The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA
Department of Architecture and Built Environment
Faculty of Engineering

THE APPLICATION OF THE 'FABRIC FIRST' APPROACH TO IMPROVE THERMAL COMFORT AND ENERGY EFFICIENCY IN AFFORDABLE HOUSING IN SOUTHERN BRAZIL

RENATA CAMBOIM SALATINO TUBELO
BArch, DipArch, MSc

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ABSTRACT

In 2009 the Brazilian government committed to support the construction of nearly 24 million new dwellings by 2022 through its housing programme Minha Casa, Minha Vida (My House, My Life). The initiative aims to tackle the housing shortfall of 5.546 million residential units and the 10.948 million units that are considered inadequate dwellings with poor living conditions. The potential economic, social and environmental impact of such large initiative is vast and consequently it is essential that the new dwellings are planned, designed and built to meet high levels of energy efficiency and thermal comfort.

The 'Fabric First' is widely recognised as a design approach with great potential to deliver energy efficient and comfortable housing in a variety of different climates. Its principles have already been successfully incorporated in many buildings across European countries and elsewhere. Despite its success, research to date shows that the application of this approach has not been explored yet in the Brazilian context.

In this work, ways of improving the thermal comfort and performance of Brazilian mass housing in three cities in southern Brazil (Curitiba, São Paulo and Porto Alegre) through the Fabric First principles were explored. The research was developed through sensitivity analyses of key envelope parameters and case studies. The sensitivity analysis was carried out in order to identify the best performance and the most cost-effective building envelope combination, using a simplified affordable Brazilian housing typology model that had its properties varied. A case study based on a generic representative model and a real optimised case study of typical 1-floor 2-bedroom mass housing typology were evaluated through computational thermal simulations and monitored data. The results of the sensitivity analyses were then used to inform the case studies performance analyses, developed in parallel to a cost analysis.

Key findings from this study revealed that typical Brazilian building envelopes underperformed by up to 65% compared to super-insulated envelopes in terms of thermal comfort. In the real case studied this could represent up to 75% less thermal comfort. However, the additional costs of a super-insulated envelope showed to be 56-66% higher than the typical Brazilian envelope, with a payback period nearing the lifespan of the houses. In addition, it has been shown that relatively small improvements in the current building envelope could impact the upfront costs by only 6-12% but result in comfort improvement of about 45% against typical levels. These small improvements appear to be more suited to the cultural and economic Brazilian context and therefore are recommended as the best way forward.

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LIST OF ACRONYMS

ACH: Air Changes per Hour

ASHRAE: American Society of Heating, Refrigerating and Air-conditioning Engineers

CAIXA: Caixa Econômica Federal

CAU: Conselho de Arquitetura e Urbanismo

CIBSE: Chartered Institution of Building Services Engineers

COP: Coefficient of Performance

CUB: Custo Unitário Básico

DHW: Domestic Hot Water

EPS: Expanded Polystyrene

FINEP: Financiadora de Estudos e Projetos

G-VALUE: Solar Heat Gain Coefficient

HSA: Horizontal Shadow Angle

IAQ: Indoor Air Quality

IPH: Instituto de Pesquisas Hidraulicas

IRC: International Residential Code

LSI: Laboratori di Strumentazione Industriale

MCMV: Minha Casa, Minha Vida

MVHR: Mechanical Ventilation with Heat Recovery

NORIE: Núcleo Orientado para a Inovação da Edificação

PMV: Predicted Mean Vote

PPD: Predicted Percentage of Dissatisfied

R1-B: Residência Unifamiliar Padrão Baixo

RTQ-R: Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Residenciais

SAP: Standard Assessment Procedure

SINDUSCON: Sindicato da Indústria da Construção Civil

TAS: Thermal Analysis Simulation

TCPO: Tabela de Composições de Preços para Orçamentos

UFRGS: Universidade Federal do Rio Grande do Sul

UK: United Kingdom

US: United States

U-VALUE: Thermal Transmittance or Heat Transfer Coefficient

VSA: Vertical Shadow Angle

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NOMENCLATURE

A	area	m^2
AH	absolute humidity	g/Kg
C	conductance	W/m^2K
c	specific heat capacity	J/kgK
DBT	dry bulb temperature	°C
DDH	dry degree-hours	degree-hours
dT_e	sol-air excess temperature difference	K
E	radiant heat emission	W
FS_o	solar gain factor of opaque element	%
G	global irradiance	W/m^2
I_{cl}	specific clothing insulation	clo
N	number of air changes per hour	-
Q	heat flux or heat flow	W
Q_c	conduction heat flow (gain or loss)	W
q_c	envelope conductance	W/K
Q_e	evaporative heat loss	W
Q_i	internal heat gain	W
Q_s	solar heat gain	W
Q_v	ventilation heat flow (gain or loss)	W
R	thermal resistance	m^2K/W
$R_{1,2...}$	thermal resistance of each component	m^2K/W
R_b	thermal resistance of a bridge structure	m^2K/W
RH	relative humidity	%
R_L	lower limit of thermal resitance	m^2K/W
R_{se}	external surface thermal resistance	m^2K/W
R_{si}	internal surface thermal resistance	m^2K/W
R_U	upper limit of thermal resistance	m^2K/W
T	temperature	°C
T_{comf}	comfort temperature	°C
$T_{o,}\ \theta_o$	indoor operative temperature	°C
T_{od}	daily mean outdoor temperature	°C
$\theta_{i\,max}$, $T_{max,\ Icl}$, $t_{o\ upper}$	upper limit of indoor operative temperature	°C
$\theta_{i\,min}$, $T_{min,\ Icl}$, $t_{o\ lower}$	lower limit of indoor operative temperature	°C
θ_{rm}, T_{rm}, t_{mpa}	weighted running mean outdoor temperature	°C

U	thermal transmittance (U-value)	W/m^2K
V	volume	m^3
vr	ventilation rate	m^3/s, l/s
-	energy consumption	kWh, Wh
-	energy demand, annual energy demand	kWh/m^2, kWh/m^2a
-	power	kW, W
-	unit of clothing insulation	clo
-	unit of metabolic rate	met (58.2 W/m^2)
Y	admittance	W/m^2K
ϑ	annual mean outdoor temperature	°C
α	absorptivity or thermal diffusivity	- or m^2/s
μ	decrement factor	-
ρ	density or reflectivity	kg/m^3 or –
ε	emissivity	-
θ	solar gain factor (g-value)	-
λ	thermal conductivity	W/mK
β	thermal effusivity	$Ws^{1/2}/m^2K$
φ	time lag	h
τ	transmissivity	-
ΔT	temperature difference	K

INTRODUCTION

''Research design is a logical plan for getting from 'here' to 'there', where 'here' may be defined as the initial set of questions to be answered and 'there' is some set of conclusions about these questions. Between 'here' and 'there' may be found a number of major steps, including the collection and analysis of relevant data.''
Yin (2009, p. 26).

''A 2010 census found 11.4m Brazilians living in favelas (slums). Millions more squeeze in with relatives or live in formal but substandard housing.''
The Economist (2013, p. 40)

In Brazil the housing sector is currently responsible for 22% of its construction activities (IBGE, 2011b, p. 38) and has been growing in recent years due to the expansion of mortgage credit availability and the number of private dwellings financed (IBGE, 2010b, p. 34). Despite the fact that a remarkable expansion of the housing sector has been noted recently, Brazil is still facing a long-term housing shortfall, estimated to be around 5.546 million and also a large proportion of inadequate dwellings with poor living conditions, which are estimated to be nearly 10.948 million (Fundação João Pinheiro, 2011, p. 59, 87).

As a solution for the housing deficit and inadequacy, which is higher for low-income households, the Brazilian government is committed to an ambitious target of up to 24 million new dwellings by 2022 through its housing programme Minha Casa, Minha Vida (MCMV, *My House, My Life*, in English) (Carbon Trust, 2012a, p. 47). This government sponsored programme was launched in 2009 to help provide the means for low- and middle-income households to acquire new affordable homes.

The number of households is predicted to increase by 2.1% per year until 2023 (EPE, 2013c, p. 55). Similarly, the energy consumption in the residential sector is also on an upward trend. The housing sector energy consumption grew 4.4% between 2010 and 2011 (EPE, 2012, p. 16) and 2.1% between 2011 and 2012 (EPE, 2013b, p. 16). Until 2023, the energy consumption in the sector is predicted to rise by 4.3% per year (EPE, 2013c, p. 55). The average monthly consumption estimated to be 164 kWh per household in 2013 is predicted to rise to an average monthly consumption of 202 kWh per household until 2023, which represents a growth rate of 2.1% per year in national energy consumption (EPE, 2013c, p. 56).

About 20% of the overall housing energy consumption is used for space conditioning (ELETROBRAS and PROCEL, 2007, p. 15). Even though the use of heating and cooling systems is still limited as the majority of households in Brazil do not currently have such systems, the rise in income and standard of living are expected to increase the numbers of households that utilize active means for space conditioning as this will

be within economic reach (Ghisi et al., 2007). Therefore, mitigation strategies should consider energy efficiency improvements in residential buildings, especially for the poorer Brazilian people facing energy transition process, energy security and a gradual increase in temperatures caused by climate change in progress (Alves et al., 2015).

Housing energy consumption in Brazil has electricity as its main energy source, which corresponds to 43% of the overall sector's energy consumption (EPE, 2013b, p.77). Brazilian electricity is sourced from hydro, biomass, wind, natural gas, nuclear, oil and coal products (EPE, 2013b, p. 16). The majority of the electricity comes from hydroelectric power but its share has decreased over the years, replaced by non-renewable thermoelectric power.

It is believed that mostly due to the increase of the thermal energy supply, residential electricity tariffs have suffered a progressive increase in prices recently. In 2014, the residential electricity tariffs were increased by 18.2% (Banco Central do Brasil, 2014b, p. 74) and in 2015, the prices were increased by about 33% (AES Eletropaulo, 2015a).

Due to all these factors linked to the increase of the number of dwellings, energy consumption and energy costs, it is therefore critical that the new houses become increasingly more thermally comfortable and energy efficient in order to reduce energy demand.

In order to support the design and construction of more thermally comfortable and energy efficient homes, the government has launched three main building energy regulations. The *NBR 15220: Thermal Performance in Buildings* (ABNT, 2005a, ABNT, 2005b, ABNT, 2005c, ABNT, 2005d, ABNT, 2005e), published in 2005, recommends design guidelines for thermal comfort in affordable dwellings. The *NBR15575: Residential buildings – Performance* (ABNT, 2013a, ABNT, 2013b, ABNT, 2013c, ABNT, 2013d, ABNT, 2013e, ABNT, 2013f), came into force in 2013, and is the newest standard to deal with the building performance in different aspects of a building, including thermal performance. The *Energy Labelling Scheme for Residential Buildings* (RTQ-R) (INMETRO, 2012), launched in 2010, is a voluntary standard to certify residential buildings, rating them according to their level of energy efficiency.

Whilst the Brazilian building energy regulations are a step forward to help deliver more thermally comfortable and energy efficient homes, there is still a potential for better results in terms of energy efficiency and, hence, in carbon emissions reduction in the housing sector. Carbon emissions are the major contributors to greenhouse gas emissions, which are understood to be one of the causes of climate change. The effects of climate change are widely acknowledged and they have been observed by the rise in the occurrence of severe events and extremes of temperatures. Buildings are one of the main factors responsible for climate and environmental change, because they are

major contributors to this environmental damage, from the sourcing of raw material through the energy used for their functioning and to the disposal of their elements when their life cycles end (Rodrigues, 2009).

A report published by McKinsey & Company (2012, p. 23), which investigated means of reducing carbon emissions, has estimated that Brazilian emissions in the housing sector would grow by 43% by 2030, possibly reaching 36 $MtCO_2$. According to the report, from the overall amount of potential abatement estimated to be around 8 $MtCO_2$, there is a potential for energy demand reduction of 20%, which can be achieved through improved insulation and internal air flow in new buildings as well as more energy efficient building materials and techniques to construct the building envelope.

