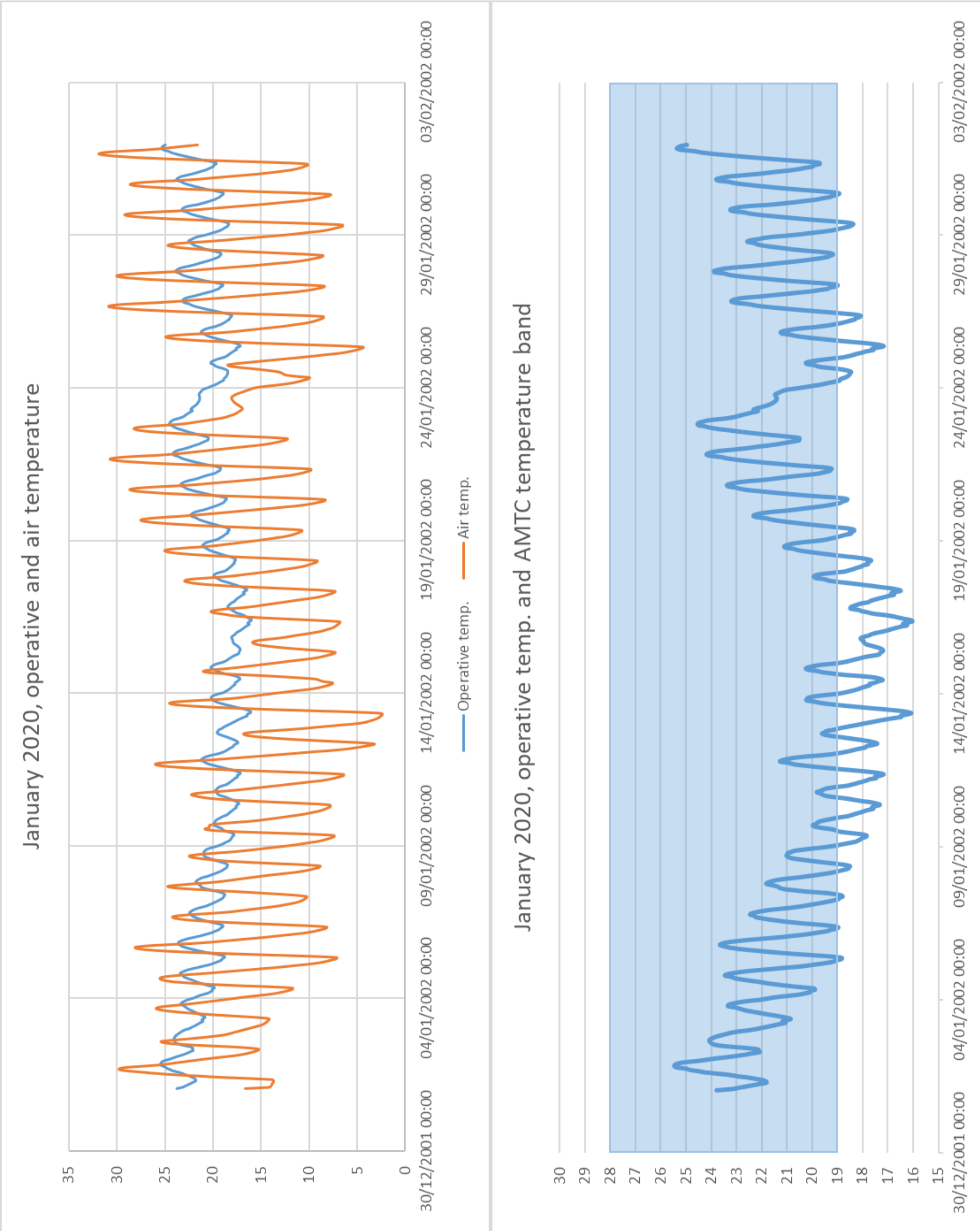

Figure 7.12 January 2020, operative, outside dry bulb, and AMTC temperature band.

Figure 7.13 May 2020, operative, outside dry bulb, and AMTC temperature band.

Figure 7.13 shows some discomfort due to high temperatures with a magnitude of almost 2°C above the 28°C from the AMT for 25 hours; with the highest temperatures from 17:00-22:00 hours on the 28th. Temperature distribution suggests that bedroom ceiling fans might be suitable to deal with discomfort temperatures because of their magnitude, and because they occur around what would be bedtime for most working families.

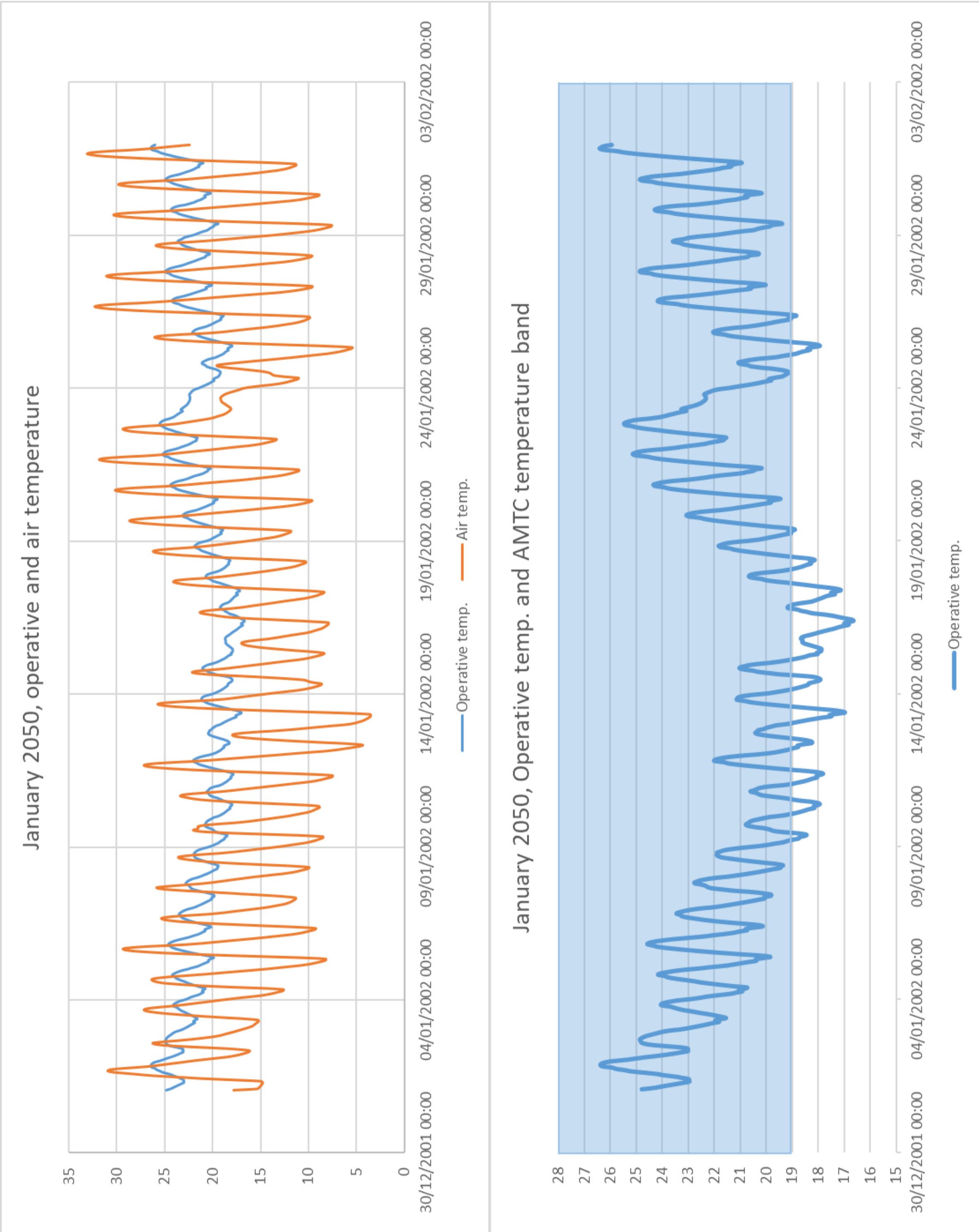

Figure 7.14 January 2050, operative, outside dry bulb, and AMTC temperature band.

Figure 7.14 shows how discomfort time due to low temperatures is greatly reduced by year 2050 both in duration and intensity. With 140 hours of discomfort time and the lowest temperatures around 17°C which is only 2°C below comfort temperature. During the coldest day January 6th, discomfort is felt from 24:00-14:00 with the lowest temperature from 6:00-11:00 hours (16-17°C though all discomfort time).

Figure 7.15 shows an increase in discomfort time for year 2050 with 108 hours of discomfort time and a maximum temperature of 30ºC, which is 2ºC above the AMTC temperature band.

Figure 7.15 May 2050, operative, outside dry bulb, and AMTC temperature band.

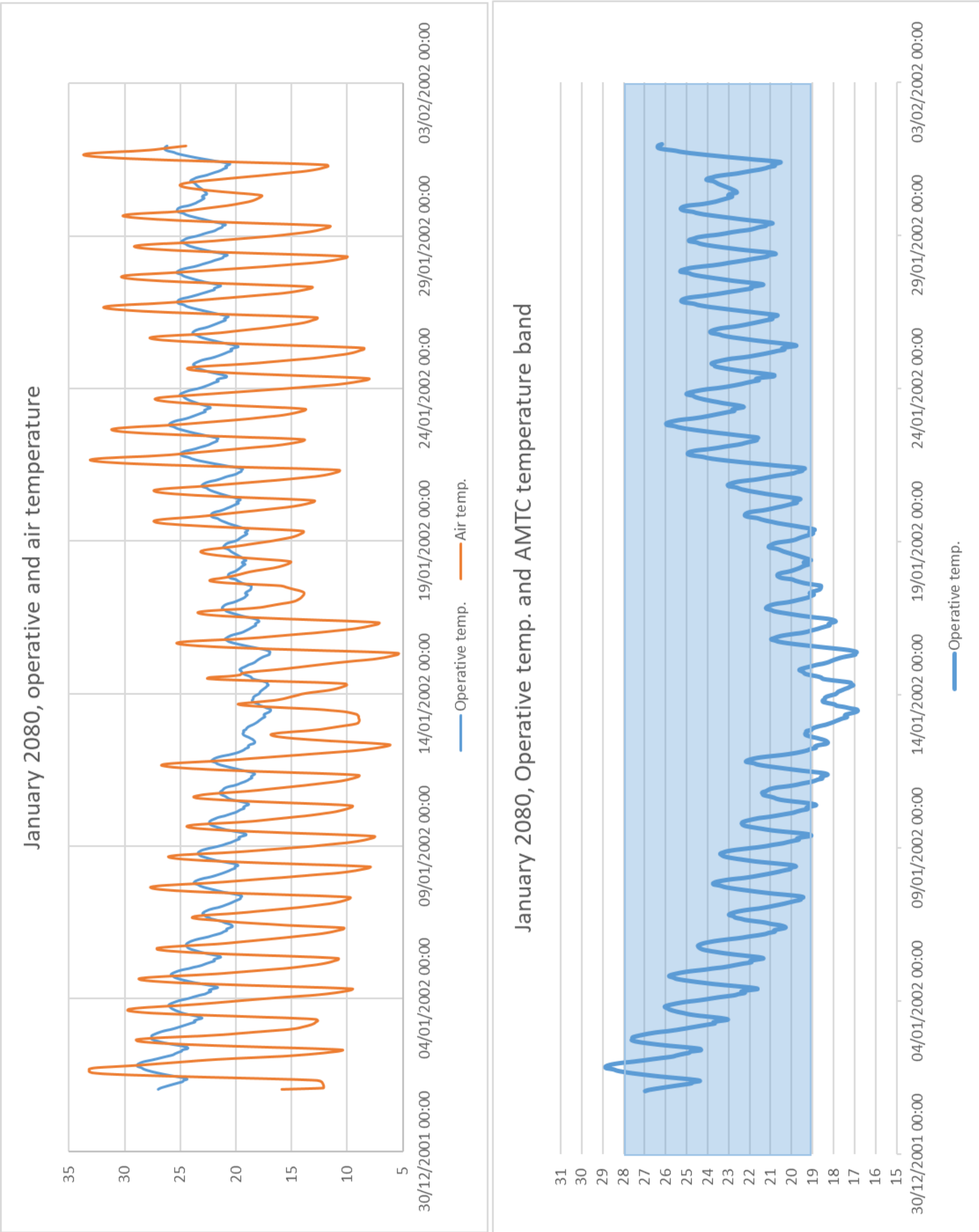

Figure 7.16 January 2080, operative, outside dry bulb, and AMTC temperature band.

Figure 7.17 May 2080, operative, outside dry bulb, and AMTC temperature band

Figure 7.16, January 2080 shows that by year 2080 discomfort due to low temperatures is greatly reduced in length (36 hours) and intensity remaining at 2ºC below comfort band (17ºC) similarly to year 2050. Interestingly, simulations show a day with discomfort due to high temperatures during January which according to epw weather files analysis will still be the coldest month of the year. In year 2080 temperatures will reach almost 29ºC in January

1th from 16:00-23:00 hours. During the coldest month the lowest temperature will be 5ºC and a maximum of 34ºC with daily fluctuations as large as +20ºC in the outside dry bulb temperature. During the studied time period, the maximum fluctuation in operative temperature will be of 5ºC, which means that even if high, temperatures inside the building will remain stable.

Figure 7.17, May 2080 shows an increase in discomfort time due to high temperatures of around 191 hours which represent 32% of heat discomfort time for the year with a maximum temperature of +31ºC, almost 4ºC above the AMTC temperatures during the hottest day (20th). Heat discomfort magnitude and length for year 2080 suggest that cooling might be necessary.

Overall, simulation results show that in the worst-case scenario, discomfort will have a maximum magnitude of 3ºC beyond comfort band (AMTC) during the cold and hot seasons. It will be until year 2080 that discomfort due to high temperatures will be greater than 4ºC above comfort.

7.6 Conclusion

Before going in detail with the general conclusions, it's important to highlight the simulation research pitfalls so that due caution is taken when considering results. Firstly, the natural ventilation regime was automated most of the time due to the lack of surveys that could account for representative users´ behaviour. Secondly, it is important to take into consideration that the validation of simulation parameters was conducted over a small time period and during the cold season (December-January 2015-2016). Finally, all of the above holds a potential impact in quantitate terms, therefore, results should be considered from their qualitative value.

In a cross comparison of the prototype dwelling with the three different wall construction materials (red brick, hollow concrete block and extruded brick), and when employing the static model for discomfort time analysis, the hollow concrete block (HCB) prototype performs slightly better than the extruded brick prototype, with a 20 hour difference in discomfort time. In contrast, the worst performing prototype was the red brick one with 223 hours more discomfort time when compared with the best performing.

When employing the adaptive model of thermal comfort, the red brick prototype was still the worst performing, showing the largest sensitivity to low temperatures and around 466 hours difference in thermal comfort when compared with the extruded red brick prototype (best performing). Note that the difference in discomfort time between the red brick and the hollow concrete block prototypes is small, of nearly 221 hours.

Continuing with the AMTC analysis, the extruded block prototype performed better, with 245 less hours of discomfort when compared with the HBC prototype which is the second best performing.

When employing the AMTC for discomfort time analysis, none of the construction materials would generate sufficient discomfort time as to require heating or cooling systems. Still, the extruded brick prototype was the best performing with the least number of discomfort hours. It will show no discomfort due to high temperatures in 2010. As soon as 2020, the number of discomfort hours will start to increase constantly, going to 531 hours by 2080. Discomfort due to low temperatures will be felt, particularly in 2020, due to the change in comfort temperature ranges (thermal band), after that, the number of discomfort hours will continuously decrease until year 2080 when it will be of 66 hours. In that sense, the extruded brick prototype is the one that better withstands discomfort due to low temperatures.

As for the prototypes with hollow concrete block, in 2010 and 2020 most of the discomfort will be due to low temperatures. It is only until 2050 and up to 2080 that the majority of discomfort will be due to high temperatures.

Simulation results show that a building made from common red brick will be more vulnerable to low extreme temperatures providing the worst performance in terms of discomfort time from the three construction materials however, the difference in performance is rather small.

Overall, the three construction materials provided less than 10% discomfort time (year-round) in all the studied scenarios, making all of them suitable for climate change resilient construction in San Luis Potosi City, Mexico from the thermal comfort perspective. Also, the three prototypes showed a similar responsiveness to external temperatures since none of them registered discomfort due to high temperatures in 2010 and all of them will experience increasing discomfort due to high temperatures from year 2020 up to 2080. Also, all prototypes will experience a ‘peak’ in discomfort due to low temperatures in year 2020 as a result of the change in the AMTC temperature band.

It can be concluded that when employing bioclimatic design principles with an emphasis on the building orientation, complementing the design with locally available high thermal mass construction materials and natural ventilation, it is possible to create climate change resilient houses in San Luis Potosi City when employing the AMTC for analysis. Such houses will be able to cope with rising temperatures due to global warming with natural ventilation alone up to year 2080.

Despite the fact that all wall construction materials can aid in providing thermal comfort year-round, it is important to keep in mind that the small differences between them will have an impact on the amount of time that people will feel thermally comfortable, thereby reducing energy demand for heating/cooling. Table 7.7 shows a negligible difference in discomfort time when employing either extruded brick or hollow concrete block. It also highlights more discomfort time when employing Red brick as wall construction material.

Table 7.7 Discomfort time (hours) by wall construction material when employing the AMTC

Discomfort time (hours) by wall constr. material AMTC			
Year	**Extruded Brick**	**Hollow CB**	**Red Brick**
2010	285	267	310
2020	426	413	468
2050	344	340	396
2080	597	592	659

These small improvements in discomfort time when employing either wall construction material should not be overlooked, given that it is usually easier and more cost-effective to improve an overall building performance by adding up small changes in different areas than focusing all efforts on a single strategy/area/construction material. Moreover, general results highlight the interchangeability between construction materials in the building sector. This means that it is possible to use either of the wall construction materials and still manage to get fairly good results from the thermal comfort perspective (AMTC), keeping always in mind that extruded brick will provide the best performance followed up closely by hollow concrete block and that the worst performing construction material in providing thermal comfort would be red brick.

Results could have important implications for the social housing sector in the region in terms of potential energy savings by avoiding the use of heating/cooling systems provided that bioclimatic design principles are implemented early in the architectural design process. It is also relevant for home buyers who would be naturally comfortable inside their own houses without having to spend extra money for thermal comfort especially for low income and mid income families. Finally, it is necessary to perform further research that would help reinforce simulation results, such as extensive building and occupants monitoring and weather data collection for simulations.

Chapter 8. Parametric optimization

After identifying extruded red brick as the most thermally comfortable performing locally available construction material (Chapter 7) in San Luis Potosi City, Mexico, and as part of the parametric analysis, windows size optimization and the effects on changes in slab thickness were conducted. The modelling process was done employing the '*shoe box*' method which consists of modelling only the part of the building that is of our interest. This approach is often used, but is not limited to, the early design stages since it allows to represent a small part of the building and to include the most important elements that need a better and deeper understanding (L. Hemsath & Bandhosseini, 2018).

8.1 Windows size optimization

The living/dining area as well as a bedroom were simulated in isolation from the rest of the prototype. The decision was based on their south orientation, which makes them sensitive to changes in windows sizes and, therefore, in sun availability and thermal comfort (note that the prototype does not have East nor West facing windows). By simplifying the model, it was possible to cut down simulation time by reducing the information load on the PC, thus allowing it to carry out a large number of simulations in a relatively reduced amount of time. In this case 20 simulations were performed for the bedroom and 28 for the living/dining area plus 4 whole building simulations after optimization for each prototype (roughly 156 simulations by prototype).

Note that one of the goals of simplifying the model was to find the best performing window size in relationship to the relevant space in a shorter amount of time than if performing a whole building simulation. On the one hand, this means that the number of discomfort hours can only be compared for the set of simulations in this chapter and that they are not directly comparable with previous simulations in quantitative terms. On the other hand, this also means that the best results in terms of a smaller number of discomfort hours from the optimization simulations are still valid for the simulated prototype. In consequence, after the window size optimization was done (shoe box approach) a new set of simulations were produced for the whole building applying the best performing windows sizes from this section in order to compare and then measure the reduction in discomfort time due to the changes at present time and for future weather scenarios (climate change resilience).

The prototype design was originally developed without considering a specific percentage of glazing area, this means that the baseline windows size was arbitrarily designed. However, verticality in the windows proportion is due to literature review (Secretaria de Economia, 2013) which showed that keeping such proportions would allow for a deeper sun penetration that is particularly beneficial for high thermal mass as bioclimatic design strategy. It is also important to note that there are two ways to look at windows size in relationship to the building. The first one is windows size as a percentage of the relevant space/room south façade and it is recommended to be between 40-50% of it since a larger window proportion would lead to overheating during summer time (mpa The Concrete Centre, 2012, p. 7). The second one measures windows size as a proportion of the space/room floor area and focuses more on natural light availability and the recommended ratio is between 15-50% (mpa The Concrete Centre, 2012, p. 7).

Either way, from the thermal comfort perspective, windows size should provide a balance between heat gains during wintertime whilst avoiding excessive heat gains during summertime. As seen in previous chapters this process happens naturally due to the Earth's inclination in relationship to the sun through the year. During wintertime low solar altitudes provide a deeper sun light penetration through windows, so even if outside temperatures are low and days are short the amount of radiation should be enough to provide some natural heating. During summer time the sun's high altitude reduces the amount of time that solar radiation will penetrate a window provided that it is south oriented (±30°); so, even if temperatures are high during summer a reduced exposure to solar radiation inside the building should generate cooler conditions than outside. Hence, windows size optimization consists in finding that window size that will provide the best performance in terms of thermal comfort during winter as well as during summertime. For natural ventilation, 50% of the window area was set as openable regardless of window size.

The optimization process took into consideration the window-to-south wall ratio since this is a more straightforward parameter that can be more easily manipulated as part of the façade design as will be further detailed in the forthcoming sections.

8.1.1 Extruded brick prototype window size optimization

Windows sizes in Table 8.1 were the leading point for optimization; in all cases the window height was kept at 2.20m with changes only in the widow width. The percentage of glazing area in relationship to the internal south wall surface for the living/dining baseline was 60.5% (2.20 x 2.20 m) and for the bedroom is 32.3% (2.20 x 1.10 m), with decrements/increments of 10% (Tables 8.1 & 8.2). The simulated years were 2010, 2020, 2050 and 2080. Also, the adaptive model of thermal comfort was employed in the analysis for the sake of consistency in determining discomfort hours for every simulation.

Table 8.1 Baseline window size by room type

Baseline window size by room type					
Room	South wall M2	window size		Glass area M2	%
		Height	Width		
Living/Dining	8.00	2.20	2.20	4.84	**60.5**
Bedroom	7.50	2.20	1.10	2.42	**32.3**

Table 8.2 shows a south façade glass to wall ratio ranging from 30-70% in increments-decrements of roughly 10% for the living/dining room area. The grey-coloured line shows results for the baseline window as originally designed with a 60.5% of glazing area. It is a coincidence that this proportion is the best performing in term of discomfort time since it is the one that will generate less discomfort hours throughout the studied time period. Note that in all cases most of the discomfort is due to low temperatures and very little discomfort is due to high temperatures. This means that no changes in widow size are needed in the living/dining area since the current size (2.20 x 2.20 m) will provide the best thermal performance during winter, summer, at present time, and under future weather scenarios of climate change (climate change resilience).

Table 8.2 Living/Dining room south façade window parametric optimization results highlighted

Extruded brick prototype Living/Dining room south façade window parametric optimization results in discomfort hours															
	South wall M2	window size		Glass area M2	%	2010		2020		2050		2080		Total hrs.
		Height	Width			High T	Low T	High T	Low T	High T	Low T	High T	Low T	
Living/Dining	8.00	2.20	1.10	2.42	**30.0**	0	696	19	760	62	418	129	270	2354
	8.00	2.20	1.35	2.97	**40.0**	0	652	22	721	69	396	139	259	2258
	8.00	2.20	1.80	3.96	**50.0**	0	604	25	669	81	367	159	244	2149
	8.00	2.20	2.20	4.84	**60.5**	0	570	26	635	99	354	185	238	2107
	8.00	2.20	2.50	5.50	**70.0**	0	555	29	611	124	350	220	229	2118

Table 8.3 shows a south façade glass to wall ratio ranging from 20-80% in increments of 10% on the bedroom glazing area. The grey coloured line show results for the baseline window as originally designed with a 32.3% of glazing area. Simulation results show that a decrease in window size to 20% generates more discomfort due to low temperatures. On the other hand, by increasing windows size to 40% the amount of discomfort time is reduced. Further increments in windows size generate more discomfort time due to high temperatures especially for future weather scenarios. Note that 3-4mm clear glass and single glazing was set up for all the thermal comfort simulations. This solution was chosen over double glazing because according to the literature (Mora Juarez, 2014) it is the most effective way for solar

radiation and heat to be transferred to the internal building surfaces, thus, making the most out of the high thermal mass strategy.

Table 8.3 Bedroom south façade window parametric optimization results

Extruded brick prototype Bedroom south façade window parametric optimization results in discomfort hours														
	South wall M2	window size		Glass area M2	%	2010		2020		2050		2080		Total hrs.
		Height	Width			High T	Low T	High T	Low T	High T	Low T	High T	Low T	
Bedroom	7.50	2.20	0.70	1.54	**20.0**	0	829	34	821	132	461	220	298	2795
	7.50	2.20	1.10	2.42	**32.3**	0	721	42	735	163	404	258	265	2588
	7.50	2.20	1.45	3.19	**40.0**	0	652	54	668	212	366	318	245	2515
	7.50	2.20	1.70	3.74	**50.0**	0	623	61	647	231	357	394	238	2551
	7.50	2.20	2.00	4.40	**60.0**	0	594	81	615	300	346	490	229	2655
	7.50	2.20	2.40	5.28	**70.0**	2	566	160	586	405	336	673	220	2948

Surprisingly, a direct comparison of discomfort time before and after the whole building windows size optimization through years 2010, 2020, 2050 and 2080 showed very little change and, in fact, discomfort time was slightly increased by 10 hours as can be seen in the total number of discomfort time in Table 8.4. This means that in this case, the original window size was the one that will provide a better balance between heat gains/losses during winter and summer both at the present time and for future weather scenarios of climate change.

Table 8.4 Extruded brick AMTC windows size optimization & discomfort time comparison (whole building)

Extruded brick AMTC windows optimization comfort time comparison								
Year	Baseline			Optimized			Discomfort Time	
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	Hours	%
2010	0	285	285	0	290	290	**-5**	**1.75**
2020	46	380	426	40	404	444	**-18**	**4.23**
2050	241	103	344	236	113	349	**-5**	**1.45**
2080	531	66	597	507	72	579	**18**	**-3.02**
Total	**818**	**834**	**1652**	**783**	**879**	**1662**		

The method employed for simulations reduces the quantitative accuracy of the results shown and the sensitivity of an oversimplified model should be taken into consideration in future/other projects according with the characteristics of the project to be analysed (this is true for the rest of the present chapter). Nevertheless, for this project simulation results seemed to conclude that for the extruded brick prototype a 60-70% of glazing area (2.20 x 2.20m) in the living/dining area was the optimum window size. Also, a 30-40% of glazing area was the optimum window size for the bedrooms and both will provide the least number of discomfort hours year-round at present time and up to year 2080.

In both scenarios there is a clear tendency in the increasing number of discomfort time due to high temperatures for future weather scenarios. Simultaneously, discomfort time due to low temperatures will be significantly reduced. Overall, the fact that discomfort time occurs for less than 10% of the year[14] in number of discomfort hours leads to the conclusion that neither mechanical heating nor cooling is necessary to keep thermally comfortable conditions in a naturally ventilated building with extruded brick walls in San Luis Potosi City, Mexico provided that high thermal mass and a careful south orientation and widow sizing are taken in to consideration in a building design/construction.

Finally, and beyond the simulation/data accuracy limitations, the importance of window size optimization is highlighted for its potential capacity to provide thermal comfort in a naturally ventilated building and should not be overlooked. Just because it was a coincidence that windows sizes as originally designed happened to be the best performing ones does not mean that the optimization process does not hold a significate potential for improving thermal comfort. Consequently, it is strongly advisable to optimize windows sizes as part of the early design process and a time saving way to do it is by employing the 'shoe box' simulation approach which saves computing time and allows to compare between several options.