Improvements in the thermal efficiency of the building envelopes are the key strategies used in many countries to achieve high levels of energy performance in dwellings. Most of the existing building energy regulations have been strengthened in these counties in order to achieve these high levels of energy performance (Pacheco and Lamberts, 2013). For instance, the building energy regulations of European Union member countries have been revised to become stricter in terms of building energy performance, as a result of the *Energy Performance of Buildings Directive* (Directive 2002/91/EC, 2002) and its *Recast Directive* (Directive recast 2010/31/EU, 2010), launched in 2002 and 2010, respectively. This directive was created as a result of the compliance to the Kyoto Protocol and designed to tackle climate change through a long term commitment to reducing the amount of carbon produced by a building and, consequently, its energy consumption. Most of the building energy regulations aiming for high levels of energy efficiency in buildings have focused on the Fabric First approach.

Fabric First is a design approach that prioritizes the building envelope efficiency and the building services in order to make a major contribution to increase the building energy performance. The Fabric First approach refers to a building envelope with optimized level of insulation and controlled air flow permeability. Its adoption has great potential to deliver low energy houses in a variety of different climates and it has been adopted across Europe and beyond, as part of a broader and holistic strategy for reducing energy consumption (Tubelo et al., 2014b). On the whole, the Fabric First approach adoption may lead to substantial energy savings, improved thermal comfort and reduced greenhouse gas emissions (Carbon Trust, 2012b).

One of the well-recognized examples based on the Fabric First approach is the Passivhaus standard (*Passive House,* in English). Passivhaus is a voluntary standard and it has been largely adopted because it perhaps has the most stringent requirements and generally offers better results if compared to other compulsory building energy regulations across Europe (Tubelo et al., 2014a, Tubelo et al., 2014b).

Compared to conventional new buildings, the Passivhaus standard has achieved energy savings of more than 50% in useful, final and primary energy demand (Feist et al., 2005, p. 1191, Schnieders and Hermelink, 2006, p. 151-158) and its space conditioning demand corresponds to only 20% of the space conditioning demand used by conventional new buildings (Schnieders and Hermelink, 2006, p.151-158). The Passivhaus standard was originally designed for cold climates and one of its main characteristics is a highly insulated and airtight building envelope, which results in a thermally comfortable and energy efficient building (Feist et al., 2005).

Many studies about the adoption of the Fabric First approach in warmer climates start from the Passivhaus standard. Findings of studies conducted in warmer climates using the Passivhaus criteria have demonstrated significant energy savings benefits (Ford et al., 2007b, Passive House Institute, 2012b, Hatt et al., 2012, Schnieders et al., 2012). These findings have suggested that the Passivhaus standard might still be a cost-effective approach in these climates, because its adoption showed a considerable reduction in space conditioning and increase of thermal comfort. They also indicated that buildings located in warmer climates may not require the same levels of insulation and airtightness when compared to buildings in colder climates.

Even though there is a large body of evidence that has supported the benefits of using the Fabric First approach, a certain level of criticism has been raised over the direct application of this insulated and airtight envelope approach for locations that have climates that differ from the original cold climate (Pacheco and Lamberts, 2013).

Pacheco and Lamberts (2013) stated that energy regulations based on super insulated models are regarded suspiciously in warmer climates, especially in Brazil. The authors suggested that super insulated envelopes are not a design strategy of energy efficient buildings in hotter climates or even for milder climates as those found in the south and southeast of Brazil. Although southern Brazil has more favourable climate conditions to adopt these insulated and airtight envelopes, the idea of airtight envelopes with sealed windows feels contrary to the cultural habits of naturally ventilated building occupants. The authors suggested that Brazil cannot import the same strategy of insulated and airtight envelopes from the developed and cold countries, but should create its own envelope strategies based on its own climatic, cultural and economic conditions.

This research aims to fill this gap and it explores the potential implementation of the Fabric First approach in affordable houses in southern Brazil, which endures hot summers and cool winters. In addition to the differences in climate, there are also differences in terms of the economy, the housing and construction market, and the workforce in Brazil when compared to developed European countries.

Research Aims and Objectives

The aim of the present research is to investigate whether the application of the Fabric First approach leads to an increase of indoor thermal comfort and energy efficiency in a typical southern Brazilian mass housing typology. Moreover, the research discusses the viability of the approach's implementation and its potential impact in Brazil due to the large cultural, market, climatic and economical differences between the country and European countries where the approach is widely used.

It is therefore critical to understand to which extent the implementation of the Fabric First approach through the optimisation of the building envelope in dwellings leads to energy performance improvement in those climates and also to what extent this is cost-effective and culturally acceptable.

The applicability of the Fabric First approach in Brazil is a largely underdeveloped area of research and is, consequently, the focus of this study.

The starting hypothesis is that currently most Brazilian housing building envelopes underperform in terms of thermal comfort and energy efficiency when compared to optimised envelopes based on the use the Fabric First approach concepts. Based on that, it is further hypothesized that optimised envelopes that adopt these fabric first concepts could lead to significant energy and thermal comfort improvements in housing.

The scope of the research was limited to the investigation of affordable housing located in the southernmost regions of Brazil. The research was carried out in 3 cites - Curitiba, São Paulo and Porto Alegre. The areas for investigation were selected because they have a moderate climate, which presents more similarity with the locations where the Fabric First approach has been implemented so far.

Research outcomes aimed to clarify how a typical southern Brazilian mass housing typology performs in terms of thermal comfort and energy efficiency and how it would perform comparatively when optimised in terms of its envelope, with the adoption of the Fabric First approach at various levels.

In order to ensure that the aim of the research is met, several objectives have been defined:

i. To define typical affordable Brazilian housing, its typical envelope and its typical energy use;
ii. To investigate how typical Brazilian housing performs in terms of thermal comfort and energy efficiency;

iii. To explore potential building envelope improvements through the adoption of the Fabric First approach concepts;
iv. To assess which elements of the building envelope are the most sensitive in terms of thermal comfort to establish a benchmark for improving envelope performance for the selected locations in a cost-effective way;
v. To examine the impact of increased insulation and levels of airtightness;
vi. To explore potential building running cost savings and payback period of optimised housing envelopes when compared to the typical ones.

The present research aims to make a significant contribution to existing knowledge in terms of affordable houses as it seeks to inform ways of designing these houses with higher levels of thermal comfort and energy efficiency.

Research Method

The present research required different research methods in order to answer the research questions and meet the research objectives.

In order to gain a full understanding of the research context, key areas of literature search covered the Fabric First approach and the Passivhaus standard theory and application, housing and energy use in Brazil, local climate, thermal comfort criteria and vernacular housing architecture.

The research undertaken in this work utilised two main methods. The first method comprised of an extensive parametric study, based on the sensitivity analysis method and executed though the development of dynamic computational tools. The parametric study investigated the building envelope optimisation, underpinned by the Fabric First approach concepts. The aim of this study was to identify the best performance and the most-cost effective envelopes for the locations investigated by using as a starting point the typical Brazilian envelope and afterwards by performing different degree of envelope optimisation in terms of its thermal resistance and air infiltration rate.

The second method comprised case studies analyses. A case study is the method that allows the researcher to investigate real-life events so that the researcher has no control over all possible variables (Yin, 2009). The case study evaluation of the present research relied on a multiple source of evidence such as documentation and archival records and used the logic models technique. Logic models stipulates a sequence of events over an extended period and the events are staged in a repeated cause-and-effect sequence of events, all linked together (Yin, 2009). In this case, a dependent variable at an earlier stage becomes the independent variable for the next stage in order to understand the impact of the variables investigated.

Two case studies were considered to support the development of this research – '*Minha Casa, Minha Vida*' House and 'Alvorada' House. Despite the fact that both case studies replicate the same structure of investigation, each case study presupposed the influence of different aspects of buildings such as design, fenestrations, materials and form. It should be noted that evidence from multiple cases is more robust and provides more compelling support for the findings than single cases (Yin, 2009). Hence, analytical conclusions, independently arising from two cases, are more powerful than using a single case (Yin, 2009).

The case studies were selected in a complementary manner in the context of Brazilian mass housing typology. The '*Minha Casa, Minha Vida*' House has traditionally been recognised to be dependent upon support from the government and is the most representative of a typical affordable Brazilian house, widely implemented across the country. In the research, a representative model of the MCMV House typology was adopted for further dynamic thermal modelling analysis. Similarly, the 'Alvorada' House is a real case study, based on a mass housing typology with an optimised design and built in the city of Porto Alegre. Alvorada House was adopted for further simulation analysis and empirical data collected insitu was used to validate the simulation model. The case studies were used to endorse the building optimisation analysis of the parametric study for a real housing context, supported by a cost analysis and therefore, they were used to state recommendations as the best way forward.

The path chosen by this research was instrumental to fulfil the stated objectives as due to the lack of fabric first examples in Brazil, the conduction of an exploratory approach at first through the parametric study, followed by testing these findings individually in representative Brazilian case studies were more advantageous for the present research purpose.

Research Structure and Key Outcomes

The thesis is structured into 7 Chapters. Chapters 1 and 2 are the lead-in chapters to clarify the foundation of the research. Chapter 3 introduces the climate in the areas of research and the preamble for the development of the work. Chapters 4 to 6 are the core of this research, the first showing the parametric study and the last two developing the case study analysis. Chapter 7 is the lead-out chapter to show the final outcomes. The detailed content of each chapter is as follows:

i. Chapter 1 - The Fabric First Approach in Housing: This chapter describes the context of this study and introduces the theory related to the Fabric First approach, including the building physics, the key elements to be considered, housing size and energy use. Relevant building energy standards are also

examined, including the Passivhaus. All these cited elements of the literature review are correlated to inform this study and additionally expand current knowledge of the fabric first approach.

ii. Chapter 2 - Housing and Energy in Brazil: This chapter establishes the basis of the present research and defines the state-of-the-art of the Brazilian housing sector. This includes a new array of housing patterns, household energy trends and current building energy regulation in Brazil, which are relevant to support the analytical appraisal of this study. The investigation of this chapter is an addition to existing knowledge as the information about houses in Brazil is not easily accessible. Its originality lies on the definition of affordable and also middle-class houses, regarding their typology, size energy-use, household income, typical occupancy and materials used.

iii. Chapter 3 - Climate and Architecture in Brazil: This chapter includes a climate assessment and lessons learnt from vernacular housing in Brazil. It also discusses thermal comfort criteria and environmental design strategies that guide the focus of this work. The originality of this chapter lies in the way that the investigation of the vernacular housing was conducted to explore applicable environmental design strategies for the locations investigated and to corroborate the definition of the southern Brazilian housing typology.

iv. Chapter 4 - Parametric Study Using the Fabric First Approach: A parametric study using sensitivity analysis is used to examine thermal comfort and performance of Brazilian dwellings through changes in a number of envelope parameters and conditions, evaluated by dynamic simulations. Furthermore, this chapter establishes the research method utilised in the rest of the work. This is the first complete study in terms of Brazilian housing that investigated a variety of different levels of envelope optimisation, supported by a cost analysis for estimating the cost-effectiveness of the strategies investigated.

v. Chapter 5 - Case Study: The MCMV House: A case study based on a typical affordable house is explored in terms of design, environmental design strategies, materials used and its thermal performance. The house is assessed through the use of dynamic building simulations, and changes in the envelope parameters are implemented and analysed with the aim of improving the house's thermal performance. The originality of this study lies on the fact that it estimates for the first time potential running costs and payback period of this house and its proposed improvements, supported by a detailed cost analysis.

Cost equations are also formulated for estimating costs of the house design and construction for the scenarios investigated.

vi. Chapter 6 - Case Study: The Alvorada House: A real case study is explored in this chapter and the investigation follows the same framework as Chapter 5. However, this case study consists of a step up of the investigation, as it adopts a case study already built with design strategies to improve thermal comfort and also uses empirical data to corroborate the thermal response of the simulation model.

vii. Chapter 7 - Conclusion and Further Work - This chapter shows the outcomes of the present research and recommendations for further work.

CHAPTER 1: THE 'FABRIC FIRST' APPROACH IN HOUSING

This chapter describes the Fabric First approach theory. Housing and energy use, where the Fabric First approach is mostly used, are examined to support the development of this research. Building energy regulations based on this approach are also discussed, including the Passivhaus standard, which is shown in detail.

''It is easy to think about housing in numbers, percentages, bricks and mortar. But we should not forget that housing is fundamentally about people.''
(RIBA, 2011, p. 7).