8.1.2 Hollow concrete block (HBC) prototype windows size optimization

As for the extruded brick prototype, windows height was kept at 2.20m with changes only in the widow length. The baseline percentage of glazing area for the living/dining was 60.5% and 32.3% for the bedroom with decrement/increments of 10% on the glazing area. The simulated years were 2010, 2020, 2050 and 2080. Also, the adaptive model of thermal comfort was employed in the analysis for the sake of consistency in determining discomfort hours for every simulation. Table 8.5 shows a south façade glass to wall ratio range from 30-70% in increments-decrements of 10% for the living/dining room area. The grey coloured line shows results for the baseline window as originally designed with a 60.5% (2.20 x 2.20 m) of glazing area which coincidentally is the best performing as it is the one that manages to generate less discomfort time.

[14] Considering that a year has 8,760 hours.

Table 8.5 Hollow concrete bock Living/Dining room south façade window parametric optimization results

HCB Living/Dining room south façade window parametric optimization results in discomfort hours														
	South wall	window size		Glass area	%	2010		2020		2050		2080		Total hrs.
	M2	Height	Width	M2		High T	Low T	High T	Low T	High T	Low T	High T	Low T	
Living/Dining	8.00	2.20	1.10	2.42	**30.0**	0	629	0	805	0	497	13	348	2292
	8.00	2.20	1.35	2.97	**40.0**	0	600	0	777	0	478	22	329	2206
	8.00	2.20	1.80	3.96	**50.0**	0	568	0	715	2	459	37	305	2086
	8.00	2.20	2.20	4.84	**60.5**	0	543	1	694	24	438	87	293	2080
	8.00	2.20	2.50	5.50	**70.0**	0	533	7	680	61	435	161	291	2168

Table 8.6 shows a south façade glass to wall ratio range from 20-80% with 10% increments in the bedroom glass area. The grey coloured line show results for the baseline window as originally designed with a 32.3% of glassing area which again happens to be the best performing of them all. Further increments in window size generate more discomfort due to high temperatures. This means that the prototype already performs at its best in relationship to windows size and orientation and no changes are necessary. This means that a window-to-wall ratio of 50-60% for the living room and of 30-40% in the bedroom are the optimum windows sizes for the HCB prototype since they would provide the least number of discomfort time at present time and for future weather scenarios.

Table 8.6 HCB Bedroom south façade window parametric optimization results

HCB Bedroom south façade window parametric optimization results in discomfort hours														
	South wall	window size		Glass area	%	2010		2020		2050		2080		Total hrs.
	M2	Height	Width	M2		High T	Low T	High T	Low T	High T	Low T	High T	Low T	
Bedroom	7.50	2.20	0.70	1.54	**20.0**	0	825	3	922	9	583	49	406	2797
	7.50	2.20	1.10	2.42	**32.3**	0	721	7	824	28	523	94	360	2557
	7.50	2.20	1.45	3.19	**40.0**	0	668	16	768	104	486	227	333	2602
	7.50	2.20	1.70	3.74	**50.0**	3	650	68	745	200	461	351	319	2797
	7.50	2.20	2.00	4.40	**60.0**	71	622	296	713	469	448	684	301	3604
	7.50	2.20	2.40	5.28	**70.0**	136	618	374	709	588	450	841	300	4016

8.1.3 Red brick prototype windows size optimization

As with the previous prototypes, window height was kept at 2.20m with changes only in the widow length. The percentage of glazing area for the living/dining baseline is of 60.5% and for the bedroom 32.3% with decrement/increments of 10% on the glazing area. The simulated years were 2010, 2020, 2050 and 2080. Also, the adaptive model of thermal comfort was employed in the analysis for the sake of consistency in determining discomfort hours for every simulation.

Table 8.7 shows the living/dining south façade glass-to-wall ratio range from 30-70% in increments of 10%. The grey coloured line show results for the baseline window as originally designed with a 60.5% (2.20 x 2.20 m) of glazing area. Simulation results show that for the red brick prototype the best performance (reduced number of discomfort hours) was achieved with a 70% of glazing area which is 10% larger than originally designed (60.5%). However, the improvement is rather small with only 8 hours of less discomfort time and therefore, it can be concluded that a window size between 60-70% would provide an adequate performance.

Table 8.7 Red brick concrete bock Living/Dining room south façade window parametric optimization results

Red brick Living/Dining room south façade window parametric optimization results in discomfort hours														
	South wall	window size		Glass area	%	2010		2020		2050		2080		Total hrs.
	M2	Height	Width	M2		High T	Low T	High T	Low T	High T	Low T	High T	Low T	
Living/Dining	8.00	2.20	1.10	2.42	**30.0**	0	1014	34	1043	103	660	178	463	3495
	8.00	2.20	1.35	2.97	**40.0**	0	964	37	1009	113	627	190	437	3377
	8.00	2.20	1.80	3.96	**50.0**	0	896	43	949	136	595	210	410	3239
	8.00	2.20	2.20	4.84	**60.5**	0	849	47	898	155	567	241	379	3136
	8.00	2.20	2.50	5.50	**70.0**	0	825	49	874	173	549	278	380	3128

Similar to Table 8.7, Table 8.8 shows a south façade glass to wall ratio range from 20-80% with 10% increments in the bedroom glass area. The grey coloured line show results for the baseline window as originally designed with a 32.3% of glazing area. The least number of discomfort hours is found within 40-50% of glazing area (3740-3737 hours respectively). It is important to note that the reduction in discomfort time from 32.3% to 50% is of just 76 hours, therefore any windows size between 40-50% should work similarly well. Further increments in glazing area from 50% onwards generate an increasingly worst performance driven chiefly by a rising in the number of discomfort hours due to high temperatures.

Table 8.8 Red brick Bedroom south façade window parametric optimization results

Red brick Bedroom south façade window parametric optimization results in discomfort hours															
	South wall	window size		Glass area	%	2010		2020		2050		2080		Total hrs.
	M2	Height	Width	M2		High T	Low T	High T	Low T	High T	Low T	High T	Low T	
Bedroom	7.50	2.20	0.70	1.54	**20.0**	0	1177	49	1150	169	728	274	515	4062
	7.50	2.20	1.10	2.42	**32.3**	0	1052	57	1052	192	655	336	469	3813
	7.50	2.20	1.45	3.19	**40.0**	1	990	74	985	239	619	399	433	3740
	7.50	2.20	1.70	3.74	**50.0**	2	939	87	942	285	590	481	411	3737
	7.50	2.20	2.00	4.40	**60.0**	6	892	127	909	350	571	587	394	3836
	7.50	2.20	2.40	5.28	**70.0**	19	856	211	873	465	544	248	391	3607
	7.50	2.20	2.70	5.94	**80.0**	46	839	316	854	577	527	917	374	4450

Note that Table 8.8 shows a discrepancy in simulation results for year 2080 and a 70% of glazing area (highlighted in blue). The rest of the simulations consistently showed a tendency towards an increasing number of discomfort hours due to high temperatures whilst decreasing discomfort time due to low temperatures. The highlighted data set suddenly shifts this tendency by a large decrease in discomfort due to high temperatures and this can be attributable to a glitch in the simulated data set and therefore will not be taken in to consideration for the optimization analysis, even though it shows the best performance in terms of discomfort time.

After optimizing windows sizes on the red brick prototype, Table 8.9 shows a rather small reduction in discomfort time when simulating the whole building. Living/dining windows size was set to 70% or 2.20x 2.50m and the bedroom up to 50%. As figures show the difference in the total number of discomfort time, the prototype only managed to reduce discomfort by 15 hours.

Table 8.9 Red brick AMTC windows size optimization & discomfort time comparison (whole building)

Red brick windows size optimization & discomfort time comparison								
Year	Baseline			Optimized			Discomfort time	
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	Diff. Hours	%
2010	0	310	310	0	299	**299**	11	**-3.55**
2020	56	412	468	49	443	**492**	-24	**5.13**
2050	274	122	396	262	144	**406**	-10	**2.53**
2080	585	74	659	536	85	**621**	38	**-5.77**
Total	**915**	**918**	**1833**	**847**	**971**	**1818**		

The small reduction in discomfort time after the optimization process can be explained by the also small difference in discomfort time found between the baseline and the optimized window sizes shown in Tables 8.8 and 8.9. Overall, the modest improvement might not justify an increase in window size given that this would only add up to final construction costs without providing a substantial return in thermal comfort. This is the case for which retaining the original windows size is advisable given the meagre improvement that larger and allegedly more costly windows seem to provide

8.1.4 Summarizing

It was a coincidence that windows sizes as originally designed proved to be the best performing for all the prototypes. It was also surprising that an increase of 10-20% in windows size happened to have very little effect on thermal comfort if at all. This is true for the prototypes and windows sizes that showed a slightly better performance when changing the baseline window size. This can be explained by the fact that the original windows size (as designed) fall within the parameters found in the literature review from the two perspectives: window to south façade ratio (no more than 50%) and as window to internal floor ratio (15-50%) as shown in Table 8.10.

Table 8.10 Baseline window sizes and ratios

Baseline window sizes and ratios							
Area	south wall M2	Window size		Glass area M2	Window/wall ratio (%)	Floor area M2	Window/floor area ratio (%)
		Height (ML)	With (ML)				
Living/dining	8.00	2.20	2.20	4.84	**61**	16.84	**29**
Bedroom	7.50	2.20	1.10	2.42	**32**	9.00	**27**

Note that windows as originally designed happened to be the optimum size even though the living/dining widow to south façade ratio surpasses the recommended 50% limit that allegedly would generate excessive overheating during the hot season. The fact that no significate excessive overheating occurs throughout the simulated years can be explained by San Luis Potosi City's latitude being close to the Equator, which creates self-shading façades during the hot season as further studied in Section 3*.6 (Sun shaded windows as bioclimatic design strategy).* On the other hand, when looking at the window to floor area ratio the percentage falls within the recommended 15-50% parameter (Table 8.10).

Overall, windows size optimization can still be considered as a cost-effective early design stage strategy that can help improve thermal comfort and should not be overlooked. In that sense, the shoe box simulation approach might as well be considered as a 'fast' manner to achieve it. However, when a high degree of accuracy is required the shoe box simulation might not be the best option as it oversimplifies the model and the interactions between inner/outer surfaces and general adjacencies which actually impact on the thermal performance of a building.

Note that, although it was just a coincidence that the baseline design happened to have the optimum windows size for this particular project, it is highly advisable to optimize windows size on a project-by-project basis using the recommended ratios just as rough guidelines. Also, for San Luis Potosi City it seems to be possible to go slightly above the recommended window to south façade ratio in domestic architecture without greatly compromising thermal comfort due to overheating. This seems to be true at present time but also for future weather scenarios.

Finally, these results support the argument about the importance of having locally appropriate research on bioclimatic design strategies and their climate change resilience as it is one of the main goals of this research.

8.2 Slabs thickness analysis

After performing window size optimization, the next step consisted of examining the impact that different slab thicknesses would have on the prototype's thermal comfort performance. This is particularly interesting given that the main bioclimatic design strategy is 'high thermal mass' and changes to slab thicknesses would modify the amount of available mass. The impact of those changes in terms of thermal comfort are explored in this sub chapter.

Simulations in Chapter 7 *Thermal Comfort Simulations* began by employing poured concrete with 200mm thickness for the internal floors and roof slabs as this is the regular practice in the social housing sector in San Luis Potosi City, Mexico. Tables 8.11, 8.12 and 8.13 show a direct comparison between the baseline extruded brick prototype (best performing) with 200mm concrete slabs and with ±50mm variations in slab thickness. Simulations were performed in order to find out the impact of such variations in terms thermal comfort and their climate change resilience.

The decision to only simulate a ±50mm slab thickness variation over the 200mm thickness baseline was because a thinner than 150mm slab thickness would generate additional acoustic and structural challenges that would make it impracticable in real life. In opposition, going beyond a 250mm slab thickness would risk being impracticable due to the economic burden imposed by the additional concrete volume given that social housing is rather cost sensitive. Overall, the changes in slab thickness were an attempt to represent feasible and probable changes that could be implemented in order to improve thermal comfort without compromising structural stability nor adding an economic burden on a social housing construction project.

Table 8.11 shows that for the extruded brick prototype a 50mm reduction in slab thickness (150mm) would increase discomfort time by 179 hours across the studied time period when compared with the 200mm baseline. On the other hand, a 50mm increase in thickness (250mm) would decrease discomfort time by 162 hours. Overall it can be concluded that a slab thickness between 200-250mm would provide a good thermal comfort at the present time and for future weather scenarios (climate change resilience).

It is important to note that in all the studied scenarios the extruded brick prototype discomfort time was always less than 10% of the year (<876 hours). This means that bioclimatic design (high thermal mass) and a natural ventilation regime might be enough for thermally comfortable conditions in the prototype almost year-round. Results are relevant for the residential sector and when employing the adaptive model of thermal comfort (AMTC) given that those provide flexibility in terms of the adaptation measures that house inhabitants can take to make themselves thermally comfortable. This is also possible due to the relatively mild weather conditions prevailing in San Luis Potosi City and the large diurnal temperature shifts that allow for the effective use of high thermal mass.

Table 8.11 Extruded red brick prototype slab thickness & discomfort time comparison by year

Extruded brick prototype slab thickness & discomfort time comparison by year									
Year	150mm			Baseline 200mm			250mm		
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	High temp.	Low temp.	Total
2010	0	314	314	0	285	285	0	257	257
2020	59	419	478	46	380	426	31	338	369
2050	270	129	399	241	103	344	223	82	305
2080	565	75	640	531	66	597	506	53	559
Total	894	937	**1831**	818	834	**1652**	760	730	**1490**

Note that, although quantitative changes in discomfort time (number of hours) do not seem to be particularly large, they are still relevant as any reduction in discomfort time would benefit the building occupants especially since the studied prototype is a free running building with no mechanical heating/cooling systems.

Table 8.12 shows the impact of a ±50mm variation on slab thicknesses for the hollow concrete block (HCB) prototype which is the second best performing. In this case a 50mm reduction on slab thickness would increase discomfort by 185 hours whilst an increase of 50mm would reduce discomfort time by 166 hours.

For all the studied scenarios discomfort time occurred during less than 10% of the year (<876 hours), which makes it feasible not to have mechanical heating nor cooling since the building would be naturally comfortable year-round just by the implementation of high thermal mass as the main bioclimatic strategy coupled with a careful south orientation design and natural ventilation. Also, an adequate window size plays a major role on achieving this, as seen on Section 8.1.

Table 8.12 Hollow concrete block prototype slab thickness & discomfort time comparison by year

Hollow concrete block prototype slab thickness & discomfort time comparison by year									
Year	150mm			Baseline 200mm			250mm		
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	High temp.	Low temp.	Total
2010	0	296	296	0	267	267	0	236	236
2020	60	401	461	46	367	413	31	326	357
2050	270	120	390	243	97	340	225	79	304
2080	577	73	650	528	64	592	500	49	549
Total	907	890	**1797**	817	795	**1612**	756	690	**1446**

Table 8.13 shows the impact of a ±50mm variation in slab thicknesses for the red brick prototype, which is the worst performing. In this case a 50mm reduction in slab thickness would increase discomfort by 198 hours whilst an increase of 50mm would reduce discomfort time by 156 hours.

Table 8.13 Red brick prototype slab thickness & discomfort time comparison by year

Red brick prototype slab thickness & discomfort time comparison by year									
Year	150mm			Baseline 200mm			250mm		
	High temp.	Low temp.	Total	High temp.	Low temp.	Total	High temp.	Low temp.	Total
2010	0	347	347	0	310	310	0	285	285
2020	73	444	517	56	412	468	49	378	427
2050	308	149	457	274	122	396	252	99	351
2080	621	89	710	585	74	659	547	67	614
Total	1002	1029	**2031**	915	918	**1833**	848	829	**1677**

Even though the red brick prototype is the worst performing of the three prototypes, discomfort time for all the simulated scenarios occurs for less than 10% of the year (<876 hours) which means that the prototype will still manage to be comfortable almost year-round without having to rely on mechanical heating nor cooling when employing the adaptive model of thermal comfort.

Overall, with the employed simulation parameters, every studied wall construction material, regardless of slab/roof thickness, managed to generate discomfort time for less than 10% of the year (<876 hours) which, in turn, suggest the possibility of not to rely on mechanical heating nor cooling. Results seem to point out that it might be possible to build year-round comfortable climate change resilient social housing in San Luis Potosi City, Mexico by implementing bioclimatic design with locally available construction materials and natural ventilation. This would be particularly true for the residential sector for which any increase beyond 200mm thickness in the roof and internal slabs thickness seems to improve thermal comfort conditions by the added thermal mass, hence, it would be advisable for the concrete slabs to be at least 200mm thick or more.

As mentioned in previous chapters, the quantitate results of the building energy simulations should be taken with due care. In this particular case, although results seem to point at the possibility of not needing mechanical cooling/heating, a more in-depth analysis is necessary to validate such statement. Especially because extreme weather conditions seem to become more common due to climate change, such as heat waves. Therefore, the results shown are not meant to be considered as design prescriptive as they only depict the analysed prototype scenario with its simulation pitfalls.

Final steps consisted of a floor by floor temperature and energy balance analysis to better understand how thermal mass behaves during summer and winter design days in providing thermal comfort. This will be studied in the next chapter.

Chapter 9. Summer and winter design days analysis

Summer and winter design days represent the worst-case scenarios in terms of temperatures that the building will have to cope with. For the sake of analysis 20th May for summer (May is historically the hottest month in San Luis Potosi City) and 24th December for winter were chosen. Note that at this point, a temperature comparison by habitable area was done in order to rule out the possibility of strong temperature variations that could be masked by using a flat's average temperatures. Simulations show a maximum temperature difference between habitable areas by flat of around 2ºC (Appendix 4) throughout the studied period. This means that the use of average flat temperatures is appropriate for general analysis, as one of the research objectives was to find out general design guidelines. Therefore, the quantitate accuracy can be considered as 'diffused' and results shown in this chapter should be considered with due care.

For this chapter, a 24-hour temperature and energy balance analysis were done by flat (floor level) for those dates to better understand the thermal behaviour of the different construction elements and their role in providing or not thermal comfort. The analysis also allowed understanding of the differences in performance by flat, shedding light on floor-by-floor design strategies that will help to improve their climate change resilience and thermal comfort.

It is also important to mention that the heat balance graphs shown in this chapter only contain the most relevant concepts in quantitative terms for the sake of clarity (visual oversaturation avoidance); this means that concepts such as internal natural ventilation, external air, general lighting and occupancy loads were not included, given that their contribution to the energy balance was rather small. Also, for the energy balance calculation it is important to note that no mechanical heating nor cooling were set up for the simulations as the design is of a free running building that relies only on natural ventilation.

The reference year employed for the simulations was 2010 which means that the adaptive model of thermal comfort (AMTC) was employed with a comfort temperature band of 18-28°C and a slab thickness of 200mm was employed. In short, the same extruded brick prototype parameters employed in Chapter 8 were used for this chapter simulations.

9.1 Summer design day

The summer design day is May 20th and was chosen using DesignBuilder software simulation tools which speedily identified the hottest week (and days) of the simulated year.

The analysis is shown floor by floor, beginning with the ground floor flat, followed by the first floor flat and finally the second floor flat. The analysis commences by looking at operative and outside dry-bulb temperatures followed up by the energy balance analysis to better understand how energy is transferred in and out of the building to generate the operative temperatures (and comfort/discomfort) inside of each flat

9.1.1 Ground floor flat summer design day

Figure 9.1 shows the operative temperature (blue) and the outside dry bulb temperature (red) in the ground floor flat on a summer design day over a 24 hours period for May 20th in San Luis Potosi City, Mexico. The figure shows an outside dry-bulb temperature fluctuation of 14°C throughout the day with a minimum of 20°C on the early morning (1:00-6:00 hours) and a maximum of 34°C at 13:00 hours. In contrast, operative temperature managed to remain stable with a 3°C variation inside the building over the same time period, with a minimum of 22°C and a maximum of 25°C, which falls within the comfort zone of the AMTC. This means that in a hot summer day the ground floor flat will be comfortable during the whole day.

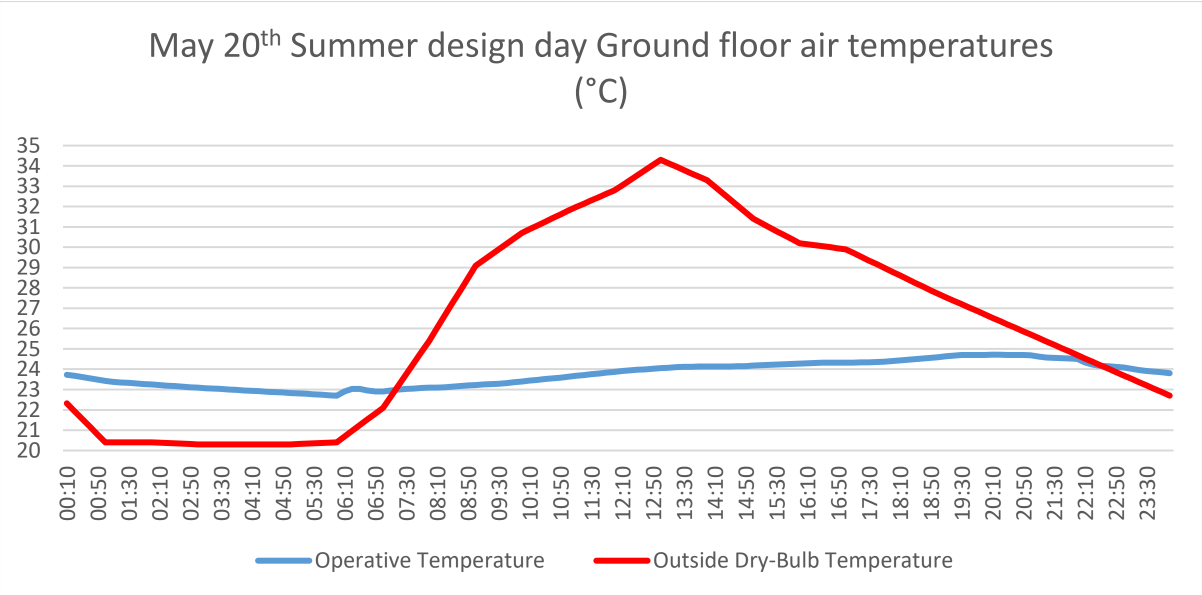

Figure 9.1 May 20th summer design day ground floor air temperatures (°C)

Figure 9.2 shows that most of the heat is transferred into the building through the walls (red colour) in a cycle in which between 8:00-10:00 hours the walls are almost energy neutral i.e. they do not add or subtract energy (heat) from the building. Most notably, the ground floor (green) behaves as a ‘heat sink’, absorbing the excessive heat, and playing a key role in keeping inside temperatures comfortable. This construction element alone outweighs the energy transferred inside the flat by the rest of the construction elements.

It takes 9 hours (8:00-15:00 hours) for the external walls (red) to get fully energy/heat charged. Then, it takes 15 hours for it to transfer (discharge) that energy inside the flat. From all the construction materials in the ground floor, extruded brick is the one that transfers more energy into the flat with a maximum of 25 W/m^2.

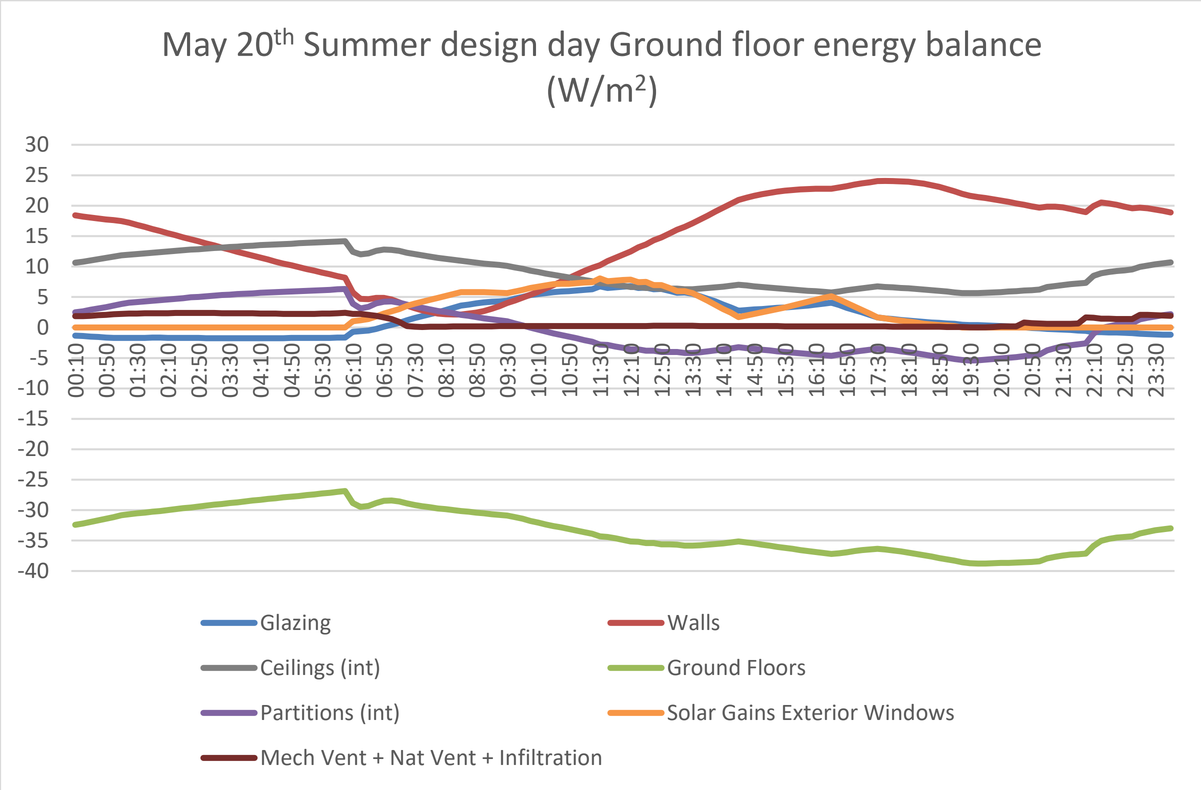

Figure 9.2 May 20th summer design day ground floor energy balance (W/m^2)

Ceilings (grey) and partitions (purple) behave in a symmetric way. However, ceilings add energy constantly to the flat, taking 10.5 hours (from 19:30-6:00 hours) to reach their maximum energy peak of 15W/m^2. After this, energy drops and remains relatively stable for 13.5 hours (from 6:00-19:30) with a minimum of 5W/m^2. Partitions, on the other hand, have exactly the same time cycle; however, unlike ceilings, they absorb energy and so aid in cooling the flat for 12 hours (from 10:00-22:00 hours) with a maximum of -5W/m^2. Solar gains in the ground floor flat are rather small, with a maximum of 7.5W/m^2 at midday and a 12 hour cycle from 6:00-6:00. Figure 9.2 clearly shows that the ground floor slab is the greatest contributor in keeping comfortable temperatures, it works as an energy sink retrieving a maximum of -39W/m^2 in a time cycle symmetric to that of the ceilings and partitions.

9.1.2 First floor flat summer design day

Figure 9.3 shows how operative temperature inside the first floor flat remain within the comfort zone most of the time with roughly 8 hours (from 14:00-22:00 hours) above 28°C but still below 29°C.

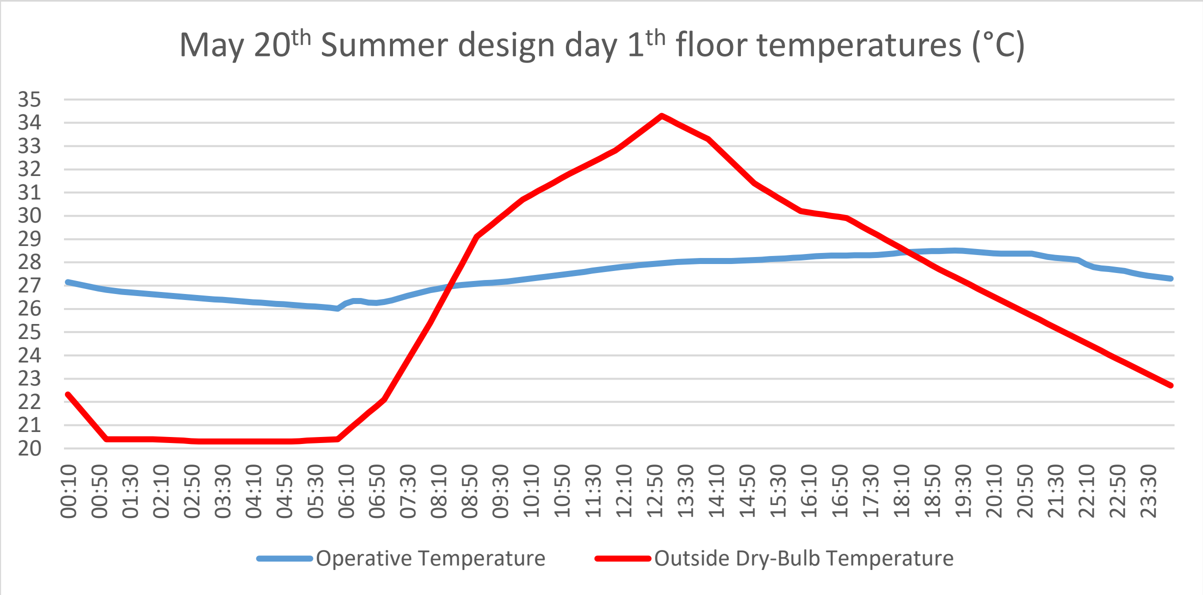

Figure 9.3 May 20th summer design day first floor temperatures

Figure 9.4 shows that the maximum amount of energy transferred through the walls is almost halved to 12W/m2 when compared with the ground floor; the material performance also changes and it takes out energy during 7 hours from 5:00-12:00hours and adds energy during 17 hours from 12:00-5:00 hours; the energy charging process takes 10 hours from 8:00-18:00 hours, then after, energy is slowly released from 18:00-8:00 hours (14 hours).

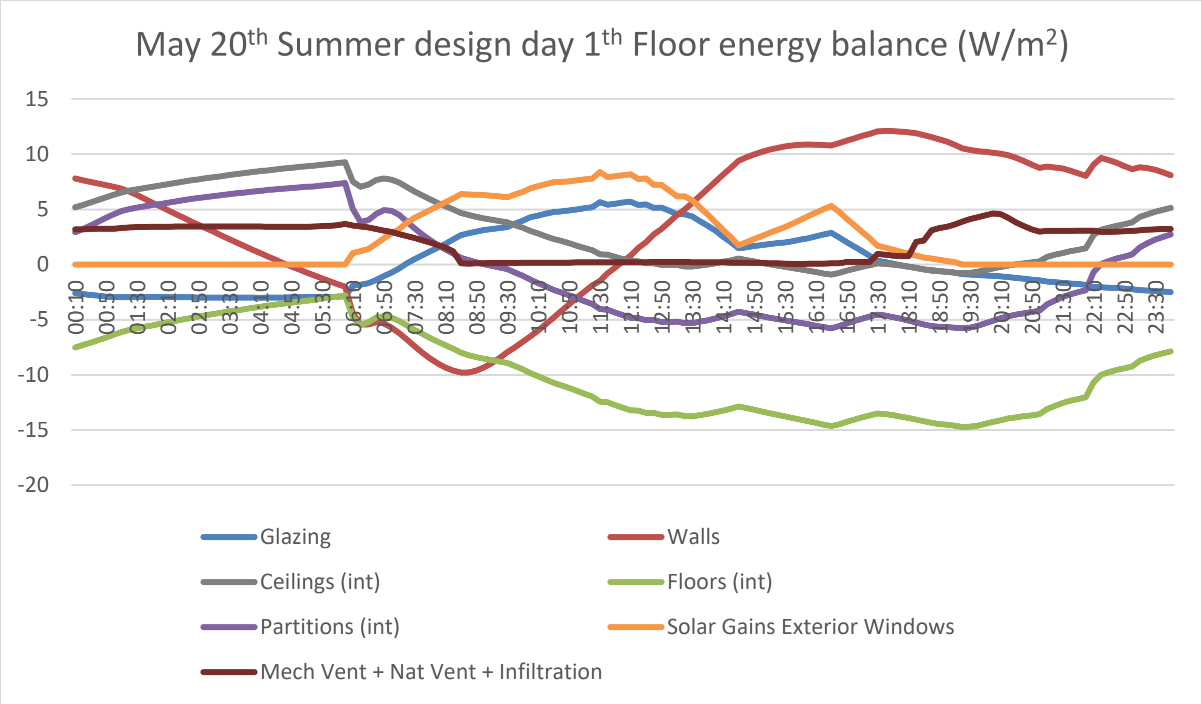

Figure 9.4 May 20th summer design day first floor energy balance (W/m²)

Ceilings (grey), partitions (purple) and internal floors (green) behave symmetrically, this means that they reach their maximum and minimum energy loads at the same tame but with a very different behaviour. Ceilings are energy neutral during most of the day (11:00-20:00), and it takes them 10 hours to get fully charged from 20:00-6:00 hours. After that it takes them 6 hours 6:00-12:00 hours to fully discharge and become neutral for 8 hours 12:00-20:00 hours. In this case, internal partitions, instead of becoming neutral for 8 hours, absorb energy/heat during 11 hours from 9:00-22:00. Here, the internal floors also absorb energy/heat constantly but less intensely than the ground floor slab with a maximum of -15W/m². Overall, Figure 9.4 shows that the combined energy from walls, direct solar gains and glazing are enough to generate 8 hours of discomfort time. It is important to note that discomfort temperatures hardly reach 29°C, just 1°C above the 28°C comfort band. Also, temperatures inside the flat remain stable all day long, with just a 3°C temperature variation.

The energy balance shown in Figure 9.4 also infers that without considering external wall insulation, summer windows shading seems to be a plausible, feasible and affordable way to reduce energy gains from direct solar gains and glazing as long as the shading elements can be removed during winter time as they would be counterproductive during the cold season (Chapter 4). Alternatively, fan forced ventilation with a 0.8m/s speed can reduce thermal sensation by 3°C, which makes it a good alternative to compensate for that 1°C above the comfort zone.

9.1.3 Second floor flat summer design day

Figure 9.5 shows operative temperatures for the second floor flat; in this case discomfort would happen most of the day during 19 hours with only 5 hours within comfort from 2:00-7:00 hours. The highest temperatures would be of 29-30°C from 12:00-22:00 hours with the maximum temperature (30°C) at 16:00 hours. This represents 2°C above the 28°C maximum comfort temperature. Note that internal temperatures vary only 3°C, from 27-30°C which even if out of the comfort zone are still rather stable temperatures if considering an outside dry-bulb temperature variation of 14°C (20-34°C).

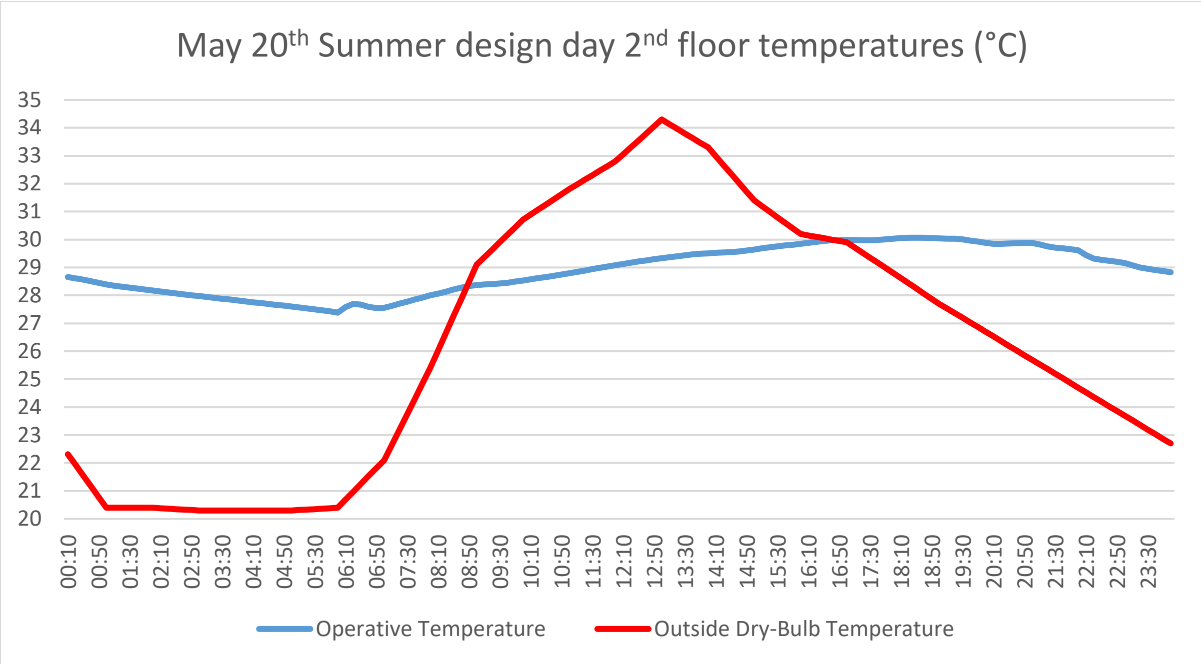

Figure 9.5 May 20th summer design day second floor temperatures

Figure 9.6 shows that the roof (grey colour) adds energy almost constantly, from 13:30-9:30 hours (for 20 hours) with only 4 hours of thermal neutrality. It is followed up by the direct solar gains (orange colour) which add energy from 6:00-18:00 hours (for 12 hours); both are the main construction elements through with which heat is transferred into the flat. Although, energy (heat) is transferred through the walls (red colour) in to the flat, the transference is not as intense as in the ground and first floors with only a maximum of 5 W/m^2. Energy is added through the walls from 13:00-2:00 hours (13 hours) and then it is subtracted during 11 hours from 2:00-13:00 hours.

The elements through which heat is taken out of the second floor flat are the internal floor (green) from 8:00-1:00 hours (17 hours) followed up by the walls (red) from 2:00-13:00 hours (11 hours) and the internal partitions from 10:00-22:00 hours (12 hours), however they are not enough to compensate for the energy that is added through the rest of the construction elements generating discomfort for 19 hours.

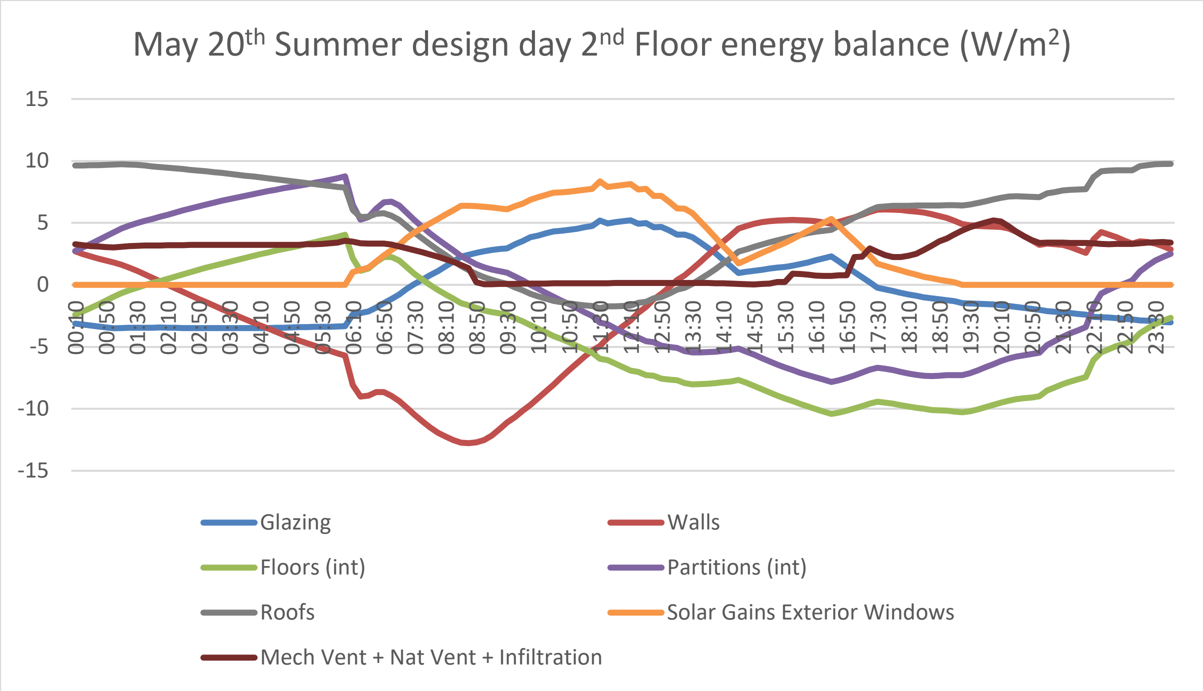

Figure 9.6 May 20th summer design day second floor energy balance (W/m2)

The energy balance in Figure 9.6 clearly shows that the roof is a major source of heat in the second floor flat. Therefore, adding insulation and a reflective finish would help improve thermal comfort conditions now and in future weather scenarios for which temperatures will be increasingly higher. Complementarily, energy gains can be further reduced by blocking direct solar gains by the use of solar shading devices during summertime only if those can be removed during winter time to prevent discomfort due to low temperatures. Alternatively, fan forced ventilation can also help improve thermal comfort as it can reduce thermal sensation by 3°C and maximum discomfort is 2°C above the comfort zone.

9.2 Winter design day analysis by floor

The chosen winter design day was December 24th and, as with the summer design day, the date was chosen using DesignBuilder software simulation tools which speedily identify the hottest and coldest weeks (and days) of the simulated year - in this case 2010. Like the summer design day, the analysis for the winter design day was done floor by floor, beginning with the ground floor flat up to the second floor flat. The analysis began by looking at operative and outside dry-bulb temperatures followed up by the energy balance analysis to better understand how energy is transferred in and out of the building to generate the operative temperatures inside of each flat.

9.2.1 Ground floor winter design day

Figure 9.7 shows the operative temperature (blue) and the outside dry bulb temperature (red) in the ground floor flat on a winter design day over a 24 hours period on December 24th in San Luis Potosi City, Mexico. The figure shows an outside dry-bulb temperature fluctuation of 22°C throughout the day with a minimum of 0°C in the early morning and a maximum of 22°C at 15:00 hours. In contrast, operative temperatures managed to remain stable with a 3°C variation inside the building over the same time period, with a minimum of 17°C and a maximum of 20°C, with only 5.5 hours (from 4:00-9:30 hours) below the comfort zone of the AMTC and by just 1°C. This means that in a cold winter day the ground floor flat will be comfortable for 18.5 hours and will only experience discomfort during the early morning hours but with a magnitude that can be easily dealt by the inhabitants.

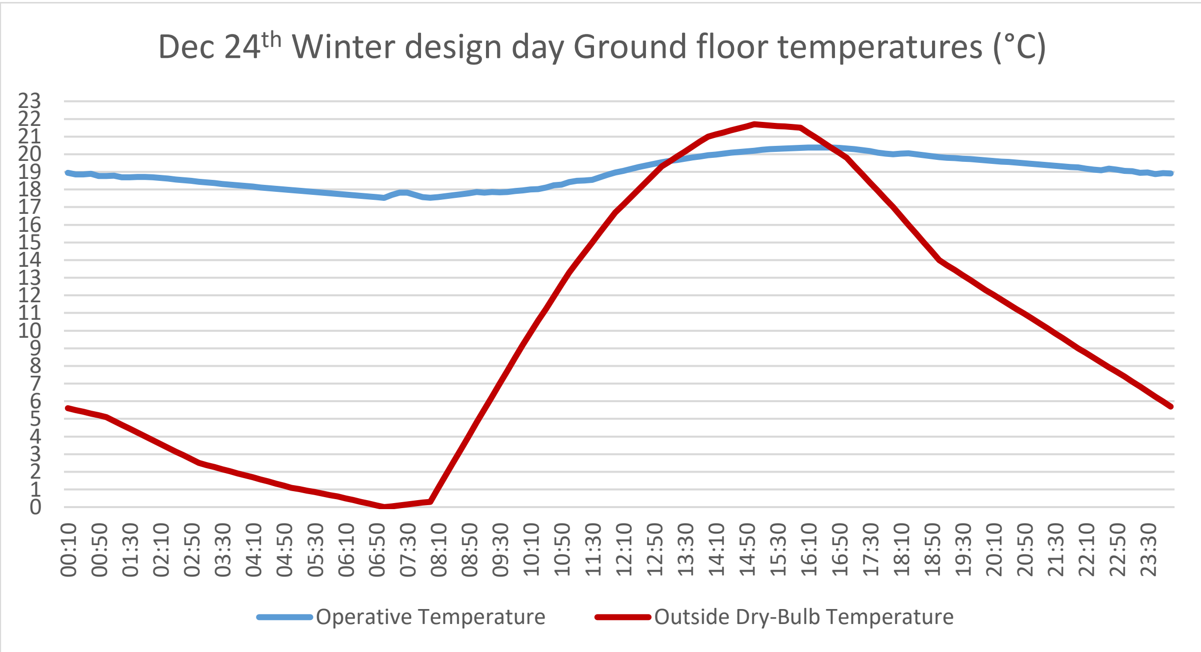

Figure 9.7 Dec 24th winter design day ground floor temperatures (°C)

Figure 9.8 shows that the main energy sources for the ground floor flat are the solar gains through the windows (orange) with 8.5 hours of sunlight from 7:30-16:00 hours. During the same time period, gains through glazing (blue) also played an important role in the energy balance and thermal comfort. In a smaller magnitude ceiling (grey) and internal partitions (purple) perform in a symmetric way absorbing energy from 10:00-16:00 hours and releasing it from 16:00-10:00 hours with the internal partitions absorbing energy for an extended time period between 10:00-22:00 hours (12 hours).

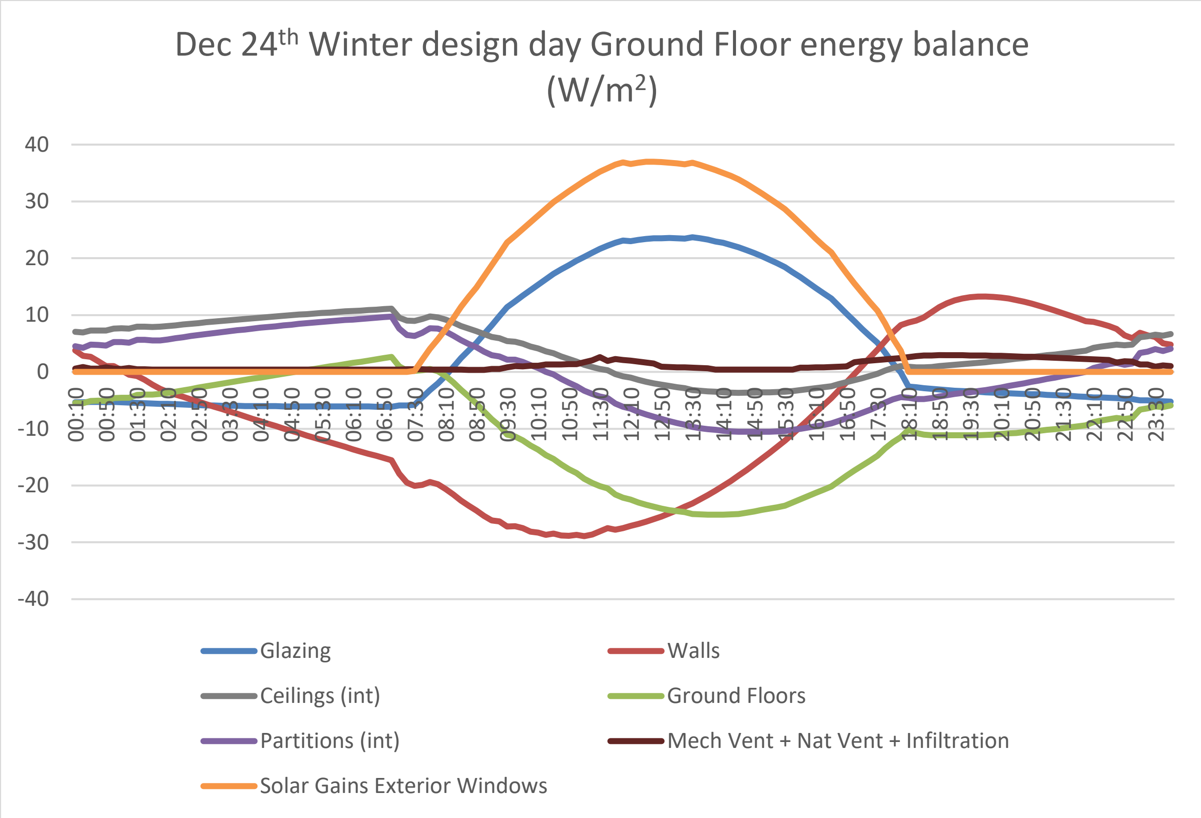

Figure 9.8 Dec 24th winter design day ground floor energy balance (W/m²)

The elements that absorb most energy, and so contribute the most in generating discomfort, are the walls (red), through which energy is lost from 1:00-17:00 hours; this represents 17 hours until the walls can heat up enough to release energy into the building for a period of 8 hours from 17:00-1:00 hours. Next is the ground floor (green) which absorbs energy from 7:30-5:30 hours over a 22 hour time period. However, discomfort produced by this element only lasts 5.5 hours and it is only 1°C below the comfort thermal band with a minimum operative temperature of 17°C.

Discomfort time in the ground floor flat can be considered rather small and as temperatures rise due to climate change discomfort time will be considerably reduced. For this particular flat/design no additional heating sources are advisable given that operative temperatures are quite stable and that the discomfort temperature is just 1°C below the thermal comfort band of 18°C.

9.2.2 First floor flat winter design day

Figure 9.9 shows operative (blue) and outside dry-bulb (red) temperatures for the 1th floor flat during December 24th, as seen previously, outside temperatures fluctuate from 0-

22°C during the day while operative temperatures remain within the AMTC comfort zone throughout the day with a roughly 3°C temperature variation from 18-21°C.

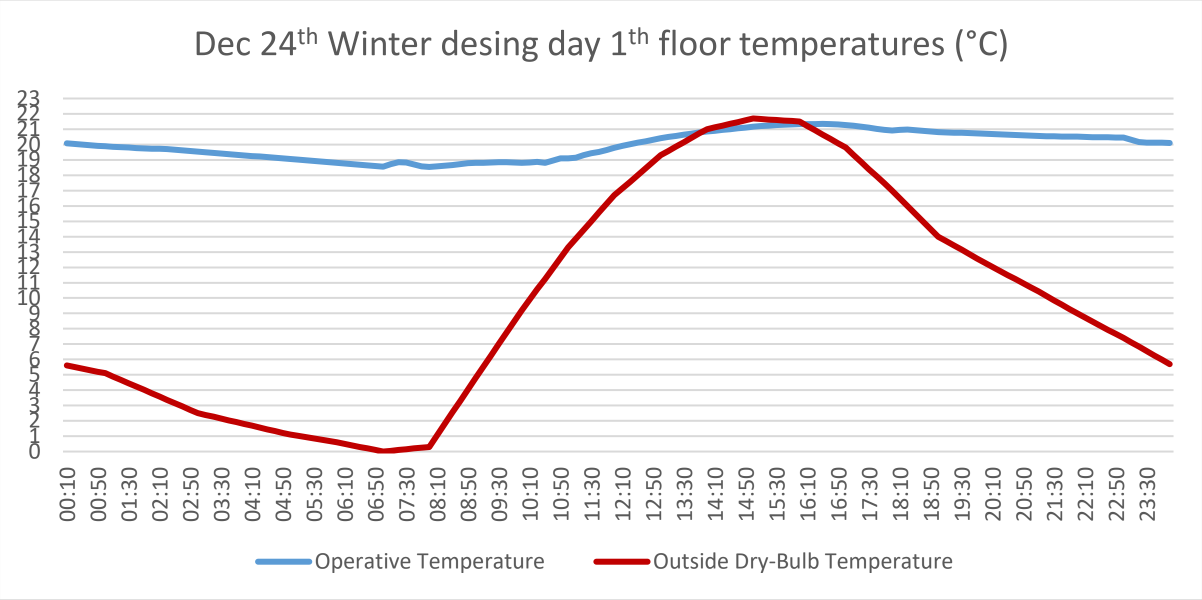

Figure 9.9 Dec 24th winter design day first floor temperatures (°C)

Figure 9.10 shows that, like the ground floor flat, in the first floor flat, energy is lost chiefly through the walls (red) from 00:00-17:00 hours (17 hours) and with less intensity through the floors (green) from 8:50-21:00 (12 hours). However, this energy loss is outweighed by the energy added through solar gains (orange) from 7:30-16:00 hours (10.5 hours) and through glazing (blue). This is because during winter the sun is low in the sky, allowing solar radiation to penetrate deeper into the flat, thereby heating it. Figure 9.10 also shows that the energy is stored in the floor (green), ceiling (grey), and partitions (purple) during the day and then slowly released during nigh time, allowing for stable and comfortable temperatures.

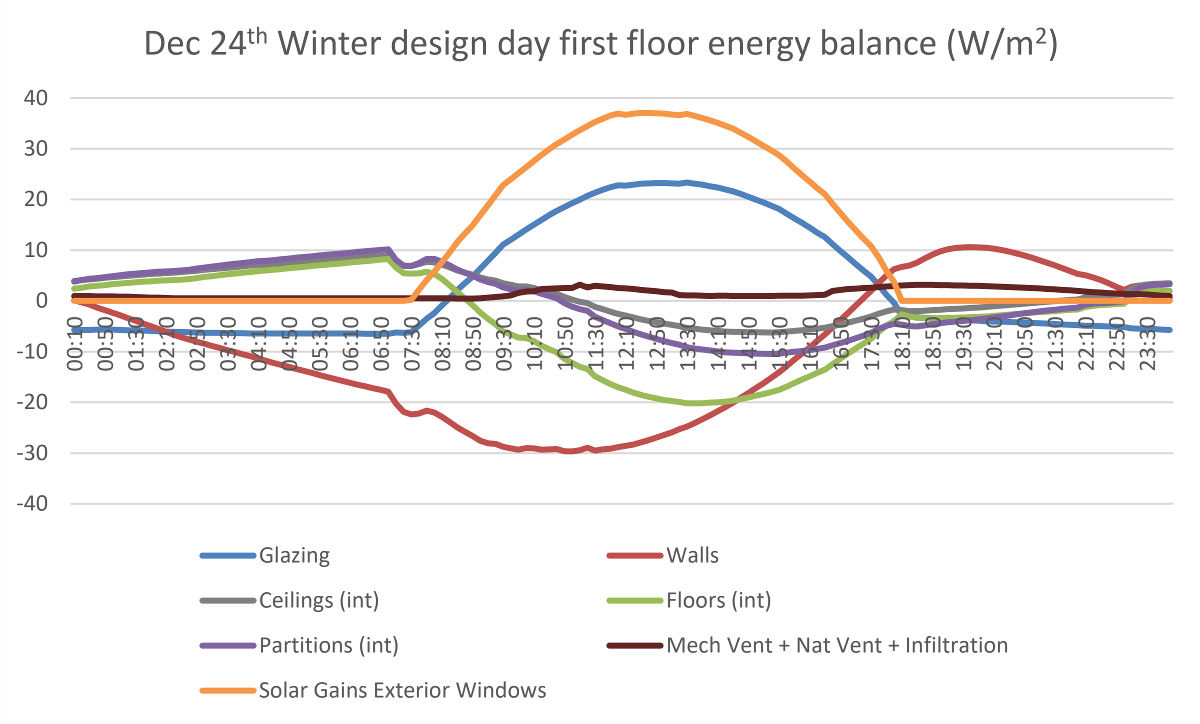

Figure 9.10 Dec 24th winter design day first floor energy balance (W/m²)

9.2.3 Winter design day second floor flat

Figure 9.11 shows that on a winter design day over a 24 hours period when the outside dry-bulb temperature fluctuates from 0-22°C, the interior of the second floor flat manages to remain within the comfort zone when employing the AMTC with a fluctuation of roughly 3°C and an operative temperature between 18-21°C similarly to the First floor flat.