''For the first time people began to understand a building as an enclosure for a bubble of warmed air and realized that attention had to be paid to making the building more airtight. Simply blocking out the rain and wind isn't sufficient in air-heated house, for if a building still leaks air, pressure from the wind can drive all of the heat air to one side of the house and out through the walls.''
(Heschong, 1979, p. 14).

''The Passivhaus standard sets a new reference for low-energy buildings for several important reasons […] it requires a much higher energy efficiency than any other standard it can be compared to.''
(Dequaire, 2012, p. 378).

1 THE ‘FABRIC FIRST’ APPROACH IN HOUSING

The most effective way to increase thermal comfort and energy efficiency in buildings is by means of acting on the elements which constitute the exterior-interior exchange system, controlling the heat transfers through the envelope (Dominguez et al., 2012). In order to meet this, the adoption of a holistic approach that encompasses all aspects of a building envelope is needed and it consists mostly of increasing insulation, reducing thermal bridges and promoting effective infiltration and ventilation strategies (Energy Saving Trust, 2010).

There is, however, a critical point of view contrary to this argument, which states that buildings cannot be insulated or isolated from large scale energy systems and, therefore, this kind of approach is limited (Moe, 2014). Moreover, this insulation-based approach neglects the building as an open thermodynamic system and to do so, it perpetuates the metabolic rift of architecture and diminishes the architecture capacity. According to this argument (Moe, 2014), architects need to deal with the maximal ecological power and its architectural potential, instead of efficiency or optimization. Before any claim on performance, an architect must first know the inputs, throughputs, and outputs of the overall system: the energy hierarchy of the process. Without this comprehensive view of energy hierarchies, the efficacy of a particular design cannot be evaluated. The architect’s task might include to deal with specific transmittance properties but in other cases the key energetic functions of mixing, slowing, delaying, or storing might matter more and have greater thermodynamic efficacy.

The Fabric First approach relies on the first concept mentioned above. Fabric First is one of the most stringent design approaches. It prioritizes the building envelope and services in order to make a major contribution to increase the building’s energy performance and the occupant’s thermal comfort and it mainly considers the optimized level of insulation and controlled air infiltration. Consequently, this optimisation of the envelope leads to a potential reduction of heating and cooling requirements when compared to conventional envelopes and also to the downsizing of heating and cooling systems or the elimination of them at all (Carbon Trust, 2012b). Hence, the adoption of the Fabric First approach has great potential to deliver low energy buildings and it has been adopted as part of a broader strategy for reducing energy consumption in buildings.

Nevertheless, the Fabric First approach was initially designed for central European climates and it might consider specific characteristics in terms of housing’s typology, internal gains, energy use and thermal comfort criterion that might not be adequate for use in other climates such as Brazil.

Therefore, building physics, key design elements and characteristics of the Fabric First buildings in terms of housing and energy use, building energy regulations and the Passivhaus standard were revised in the present chapter. The main aim was to support the development of the research, presenting detailed theory related to the Fabric First approach in housing, which will be later correlated to the Brazilian context.

1.1 Thermal Performance in Housing

Heat transfer in buildings occurs by conduction, convection or radiation.

Heat transfer by conduction happens due to the contact of particles of bodies, more often between solids. Heat transfer by conduction depends on the thermal conductivity (λ, in W/mK), which is a material property that represents the ability of the material to conduct heat, measured as the heat flow density (W/m^2) in a 1 m thick body with a one degree temperature difference (Szokolay, 2008, p. 9). Thermal conductivity of a material is related to its bulk density and its moisture content (CIBSE, 2006b). For instance, insulation materials have low thermal conductivity and this explain why they reduce heat transfer. Its corresponding property of a physical body is conductance (C, in W/m^2K), which takes into account the thickness of the body (Szokolay, 2008). The increase of the layer thickness results in a higher resistance to the heat exchange by conduction. Thermal resistance of a material (R, in m^2K/W) is the relationship between the material thickness and its thermal conductivity. On the other hand, thermal transmittance (U-value, in W/m^2K) determines the amount of heat transmitted (in Watts) per square metre of material at a difference of one degree of temperature (in Kelvin). Thermal transmittance is a major factor in the determination of steady-state heat losses and gains (CIBSE, 2006b).

Thermal transmittance of a building element composed by homogenous layers is calculated by the sum of its component layers, as shown in Equation 1-1. The total thermal transmittance of a building element composed by bridged layers is calculated by a reasonable approximation considering the upper and lower limits of its thermal resistance[1], as illustrated in Equation 1-2. The resistance lower limit is obtained by adding together the thermal resistances of the various layers, each being calculated separately, whereas the resistance upper limit is obtained by the division of each layer into isotropic sections, the thermal resistances of which are added together on an area-weighted basis (CIBSE, 2006b). The procedures are detailed in The Chartered

[1] If the difference between the thermal resistances of the bridged layer and non-bridged layers is less than 0.1 m^2K/W, the effect of thermal bridging could be neglected. p. 3-9. CIBSE 2006b. Environmental Design: Guide A. London, United Kingdom: The Chartered Institution of Building Services Engineers (CIBSE).

Institution of Building Services Engineers (CIBSE) Environmental Design Guide (CIBSE, 2006b, p. 3-10).

Equation 1-1: thermal transmittance of a building element (CIBSE, 2006b, p. 3-7)

$$U = \frac{1}{(R_{si} + R_1 + R_2 + \cdots + R_a + R_{se})}$$

Where,
U = sum of thermal transmittance of a building element, in W/m^{2}K
R_{si} = internal surface resistance, in m^{2}K/W, depends on the heat flow direction that is perpendicular to the plane of the structure (upward heat flow direction: 0.10, horizontal heat flow direction: 0.13, downward heat flow direction: 0.17)
R_1, R_2 = thermal resistances of components, m^{2}K/W
R_a = thermal resistance of air spaces (if present), m^{2}K/W
R_{se} = external surface resistance, m^{2}K/W, depends on the heat flow direction that is also perpendicular to the plane of the structure (for upward, horizontal and downward heat flow direction: 0.17)

Equation 1-2: thermal resistance of a building element with a bridge structure (CIBSE, 2006b, p. 3-9)

$$R_b = \frac{1}{2}\ (R_L + R_U)$$

Where,
R_b = thermal resistance of a building element composed by a bridge structure, in m^{2}K/W
R_L = lower limit of thermal resistance, in m^{2}K/W
R_U = upper limit of thermal resistance, in m^{2}K/W

Table 1-1 shows the thermal properties of typical materials used to build dwellings and Table 1-2 shows the thermal properties of typical insulation materials.

Table 1-1: Thermal properties of typical materials used in dwellings

	Material	Density ρ (kg/m^3)	Thermal conductivity λ (W/mK)	Specific heat capacity c (J/kgK)	Source
Walls	Hollow ceramic block	1300	0.9	920	(ABNT, 2005b, p. 13-16)
	Solid ceramic brick	1800	1.0	920	
	Lime cement plaster	2000	1.15	1000	
	Ceramic wall tiles	2000	1.20	850	(CIBSE, 2006b, p. 3-36)
Windows	3 mm glass	2500	1.0	840	(ABNT, 2005b, p. 13-16)
	Hard wood frame	900	0.29	1340	
	Soft wood frame	600	0.23	1340	
	PVC frame	-	0.176	-	TAS database (EDSL, 2013a)
Roof	Ceramic roof tiles	2000	1.05	920	(ABNT, 2005b, p. 13-16)
	Aluminium foil	2700	230	880	
	Wood ceiling	600	0.23	1340	
Ground floor	Stone chippings	2000	2.0	1000	TAS database (EDSL, 2013a)
	Screed concrete	2200	1.75	1000	(ABNT, 2005b, p. 13-16)
	Ceramic floor tiles	2000	1.30	840	(IBO - Austrian Institute for Healthy and Ecological Building, 2009, p. 330-331)

Table 1-2: Thermal properties of typical insulation materials. Based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 330-331)

Material	Density ρ (kg/m^3)	Thermal conductivity λ (W/mK)	Specific heat capacity c (J/kgK)
Expanded Polystyrene (EPS)	30	0.035	1450
EPS for facade	18	0.040	1450
Mineral wool	33	0.040	1030

Heat transfer by convection happens when there is a contact among particles of bodies and at least one of them is a fluid, such as the air. Heat transfer by convection depends

on the temperature difference between the surface and the air, the surface roughness, the air velocity and the direction of the heat flow[2] (CIBSE, 2006b, p. 3-7).

Heat transfer by radiation occurs when a body emits a radiant energy, which is absorbed by another body and the radiant energy is converted into thermal energy. Heat transfer by radiation depends on the surface properties of an absorber and an emitter material and their temperatures. The surface properties of an emitter body is emissivity (ε), which is a measure of the ability of a body to emit radiation (Szokolay, 2008); in other words, it is the relationship between the radiation rate emitted by a surface and the radiation rate emitted by a black body in the same temperature. It is defined between 0 and 1, where 1 corresponds to a black body, theoretically a perfect emitter of heat. Metallic surfaces have a low emissivity coefficient, being the lowest values associated with polished metallic surfaces. Non-metallic surfaces have a high emissivity coefficient. Most common building materials have high emissivities, generally higher than 0.9 (CIBSE, 2006b, p. 3-6). The emitted radiant energy varies with the temperature of the wavelength emitted by the source. The emitted radiant energy by long wavelength occurs in bodies at low temperature whereas the emitted energy by short wavelength occurs in bodies at high temperature, such as the sun.

When the radiant energy reaches a surface of an element it is split into three parts: absorbed, reflected and transmitted parts, as shown in Equation 1-3. The proportion of energy absorbed, emitted or transmitted will be determined by the surface of the material where the radiant energy hits and by the incident wavelength. Absorptivity (α) determines how much of the incident radiation is absorbed by the surface of the material and it is related to the surface capacity of material to absorb incident radiant energy. Reflectivity (ρ) is the capacity of the surface of the material that determines how much of the incident radiation is reflected. Transmissivity (τ) is capacity of the surface of the material that determines how much of the incident radiation is transmitted.

Equation 1-3: Incident radiant energy (Szokolay, 2008, p. 39)

$$\tau + \rho + \propto = 1$$

Where,
τ = transmitted part
ρ = reflected part
α = absorbed part

A practical example of this equation is the exposure of a roof surface to solar radiation. A sun-exposed roof surface has its temperature raised due to solar radiation and this sets up a downward heat flow. The downward heat flow can be reduced by the use of

[2] Values of the convective heat transfer coefficient for the air - horizontal heat flow direction: 2.5 W/m^{2}K, upward heat flow direction: 5.0 W/m^{2}K, downward heat flow direction: 0.7 W/m^{2}K. p. 3-7. Ibid.

reflective foil under the roof skin because this material surface has both low emissivity and absorptivity coefficients. Table 1-3 shows emissivity and absorptivity coefficients of typical material surfaces.

Table 1-3: Absorptivity and emissivity coefficients of typical material surfaces. Based on ABNT (2005b, p. 12)

Material surface	Absorptivity (α)	Emissivity (ε)
Aluminium foil	0.05	0.05
Ceramic roof tile	0.75/0.80	0.85/0.95
Ceramic brick	0.65/0.80	0.85/0.95
Plaster	0.30/0.50	0.85/0.95
Transparent glass	0.06/0.25	0.84
White coating	0.20	0.90
Yellow coating	0.30	0.90

1.1.1 Steady-state Heat Transfer

Heat transfer through a building envelope occurs when there is a difference of temperature between the inside and the outside of the building. In steady-state heat transfer calculations, the temperature is considered as remaining unchangeable during the heat transfer period. When the sum of all heat transfer that occurred through the building envelope is null, this means that the building is in thermal balance (Szokolay, 2008). Equation 1-4 shows thermal balance equation with its corresponding typical heat gains or heat losses of the building. In cold climates, which for most of the time have indoor temperatures higher than the outdoor temperatures, building heat gains correspond to internal heat gains due to the occupancy and solar radiation; and building heat losses correspond to conduction through the building envelope and ventilation (Yannas, 1994). In moderate and warm climates, which can have the outdoor temperatures higher than the indoor, conduction through the building envelope and ventilation can also contribute to heat gains.