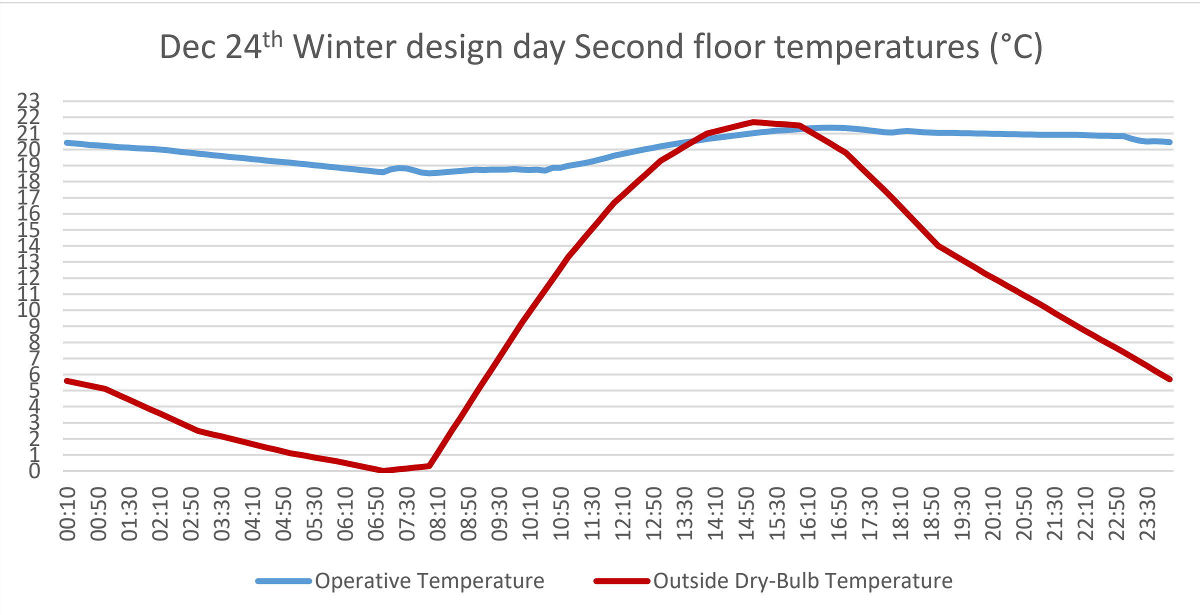

Figure 9.11 December 24th winter design day second floor temperatures (°C)

Figure 9.12 shows that in the second floor flat the role of the floors (green colour) in absorbing energy was smaller than in the other flats with less than -20W/m^2 when at its maximum and a duration from 9:00-22:00 (13 hours). On the other hand, energy loses through the roof (grey colour) were more intense than in the rest of the flats with a maximum of -10W/m^2 and also last longer, from 8:00-18:00 hours (10 hours) as is expected from a concrete roof with no insulation. However, the walls were still the main energy loss source for the second floor flat with a maximum of -29W/m^2 (similarly with the rest of floors) and a duration from 23:00-17:00 hours (18 hours).

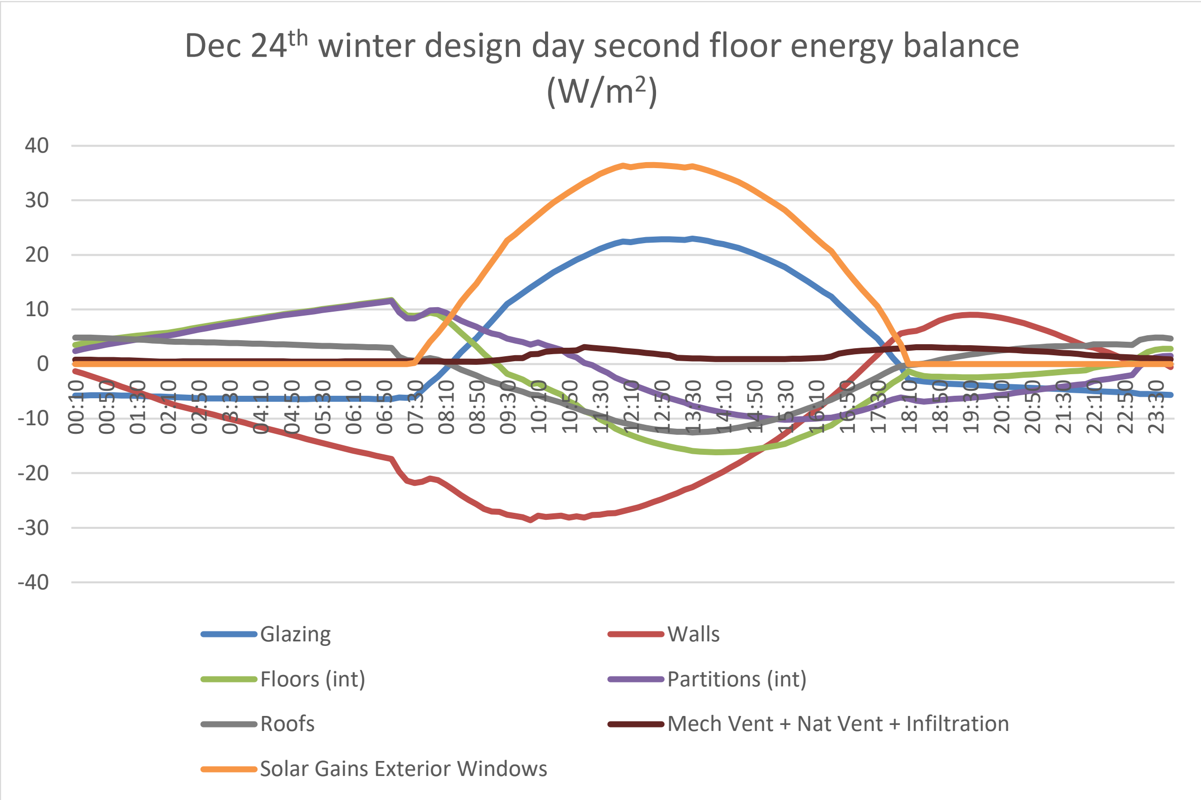

Figure 9.12 December 24th winter design day second floor energy balance (W/m^2)

Energy losses were outweighed by solar gains (orange) from 7:30-16:00 hours (8.5 hours) and through glazing (blue) from 8:00-16:00 hours (8 hours) with some help from the internal partitions (purple) which absorb energy from 11:30-23:00 hours (11.5 hours) and then slowly release it back from 23:00-11:30 hours (for 12.5 hours). Construction elements such as floors (green) and even the roof (grey) also add up some energy but in a smaller proportion and for a shorter time.

With the current construction/design set up, the second floor flat managed to remain comfortable on a cold winter day with stable internal temperatures that varied by only 3°C through a 24 hours' time period. As can be seen in Figure 9.12, direct solar gains and glazing are the main energy sources that keep temperatures comfortable inside the flat.

9.3 Conclusion and discussion

From the summer and winter design days analyses it can be inferred that thermal comfort can be improved by employing strategies on a floor by floor basis, given the differences in the thermal comfort observed seasonally by flat. For the ground floor during summertime, the uninsulated floor slab behaves like an energy/heat sink that outweighs the energy added through the rest of the construction elements providing comfortable temperatures. This very same characteristic produces some discomfort during the winter design day. However, discomfort is rather small (1°C) during winter and temperatures remain stable inside the flat with only a 3°C temperature variation throughout the day for both seasons, situation that is expected to improve as temperatures rise due to climate change.

For the first floor flat, discomfort occurs only during the summer design day (8 hours), however, average discomfort temperature is only 1°C above the 28°C comfort band and it is chiefly driven by solar gains and glazing. This seems to suggest that it can be dealt with in an affordable way by adding windows shading devices under the condition that they can be removed during winter time since winter design day analysis shows that the same solar gains and glazing are the main energy sources that provide thermal comfort throughout a cold winter day.

The second floor flat experienced discomfort only for the summer design day but for a long time period (19 hours). However, temperatures were stable, with only a 3°C variation throughout the day from 27-30°C. Similar to the first floor flat, windows shading devices would be an affordable way to improve thermal comfort. The other design strategy that would improve thermal comfort would be adding an insulation layer to the rooftop and a reflective finishing coating while keeping the thermal mass in the interior. This would help to reduce the energy added through the roof in summer. In the winter design day, the second floor flat was thermally comfortable all day long and, since the main energy sources are the solar gains and glazing, windows shading during this season should be avoided.

Note that most of discomfort time happened during summer, this is particularly interesting given that temperatures are expected to rise due to global warming and therefore, such conditions will be exacerbated. In consequence, fan forced ventilation could be considered as a cost-effective alternative to provide thermal comfort given that the maximum discomfort is of only 2°C above the thermal band and fan forced ventilation can reduce thermal sensation by 3°C with a maximum wind speed of 0.8m/s

It is also important to stress that no windows shading should be employed in the ground floor since that would only increase discomfort during the cold season and is not necessary during the hot season (ground floor only). Complementarily, no insulation should be employed under or above the ground floor slab since it greatly helps to improve thermal comfort conditions in summer time by absorbing excessive energy, this characteristic will become more effective and relevant as temperatures rise due to climate change, therefore, at least 100mm thickness or more of a high thermal mass material such as e.g. concrete should be specified.

As global temperatures rise due to human induce climate change, rooftop insulation is highly advisable regardless of building typology (single or multi floor buildings).This would constitute a climate change resilience strategy, especially because rooftop insulations is not currently a standard for the social housing sector in San Luis Potosi City. For single floor buildings, windows shading devices should be avoided in summer as in winter. Adding thermal mass to the floor slab (100mm or more) would also help to keep comfortable and stable indoor temperatures because this element behaves like a heat sink. During wintertime, sun availability should be maximized to warm the interior. Therefore, windows shading devices should be avoided in single floor buildings.

Overall, with the simulation parameters employed, the building managed to remain comfortable on a cold winter day as long as the sun was shining, which is quite common in San Luis Potosi City, where winters are mostly sunny with few consecutive cloudy days during the season. Complementarily, results from the general thermal comfort analysis conducted for the reference year 2010 (Chapter 8) showed that most of the discomfort happened during wintertime due to low temperatures; still, discomfort occurred for less than 10% of the time regardless the wall construction material employed.

The main benefit of the floor by floor analysis from this chapter was the better understanding of the different strategies that can be employed to improve thermal comfort conditions, especially during summertime. Surprisingly, the potential benefits of windows shading during summertime rather than contradicting previous results that neglected them, makes their use constrained to multi storey buildings (but avoiding its implementation on ground floors). Results highlighted the importance of avoiding the overgeneralization in the implementation of bioclimatic design strategies since factors such as the number of floors in a building have a differentiated impact on thermal comfort that should be addressed accordingly.

The more detailed analysis by habitable area shown in Appendix 4 highlights the differentiated temperature behaviour by floor, with the worst performing being the second floor. As early as 2010, the 1st floor bedroom 1 and second floor bedroom 1 reach 29°C and 30°C respectively; 1 and 2°C above the adaptive comfort temperature. Year 2020 showed a better performance, with temperatures under 28°C in all floors and habitable areas (no explanation available on the difference in performance in year 2020 as weather files were used directly as generated by Meteonorm which employs IPCC algorithms). By year 2050 discomfort shifts to the living/dining area and reaches a maximum of 32°C on the 1st floor and 34°C in the second floor. In 2080 the living/dining area and bedroom1 have a very similar temperature performance, reaching both areas almost 33°C in the first floor and almost 34°C in the second floor.

High temperatures in bedroom1 (first and second floors) is explained by their west wall being fully exposed to the sun, and even though it has no west windows, solar radiation was strong enough to transfer heat through the wall causing discomfort, especially as above the ground floor the flats do not have a ground floor slab to absorb excessive energy and thus moderate high temperatures. Although more research is needed in order to find effective ways to counteract overheating in west oriented habitable areas (especially in multi storey buildings), it might be advisable to use thicker walls with more thermal mass and/or the use of insulation for this orientation in habitable areas. Also, simulation results suggested that the use of rooftop insulation is necessary to prevent excessive overheating in multi storey buildings, however, more research on its effectiveness is necessary in order to better understand the performance of different insulation materials and recommended thicknesses. However, results shown point at the increasing effectiveness of insulation as temperatures rise due to human induced climate change.

Finally, even though the quantitative accuracy of this research should be taken with caution due to the potential simulation pitfalls highlighted in Chapter 5 (short amount of time for monitoring and validating general parameters) and throughout the research (non-standardize thermal conductivity values for construction materials), the general findings and strategies could be used as design guidelines for similar build typologies as long as adequate climate analysis, sun studies, and optimization are carried out. Again, it is important to stress that simulations hardly provide quantitate accuracy and thus, result should be taken with due care. Particularly in this chapter, high temperatures during summer design days might point towards scenarios that will become more frequent due to rising temperatures by human induced climate change.

Chapter 10. Discussion

Demographic growth will add pressure to the urban expansion of Mexican cities up to year 2050, and it is expected that by year 2030 about 83% of the population will be urban. Mexico is a developing country with almost half of its population living in poverty. Therefore, most of the housing demand will be concentrated in low income families. It is also acknowledged that global temperatures will rise through the XXI century due to human induced climate change. Therefore, new buildings as well as the existing build stock will have to cope with higher temperatures.

This scenario poses the challenge of designing social housing that will be able to withstand the expected increases in temperature by providing a thermally comfortable environment to its inhabitants, preferably without the use of expensive HVAC systems that would add pressure to the energy network and would also imply an economic burden for social housing dwellers.

Building energy simulations, parametric optimisation (windows size), and software analysis were employed to test the climate change resilience of locally appropriate bioclimatic design strategies and construction materials for San Luis Potosi City, with climate change scenarios for years 2010 (baseline scenario), 2020, 2050 and 2080. To do so, a small scale vertical social housing prototype was designed in order to test and find out the best set of parameters that would provide thermal comfort with natural ventilation through the studied time period.

10.1 Bioclimatic design strategies resilience to climate change

Through software analysis it was found that buildings in the region can be naturally comfortable during 26-28% of the time up to year 2080. It was also found that high thermal mass will increase its efficiency as global temperatures rise and it will be capable of generating thermal comfort through 8-20% of the time; therefore, it is considered as a climate change resilient bioclimatic design strategy that is also suitable for the social housing sector. Complementary bioclimatic design strategies for San Luis Potosi City are: direct evaporative cooling and two stage evaporative cooling, internal heat gains, passive solar heat gains, natural ventilation cooling and fan forced ventilation cooling. The strategy that will become less effective as temperatures rise is *heating*, up to the point in which it will become unnecessary.

A special case was *sun shaded windows* as a bioclimatic design strategy since preliminary thermal comfort simulation results showed that its implementation would increase discomfort due to low temperatures. Complimentary sun studies supported the results since it was found that being the relatively close to the Equator location provided self-shading on the south façade during the hottest summer hours, thus aiding in preventing overheating. During wintertime for a south façade, the natural low sun angle will provide enough sun penetration to make passive solar gains an effective strategy; whereas, the use of sun shading would only exacerbate discomfort due to low temperatures.

However, as research unfolded through the energy balance analysis (Chapter 9), it was found that for a global warming scenario, south windows shading can be effective under specific conditions:

- Windows shading needs to be moveable so that they can be removed during the cold season to allow for passive solar gains.
- They are most effective in upper floors in multi-storey buildings where the spaces are more sensitive to energy exchange through all the construction elements
- They are not necessary on single floor buildings or in ground floors (multi-storey buildings) whenever the ground floor slab is in direct contact with the natural ground (without insulation). This is because high temperatures will be the major source of discomfort and the ground floor slab behaves like a 'heat sink' capable of absorbing the excessive heat dissipating it into the ground, thus, aiding in providing thermally comfortable conditions.

Instead of contradicting the initial findings, it was quite interesting to find out under which conditions it is advisable to use windows shading as a bioclimatic design strategy. This is important because it offers a wider range of low energy and cost-effective strategies to provide thermal comfort in the social housing sector that can also be employed for the wider residential sector in San Luis Potosi City, Mexico.

10.2 The role of the adaptive model of thermal comfort and its implementation for the research project.

It was found that the adaptive model of thermal comfort and acceptability (AMTC) as developed for the ASHRAE-55 2013 is quite suitable for measuring thermal comfort in naturally ventilated buildings in San Luis Potosi, especially because monthly average temperatures are within the applicability parameters, but also, because the residential sector inherently offer several adaptation opportunities like opening/closing windows and clothing layering. Particularly relevant parameters that allowed for a direct application of the ASHRAE's AMTC in San Luis Potosi City are:

- The building has no mechanical cooling/heating systems.
- Occupants have metabolic rates from 1.0 to 1.3 met.
- Occupants can adapt their clothing to the indoor and/or outdoor conditions within a range at least as wide as 0.5 to 1.0 clo.
- The prevailing monthly mean outdoor temperature is greater than 10°C and less than 33.5°C (as was found in Sections 3.3 & 3.4).

The direct application of the standard (Chapter 4) allowed using a locally appropriate thermal comfort parameter that better reflects the cultural acceptancy of naturally ventilated buildings with the following thermal bands:

- 18-28°C for year 2010 (reference year)
- 19-28°C for years 2020-2080 (due to global warming)

The use of the AMTC was a very important finding during the research. Early simulations results were analysed employing the static model of thermal comfort which showed discrepancies between the amount of discomfort time and the intensity of such discomfort (Pierce PMV ET). Also important was the difference in discomfort time which, as was found in Chapters 8 & 9, can be 500% larger when employing the static model. Most importantly, it allowed measurement and comparison, providing a quantitative dimension to the research. It can also be considered as a precedent for further research on the subject.

Complementarily, national research on HVAC systems penetration by climatic region and income level (Chapter 2.6.5) showed a low penetration of such technologies in the region but a larger adoption of fans (still with a low adoption rate in relationship to the housing stock in the studied region). This accounts for a construction industry dominated by natural ventilation that when necessary employs fan forced ventilation as a coping mechanism during the hot season. This scenario supported the adoption of the AMTC especially in the social housing sector in which the implementation of HVAC systems would represent an economic burden for homeowners (families).

10.3 Building energy simulations and parametric optimisation results

As mentioned in Chapter 5 there is a gap between simulation and reality and, although it is acknowledged that any local research would benefit from extensive monitoring of weather, natural ventilation, and user's behaviour (chiefly) in order to gain quantitate confidence, there is also reasonable methodological consistency throughout the research that allows for the general discussion presented in this and the following chapter. Hence, it can be reasonably argued that *high thermal mass* (Table 3.8) is one of the most resilient bioclimatic design strategies (up to 2080) suitable for the social housing sector, along with natural ventilation. In consequence, the three most commonly employed wall construction materials with high thermal mass (red brick, hollow concrete block and extruded red brick) were simulated in order to find out if they would be capable of providing thermal comfort with natural ventilation.

It was found that the three construction materials, when employed as part of a bioclimatic design that took in to account careful building orientation and windows sizing, could provide thermally comfortable conditions almost year-round when employing the AMTC for analysis. The most effective wall construction material was extruded brick, followed by hollow concrete block and lastly red brick; all of them displayed relatively small differences in their capacity to provide thermal comfort. The results were consistent for the present time but also for future weather scenarios. This means that the three construction materials might be able to provide climate change resilience (from the thermal comfort perspective) since they managed to produce comfortable conditions for 90% of the time or more under ideal simulated conditions, with less than 876 hours out of the comfort thermal band in a year for every studied scenario.

It was also found that discomfort due to low temperatures will prevail until the year 2020. After then, discomfort will shift to being predominantly due to high temperatures, a phenomenon that will be exacerbated by global warming. This means that by 2080 most of the discomfort will be due to high temperatures, and even though the three construction materials were effective in providing comfortable temperatures most of the time, fan forced ventilation will become increasingly effective. This is because discomfort high temperatures are roughly 3°C above the comfort band and it is acknowledged that fan forced ventilation can reduce the thermal sensation by as much as 3°C, making it particularly effective for hot summer days up to 2080.

Parametric optimization, and particularly window sizing, should be a regular practice for passive design given the strong dependency on sun availability for passive gains in winter and its avoidance during the hot season. Although it is advisable to do this for every project as conditions and needs change. It was found that a window to south wall ratio between 40-60% would provide a good balance between natural lighting, sun availability in winter and its avoidance in summer. Further research is necessary for windows sizing for other orientations.

Slab thickness also plays a role in thermal comfort and it is recommended to have slabs/rooftops of at least 200mm thick (more if possible) since this would aid in generating more comfortable and stable internal temperatures. Particularly interesting was to find out that an un-insulated ground floor slab would behave as a heat sink, absorbing most of the heat, and dissipating it into the ground, thus, playing a major role for thermal comfort on single floor buildings, and in ground floors in multi-storey buildings.

On single floor buildings, a 200mm thick roof top slab with waterproofing and reflective finish should be enough to provide thermal comfort conditions, as the floor slab would be able to manage discomfort due to high temperatures. This is not the case for multi-storey buildings, which are more sensitive to gains though walls and the roof top. In this case, insulation on the external side of the roof top slab is advisable as this would retain the advantages of the internal high thermal mass while avoiding excessive energy gains. This feature will become more relevant as temperature rise due to climate change.

10.4 Final considerations

This research has been made possible by incremental steps that follow the structure of the dissertation in which each chapter helps and supports the next one. Results and analysis being based on simulations hold an intrinsic series of limitations that need to be addressed before going though the final considerations. On a first instance, the climate change scenarios are based on algorithms from year 2014 and future updates on IPCC climate change scenarios will affect the results shown, especially from the quantitate perspective. On another hand, the general validation of simulation parameters rest on a small amount of monitored data sets during winter time and although, construction materials and design strategies of the monitored house are similar to the ones employed for the prototype, a more extensive monitoring (at least internal/external temperature for a whole year) would greatly reduce uncertainty on the buildings' behaviour. Hence, simulation results shown should be considered form a general perspective rather than from a quantitate one.

The findings open a discussion at various tiers. Firstly, they highlight the relevance of updating the curricula in local architecture schools to incorporate bioclimatic design as part of their programme. This should be done in such a way that incorporates digital design and evaluation especially during the early design stages when the energy saving strategies are more efficient. This would imply, among other things, the evaluation/adoption of software capable of sun studies and thermal comfort simulations with an architecture friendly interface.

Secondly, the adoption of the AMTC should be accompanied by the creation of minimum bioclimatic design standards, or the publication of bioclimatic normativity that would promote the adoption of bioclimatic design as a regular practice and with measurable targets/outcomes of thermal comfort. On the other hand, more detailed research should be done in order to validate and, if necessary, modify the adaptive thermal band for San Luis Potosi from this research. It follows that another potential impact is the use of the adaptive thermal band to regulate maximum and minimum temperature set up in locally commercialized AC systems so that temperatures in mechanically ventilated buildings remain close to their naturally ventilated counterparts. This can be considered as a local energy efficiency strategy that would avoid a 'lock in' for peoples' preference over AC systems in buildings, situation that would only increase cooling energy demand with its pervasive effects on the environment, doing so would be consistent with the already mentioned low AC penetration on the region, but most importantly, as a socially responsible policy sensitive to low income families and their right to a healthy and thermally comfortable environment.

Finally, research results seem to support the idea that it might be possible to build thermally comfortable climate change resilient social housing in San Luis Potosi City, Mexico by employing locally available construction materials with high thermal mass and natural ventilation as the main bioclimatic design strategies, especially for single floor buildings. As results show, in multi storey buildings, the temperature behaviour changes, making upper floors more sensitive to high/low temperatures, suggesting the need for tailored strategies that can help to counter high temperatures (because those seem to be the source of most of discomfort time and therefore, will only worsen as temperatures increase due to climate change).

Also, the effect of user's behaviour and the natural ventilation regime would benefit from more extensive research that could help to better correlate them and understand their impact on thermal comfort for the studied location. Finally, the AMTC proved to be particularly suitable for naturally ventilated buildings in the region and as a parameter that allows to measure thermal comfort in passive buildings with strong potential for future locally oriented research.

Chapter 11. Conclusion

11.1 Research significance

Although bioclimatic design is widely acknowledged as an alternative for energy efficient design in architecture, its implementation has been more a case of a *leap of faith* due to the difficulties around assessing its effectiveness and in measuring its capacity to provide thermal comfort in naturally ventilated buildings in Mexico. This research proposed the use of building energy simulations as a cost-effective manner to test the effectiveness of bioclimatic design strategies for San Luis Potosi City, Mexico for the present time and for future weather scenarios (years 2010-2080), with two main objectives: firstly, achieving energy efficiency with a passive design approach, and secondly creating climate change resilient social housing as an adaptation strategy to climate change. Through the research process it was found that the adaptive model of thermal comfort and its acceptance as developed by the ASHRAE 55-2013 is an effective approximation for developing a local standard for naturally ventilated buildings. In that sense, this is one of the few researches of this type in the region and can be considered as a precedent on which to build up future research in the subject. The research also provided some insights for the better implementation of high thermal mass as bioclimatic design strategy for social housing and for the residential sector in general. Results are topical since they potentially provide a low-cost alternative for achieving energy efficiency and thermal comfort in the social housing sector in a mid-income country such as Mexico, in which nearly 50% of the population lives in poverty.

11.2 Research Main findings

This section was structured by answering the research questions (Section1.3) where the first and more important one that helped in guiding and articulating the research was:

How to design free running social housing that will be comfortable year round at present time and during its estimated 50 years life cycle taking into consideration the expected rise in temperatures that the planet will experience due to climate change during the same time period for San Luis Potosi City, Mexico?

In order to be able to provide an answer to the complex question, it was necessary to develop the full research and by doing so, to provide and answer the complementary research questions in a knowledge incremental process. Those complementary questions are presented sequentially and in order to avoid unnecessary repetition of information and data, the reader will be referred to the specific section, table, or figure of the thesis whenever relevant.

Given San Luis Potosi City, Mexico weather conditions and geographical location, what are the most effective bioclimatic design strategies that can be implemented in the social housing sector in order to optimize thermal comfort? And *which bioclimatic design strategies will still be effective in providing thermal comfort under future weather scenarios of climate change in the social housing sector?*

Bioclimatic design strategies can be considered as design alternatives for energy efficiency, some of them are complementary whilst others can be mutually incompatible and the decision for one over another should follow a conscientious analysis of the site, local weather, building typology and locally available construction materials. Table 3.8 in Section 3.5 shows a list of bioclimatic design strategies and their changes in performance due to climate change (years 2010, 2020, 2050 and 2080) in San Luis Potosi City, Mexico. For the social housing sector, it was found that the most effective bioclimatic design strategies resilient to climate change are:

- High thermal mass
- High thermal mass with night flushing
- Internal heat gains, and
- Passive solar gains with high thermal mass

Complementarily, *natural ventilation cooling* and *fan forced ventilation* were found to be effective both now and, in the future, (up to year 2080) for the provision of thermal comfort. It was interesting and unexpected to find that *sun shaded windows* in a south oriented façade as bioclimatic design strategy can be counterproductive for thermal comfort in opposition to what literature review and software analysis suggested. Instead further research showed that its effectiveness is conditional on the following:

- Need to be removable during the cold season, otherwise, it will exacerbate discomfort due to low temperatures by diminishing the effectiveness of *passive solar gains with high thermal mass* which is quite effective in providing thermal comfort during the cold season. According with current climate change projections, this strategy will be efficient until year 2050 which translates into 30+ years of effectiveness.
- It is most effective in upper floors in multi storey buildings and can even be ruled out in single floor constructions and ground floors under the condition that an uninsulated ground floor slab is in place. This is because when coupled with the natural terrain, the ground floor slab dissipates excessive heat, thus, aiding in thermal comfort, especially during the hot season.

What locally available construction materials will be the most effective in providing thermal comfort at present time and also under future weather scenarios (climate change resilience) in tune with the locally appropriate bioclimatic design strategies?

The most commonly used and locally available wall construction materials for the social housing sector are red brick, hollow concrete block, and extruded red brick. Since all of them are characterized by their high thermal mass, they were tested in their capacity to provide thermal comfort up to year 2080. With the available simulation data, and as part of a wider bioclimatic design strategy (high thermal mass, windows optimization, orientation and natural ventilation) all of them managed to aid in generating thermal comfort for more than 90% of the time. However, the most efficient material was extruded red brick, followed by hollow concrete block and, lastly, red brick. It is very important to note that simulation results showed that the construction materials' effectiveness were conditional upon their implementation as part of a broader bioclimatic design strategy that considered building orientation, windows sizing, building typology, and local weather conditions. This meant that the sole implementation of the construction materials was not enough to consistently provide comfortable thermal comfort conditions nor climate change resilience.

On the other hand, concrete slabs and roofs are commonly used in social housing and given concrete's high thermal mass, its implementation should be encouraged with a thickness of 200mm or more. For rooftops in multi storey buildings, and when the rooftop slab has a 150mm thickness or less in single storey buildings, the use of insulation and a reflective coating finishing are advisable, as they would reduce heat gains (hot season) as well as heat loses (cold season).

How and why can the AMTC be employed as a locally appropriate index for thermal acceptancy in the residential sector?

During the research process it was found that one of the main challenges was to determine a way to measure thermal comfort in naturally ventilated buildings because all the widely employed thermal comfort indices were developed for the design of HVAC systems. In contrast, temperatures in a free running building will vary with external seasonal and daily temperature fluctuations and it is until recent years that the concept of thermal comfort has been further developed to be consider also as a climate and culture specific phenomenon for which nations such as Japan, China, and Malaysia are developing their own comfort standards (Humphreys, et al., 2012, p. 58). Although the development of a local thermal comfort standard for San Luis Potosi City would be the best practice, doing so surpassed the scope of this research and would constitute a research on its own. This limitation was overcome by the direct implementation of the adaptive model of thermal comfort as developed for the ASHRAE 55-213. This was possible because local weather conditions and the residential sector meet the requirements for the standard implementation, leading to the following temperature comfort band for San Luis Potosi City:

- Year 2010: 18-28°C
- Years 2020-2080: 19-28°C

Implications of this finding go beyond the mere capacity to measure thermal comfort, as research findings also suggested that people in the region had a wider tolerance to high temperatures than those assumed when employing the static model of thermal comfort (20-25°C). This meant that the adaptive thermal band could potentially be employed to set operative temperatures on AC systems commercialized in the region as an energy saving strategy. The implementation of the AMTC in San Luis Potosi City is also supported by recent studies on AC systems adoption in Mexico (CONUEE/GIZ, 2016) which showed a very low penetration rate, meaning that most of the people are used to a natural ventilation regime and, therefore, have a wider tolerance to higher temperatures, which supported the use of the AMTC. However, it is still necessary to develop more research on the subject in order to obtain statistically meaningful results that can be used more effectively. The situation suggests opportunities for the creation of energy norms and standards that would avoid the indiscriminate adoption of AC systems in forth coming years as global temperatures rise and for the successful widespread implementation of bioclimatic design in San Luis Potosi City, Mexico.

How can building energy simulations be employed to test the effectiveness of locally appropriate bioclimatic design strategies, construction materials and windows sizes?

Building energy simulations and parametric optimization are cost-effective ways to test the capacity of bioclimatic design strategies in providing thermal comfort for the present time and for future weather scenarios. However, it is important to make sure that the information that is input into the software reflects the real conditions of the building and its context, such as construction materials thermal values, ventilation, weather files, building orientation and, if relevant, other constructions. To do so, it is very important to make use of national and local norms and standards such as those employed for the thermal conductivity values of the local construction materials and the construction codes whose requirements where met during the design phase of the prototype studied in this research. As already mentioned in the methods (Section 1.5), for this research DesignBuilder software was chosen as the main building energy simulation tool given that it has been used by several researchers all over the world in the last decade and managed to provide results that validate its capacity to simulate thermal comfort, energy consumption and building physics in general in a consistent manner.

Complementarily, the general simulation parameters were validated to a limited extent by the use of data loggers that allowed recorded temperature and relative humidity for a short time period and compare them with the same parameters obtained by simulating the very same building with DesignBuilder software. Simulation results showed a very similar performance between the real building and the simulated one for a short period of time during wintertime and under very specific conditions (Chapter 5). Also, the validation process helped in fine-tuning the natural ventilation rate estimated for the building. Finally, it must be underlined that a simulation is not reality itself but a representation of it and as such it will always fall short when predicting the complexities and intricacies of reality itself. However, a systematic simulation process that manages to incorporate as many local variables as possible helps to produce a more reliable representation of the reality that is being studied. This was attempted through the contextual analysis phase of the research, which greatly contributed in the development of a prototype that reflects its context at many tiers.

How can simulation parameters be validated to more accurately represent reality and provide a higher degree of certainty about the expected thermal comfort simulated outputs?

The simulation parameters validation process was done using data loggers that allowed temperature and relative humidity to be recorded in a house build with the same construction materials employed for the red brick prototype over a small period of time (Chapter 5). The house employed for data gathering shared several other characteristics with the prototype that allowed the comparison for validation, chiefly:

- Bioclimatic designed
- High thermal mass
- Naturally ventilated
- Especial attention to the building orientation
- Same construction materials than those employed in the prototype
    - Same window/glazing materials
    - Same finishes and wall renderings
- Similar windows proportions and sizes

It is also important to note that the author designed the house in which the data loggers were placed and that the house was built by a local contractor during the first year of the PhD research. This situation allowed a good information exchange with the contractor and with the owners throughout the building phase. This, in turn, facilitated the digital simulation and the implementation of the data loggers. In this case, the control over the design of the house and the prototype was key for the validation process of the simulation parameters.

How can research results be used to improve thermal comfort and climate change resilience in the residential sector and the construction sector in general in San Luis Potosi City, Mexico?

Research findings pointed towards the idea that climate change resilience from the thermal comfort perspective can be achieved in the social housing sector and thus in the residential sector in San Luis Potosi City by employing natural ventilation and locally available construction materials. Although more research and monitoring are necessary to better support the building energy simulations, it is possible to draw the following general design guidelines:

- Use of high thermal mass as the main bioclimatic design strategy.
- Careful attention to the building design and orientation.
- The use of parametric optimization, especially for windows sizing during the early design stages is a very cost-effective design measure. Complementarily, a window to south wall ratio between 40-60% will perform well, however it is better to keep it as close to 50% as possible.
- Windows and doors installation should be as air-tight as possible to minimize air leaking, this is especially beneficial during the cold season.
- A 3-4mm single glazing window performed satisfactorily in this research which supports Mora's research (Mora Juarez, 2014, p. 32) who found that thermal mass is more effective in combination with single glass when external air temperatures fluctuations are large on a daily basis.
- A window design/position that promotes natural cross ventilation play a very important role for thermal comfort.
- From the best to worst performing: extruded red brick, hollow concrete block, and red brick are all efficient wall construction materials that if employed as part of a bioclimatic design strategy seem to be able to provide thermal comfort climate change resilience up to year 2080. The choice of one over another can be subjected to efficiency, budget, and practicability tests; however, it must be kept in mind that it will always be better the use of the best performing construction material because even small differences in performance, when summed up with the rest of the building components can bring about important energy savings and improved thermal comfort conditions.

- On a south oriented façade windows shading devices are only advisable on above ground floors in multi storey buildings and under the condition that they can be removed during the cold season as they would exacerbate discomfort due to low temperatures.
- Ground floor slabs perform better if un-insulated because they behave like a heat sink getting rid of excessive amounts of energy that produce discomfort, this effect will become more relevant as temperatures rise due to climate change. Also, a thickness between 50-100mm or more if possible is advisable as this adds thermal mass to the building.
- In a single storey building designed following bioclimatic design principles a rooftop with a concrete thickness of 200mm or more can be laid without the use of insulation, provided that the ground floor slab is coupled with the natural ground, that water proofing is in place, and also that a reflective finish is employed.
- In multi-storey buildings, it is divisible the use of insulation on the rooftop because the high-thermal mass of the building is not enough to cope with this large exposed area during very hot or cold days.
- Setting up HVAC systems temperature band with the AMTC (18-28°C up to year 2020 – 19-29°C years 2020-2080) is an energy saving strategy, especially as global temperatures rise due to climate change because it considers local people's thermal acceptability and preferences.

Overall, the findings can also be considered as 'pathways sketches' for local construction industry adaptation strategies for climate change resilience because their implementation seem to potentially indicate to allow for residential buildings to remain naturally comfortable up to year 2080 in San Luis Potosi City, Mexico without having to incur into extra construction or energy expenses. Although, further research is required to provide robust data sets and more quantitate certainty about the results shown in this research because in the end, simulations are not reality, just an approximation to it.

11.3 Research limitations

Research limitations are shown in this section by following the research structure and whenever appropriate the actions taken to diminish potential negative impacts are also described.

Although verticality is suggested as an alternative for tackling urban sprawl and segregation, the effect and extent in which this particular building typology would contribute to abate those issues is uncertain. The research project aimed to be responsive to a wider perspective of the urban characteristics and challenges of Mexican cities. However, the contribution to this particular aspect of the research is more of a speculative nature as no means to measure sprawl or segregation are provided because doing so would have diverted time and energy from the main focus of the research which is about thermal comfort climate change resilience. Instead, the contextual analysis contributed to physically shape the prototype opting for small scale verticality as a locally appropriated design.

During the research process, very little technical information was available about the prototypes designed to test the Mexican housing NAMA with principles from the Passivhaus Institute. Also, access to the simulation tools is relatively recent and limited to real estate developers who need to take part of special training and certification, situation that made difficult a direct comparison between the proposed prototype and its equivalent under compliance with the SISEVIVE-ECOCASA programme. Since no direct comparison in energy performance was possible, this research stands as an alternative for energy efficiency in the social and residential housing sectors and as a contribution to research on bioclimatic design and naturally ventilated buildings in San Luis Potosi City, Mexico.

Probably the most important limitation of this research is due to the fact that the results obtained are based on simulations of a single building (two if considering the house employed for validation). Although this allowed more control over the design and simulation parameters, it also meant that, especially for the adaptive model of thermal comfort, there was a lack of statistical significance that in turn would allow for its direct and wide implementation for policy making at local level.

Complementarily, the direct implementation of the ASHRAE 55-2013 adaptive model of thermal comfort can be considered both as a limitation and as an asset. A limitation because it lacks a more robust statistical significance that in turn would provide more validity for a wider and direct implementation of the simulation results[15], especially for supporting policy making. As an asset because special attention was put on employing the ASHRAE standard since the early research stages which include, weather files and bioclimatic design strategies software analysis/interpretation and DesignBuilder software set up and comfort data interpretation; but especially because the general local climatic conditions and building typology matched those form the norm, thus allowing for a direct implementation. This implies that even though there is a lack of robust local statistical data for San Luis Potosi City, the compliance with the norm suggests the viability of the adoption of a locally appropriate AMTC.

[15] This refers to the lack of local robust statistical data for San Luis Potosi City. The AMTC from ASHRAE 55-2013 is indeed based on robust statistical data.

For the validation of the simulation parameters the main limitation was the short amount of time (over a month) in which data loggers were able to record temperature and relative humidity due to technical restriction because no Wi-Fi enabled data loggers were available at the time that would have allowed for remote monitoring during a more extended time period. Also, the lack of an on-site weather station, that would have allowed a direct measurement and comparison of external-internal conditions, with a higher degree of certainty about the building's performance versus the simulated one. Finally, monitoring of users' behaviour, like window and door operations for cross comparison with abrupt temperature changes. The time limitation was, in the end, a consequence of economic restrictions that did not permit a longer stay in San Luis Potosi, Mexico for the direct measurement and data collection through the data loggers, weather station etc. Therefore, it is acknowledged that the quantitative aspect of this research should be considered with due caution in favour of the general findings and design guidelines.

Also, the parametric optimisation was limited to the aspects of the building that impacted on construction costs and thermal performance of the whole building. Although this is not bad *per se*, it restricted the set of parametric variations to those that would have a more direct impact for thermal comfort e.g. windows were simulated with a single 3-4mm glass pane and no other options were simulated such as, double or triple glazing because they would be a costly alternative.

11.4 Future research

There are still many opportunities for the development of further research on parametric optimization, especially for testing different windows types and construction materials that would allow to extrapolate results for the whole construction industry. Most importantly, it would be beneficial to explore the potential of bioclimatic design and natural ventilation in providing thermal comfort for a wider variety of building typologies, such as offices and commercial buildings. The later could also help to develop design guidelines for climate change adaptation and resilience for the local construction industry.

This research project highlights and supports the viability of developing a locally appropriate adaptive model of thermal comfort which in turn would be the foundation for policy making for:

- Buildings and AC systems temperature set up
- Energy savings in buildings for thermal comfort with measurable and achievable parameters
- Natural ventilation and bioclimatic design norms and regulations
- Potential integration of the AMTC as part of the SISEVIVE-ECOCASA programme

- Could be considered as part of the national decarbonisation strategy in the construction sector
- Could be part of climate change adaptation strategies for the residential and construction sector in San Luis Potosi City, Mexico

Complementarily, the methodology can be the foundation for analogous research in different climatic regions in Mexico. Doing so would aid in normalizing bioclimatic and passive design as a standard architectural practice with great potential for energy savings at national level while providing minimum thermal comfort standards for larger population groups in the country.

Finally, an alternative research area consists in providing technical aid for self-construction so that the population segment(s) in peripheral urban areas and/or rural areas neighbouring San Luis Potosi City, can effectively incorporate bioclimatic design principles. This strategy would require a participative methodology involving all stake holders, but especially the homeowners. The effectiveness and scope of such a project would be reinforced by incorporating the support of local universities (Architecture departments) and the public sector. Special attention should be given to studying the feasibility from a political and legal perspective since those might play a pivotal role due to the legal intricacies related with land tenure for the targeted sector.

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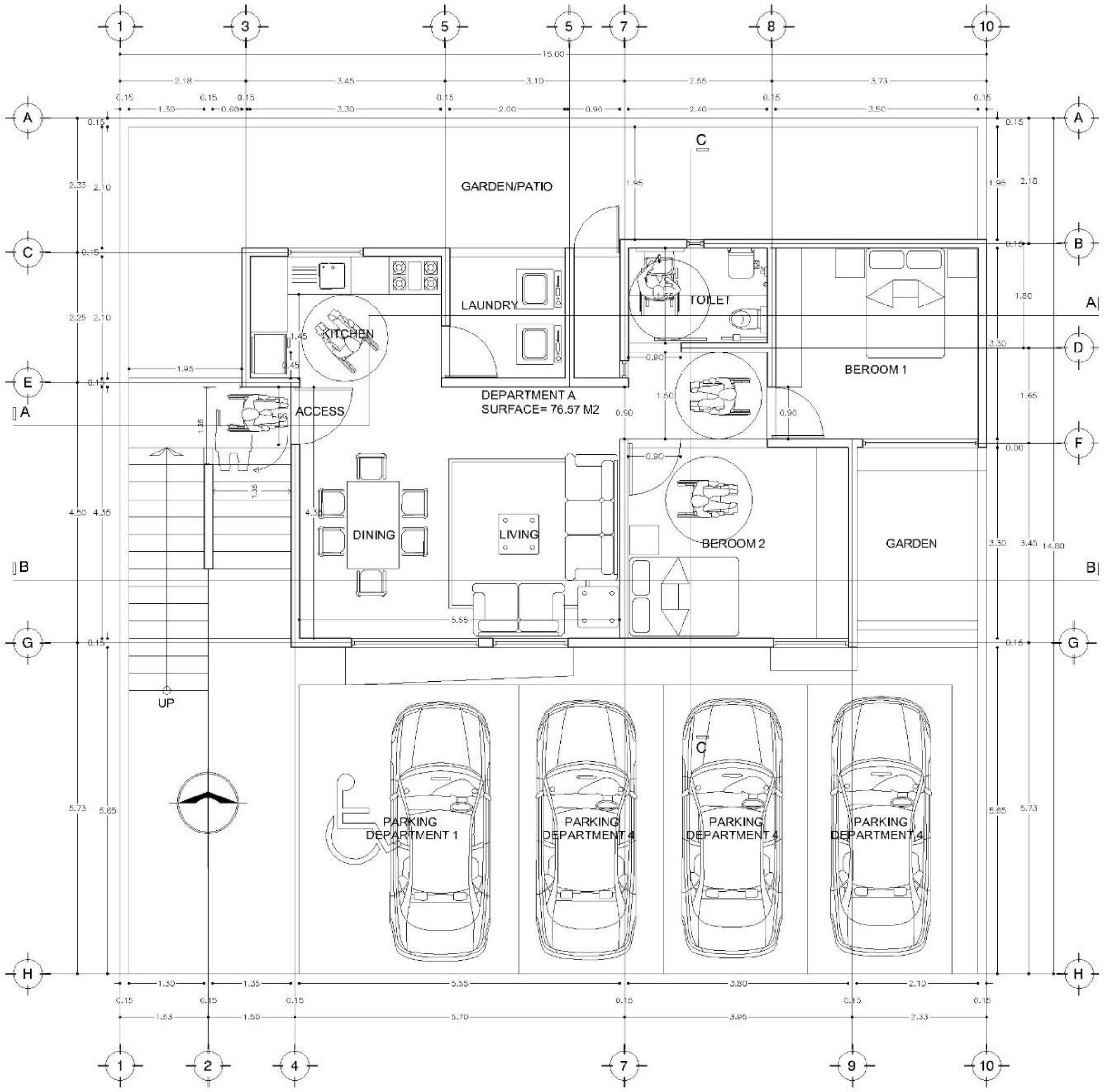
Appendix 1: Shading devices sun study

The prototype was modelled with DesignBuilder software as part of the dissertation for the MSc in Sustainable Environmental Design in Architecture (2013-2014) at the University of Liverpool titled ‘Vertical Social Housing Prototype for low income families in San Luis Potosí City, Mexico’. The prototype was designed with high thermal mass as the main bioclimatic strategy. The construction materials chosen for testing were; hollow concrete block for the walls, 20cm thick slabs/roof, cast in situ colonnades (conventional construction system for social housing in San Luis Potosí, Mexico). The thermal properties of the materials are those found in Table 3.13 as they represent the local normativity and standards, also natural ventilation was set up.

Shading devices sun study



GROUND FLOOR (DISABLED)
WITHOUT SCALE

Figure A1

Figure A1 shows the ground floor plan of the prototype employed for the sun studies and it is presented just for general information and it repeats itself in the upper floors.

The sun study was done with Ecotect for winter time December 21th at 9:00, 12:00 & 15:00 hours. For summer time, the simulated date was June 21th at 9:00, 12:00 & 15:00 hours. As can be seen, during winter time, the shading devices block the sun in the early morning hours and in the afternoon/evening adding discomfort time due to low temperatures. During summer time, the south oriented façade remains shaded by the building itself almost all day long supporting the initial conclusion of the ineffectiveness of shading devices for San Luis Potosi City, Mexico.

Sun study winter time

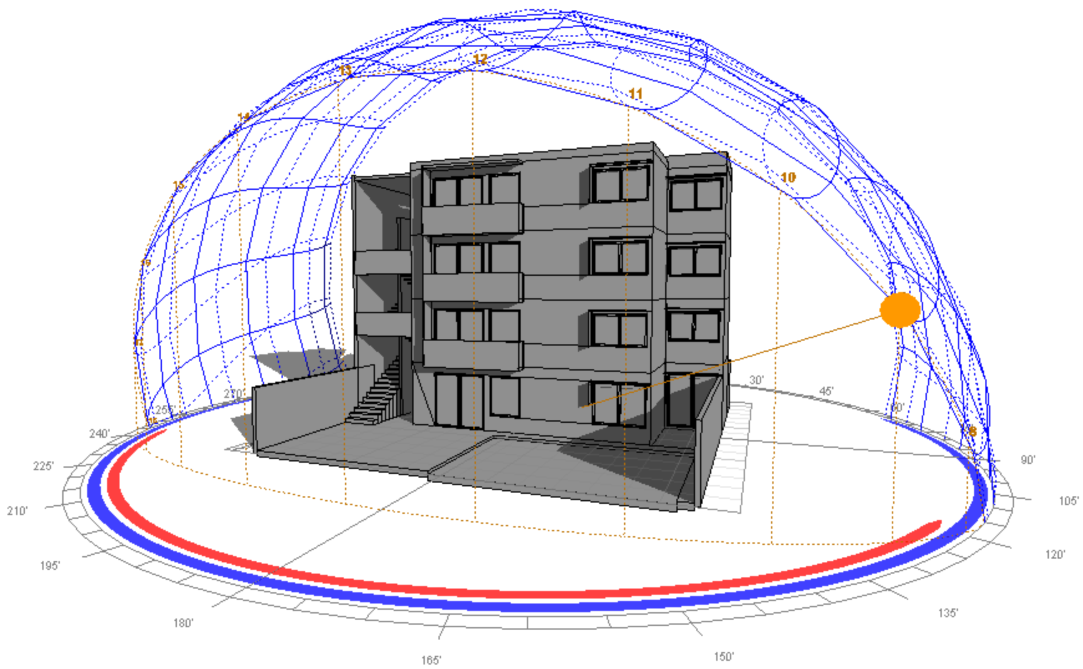


Figure A2 South façade sun study. December 21th 9:00 hours with shading devices

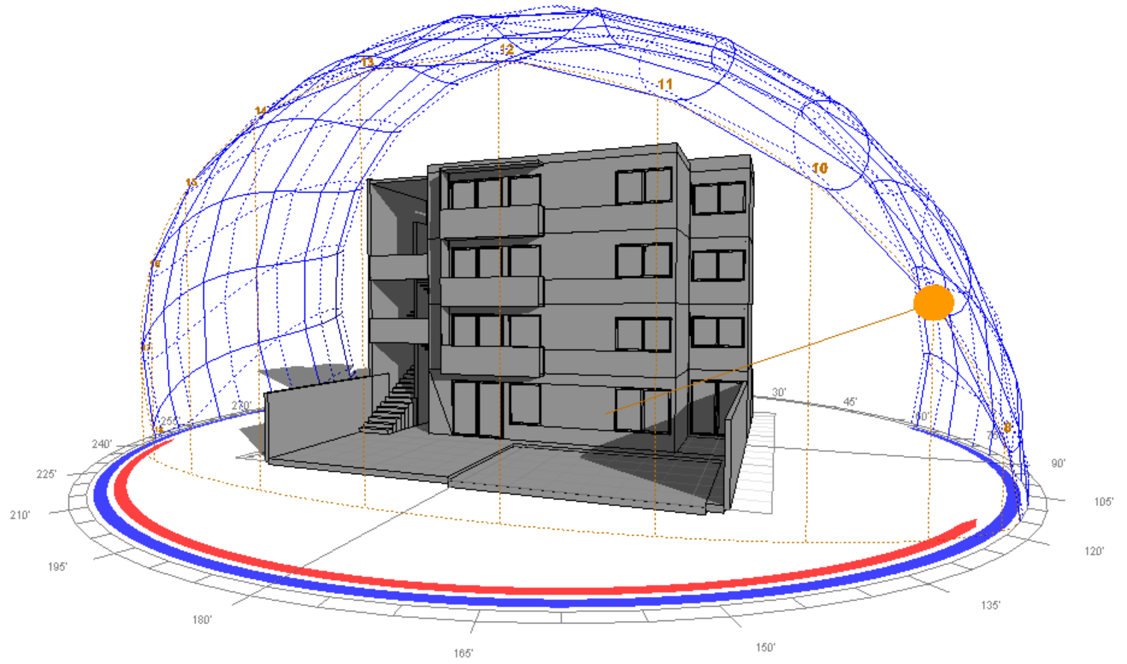


Figure A3 South façade sun study. December 21th 9:00 hours without shading devices

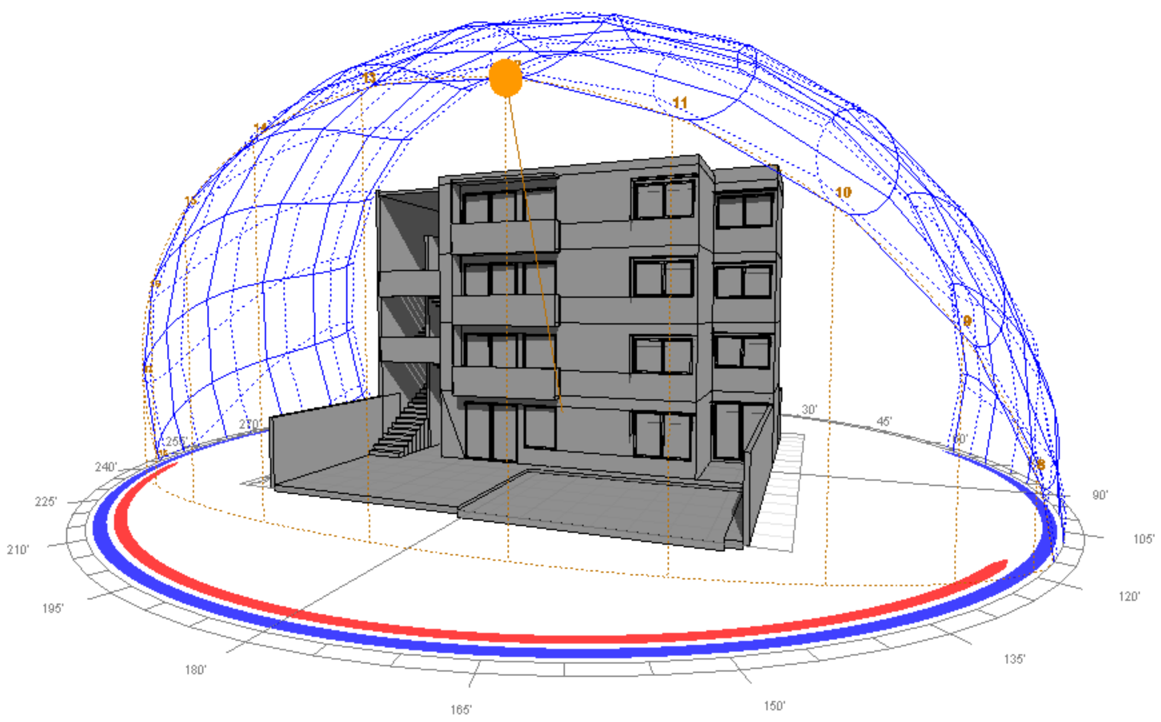


Figure A4 South façade sun study. December 21th 12:00 hours with shading devices

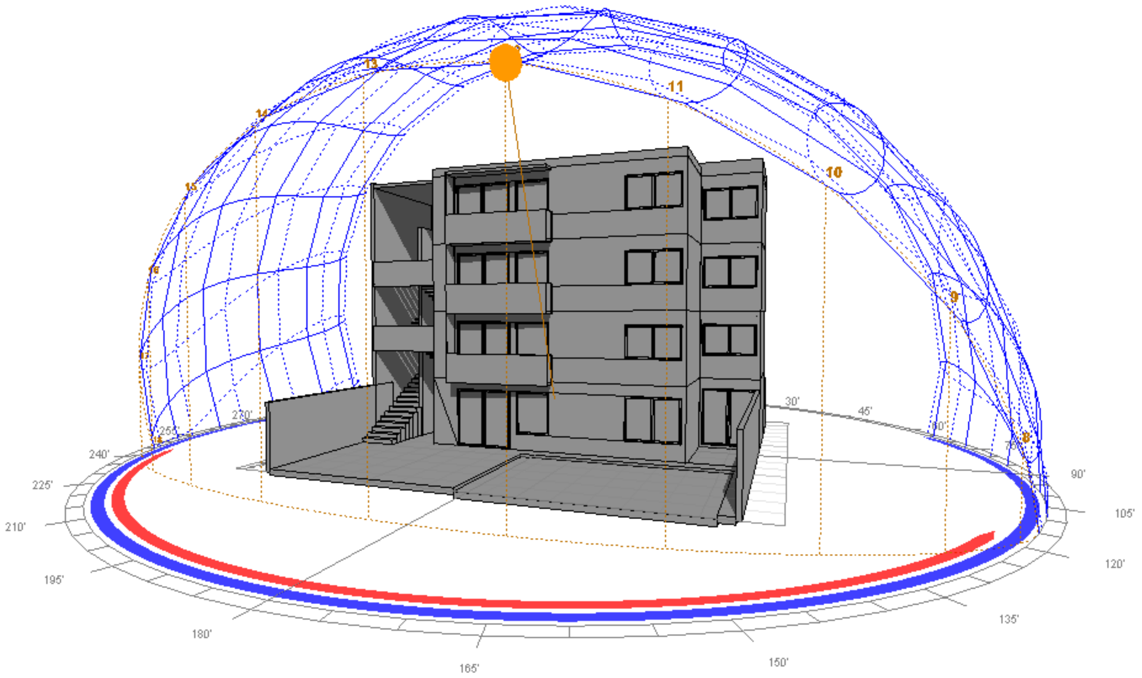


Figure A5 South façade sun study. December 21th 12:00 hours without shading devices