Passive design buildings, such as those designed based on the Fabric First approach, rely on these thermal balance assumptions.

Equation 1-4: Thermal balance (Szokolay, 2008, p. 35)

$$Q_i + Q_s \pm Q_c \pm Q_v - Q_e = 0$$

Where,
Qi = internal heat gain, in W
Qs = solar heat gain, in W
Qc = conduction heat flow (gain or loss), in W
Qv = ventilation heat flow (gain or loss), in W
Qe = evaporative heat loss, in W

Internal heat gain (Q_i) is the heat generated inside the building by the occupants, the lighting system and the operation of household appliances (Yannas, 1994). The heat output by the occupants ranges with their metabolic activity. For instance, the heat output of sedentary work is 130 W while the heat output of doing heavy work is 425 W (ASHRAE, 2009a, p. 18.4). The heat generated by lighting systems and household appliances depends on their power (in W) and usage time.

Solar heat gain (Q_s) occurs in different ways for transparent and opaque elements. For transparent elements, the solar heat gain is obtained by the product of the incident radiation by the area of the window and by the solar gain factor, which depends on the type of glazing, as shown in Equation 1-5. The part of incident radiation that enters the building interior through the transparent element includes the radiation part that is transmitted and the radiation part that is absorbed by the glass. The radiation part that is absorbed by the glass could be partially inward re-emitted and partially outward re-emitted (Szokolay, 2008).

Equation 1-5: Solar heat gain for transparent elements (Szokolay, 2008, p. 39)

$$Q_s = A.G.\theta$$

Where,
Qs = solar heat gain, in W
A = area of window, in m²
G = global irradiance, in W/m²
θ = solar gain factor of the glazing

For opaque elements, the solar heat gain is similar to the equation of conduction heat flow but it considers the relation of the sol-air temperature, which is different for each side of the building (Szokolay, 2008). Equation 1-6 and Equation 1-7 show the solar heat gain in opaque elements. The solar heat gain in opaque elements is defined by the product of the envelope conductance and the sol-air excess temperature[3], which differs for walls and roof (Szokolay, 2008).

Equation 1-6: Solar heat gain for opaque elements (Szokolay, 2008, p. 41)

$$Q_s = q_c \times dT_e$$

Where,
Qs = solar heat gain, in W
q_c = envelope conductance, in W/K
dT_e = sol-air excess temperature, in K

Equation 1-7: Envelope conductance (Szokolay, 2008, p. 43)

$$q_c = \sum (A \times U)$$

Where,
q_c = envelope conductance, in W/K
A = surface area, in m²
U = transmittance, in W/m²K

The calculation of sol-air excess temperature for the roof and the walls are shown in Equation 1-8 and Equation 1-9, respectively. The radiant heat emission (E, in W) has to be considered for the roof due to the surface being exposed to the sky (Szokolay, 2008).

Equation 1-8: dTe roof (Szokolay, 2008, p. 41)

$$dT_e = (G \times \alpha - E) \times R_{se}$$

Where,
dT_e = sol-air excess temperature, in K
G = global irradiance, in W/m²
α = absorptance coefficient
E = radiant heat emission, in W
R_{se} = external surface resistance, m²K/W

[3] Sol-air excess temperature (dT_e) is the temperature equivalent of the solar heat input, over and above the air temperature effect. p. 41. SZOKOLAY, S. 2008. *Introduction to architectural science: the basis of sustainable design,* London, United Kingdom and NY, United Stated, Architectural Press/ Routledge.

Equation 1-9: dTe wall (Szokolay, 2008, p. 41)

$$dT_e = G \times \alpha \times R_{se}$$

Where,
dT_e = sol-air excess temperature, in K
G = Irradiance, in W/m²
α = absorptance coefficient
R_{se} = external surface resistance, m²K/W

Conduction heat gain or loss through the building envelope is defined by Equation 1-10 (Szokolay, 2008). The rate of heat flow is determined by the transmittance, the exposed area and the temperature gradient.

Equation 1-10: Conduction heat flow (Szokolay, 2008, p. 44)

$$Q_c = A \times U \times \Delta T$$

Where,
Qc = conduction heat flow, in W
A = surface area, in m²
U = transmittance, in W/m²K
ΔT = temperature difference between outdoor and indoor, in K

Ventilation heat gain or loss (Q_v) depends on the infiltration and the ventilation rate and this is determined by Equation 1-11.

Equation 1-11: Ventilation heat flow (Szokolay, 2008, p. 42, McMullan, 2012, p. 67-68)

$$Q_v = 1200 \times vr \times \Delta T$$

Where,
Qv = ventilation heat flow, in W
1200 = volumetric heat capacity of moist air, in J/m³K
vr = ventilation rate, in m³/s
ΔT = temperature difference between outdoor and indoor, in K

When the value of air changes per hour (ach) is known, the ventilation rate can be obtained by Equation 1-12.

Equation 1-12: Ventilation rate with known value of air changes per hour (Szokolay, 2008, p. 42, McMullan, 2012, p. 67-68)

$$vr = \frac{N \times V}{3600}$$

Where,
vr = ventilation rate, in m³/s
N = air changes per hour
V = volume of the room or building, in m³
3600 = number of seconds in one hour

Steady-state heat transfer regime may fail as a method to estimate realistically heat flows occurring within the building as it does not consider the dynamic response of the buildings and to do so, it is not capable to properly capture the relationship of the building envelope heat flows and design variables (Clarke, 1985). Due to this reason, transient heat transfer is more appropriate to be considered when evaluating building thermal performance.

1.1.2 Transient Heat Transfer

In transient heat transfer regime, the temperatures over a heat flow period are not constant as in the steady-state heat transfer. In this regime, a fluctuation of heat flux at

one boundary of a material reaches the other boundary, being diminished in magnitude due to material storage property and shifted in time due to material's storage capacity (Clarke, 2001). More specifically, if a rise in the external temperature happens, a heat flows will progressively occur within the building element and the temperatures will be different at different locations of the envelope element until the attenuated heat arrives at the internal surface some time later (Rodrigues, 2009).

The steady-state regime does not realistically occur in a building subject to the weather. However, as the weather condition behave as a cycle during and over the days, the total heat flux can be predicted by steady-state calculations, although this regime cannot predict the heat flux in any point during the transient heat flow mechanism (Rodrigues, 2009).

Transient heat flow through the building envelope is dependent of the temperature and heat flux at exposed surfaces of material, the time, the thermo-physical properties of the individual homogeneous materials and their relative position (Clarke, 1985, Clarke, 2001). The thermo-physical material properties of interest in this regime of heat transfer are conductivity (λ), density (ρ) and specific heat capacity (c) (Clarke, 1985). By combining them, different dynamic performance indicators are established, such as thermal diffusivity and effusivity.

Thermal diffusivity indicates the speed at which the temperature profile moves through the wall (Rodrigues, 2009). Materials with high diffusivity values are able to transmit a heat flux more rapidly than those with low values (Clarke, 1985) and this is shown in Equation 1-13.

Equation 1-13: Thermal diffusivity (Davies, 2004, p. 33)

$$\alpha = \frac{\lambda}{\rho \times c}$$

Where,
α = thermal diffusivity, in m^2/s
λ = thermal conductivity, in W/mK
ρ = density, in kg/m^3
c = specific heat capacity, in J/kgK

Thermal effusivity measures the capacity of the material to exchange thermal energy and it characterises the transfer of heat influenced by the surface of the material (Rodrigues, 2009). Materials with high effusivity are able to absorb a surface heat flux more rapidly than those with low values (Clarke, 2001) and this is show in Equation 1-14. Effusivity is larger for heavy materials than for insulating materials (Davies, 2004).

Equation 1-14: Thermal effusivity (Davies, 2004, p. 33)

$$\beta = \sqrt{\lambda \times \rho \times c}$$

Where,
β = thermal effusivity, in $Ws^{1/2}/m^2K$
λ = thermal conductivity, in W/mK
ρ = density, in kg/m^3
c = specific heat capacity, in J/kgK

In steady-state, two building elements with the same U-values will conduct the same amount of heat even through the thickness and the materials differ (Rodrigues, 2009). In transient heat transfer, however, differently from steady-state, the storage capacity of the materials is considered and this means that different materials with same U-values will perform differently as they have different thermal capacity values and their time delay on the heat flow also differ. A material with high thermal capacity will deliver a smaller amount of heat flow than the other material that has lower thermal mass.

In transient heat flow regime, there is a delayed in the peak heat flow between the material surfaces, which is referred as time lag (φ), expressed in hours and this delay is higher for the building elements with high thermal mass. A material that has high thermal mass will have its heat flow delayed because the material will absorb heat to increase its temperature before it transmit any heat and this stored heat would then be emitted with some delay (Szokolay, 2008).

As mentioned before, the magnitude of the heat flux delivered will also be diminished. The ratio of the amplitude of the peak from the mean heat flow under a periodic regime undergoing transient heat process and the hypothetical non-thermal mass material undergoing steady-state heat flow is the decrement factor (μ), varying from 0 to 1 (Clarke, 1985, Szokolay, 2008). Thus, decrement factor is the reduction in the predicted heat flux relative to an steady-state regime (Rodrigues, 2009). The method for calculating decrement factor and time lag is further detailed in Szokolay (2008) and for compounding all building factors this can only be accurately calculated using dynamic building simulations (Hopfe and McLeod, 2015).

The position of the different materials and the direction of the heat flow within the construction elements also influence the transient behaviour (Clarke, 1985). Different sequence of layers of a building element will impact on its performance differently and, consequently, will result in different admittance values.

Admittance (Y), measured in W/m^{2}K, is the amount of energy entering a surface for each degree of temperature swing (Clarke, 1985) and it refers to the ability of the element to store and release heat (Szokolay, 2008). Admittance is related to the properties of the materials in the internal layers of the construction elements and this is likely to be high for construction elements that have high thermal mass in their inner layers and low for those elements that have insulating material in these corresponding layers (CIBSE, 2006b, Rodrigues, 2009). If a summer condition is considered, the most beneficial sequence of a wall layer is to have the thermal mass inside the building in order to deliver a more stable indoor temperature (Szokolay, 2008). Heavyweight materials such as concrete have larger admittance values than lightweight materials such as insulating materials (McMullan, 2012). A typical heavyweight cavity insulated

wall of brick and block has admittance of 4 W/m^{2}K whilst a typical lightweight wall of cladding and insulation has admittance of 1 W/m^{2}K (McMullan, 2012, p. 72). Admittance calculation for a solid homogeneous element is shown in Equation 1-15 and for multi-layer construction element the method is further detailed in CIBSE (2006b). A comprehensive list thermal admittance values of typical construction element is detailed in CIBSE (2006b).

Equation 1-15: Admittance for solid homogeneous element (Szokolay, 2008, p. 131)

$$\gamma = \sqrt{\lambda \times \rho \times c \times \omega}$$

Where,
Y = admittance, in W/m^{2}K
λ = thermal conductivity, in W/mK
ρ = density, in kg/m^3
c = specific heat capacity, in J/kgK
ω = angular velocity, for 1 cycle per day (0.2618 rad/h)

As show in the revision there is a need to utilise dynamic models to determine the performance of building envelopes especially when these are combined with many other design features (Clarke, 1985) and to do so, computer thermal modelling analysis software, which accounts these complex heat flows, are necessary.

Dynamic building simulation is an attempt to emulate the reality (Clarke, 2001). It is now a well-established procedure to predict building thermal performance for a given specific climate and it has become increasingly necessary to support design decisions because it improves the level of confidence in the choice of the most appropriate design solution (Pisello et al., 2012, Jankovic, 2012). Dynamic building simulation has become a concern for designers and applied researchers given the high potential for building modifications to saving energy by incorporating analyses of whole buildings rather than analysing buildings as simple additions of disconnected parts (Pisello et al., 2012). Its growing acceptance has been promoted by the consideration of the complexity in the calculation (which is not considered in traditional design methods based on steady-state regime – that embody many simplifying assumptions, with no attempt to effectively represent the energy and mass flow paths that occur in real buildings) and rapid feedback on costs and performance (Clarke, 2001). Simulation can be used in early design stage to determine the optimum constructional scheme and design configuration for a climate (Clarke, 2001). Dynamic building simulation is therefore an useful method of testing design solutions before constructing them (Jankovic, 2012).