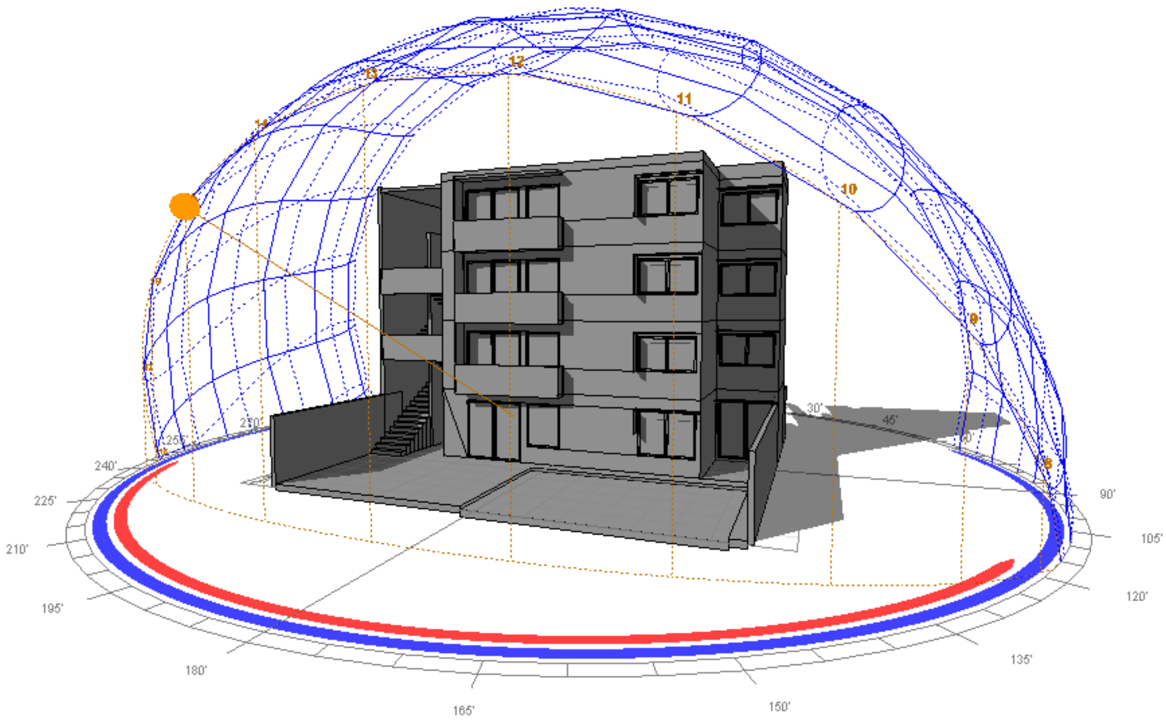


Figure A6 South façade sun study. December 21th 15:00 hours with shading devices

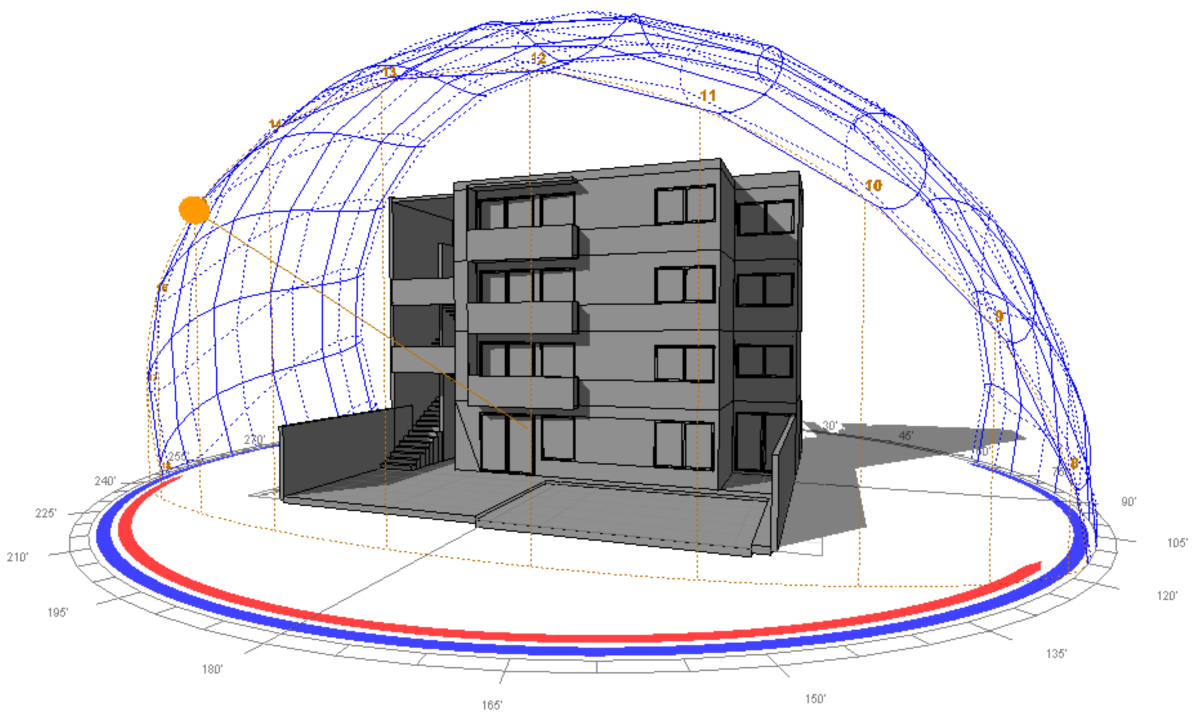


Figure A7 South façade sun study. December 21th 15:00 hours without shading devices

Sun study summer time

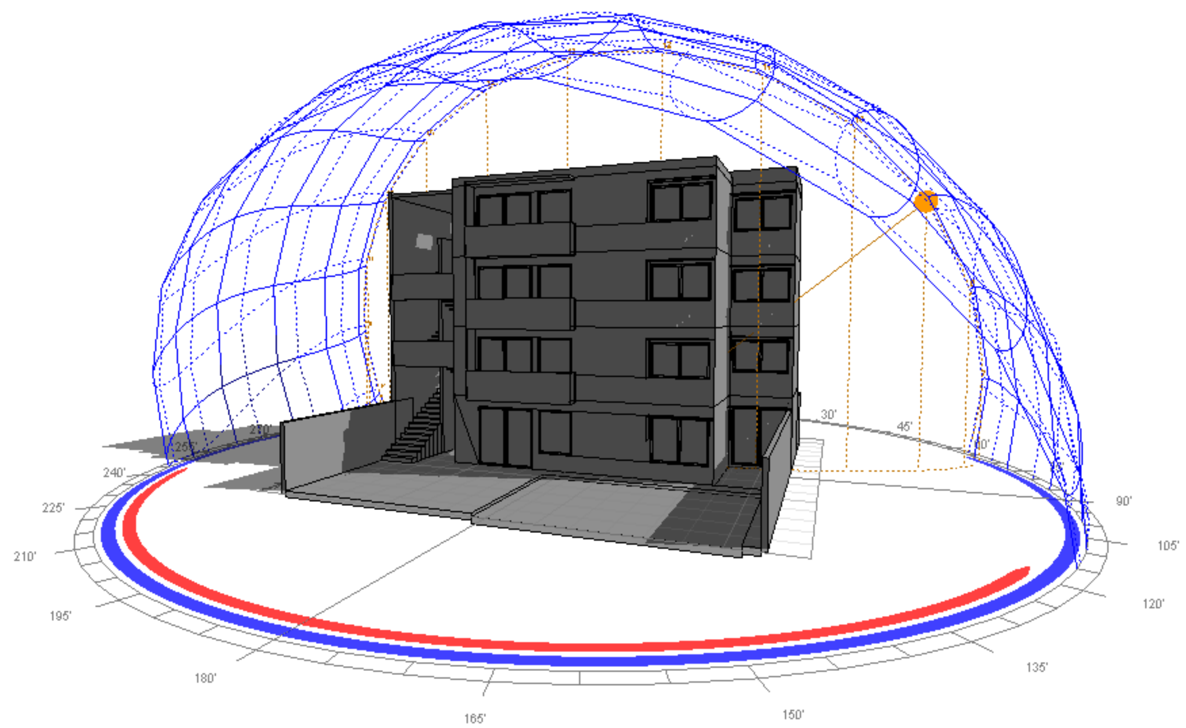


Figure A8 South façade sun study. June 21th 9:00 hours with shading devices

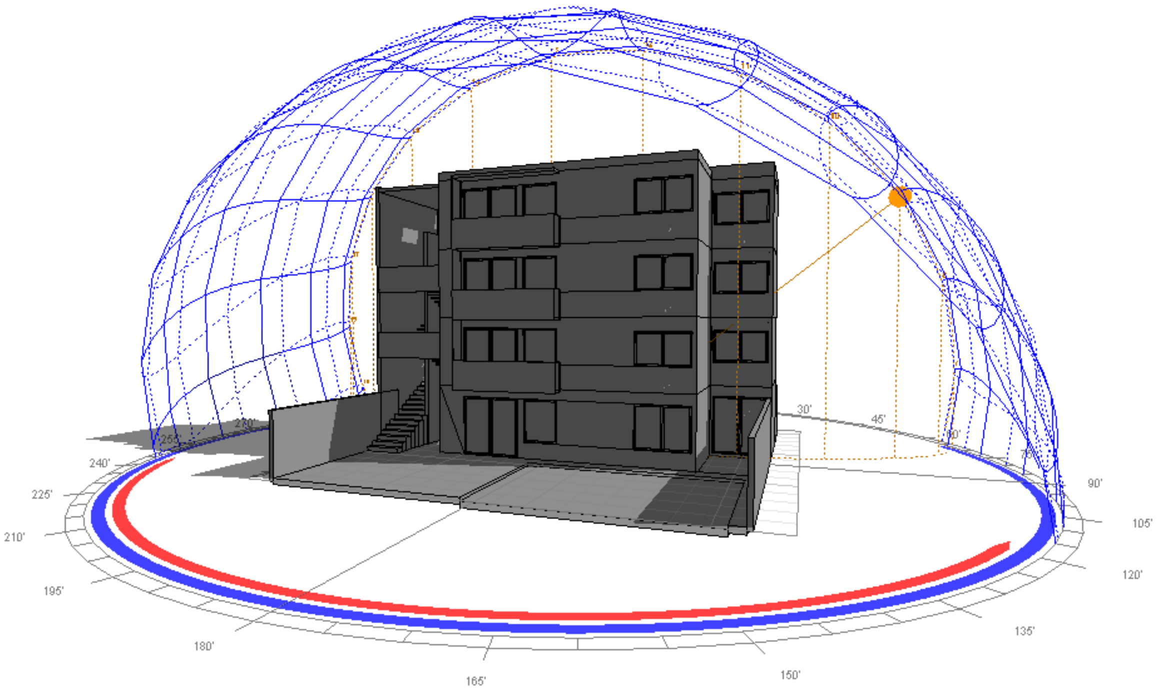


Figure A9 South façade sun study. June 21th 9:00 hours without shading devices

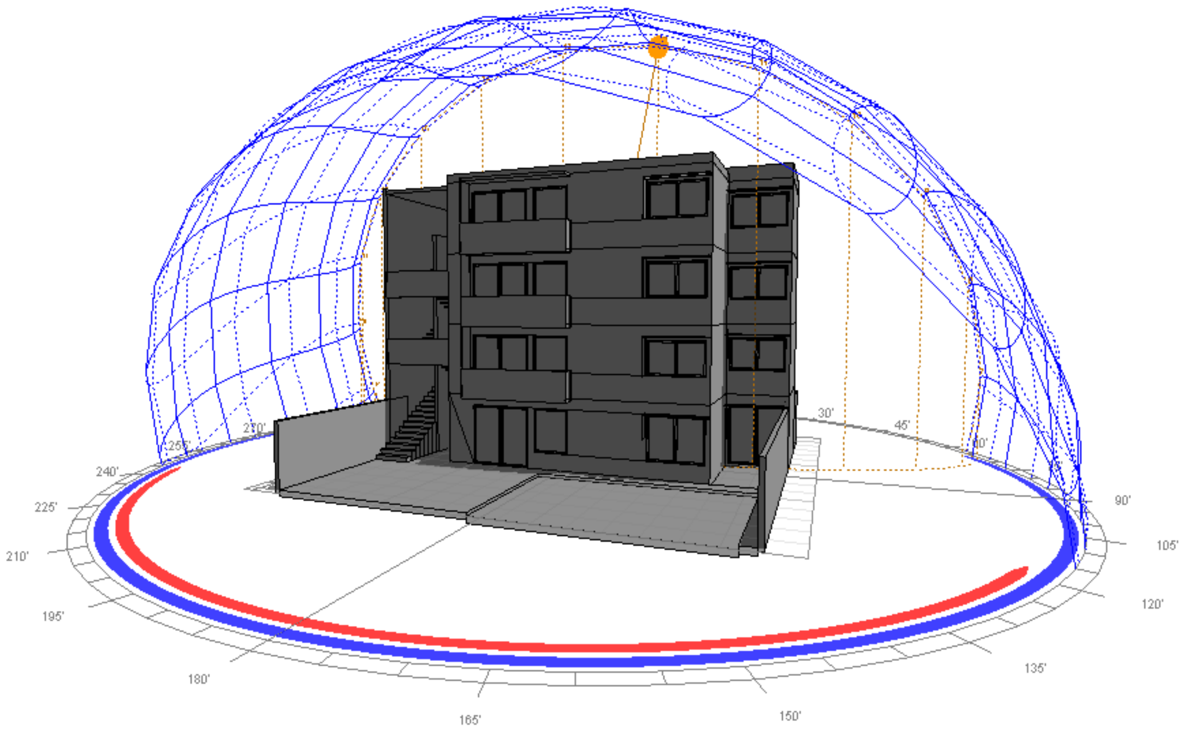


Figure A10 South façade sun study. June 21th 12:00 hours with shading devices

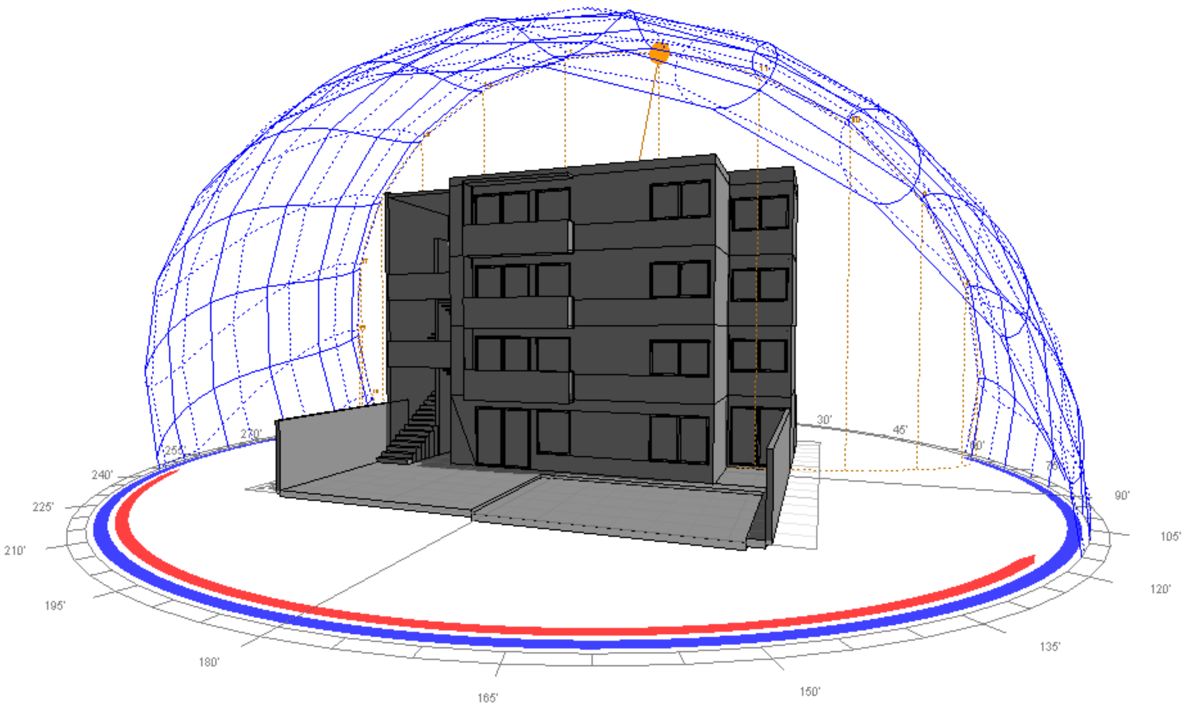


Figure A11 South façade sun study. June 21th 12:00 hours without shading devices

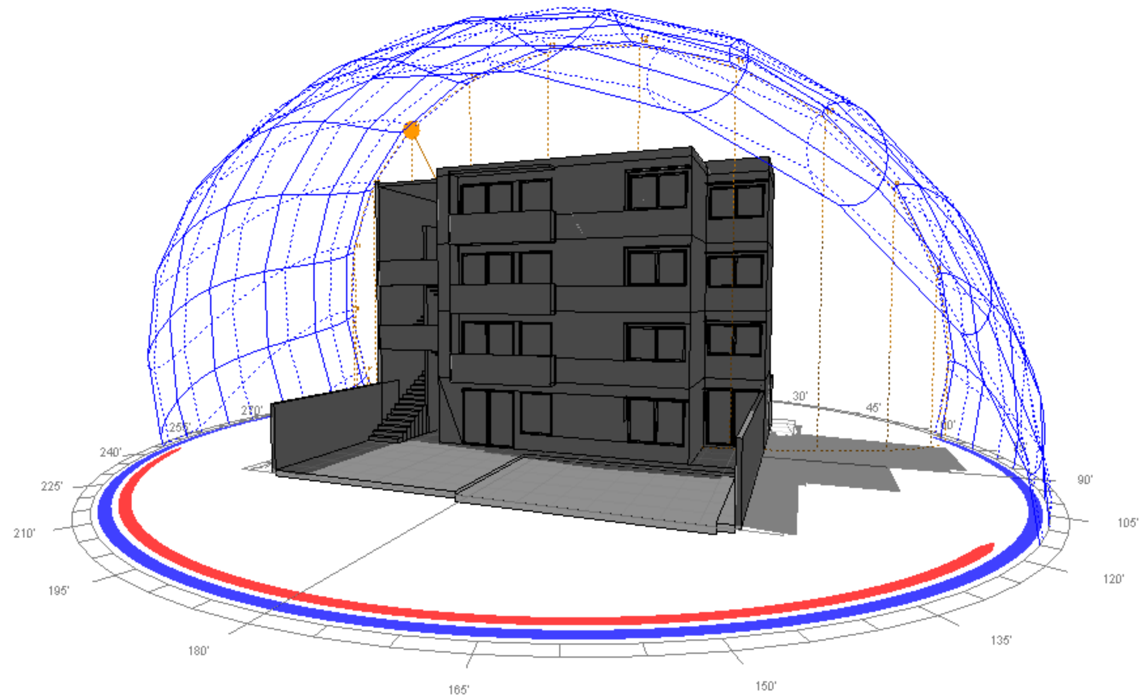


Figure A12 South façade sun study. June 21th 15:00 hours with shading devices

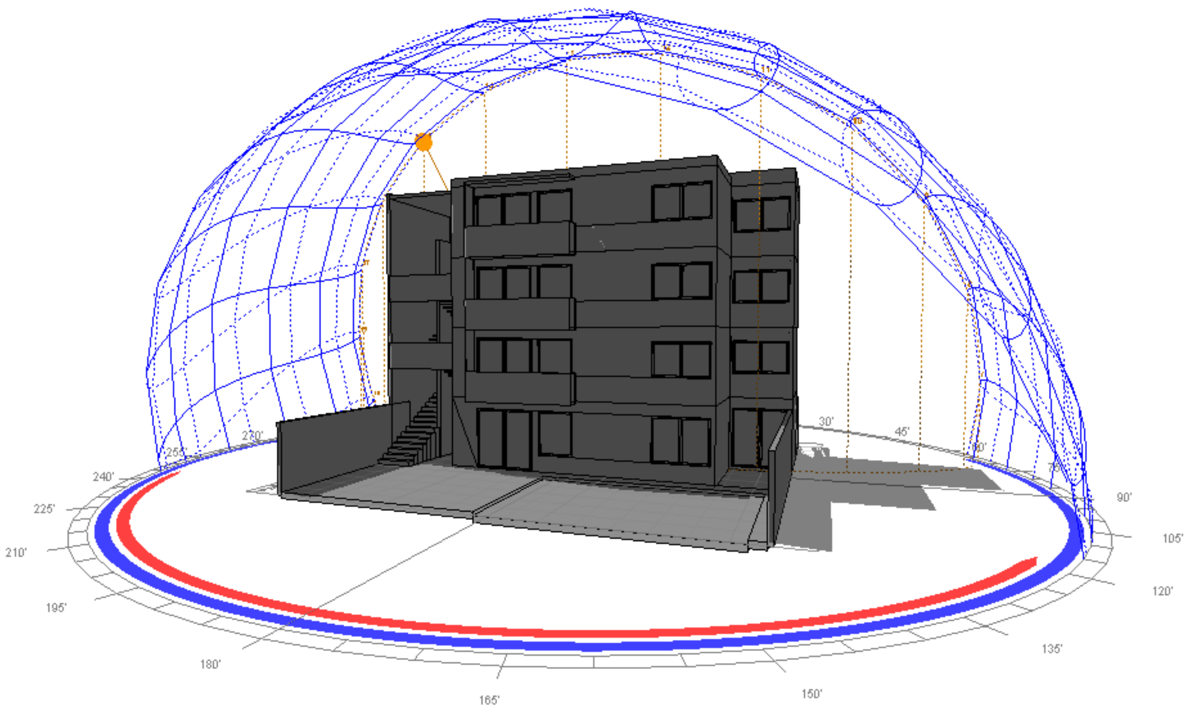


Figure A13 South façade sun study. June 21th 15:00 hours without shading devices

Appendix 2: MaLi house

MaLi house

MALI house is a 2-storey single family row house for a mid-income family whose design was commissioned in late 2012 and construction was completed in early 2014.

The clients wanted a climate responsive house in tune with local weather conditions and therefore, high thermal mass as main bioclimatic design strategy with a careful south orientation were employed during the design process. Family composition is of parents and two children (four people in total)

The plot is located in San Luis Potosi City centre with an irregular shape and 394.7m^2 of surface however, only 8.65m of the 14.65m of the front part of the plot were employed for the house as requested by the owners. The frontal part of the plot (street facing) is north oriented and the rear part is south facing. In consequence, it was decided to leave service areas to the front as follows: parking for two cars, a small laundry patio, the kitchen and a guest's toilet area in the ground floor; stairs, a corridor and a bathroom on the upper floor north facing.

The ground floor (Figure B1) is dominated by the open floor kitchen-dining-living area organized in a north-south axis in which the kitchen faces the north side and the living area is south oriented. Also in the ground floor and south oriented is the master bedroom. South oriented areas have 2.20x2.20 openable sliding windows that allow natural sun light in as well as natural cross ventilation.

The southern façade of the upper floor (Figure B2) is dominated by 2 bedrooms and a studio. Each of the bedrooms has a small terrace. To guarantee solar access on the south façade, the rear part of the plot was designed as garden area and advice was given to the owners on tree species selection and optimum distance from the façade to prevent shade from plants as they reach maturity.

Note that the main façade photos are from the building process archive, unfortunately the main files were lost and therefore, the images shown were the only ones available at the moment of writing this appendix. The house shares bioclimatic design principles, orientation, and construction materials with the red brick prototype employed for the research simulations, this allowed a direct comparison of the general thermal performance that in turn helped to fine-tune general simulation parameters as well as for validation through the implementation of data loggers.

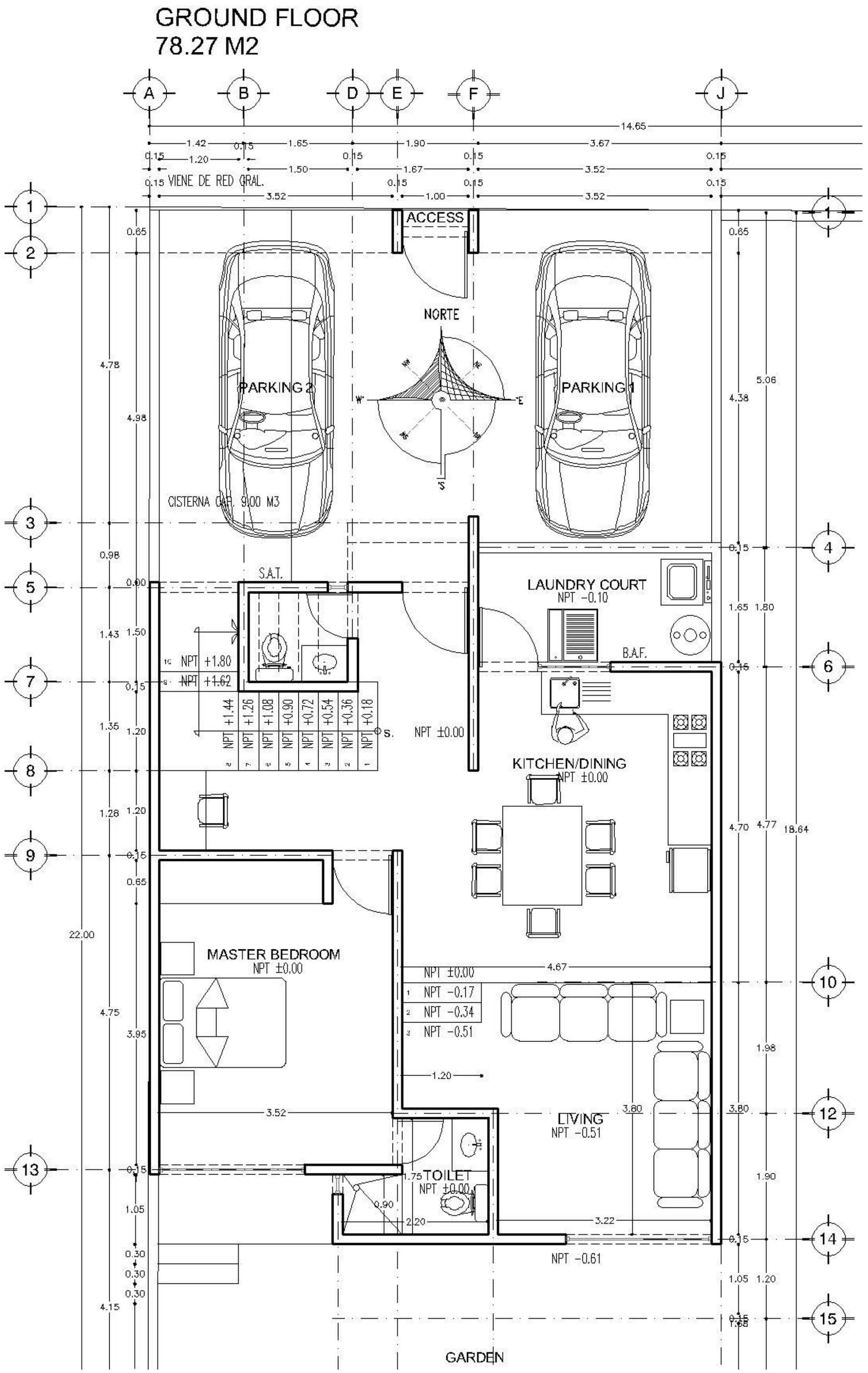


Figure B1 MaLi house ground floor (no scale)

FIRST FLOOR
62.79 M2

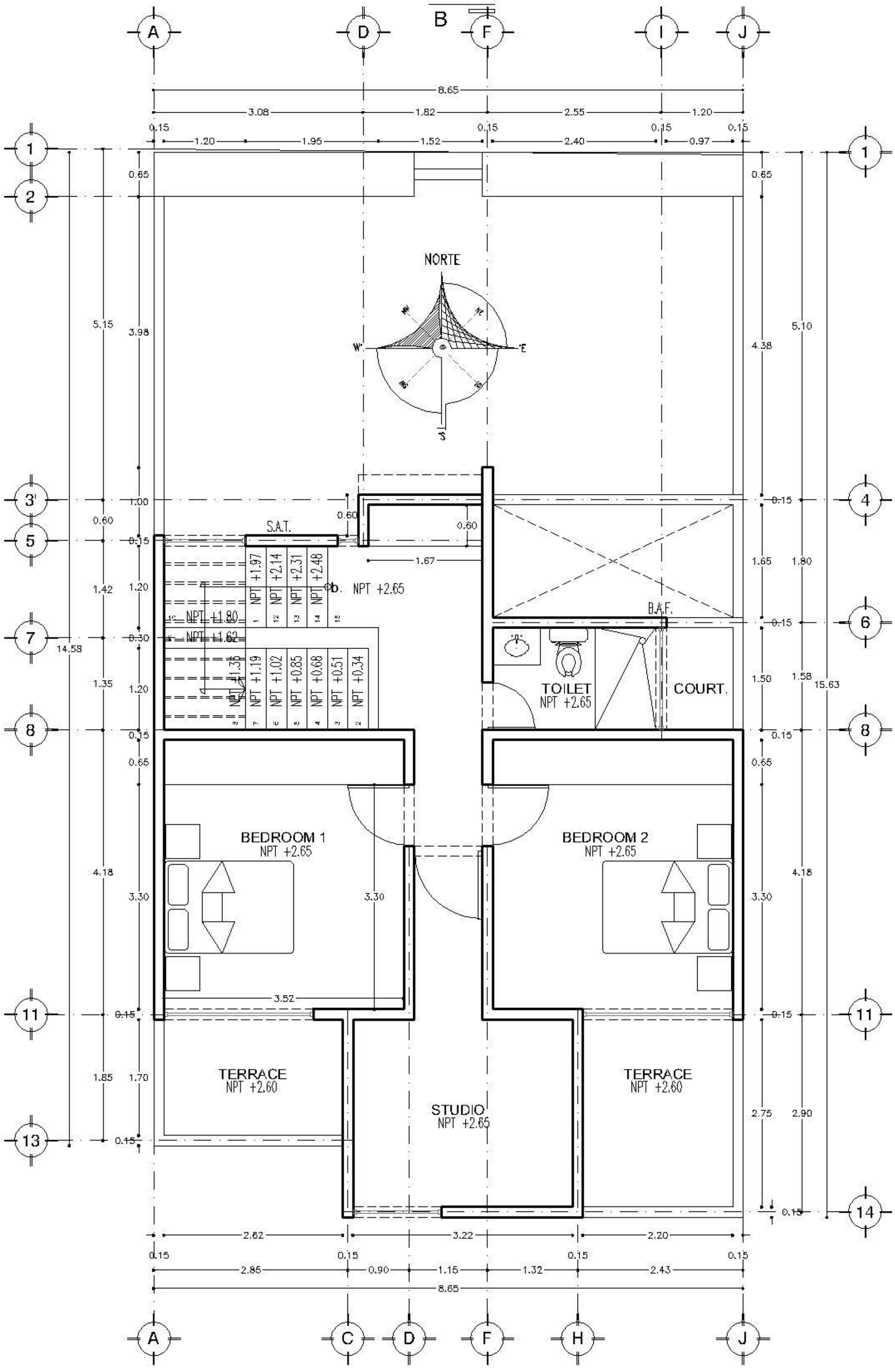


Figure B2 MaLi house ground floor (no scale)

Figure B3 Main façade as designed

Figure B4 Main façade as built

Figure B5 open floor living, dining and kitchen as designed

Figure B6 Open floor living, dining and kitchen as build

The following figures show the main construction elements conductivity values.

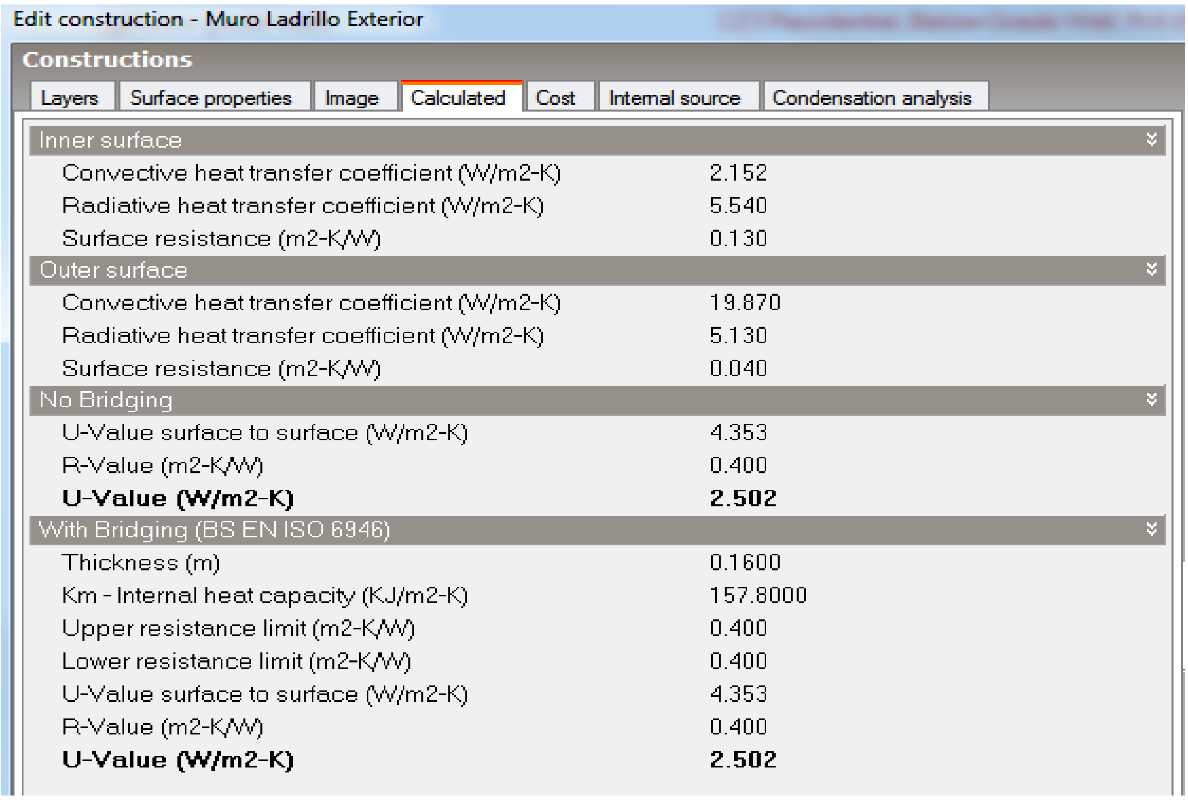


Figure B7 external wall thermal properties

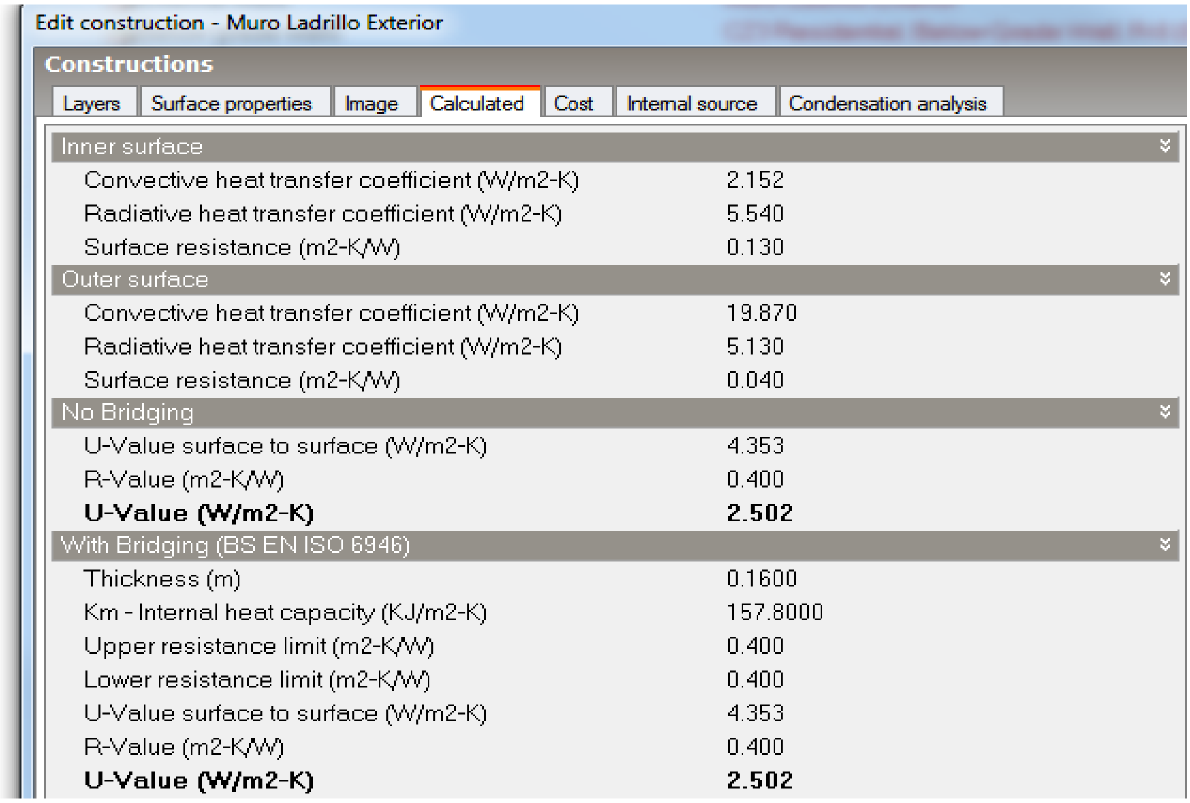


Figure B8 Internal partitions thermal properties

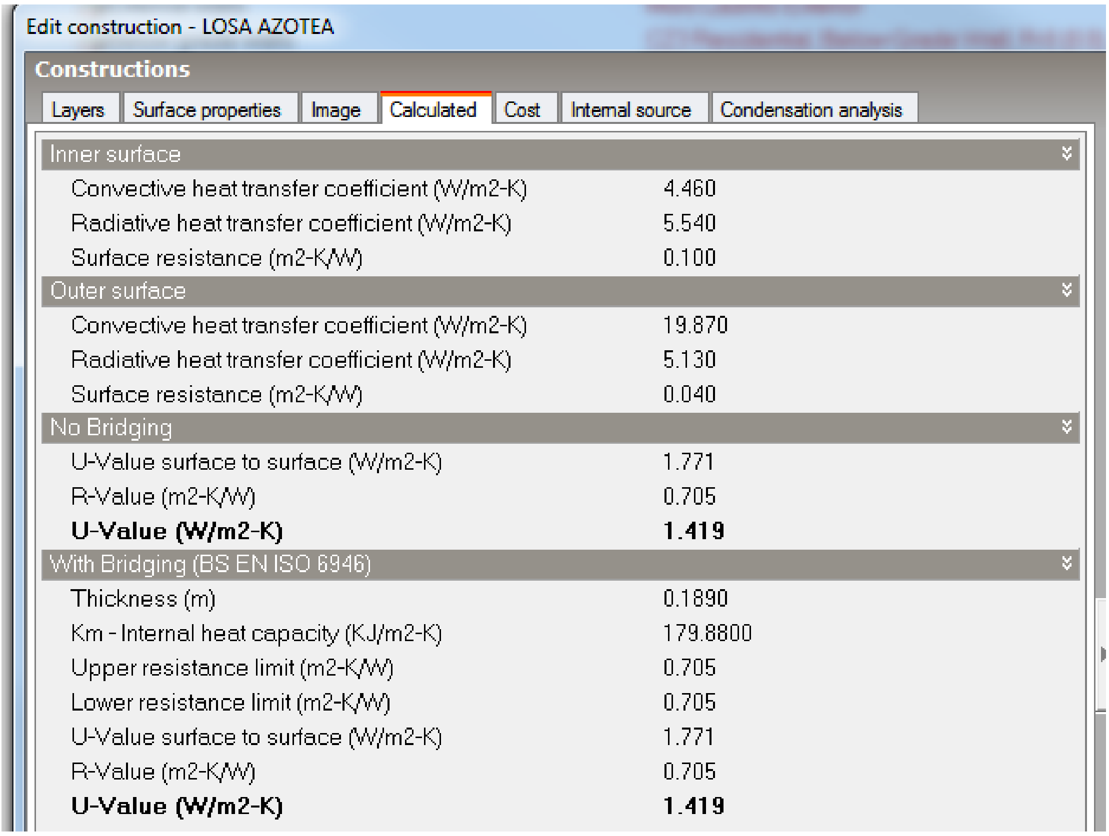


Figure B9 Flat concrete roof thermal properties

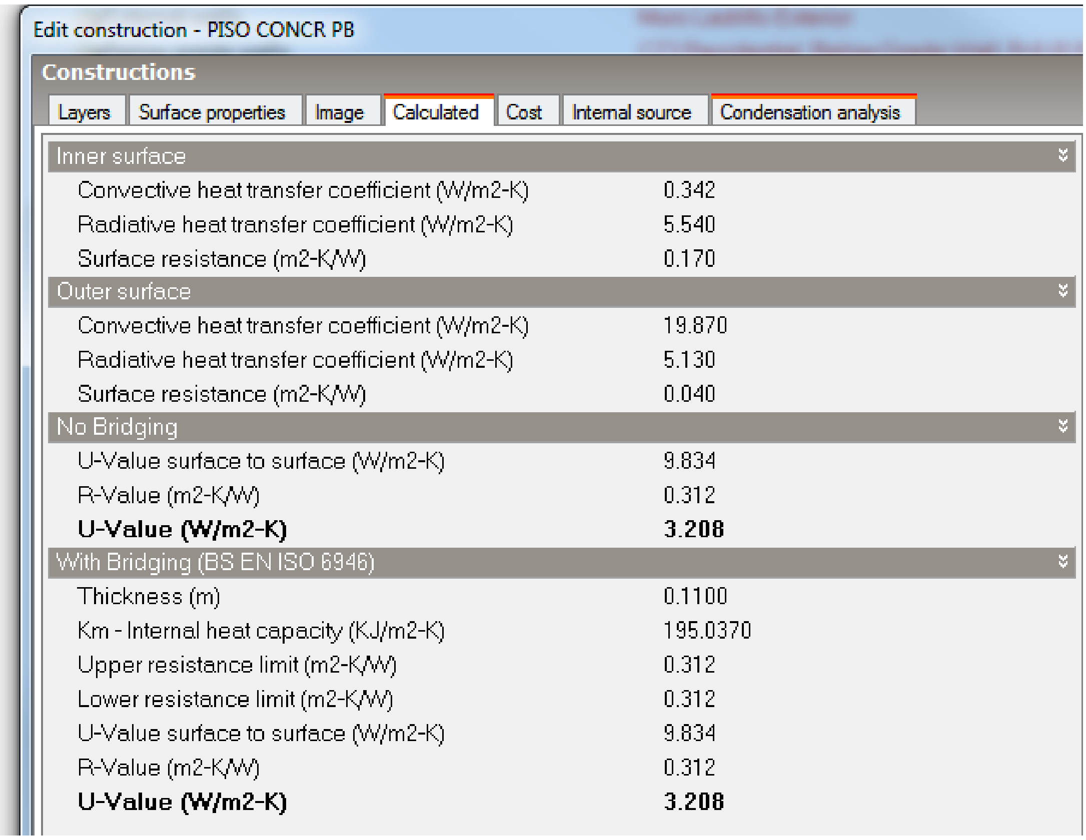


Figure B10 Ground floor slab thermal properties

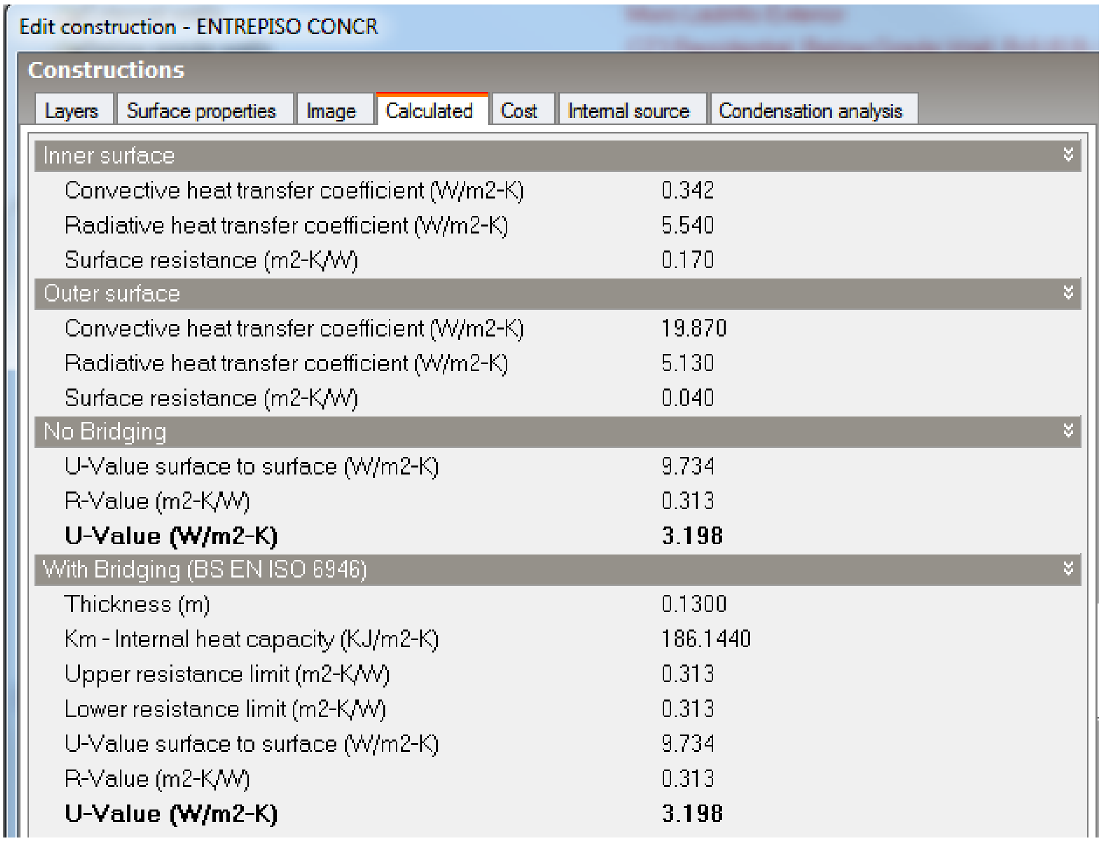


Figure B11 Concrete slab thermal properties

Appendix 3: Prototype simulation parameters

Prototype simulation parameters

In this section the general parameters and construction materials employed for the simulations on DesignBuilder software are shown. Beginning with the red brick, hollow concrete, extruded red brick and finally the concrete slabs and roofs.

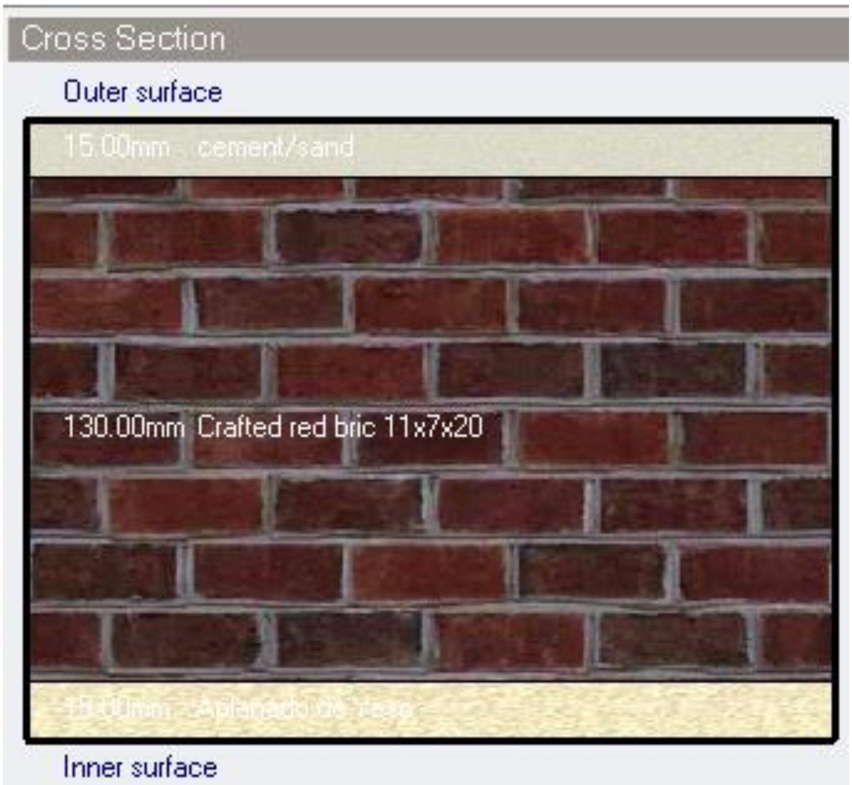


Figure C1 Red brick prototype external wall

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	3.602
R-Value (m2-K/W)	0.448
U-Value (W/m2-K)	**2.234**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1600
Km - Internal heat capacity (KJ/m2-K)	157.8000
Upper resistance limit (m2-K/W)	0.448
Lower resistance limit (m2-K/W)	0.448
U-Value surface to surface (W/m2-K)	3.602
R-Value (m2-K/W)	0.448
U-Value (W/m2-K)	**2.234**

Figure C2 Red brick prototype external wall thermal value

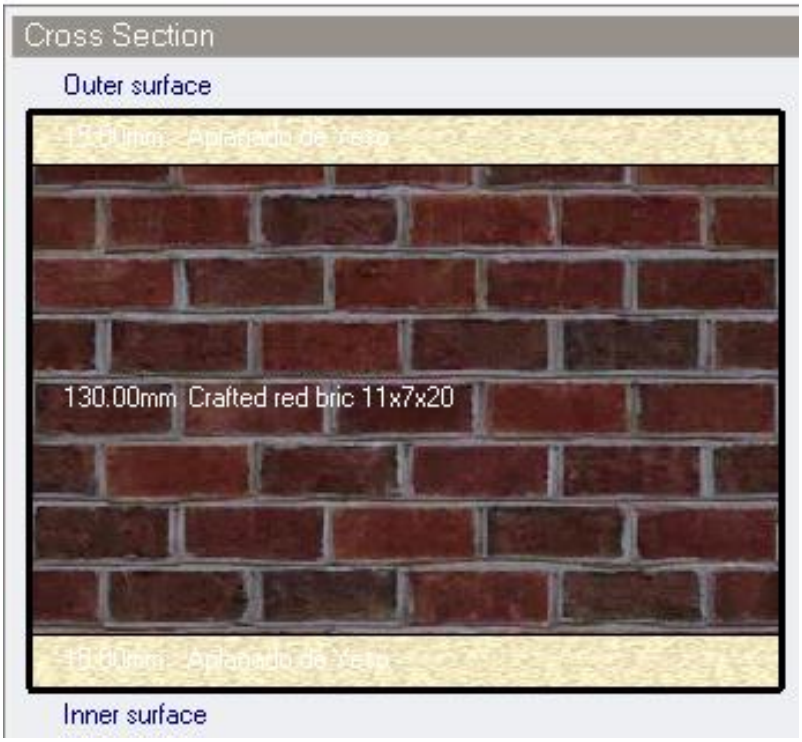


Figure C3 Red brick prototype internal partitions

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	4.353
R-Value (m2-K/W)	0.400
U-Value (W/m2-K)	**2.502**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1600
Km - Internal heat capacity (KJ/m2-K)	157.8000
Upper resistance limit (m2-K/W)	0.400
Lower resistance limit (m2-K/W)	0.400
U-Value surface to surface (W/m2-K)	4.353
R-Value (m2-K/W)	0.400
U-Value (W/m2-K)	**2.502**

Figure C4 Red brick prototype internal partitions thermal value

Figure C5 Hollow concrete block prototype external wall

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	3.327
R-Value (m2-K/W)	0.471
U-Value (W/m2-K)	**2.125**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1700
Km - Internal heat capacity (KJ/m2-K)	163.0000
Upper resistance limit (m2-K/W)	0.471
Lower resistance limit (m2-K/W)	0.471
U-Value surface to surface (W/m2-K)	3.327
R-Value (m2-K/W)	0.471
U-Value (W/m2-K)	**2.125**

Figure C6 Hollow concrete block prototype external wall thermal values

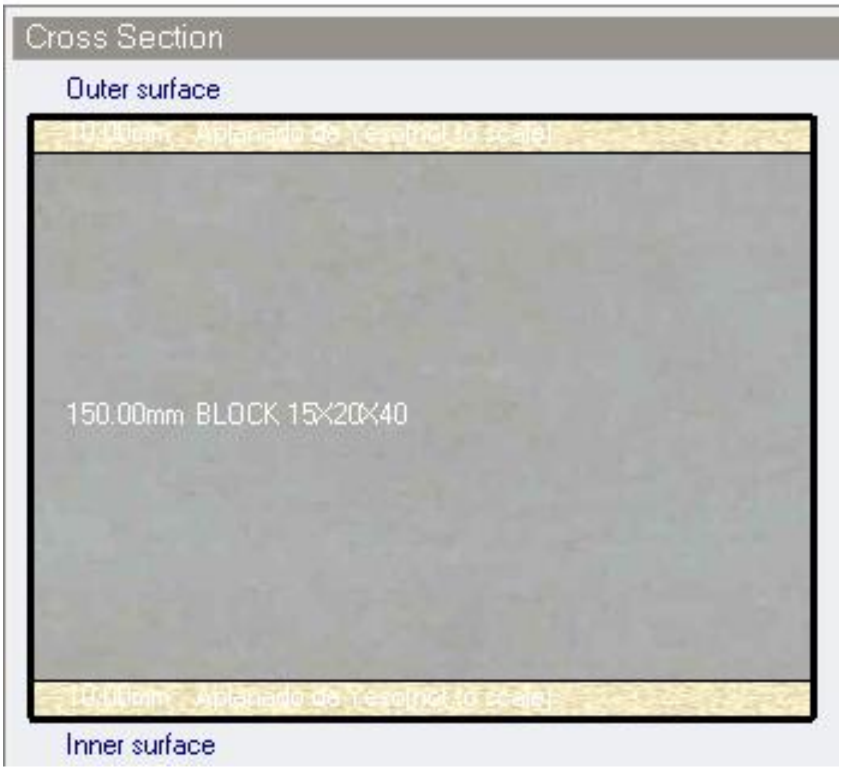


Figure C7 Hollow concrete block prototype internal partitions

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	3.722
R-Value (m2-K/W)	0.439
U-Value (W/m2-K)	**2.280**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1700
Km - Internal heat capacity (KJ/m2-K)	163.0000
Upper resistance limit (m2-K/W)	0.439
Lower resistance limit (m2-K/W)	0.439
U-Value surface to surface (W/m2-K)	3.722
R-Value (m2-K/W)	0.439
U-Value (W/m2-K)	**2.280**

Figure C8 Hollow concrete block prototype internal partitions thermal values

Figure C9 Extruded red brick prototype external walls

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	3.586
R-Value (m2-K/W)	0.449
U-Value (W/m2-K)	**2.228**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1800
Km - Internal heat capacity (KJ/m2-K)	161.3700
Upper resistance limit (m2-K/W)	0.449
Lower resistance limit (m2-K/W)	0.449
U-Value surface to surface (W/m2-K)	3.586
R-Value (m2-K/W)	0.449
U-Value (W/m2-K)	**2.228**

Figure C10 Extruded red brick prototype external walls thermal values

Figure C11 Extruded red brick prototype internal partitions

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	4.330
R-Value (m2-K/W)	0.401
U-Value (W/m2-K)	**2.494**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1800
Km - Internal heat capacity (KJ/m2-K)	161.3700
Upper resistance limit (m2-K/W)	0.401
Lower resistance limit (m2-K/W)	0.401
U-Value surface to surface (W/m2-K)	4.330
R-Value (m2-K/W)	0.401
U-Value (W/m2-K)	**2.494**

Figure C12 Extruded red brick prototype internal partitions thermal values

The ground floor, internal floor and flat roof shown next were employed in the three prototype's simulations