In the next chapters of the thesis, this research uses thermal dynamic simulations as a core of the analysis to calculate thermal performance of the houses in Brazil. Among the substantial number of simulation tools available on the market, the present research made use of the Thermal Analysis Simulation (TAS) software, distributed by EDSL (EDSL, 2013a). The rationale for selecting TAS was due to its capabilities of dynamic

simulation analyses software with an accessible and interactive graphical interface for architects and also its widely recognition in the market. Besides, the software is one of the most complete for building thermal performance analysis as it allow the user to define a variety of use schedules, shading devices, windows functioning, ventilation patterns and it is capable of accurately estimating the building thermal performance and the energy consumption for the most complex of building typologies. TAS is mainly divided into the building modelling and the simulation tools (EDSL, 2013a) and its theory manual provides further information of calculation procedures and validation (EDSL, 2013b).

All the above mentioned building physics theory is the basis of the knowledge in thermal performance in buildings. The next section introduces the key design elements of the Fabric First approach.

1.2 The Fabric First Approach

The key design elements of the Fabric First approach are those that have greater influence on the building performance and these are: shape, fabric, fenestration and ventilation. These elements are mostly related to the appropriate management between the heat gains and losses through the envelope, as discussed previously, and they have to be given close attention from the early stages of the design.

Shape

Orientation of a building for better solar management control is towards equator, along east and west axis, as it would allow maximum benefit from solar gains in winter and can be easily managed in summer with appropriate shading. Building facing up to 15° to east or west of the solar orientation makes very little difference to the amount of energy that can be gathered from the sun (Roaf et al., 2013). Also, this orientation can reduce energy demand by up to 30% in moderate climates (BRE, 2011, p. 2, Roaf et al., 2013, p. 24). East and west orientation should be kept at minimum as summer morning and afternoon sun might be intense and sun angles are low, which makes it difficult to shade these areas of the building (Hyde et al., 2008). In particular, the most difficult orientation is west, because the low western sun coincides with the hottest time of day (mid to late afternoon), making overheating of exposed west-facing spaces a probability in summer in most of the climates (Roaf et al., 2013, p. 58).

Form factor of a building is the ratio between all external surface areas of the building envelope (A) and its internal treated floor area (TFA) (BRE, 2011). It measures how compact or spread-out the building is (Cotterel and Dadeby, 2012). Reduction in the outer surface area of the envelope leads to an additional heat protection and reduces

the heat flows through the envelope because the exposed area to the environment is smaller (IBO - Austrian Institute for Healthy and Ecological Building, 2009). Form factor ≤ 3 is a useful benchmark guide to design Fabric-First-based buildings (BRE, 2011, p. 2). A form factor between 2 and 3 is a typical value found in semi-detached or compact detached houses of two or three-storey, while a form factor between 3 and 4 is a typical value found in less compact detached houses (Cotterel and Dadeby, 2012, p. 21).

Compactness of a building is the ratio between external surface area of the building envelope (A) and its internal volume (V). A compactness ratio of less than or equal to 0.7 m^2/m^3 is desirable (BRE, 2011, p. 2, Hopfe and McLeod, 2015, p. 51). A higher compact building (smaller surface containing the largest possible volume) is more cost efficient as it lower heat losses and gains that mostly depends on the exposed surface of the building envelope to the environment (Sattler, 2007, IBO - Austrian Institute for Healthy and Ecological Building, 2009). In the literature, compactness is also found as the ratio between the internal volume of the building and the external heat loss surface area of the envelope (V/A) and desirable values are set between 0.8 m and 2.2 m (Ford et al., 2007c, p. 23). Figure 1-1 shows examples of building compactness.

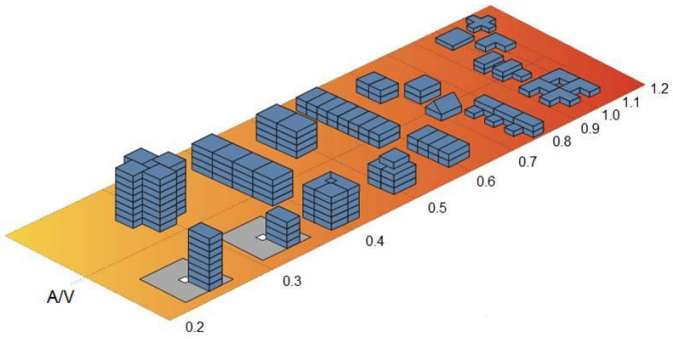


Figure 1-1: Examples of building compactness, in m^2/m^3 (BRE, 2011, p. 2).

Fabric

Thermal mass of a building envelope is a term used for any material property associated with the heat storage capacity and its use is beneficial to control internal temperature peaks and fluctuations (Rodrigues, 2009). An envelope made out of a high thermal mass material has the capacity to absorb, store and release heat and could be more appropriate for climates with daily temperature variation. In summer, thermal mass can be used to limit the peak temperature as the heat stored in the envelope structure is released when the external temperature is reduced, refreshing the building structure (Lamberts et al., 2014). In winter, the thermal mass can be used to compensate low temperature as the heat gains build up in the envelope structure during the day are released into the building at night, when the temperature goes down (Lamberts et al., 2014). In climates where thermal mass is beneficial, buildings should

also have adequate amounts of internal thermal mass such as concrete floors and internal brick walls (Hyde et al., 2008). Most common heat storage materials applied to residential buildings are concrete, adobe, stone and bricks (Rodrigues, 2009). The rule of thumb when sizing thermal mass in temperate climates for diurnal use is to use a depth of mass of 100 mm for each exposed surface but it can be up to 200 mm depending on the rooms configurations (Roaf et al., 2013, p. 58)

Thermal bridges of a building envelope arise at corners, edges and junctions between different building components and in areas where the building structure has a combination of materials of different thermal conductivities (Szokolay, 2008, IBO - Austrian Institute for Healthy and Ecological Building, 2009). Thermal bridges must be avoided because of undesirable heat exchange through the building envelope and because it may also lead to mould, condensation and moisture penetration (IBO - Austrian Institute for Healthy and Ecological Building, 2009, Cotterel and Dadeby, 2012). Linear thermal bridges lead to additional heat losses and these are represented by the thermal bridge loss coefficient (ψ), in W/mK.

Insulated envelopes are identified by low U-value coefficients (W/m^{2}K) and by the use of insulation materials. The use of these thermal insulation materials on the building envelope retards conductive, convective and radiated heat flux (ASHRAE, 2009b). More specifically, it reduces the heat loss or heat gain through the envelope, controls surface temperature for thermal comfort, reduces potential water condensation on inside and outside surfaces and reduces temperature fluctuation in unconditioned or partly conditioned spaces (ASHRAE, 2009b). Insulated envelopes can include the use of reflective, resistive and capacitive insulation. Reflective insulation refers mostly to the use of foils that reflect radiant heat flow; resistive insulation uses materials such as wool and fibreglass to resist conduction and convection heat flow; and capacity insulation uses thermal mass to increase the time lag of the heat flow, acting as a form of insulation (Hyde et al., 2008).

Insulation material should enclose the entire surface of the building envelope (IBO - Austrian Institute for Healthy and Ecological Building, 2009) and it is most effective as long as it is applied as a continuous layer, without breaks (CIBSE, 2006b). In the walls, insulation tends to be more beneficial when installed outside the envelope walls because it reduces thermal bridges occurrence (BRE, 2011), whilst it does not compromise the effect of thermal mass of the inner layer. Insulation materials placed on the walls limit both the horizontal heat losses through the envelope during the winter and the horizontal heat gains through the envelope during the summer (Ford et al., 2007c). In the roofs, insulation can be placed either between the roof rafters, on top of the rafters or below the roof tiles. The roof is generally the part of a building mostly exposed to solar radiation during the summer and this is the reason that the roof is the

element of the envelope where a greater thickness of insulation is usually employed (Ford et al., 2007c). In the ground floor, insulation is much less demanding when compared to the walls and the roof insulation. Ground floor insulation during the summer could even be counterproductive in some cases and its lack can allow the internal heat to flow to the cooler ground, reducing the indoor temperatures (Ford et al., 2007c).

Fenestration

Size, position and orientation of the windows of a building affects its solar heat input and its overall thermal performance (Szokolay, 2008). The side of the building facing the sun should have more windows, and its opposite orientation very few to prevent excessive heat loss from the cold side of the building, especially in cold and moderate climates (Roaf et al., 2013). Windows area should correspond to 30% of the floor area in order to minimize summer heat gains, without compromising winter heat gains (Hyde et al., 2008, p. 323). More than 75% of the glazing areas of the building should be facing equator (Ford et al., 2007c, p. 43). Glazing areas within 30° to east or west of solar orientation will decrease the building performance by less than 10% relative to optimum glazing orientation (DeKay and Brown, 2014, p. 235). Moreover, the glazing areas should correspond to 30% of the total surface of the building in climates of mild winters and around 15-30% of the total surface in climates of more severe winters (Ford et al., 2007c, p.43). However, these indexes might be difficult to achieve given limitations on the design and on the building codes. Besides, different windows types will impact differently on the airflow inside the building when ventilation is considered. Sliding windows, for example, are poor performers as the flow rate is reduced to 50% of their areas (Hyde et al., 2008, p. 338).

Solar heat gain coefficient of a glazing or g-value is the factor that determines the amount of solar heat gain that will be delivered by the glazing and it is expressed as a fraction between 0 and 1 (Cotterel and Dadeby, 2012, p. 176). The solar heat gain is influenced by orientation and it affects the potential for overheating (Energy Saving Trust, 2010). High g-value allows for high heat gains through the glazing elements, whereas low g-value reduces the potential heat gains. This is the reason why low g-values are more appropriate for hot regions and for regions where a significant amount of solar radiation exists.

Solar Shading devices can contribute together with low g-values in reducing the amount of solar gains that can come into the building during the summer. Solar shading devices have to be designed with the purpose of allowing maximum use of direct solar gains from the lower angled winter sun when it is needed most and blocking them during the summer season (BRE, 2011). When placed externally the window, the shading devices are effective as they are able to block the radiation before it reaches

the glass, preventing the heat gains; when these devices are placed internally the window, part the heat will be trapped between the shading device and the window and part of it will be conducted to the room (Hyde et al., 2008). Both fixed or movable shading devices on facades facing equator placed horizontally are effective, whilst movable shading devices placed vertically on east and west facades are mostly advise to protect from the low sun angles in the early mornings and late afternoons (Hyde et al., 2008).

Ventilation

Infiltration is the tem used for uncontrolled movement of air through the building envelope (Roaf et al., 2013). Infiltration rate (level of airtightness or air permeability rate) of a building envelope measures its leakage. The advantage of an airtight envelope is related to the avoidance of moisture-related building damage and to the avoidance of undesirable heat flow through the envelope (IBO - Austrian Institute for Healthy and Ecological Building, 2009). On the contrary, a leaky envelope leads to an uncontrollable heat flow through its elements, which results in heat losses in cold season or heat gains in hot season, and the magnitude of this heat flow is strongly dependent on the wind and the temperature difference between the inside and the outside of the building (IBO - Austrian Institute for Healthy and Ecological Building, 2009).

The air permeability rate can be measured in $m^3/h/m^2$ (or m^3/hm^2) at 50 Pa pressure difference[4], which means the quantity of air (in m^3) that leaks into or out of the dwelling per hour, divided by the internal area (in m^2) of the building (NHBC Foundation, 2009, p. 1). Air permeability can also be measured in air changes per hour. The difference is that the air permeability rate measured in $m^3/h/m^2$ is the function of the enclosing building envelope area, while the air permeability rate measured in ach is the function of the building's internal volume (Cotterel and Dadeby, 2012). A direct relationship between 1 $m^3/h/m^2$ and 1 ach at 50 Pa is only established for a particular building volume of 6 x 6 x 6 m (Cotterel and Dadeby, 2012, p. 126). In order to obtain air changes per hour under normal ambient atmospheric pressure (typically 4 Pa air pressure difference), the value at 50 Pa should be roughly divided by 20 (Cotterel and Dadeby, 2012, p. 126).