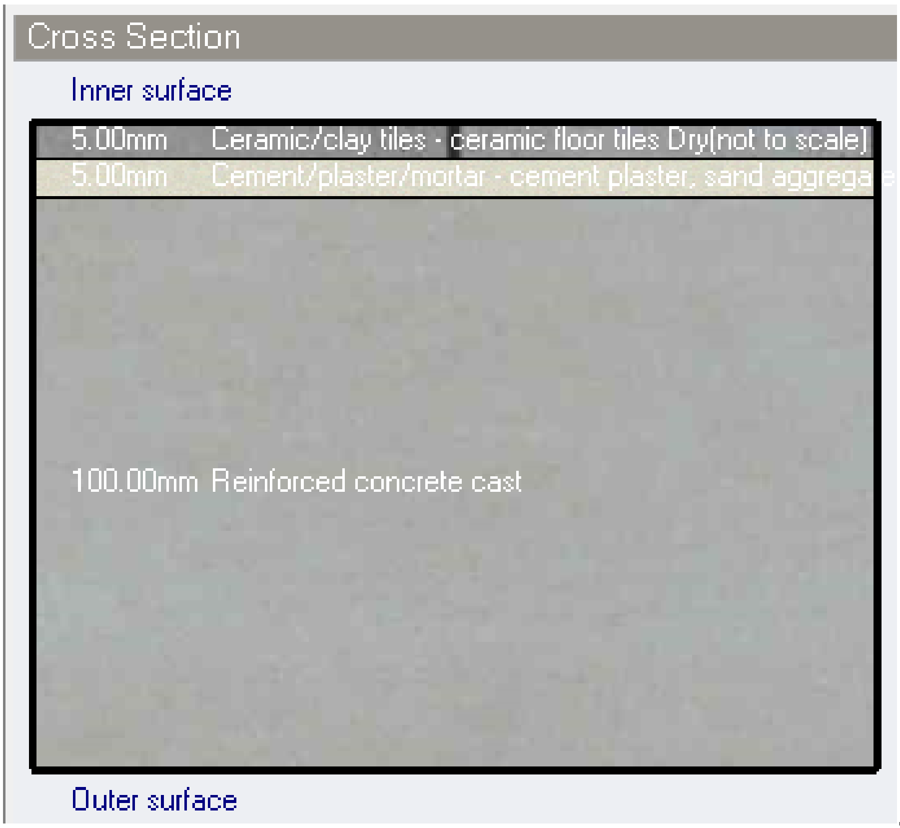


Figure C13 Ground floor concrete slab (uninsulated)

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	0.342
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.170
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	14.151
R-Value (m2-K/W)	0.281
U-Value (W/m2-K)	**3.563**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.1100
Km - Internal heat capacity (KJ/m2-K)	188.9170
Upper resistance limit (m2-K/W)	0.281
Lower resistance limit (m2-K/W)	0.281
U-Value surface to surface (W/m2-K)	14.151
R-Value (m2-K/W)	0.281
U-Value (W/m2-K)	**3.563**

Figure C14 Ground floor concrete slab thermal values

Figure C15 Internal floor concrete slab

Constructions

Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	0.342
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.170
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	5.015
R-Value (m2-K/W)	0.409
U-Value (W/m2-K)	**2.442**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.2300
Km - Internal heat capacity (KJ/m2-K)	186.1440
Upper resistance limit (m2-K/W)	0.409
Lower resistance limit (m2-K/W)	0.409
U-Value surface to surface (W/m2-K)	5.015
R-Value (m2-K/W)	0.409
U-Value (W/m2-K)	**2.442**

Figure C16 Internal floor concrete slab thermal values

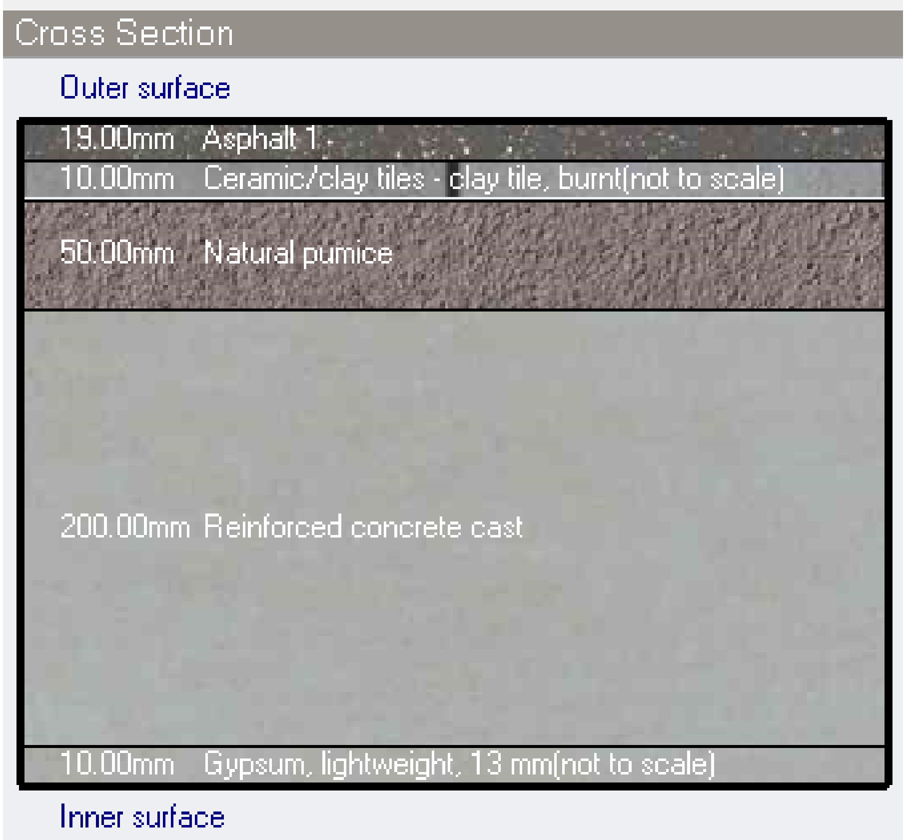
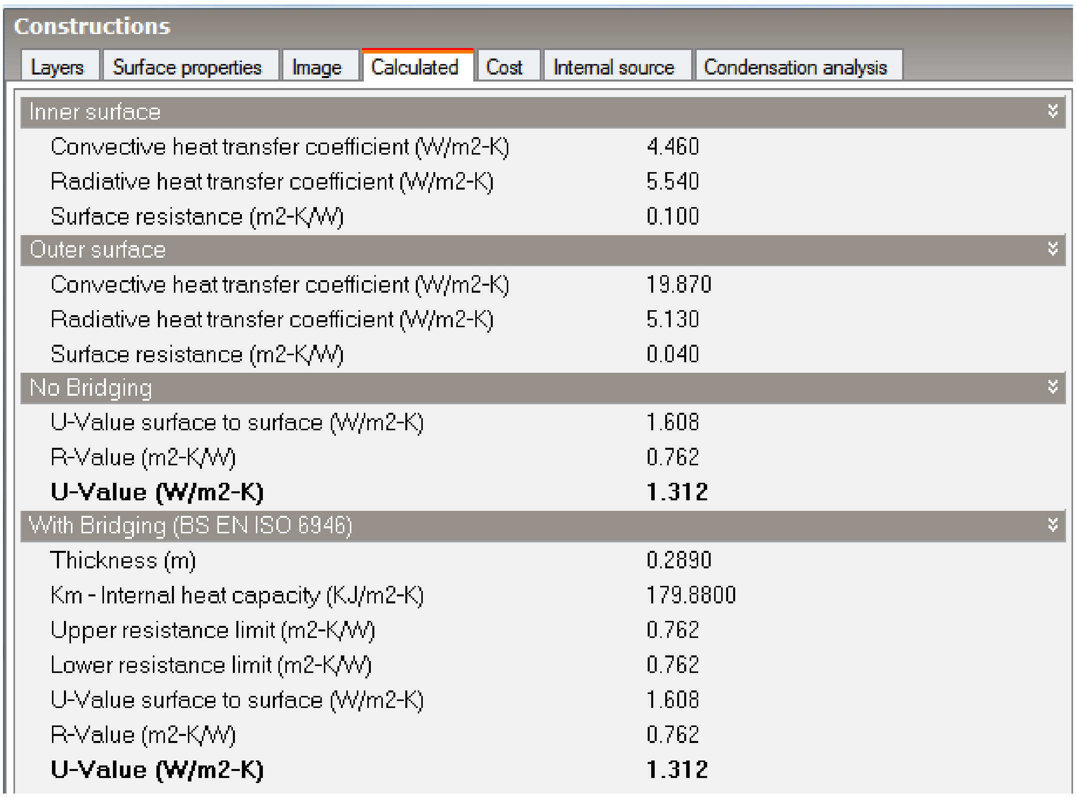


Figure C17 Flat roof concrete slab



Constructions

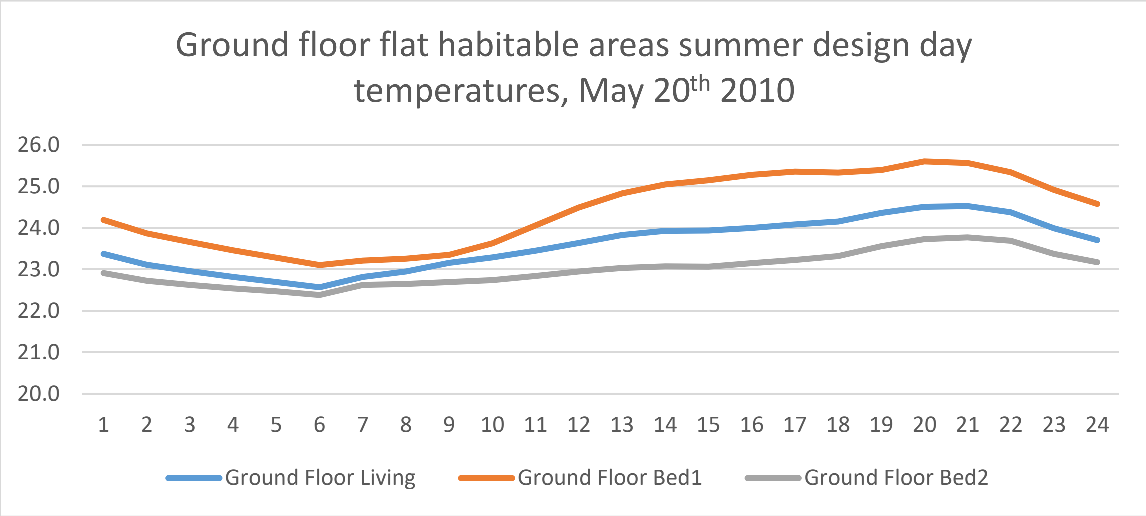
Layers | Surface properties | Image | Calculated | Cost | Internal source | Condensation analysis

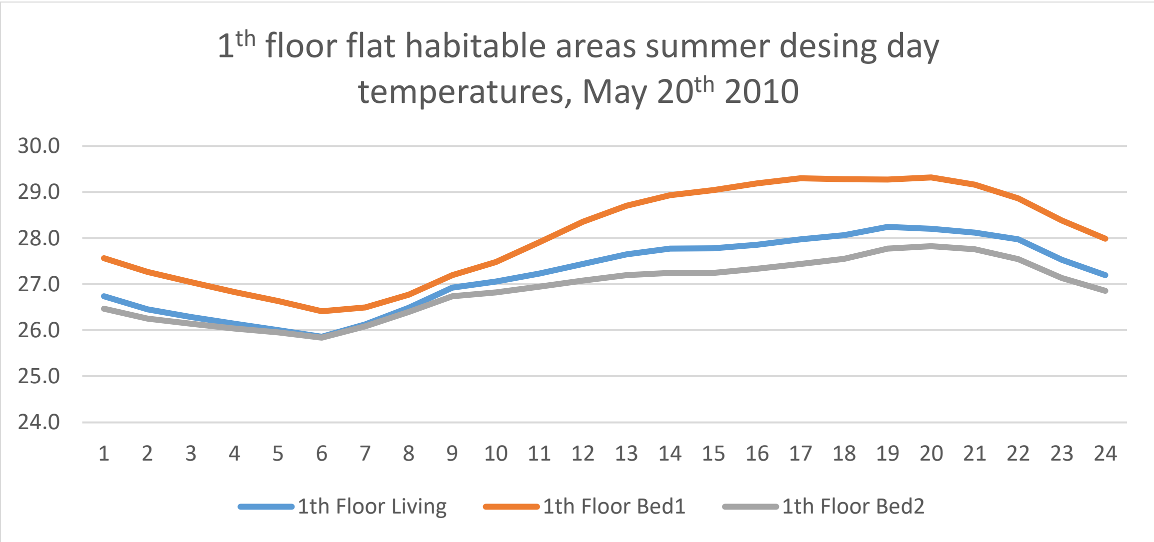
Inner surface	
Convective heat transfer coefficient (W/m2-K)	4.460
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.100
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	1.608
R-Value (m2-K/W)	0.762
U-Value (W/m2-K)	**1.312**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.2890
Km - Internal heat capacity (KJ/m2-K)	179.8800
Upper resistance limit (m2-K/W)	0.762
Lower resistance limit (m2-K/W)	0.762
U-Value surface to surface (W/m2-K)	1.608
R-Value (m2-K/W)	0.762
U-Value (W/m2-K)	**1.312**

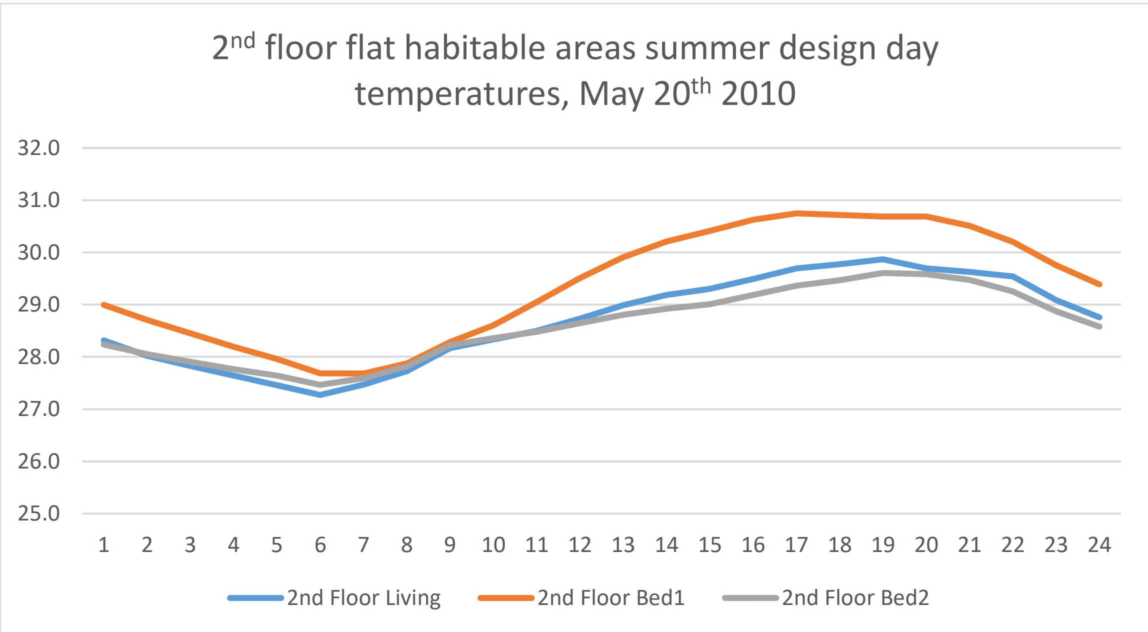
Figure C18 Flat roof concrete slab thermal values

Appendix 4: By floor habitable area temperature analysis, years 2010-2080

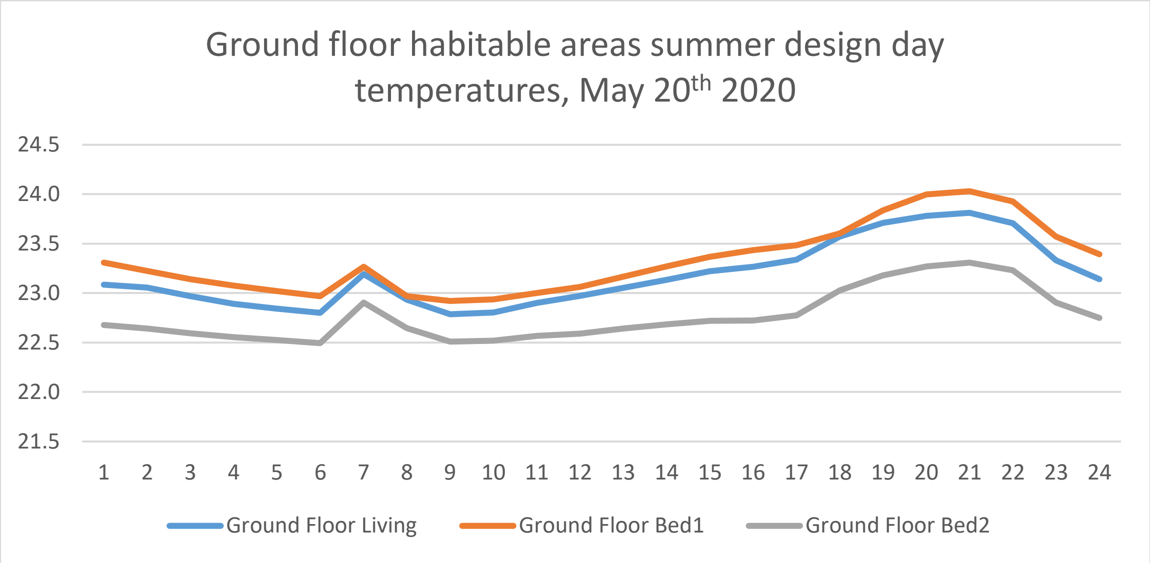
Habitable areas temperature comparison May 20th 2010

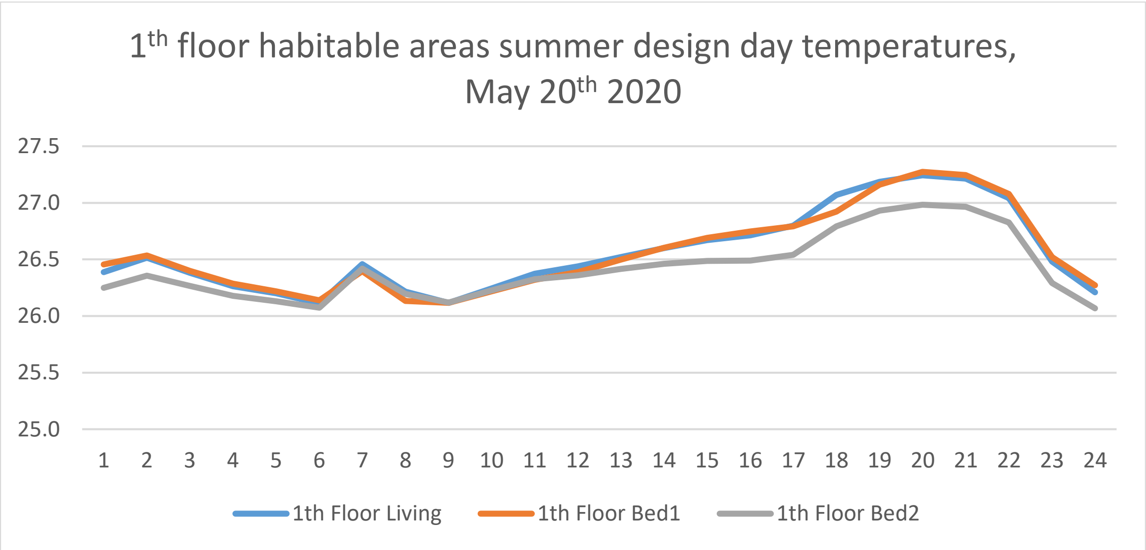


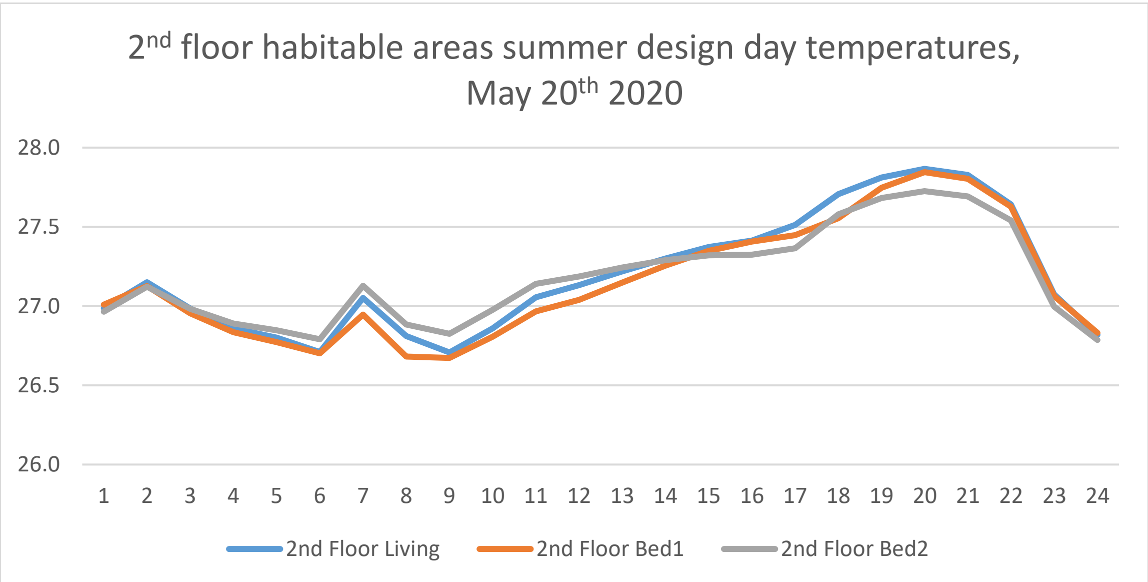




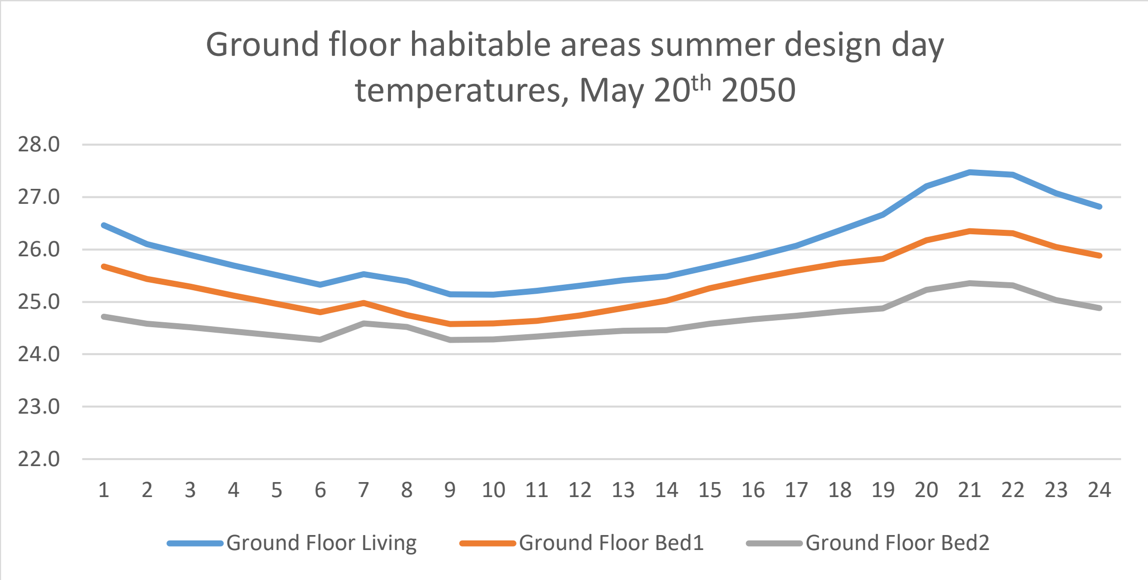
Habitable areas temperature comparison May 20th 2020

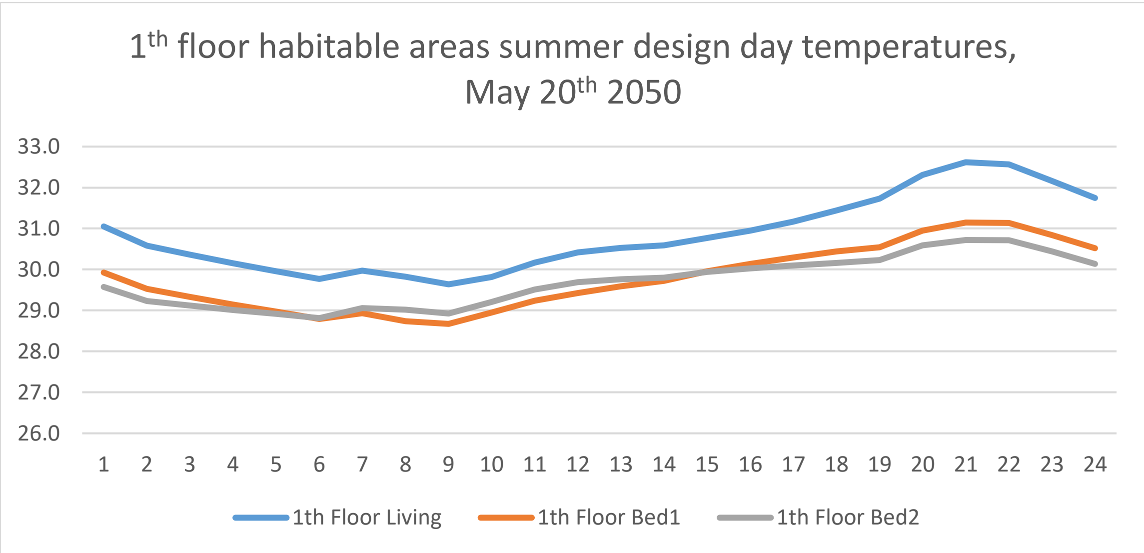


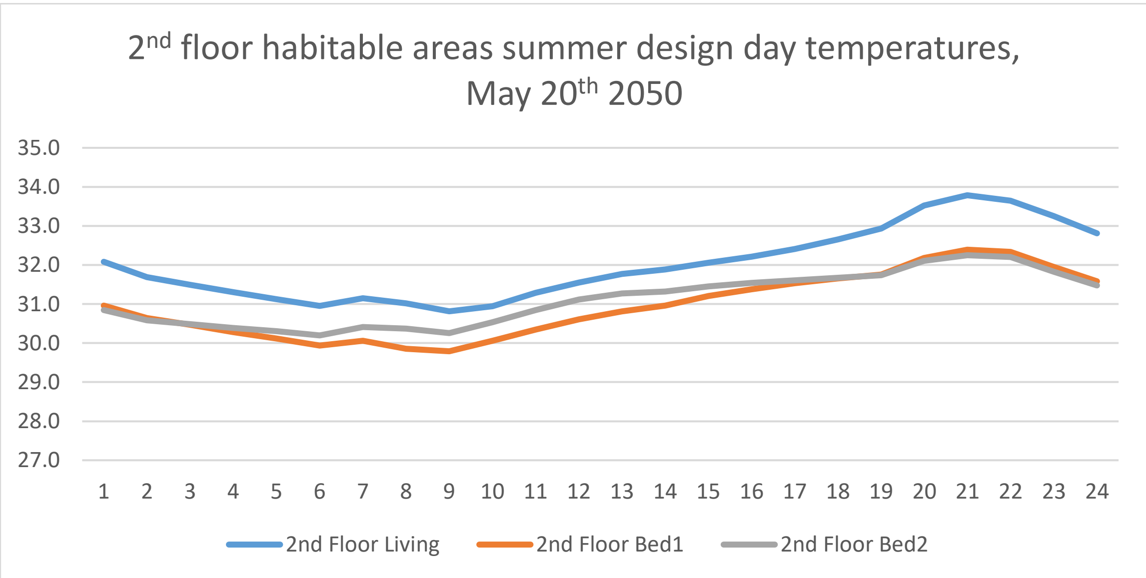




Habitable areas temperature comparison May 20th 2050







Habitable areas temperature comparison May 20th 2080