The infiltration rate contributes towards background ventilation. Adequate background ventilation through 'trickle ventilators' built into windows frames is essential for health

[4] Pressure of 50 Pa is adopted as a result of the air leakage test, which applies inside the building a pressure 50 Pa above and below ambient atmospheric pressure. COTTEREL, J. & DADEBY, A. 2012. *The Passivhaus Handbook: a practical guide to constructing and retrofitting for ultra-low energy performance,* Devon, United Kingdom, Green Books.

and condensation avoidance in houses (Roaf et al., 2013). As the infiltration rate of a building becomes lower, mechanical ventilation should be provided to ensure indoor air quality (IAQ) for the occupants. It should be noted that naturally ventilated homes should have an infiltration rate no lower than $3m^3/h/m^2$ at 50 Pa, otherwise mechanical ventilation should be provided (NHBC Foundation, 2009, p. 8, Cotterel and Dadeby, 2012, p.126). The adoption of this limit, however, restricts the benefit of the use of mechanical ventilation with heat recovery, which operates efficiently with airtightness below 1.5 ach at 50 Pa (Cotterel and Dadeby, 2012, p. 128).

Ventilation is the controlled movement of air through the building envelope, desirable for removing pollutants from the building and providing fresh air to the occupants. It is generally desirable in summer because it tends to dissipate the indoor heat, reducing the risk of overheating inside the building. The suitable ventilation strategy (daytime, overnight or selective ventilation), however, is very dependent on the outdoor conditions. Daytime ventilation is suggested when the indoor thermal comfort can be experienced at the outdoor temperature and with an acceptable indoor air speed (Givoni, 1992). Overnight ventilation is recommended during the summer to cool down the building structure when the daily temperature has a large swing and the overnight temperatures drop below the neutral temperature - but not significantly below the lower thermal comfort limit (Ford et al., 2007c, Lamberts et al., 2014). Selective ventilation can be set when the indoor temperature reaches a specific upper temperature limit and it should be considered when the outdoor temperature is below the indoor temperature.

In addition to this section that looked at the key design elements of the Fabric First approach, the next section reveals the characteristics of housing based on this approach.

1.3 Housing Form, Typology and Size

This section describes housing typology and space standards across European countries that have made use of the Fabric First approach. The main aim was to explore average dwelling size, occupancy rate per household and trends in housing.

Figure 1-2 shows average dwelling size of the housing stock in different European countries. The average dwelling size in the existing stock is relatively uniform among the countries and this data includes dwellings built in very different periods and with very different sizes. Most countries have an average dwelling size of around 80-100 m^2. The average dwelling size is higher than this range in just a few countries such as Ireland, Denmark and Luxembourg, where the average dwelling size exceeds 100 m^2 (ETC/SPC, 2013, p. 37).

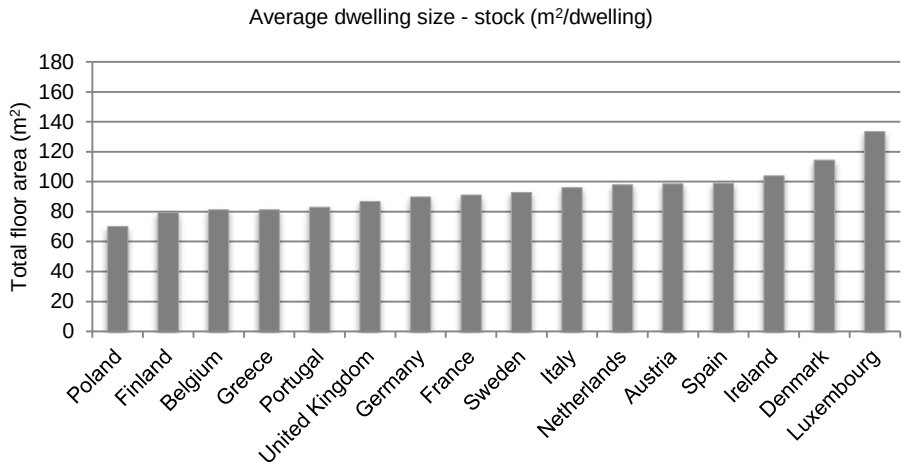


Figure 1-2: Dwelling size stock. Based on Dol and Haffner (2010, p. 51)

It is interesting to notice that the average size of new dwellings built mostly since 2000, shown in Figure 1-3, is larger than the existing stock. The average dwelling size is just over 80 m^2 in England but reaches almost 120 m^2 in Germany. A closer look at the data also reveals that except for Italy and England, which are now building slightly smaller dwellings than they were for the average of the stock, the majority of the European countries are building larger homes.

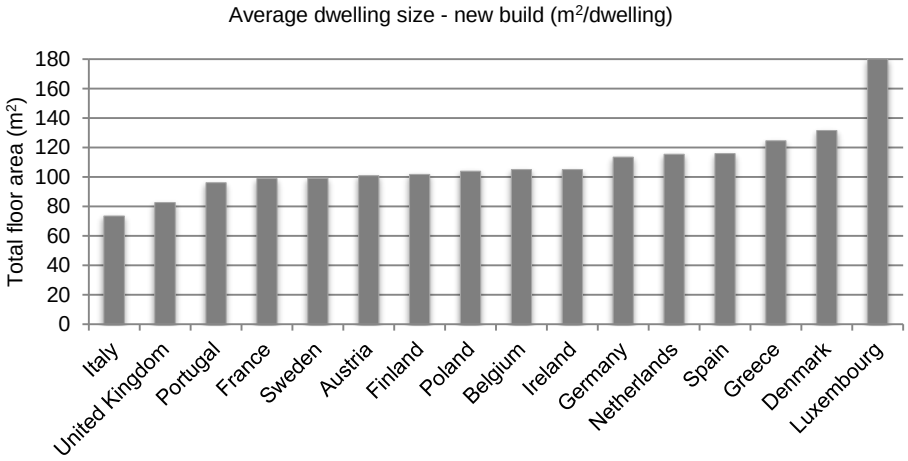


Figure 1-3: Dwelling size new build. Based on Dol and Haffner (2010, p. 51)

The trend that in England and all over the United Kingdom (UK) dwellings are getting smaller is supported by the report conducted by Royal Institute of British Architects (RIBA, 2011). According to this report, new dwellings in the United Kingdom appear to be shrinking and they are also one of the smallest among the European countries. Comparing the United Kingdom average dwelling size with the countries with bigger average dwelling areas, Ireland could have new homes 15% bigger, the Netherlands

were 53% bigger and in Denmark the average newly built homes were 80% bigger than in the United Kingdom (RIBA, 2011, p. 9). The average new dwelling in the United Kingdom was 76 m² (RIBA, 2011, p. 10). This report used data of European Union Housing Statistics of 2005 (National Board of Housing Building and Planning - Sweden and Ministry for Regional Development of the Czech Republic, 2005, p. 38), which was updated in 2010 (Dol and Haffner, 2010, p.51) but in the case of the United Kingdom the statistics have stayed constant because the data was originally based on the year 2001.

One reason many countries have bigger new dwellings than previously is that they have standards that have set minimum floor areas (RIBA, 2011). Hence, in countries where the standards have not set minimum areas, the housing spaces have got worse. As dwelling sizes tends to be regulated by both the market and the standards, and with the premises that housing land availability has reduced, building costs have increased and there has been a lack of standard minimum requirements, the expected results are that the housing spaces have got worse.

Particularly in the United Kingdom, where minimum space standards do not currently exist at national level, recent minimum space requirements have been introduced by the Greater London Authority (Mayor of London, 2010). These minimum area requirements are applied to new houses built in London in order to ensure minimum functional spaces, as shown in Table 1-4. This guidance seems to be a good referential because it is able to correlate minimum area for new houses with housing typology and number of occupants that each house is designed to accommodate.

Table 1-4: Guidance of minimum space required (Mayor of London, 2010, p. 48)

Dwelling type	Bedrooms vs. occupancy (bedroom/persons)	Minimum gross internal area (sq. m)
Single-storey dwelling	1b/2p	50
	2b/3p	61
	2b/4p	70
	3b/4p	74
	3b/5p	86
	3b/6p	95
	4b/5p	90
	4b/6p	99
Two-storey dwelling	2b/4p	83
	3b/4p	87
	3b/5p	96
	4b/5p	100
	4b/6p	107
Three-storey dwelling	3b/5p	102
	4b/5p	106
	4b/6p	113

The number of households has dramatically increased due to a significant reduction of the number of people that live in each house. One of the drivers for this trend is an increase in the number of single occupier households. From 2005 to 2013, the percentage of single person households increased from around 32% to 36% in

European countries (Eurostat, 2014b) and this is predicted to increase even more in the coming years (ETC/SPC, 2013).

The average household size in European countries declined from 3.3 persons in 1960 to 2.4 in 2011 (ETC/SPC, 2013, p. 14). However, the total number of households has increased at a much faster rate than the increase in population (ETC/SPC, 2013). The number of households in European countries grew almost 10% between 2005 and 2013, from 194 million to around 213 million households (Eurostat, 2014b). However, the population grew just around 2% in the same period (Eurostat, 2014c). With the increased number of households, there is a need for a greater number of new dwellings to meet the demand and accommodate the household's expansion.

As the houses are getting bigger (except in England and Italy) and less people live there, the occupancy rate (in m^2/ person) of households expects to be higher than previously. Figure 1-4 reveals the average occupancy rate of dwelling stock in European countries. Although the United Kingdom shows a decrease of the average dwelling size as mentioned, its occupancy is over 40 m^2 per person (Dol and Haffner, 2010), which is fairly the average among European countries.

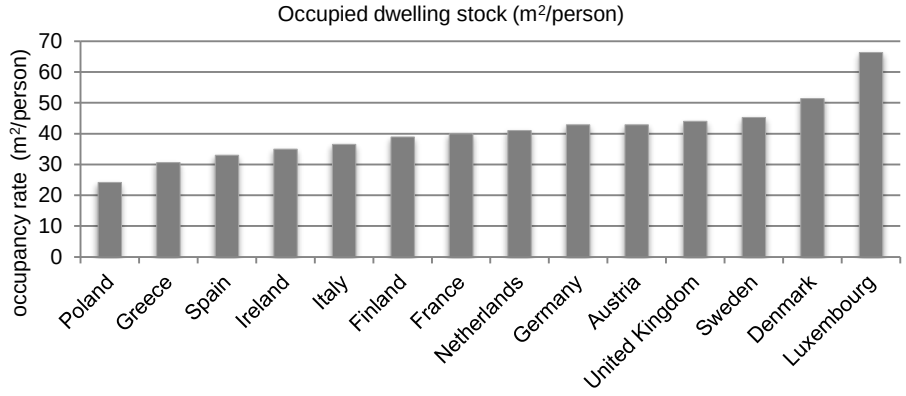


Figure 1-4: Households occupancy. Based on Dol and Haffner (2010, p. 51)

The housing stock typology across Europe can vary among flats, detached and semi-detached houses, which also covers terraced houses. The composition of European housing stock sorted by building type is illustrated in Figure 1-5, based on data of Eurostat (2014a). Based on 2012 reference data, 41.6% of European countries' population lived in flats, over one third (34.0%) in detached houses and 23.7% in semi-detached houses (Eurostat, 2014a, p. 3). As the Figure shows, the composition of the housing stock greatly varies according to each country. In particular, Spain, Greece, Germany and Italy have a major percentage of flats, whereas Norway, the United Kingdom, the Netherlands and Belgium have a major percentage of houses (detached, semi-detached or terraced). The share of persons living in flats was one of the highest

in Spain (65.0%). The share of people living in detached houses peaked in Croatia (73.0%) and Norway (60.7%), and Denmark also reported a high share (57.1%) of its population living in detached houses (Eurostat, 2014a, p. 3). The highest propensities to live in semi-detached or terraced houses were reported in the United Kingdom (60.9%) and in the Netherlands (60.0%).

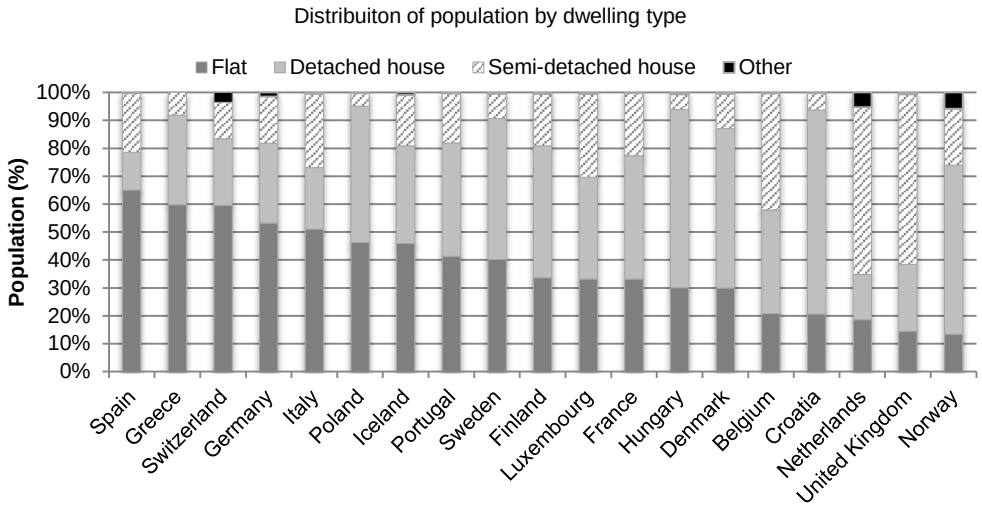


Figure 1-5: Population per dwelling type. Based on Eurostat (2014a)

With regard to housing, it is also fundamental to look at the energy end-use in houses based on the Fabric First approach, which is addressed in the next section.

1.4 Energy Use in Housing

Most dwellings under the umbrella of the Fabric First approach are located in countries of cold and moderate climates, which are mostly dependent on fossil fuels and hence responsible for a significant amount of carbon emissions.

Energy consumption in dwellings generates more than two thirds of carbon emissions of buildings in European countries (Gillott et al., 2010, p. 77), which are estimated to be 40% of the overall carbon emissions produced by these countries (Directive recast 2010/31/EU, 2010, p. 13).

One of the main factors influencing carbon emissions is the carbon intensity of the grid, which is dependent on the mix of fuels each country uses to generate energy (NHBC Foundation, 2011). Figure 1-6 shows carbon emissions based on the mix of fuels in different countries. As shown in the Figure, most Europeans countries have a grid based on fossil fuels. Comparatively, Brazil has an energy matrix based on hydro sources but many of Brazil's hydropower generating facilities are located far away from the main demand centres, which results in high transmission and distribution losses

(U.S. Energy Information Administration, 2015). In addition, carbon emissions in Brazil are increasing due to the use of thermoelectric power to supplement the country's energy demand, as shown in the country's consecutive annual energy balance (EPE, 2012, EPE, 2013b).

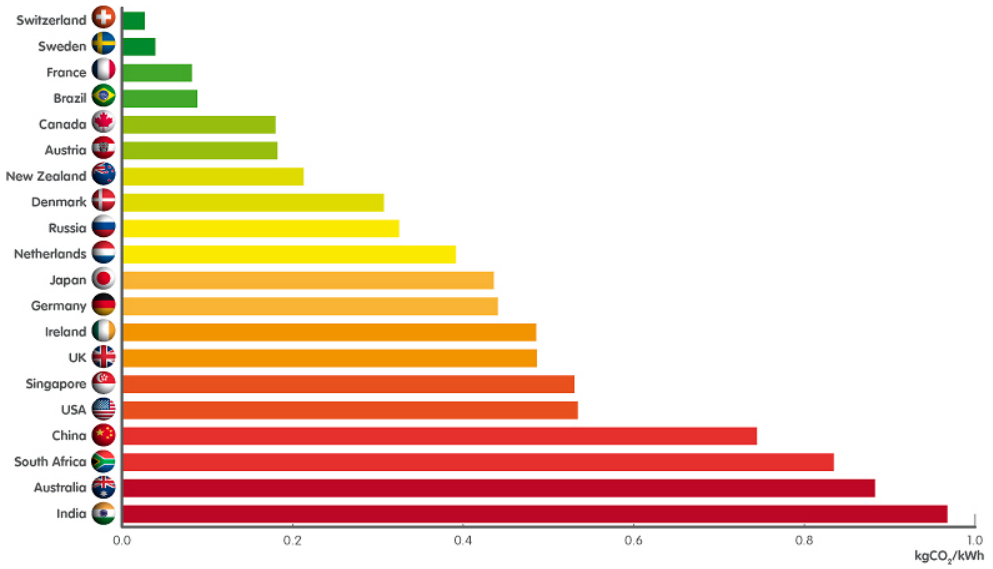


Figure 1-6: Carbon emissions per unit of energy in different countries (NHBC Foundation, 2011, p. 12)

The energy consumption in dwellings is due to space heating and cooling, domestic hot water (DHW), cooking and lighting and household appliances. Figure 1-7 shows the breakdown energy use in dwellings in different countries.

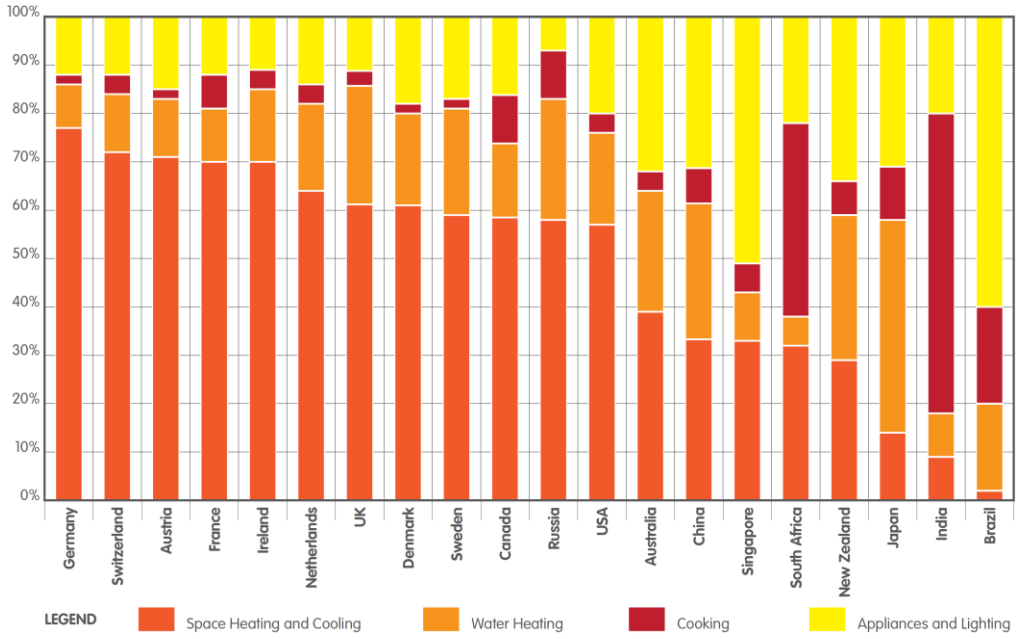


Figure 1-7: Breakdown energy use in dwellings in different countries (NHBC Foundation, 2011, p. 10).

As shown in Figure 1-7, European countries have similar energy consumption, mostly due to space heating and cooling. Energy consumption due to space heating and cooling is strongly associated to the climate, lifestyle and energy efficiency of the building envelopes. In particular, space heating is estimated to be responsible for 68% of household energy consumption in European countries (ETC/SPC, 2013, p. 7).

For instance, in the United Kingdom, space heating accounts for a further half of its energy consumption (Cotterel and Dadeby, 2012, p. 65). DHW accounts for 25% of household energy consumption, cooking accounts for only 5% and together lights and appliances corresponds to 13% of the energy consumption (Gillott et al., 2010, p. 77). Particularly, household appliances can make up the significant percentage of energy demand when associated with inefficient pieces of equipment (Gillott et al., 2010).

Comparatively, Brazil differs considerably to European countries in terms of its energy consumption in dwellings due to its distinct climate and culture. Despite the fact that the energy consumption due to the space conditioning seems to be small in Brazil, it is mostly provided by electrical air-conditioning appliances and thus, the corresponding energy consumption might be mostly shown in appliances. Moreover, appliances and lighting energy consumption are elevated in Brazil due to the use of inefficient household appliances and lighting. More information about Brazilian energy use will be explored in Chapter 2.

The next section explores building energy regulations in housing for reducing the energy use in dwellings.

1.5 Energy Regulations in Housing

Building energy regulations play a key role in influencing the way that houses have been built. Building energy regulations that have shaped the current state of housing towards the Fabric First approach are explored in this section.

Building energy regulations are mostly classified as prescriptive or performance-based approach (Pan and Garmston, 2012, Iwaro and Mwasha, 2010). The prescriptive approach sets up performance levels for the envelope and minimum requirements for equipment components, whereas the performance-based approach considers the overall performance of the building, prescribing specific energy demands (Iwaro and Mwasha, 2010). The performance-based approach tends to allow for higher flexibility in design than the prescriptive approach and to encourage innovations in both products and processes in order to deliver a high level of performance (Zero Carbon Hub, 2009).

Most European countries have revised their building energy regulations and have adopted regulations based on performance approach (Pan and Garmston, 2012).

Other countries such as those located in Africa, the Middle East and Latin America are still far behind the advances achieved by European countries in terms of buildings' energy efficiency, although they have shown systematically improvement in their building energy regulations (Iwaro and Mwasha, 2010). They have mostly adopted simplified methods to evaluate the building envelope instead of evaluating the whole building performance (Iwaro and Mwasha, 2010).

Building energy regulations have strengthened across Europe as result of the current calls by governments for increased energy efficiency in buildings and reduced carbon emissions. One of the major steps forward to increase building energy efficiency in Europe was taken by the standard Energy Performance of Buildings European Directive (Directive 2002/91/EC, 2002) and by the recast of the European Directive (Directive recast 2010/31/EU, 2010). European countries have pushed to set minimum building envelope requirements aiming to achieve high energy efficiency levels. They have supported the Fabric First approach and endorsed improvements in the building envelope such as controlled air infiltration rate and optimised level of insulation.

Mandatory and voluntary building energy regulations have progressively required building envelopes with reduced U-values. Figure 1-8 shows the average U-values for walls, roof and floor for several building energy regulations. According to this, the voluntary Passivhaus standard, conceived in Germany, seems to be the strictest building energy regulation in terms of its average U-value, equivalent to 0.10 W/m^2K (NHBC Foundation, 2011). Among the examples, the United Kingdom has also one of the lowest average U-values and this has progressively become stricter, as shown in the Figure 1-8.

Building energy regulations have also required controlled infiltration rates in buildings. The reduced infiltration rate has been adopted as a trend in buildings in order to avoid energy waste through the building envelope (Dimitroulopoulou, 2012). Table 1-5 illustrates typical infiltration rates for several building energy regulations. In locations where infiltration rate is required to be significantly low, mechanical ventilation should ensure the fresh air to be supplied inside the building. As an example, the United Kingdom set out a maximum limit for infiltration rate of 10 $m^3/h/m^2$ at 50 Pa (HM Government, 2014, p. 15). However, an infiltration reduction up to 3 $m^3/h/m^2$ at 50 for naturally ventilated homes would be sufficient to provide reasonable air quality without the use of mechanical ventilation (NHBC Foundation, 2009, p. 8, Cotterel and Dadeby, 2012, p. 126). On the contrary, the Passivhaus standard requires very low infiltration rate below 0.6 ach at 50 Pa, mostly between 0.2 ach and 0.5 ach at 50 Pa, which requires that the buildings would be equipped with mechanical ventilation in order to provide a sufficient amount of fresh air (IBO - Austrian Institute for Healthy and Ecological Building, 2009, p.16).

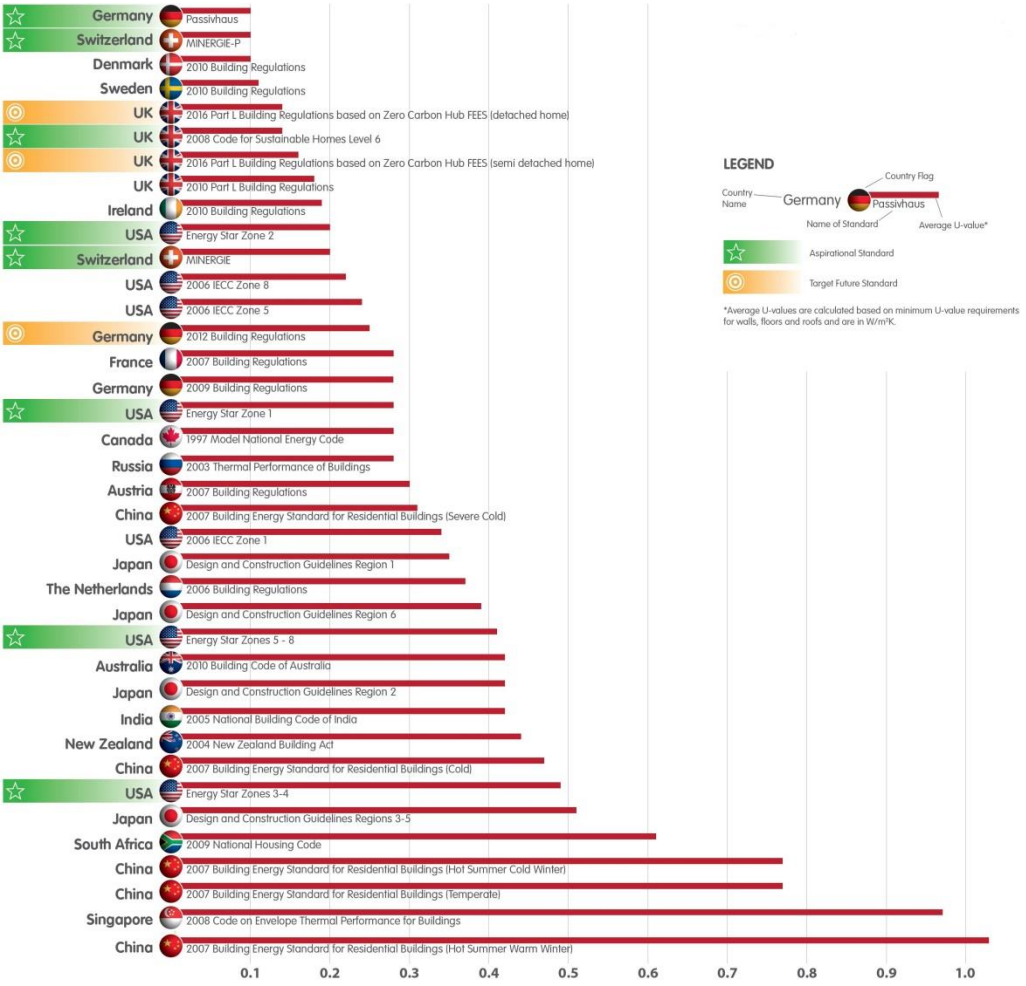


Figure 1-8: Average U-values for walls, roof and floors according to national building regulations (NHBC Foundation, 2011, p. 11).

Table 1-5: Infiltration rates of different building energy regulations. Based on Cotterel and Dadeby (2012, p. 127), ICC (2011, p. 484) and HM Government (2014, p. 15)

Building energy regulation	Status	Infiltration rate	Equivalent ach (50 Pa) for an average-sized house
UK Building Regulation 2010	mandatory	≤ 10 $m^3/h/m^2$ at 50 Pa	10 ach
United States (US) 2012 International Residential Code (IRC)	mandatory	≤ 3-5 ach at 50 Pa	3-5 ach
Passivhaus standard	voluntary	≤ 0.6 ach at 50 Pa	0.6 ach

In particular, a brief review of building energy regulations in England is explored as a means of informing a debate about building energy regulations, which has been strengthened progressively for increased energy efficiency in housing.

Restrictions in new and existing dwellings have been imposed in England in short to medium-term in order to achieve CO_2 emissions reductions. There is an intention that CO_2 emissions have to be reduced by 2050 by 80% relative to the 1990 levels

(Committee on Climate Change, 2010, p. 4, Evans, 2011, p.329). There is also an expectation that dwellings must be built to the maximum level of energy efficiency, although this level of energy efficiency is still to be decided (Committee on Climate Change, 2010).

The mandatory Building Energy Regulation in England was revised in 1995, 2002, 2006 and 2010. Its Part L 'Conservation of fuel and power' was revised in 2013 and is planned to be reviewed in 2016 and 2019, as part of the triennial review. The most important change to the Part L 2010 regulation when compared to the previous 2006 version was the reduction of CO_2 emissions by 25% (Evans, 2011, p. 329, Pan and Garmston, 2012). The Part L 2013 was strengthened to reduce the carbon emissions by 6% in new dwellings, when compared to the 2010 version (HM Government, 2014, p. 2).

The Part L 2013 for new dwellings came into force in 2014 and it focuses on reducing energy demand through improved envelope efficiency (Evans, 2014). The Part L 2013 establishes criteria in terms of the Fabric Energy Efficiency (FEE), which measures the thermal efficiency of the dwelling's envelope (in kWh/m^{2}a) and considers the envelope heat losses and gains (i.e.: conduction heat losses, infiltration losses, additional losses due to the thermal bridges, heat gains and solar gains) (Evans, 2014). The standard also requires new dwellings to achieve fabric energy efficiency and carbon dioxide targets, calculated based on the performance of a notional dwelling (HM Government, 2014). According to the regulation, the Target Fabric Energy Efficiency (TFEE) should not be smaller than the Dwelling Fabric Energy Efficiency (DFEE), as the same manner that the Target CO_2 Emission Rate (TER) should not be smaller than the Dwelling Emission Rate (DER) (HM Government, 2014). Both TER and TFEE must be calculated using Standard Assessment Procedure (SAP) 2012 methodology.

The Part L 2013 kept the same building envelope requirements as the 2010 version. Minimum U-values of 0.30 W/m^{2}K for the walls, 0.25 W/m^{2}K for the floor, 0.20 W/m^{2}K for the roof and party walls and 2.00 W/m^{2}K for windows and doors were considered to be adopted in new houses (HM Government, 2014, p. 15). The infiltration rate was set out at a maximum limit of 10 m^3/h/m^2 at 50 Pa (HM Government, 2014, p. 15), which roughly correspond to 0.5 ach at atmospheric pressure.

However, the notional dwelling specification, which would ensure the criteria of carbon dioxide and fabric energy efficiency targets are met, proposes more strict values. U-values of 0.18 W/m^{2}K for the walls, 0.13 W/m^{2}K for the floor, 0.13 W/m^{2}K for the roof and 1.4 W/m^{2}K for windows and glazed doors were considered (HM Government, 2014, p. 25). In addition, the airtightness should be no more than 5 m^3/h/m^2 at 50 Pa (HM Government, 2014, p. 25).

1.6 The Passivhaus Standard

The voluntary Passivhaus standard is the global leader in the Fabric First approach. The Passivhaus standard applies building physics theory to achieve low energy-use and thermal comfort in buildings (Cotterel and Dadeby, 2012).

A post-occupancy evaluation study (Schnieders and Hermelink, 2006, p.151, 158) assessed 221 Passivhaus units built in five different European countries. The study suggested that Passivhaus buildings might be able to reduce the space conditioning to 20% and to achieve energy savings of more than 50% in primary energy demand[5,6] when compared to conventional new buildings. In other words, this means that Passivhaus buildings have lower running costs than conventional new buildings.

However, the upfront cost of a Passivhaus building is higher than typical buildings. For example, in Germany, the additional costs of Passivhaus dwellings are estimated to be 8% more than conventional new dwellings (iPHA, 2015). In the United Kingdom, affordable certified Passivhaus dwellings were estimated to have an uplift of 15-20% in their upfront cost when compared to typical dwellings built in the country[7] (Passivhaus Trust, 2015, p. 11, Hopfe and McLeod, 2015, p. 303, Newman, 2012, p. 4). The walls and the windows were pointed out as the major contribution to the uplift cost for constructing affordable certified Passivhaus dwellings and their impact represents 15% and 30% more than typical costs, respectively (Passivhaus Trust, 2015, p. 10). It should be remembered, however, that the impact on the Passivhaus dwellings cost depends on the dwelling's energy efficiency reference. In other words, it depends what you are comparing it with and there is no obvious standard for comparison (De Selincourt, 2014).

The Passivhaus standard was a result of the studies by Dr Wolfgang Feist and Prof Bo Adamson, which led to the construction of the first building prototype in 1991, in Darmstadt-Kranichstein, Germany. Over the years since its first inception, the Passivhaus standard has kept almost the same requirements but has introduced requirements for warmer climates.

[5] Primary energy demand is the energy used to produce the energy delivered to the building. It is related to the energy embodied in non-renewable natural resources calculated or projected according to specific design. FEIST, W., SCHNIEDERS, J., DORER, V. & HAAS, A. 2005. Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings,* 37**,** 1186-1203.

[6] It includes heating, cooling, DHW, auxiliary electricity, domestic and common area electricity. PASSIVE HOUSE INSTITUTE 2012a. Passive House Planning Package: Energy Balance and Passive House Design Tool - for quality approved Passive Houses and EnerPHit retrofits. Darmstadt, Germany: Passive House Institute.

[7] It considers an affordable dwelling typology with a house's level of efficiency equivalent to level 4 of the Code for Sustainable Homes.

The Passivhaus standard has mandatory requirements for energy consumption (Passive House Institute, 2012a, p.22):

i. Primary energy demand ≤ 120 kWh/m²a;
ii. Heating criteria:
    - Space heating demand ≤ 15 kWh/m²a; or
    - Heating load[8] ≤ 10 W/m² over the day;
iii. Cooling criteria (*provisional criteria*):
    - Space cooling demand ≤ $15\frac{kWh}{m^2a} + 0.3\frac{W}{m^2aK} \times DDH$; or
    - Cooling load ≤ 10 W/m² over the day; and
    - Space cooling demand ≤ $4\frac{kWh}{m^2aK} \times \vartheta + 2 \times 0.3\ W/m^2aK \times DDH - 75\ kWh/m^2a$; but not exceeding the following equation $45\ kWh/m^2a + 0.3\frac{W}{m^2aK} \times DDH$; where ϑ corresponds to the annual mean outdoor temperature (°C) and DDH corresponds to the dry degree-hours for a dew point of 13 °C
iv. Infiltration rate ≤ 0.6 ach at 50 Pa, verified by air leakage test;

These aforementioned requirements are supposed to represent the most effective solution in buildings. In terms of space heating demand, the requirements represent a better balance between energy saving vs. costs. In terms of primary energy demand, the requirements establish the use of efficient hot water systems and household appliances, discouraging the use of electricity for both heating and DHW (Cotterel and Dadeby, 2012).

Also, in order to keep the internal heat gains at minimum (2.10 W/m²) the Passivhaus standard suggests the use of energy efficient appliances and an average occupancy rate of 35 m²/person and no less than 20 m²/person is accepted (Passive House Institute, 2012a, p. 28). These levels are consistent with the average size of the houses in Europe, where the standard is mostly widespread.

The Passivhaus standard also suggests other parameters for helping achieve energy consumption targets (Passive House Institute, 2012a, p. 22):

i. U-value of opaque envelope elements ≤ 0.15 W/m²K;
ii. U-value of windows ≤ 0.80 W/m²K, and glazing g-value of at least 0.5;
iii. Negligible thermal bridges, Psi < 0.01 W/mK;
iv. Mechanical ventilation with heat recovery (MVRH) efficiency ≥ 75%;

[8] Heating load is the heating power necessary to maintain the room temperature at a given value. FEIST, W., SCHNIEDERS, J., DORER, V. & HAAS, A. 2005. Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings,* 37**,** 1186-1203.

The envelope U-values are, however, determined by the climate which the building is designed for. In the case of glazing elements, the use of double glazing, which has a higher U-value than triple glazing, allows for slightly higher solar gains but it has heat losses approximately 80% higher than triple glazing (Feist and Schnieders, 2009, p. 147). In addition, whilst a glazing with a g-value of at least 0.5 is suggested in cool-moderate climates, a glazing with a g-value of a maximum 0.35 is suggested in hot climates (Cotterel and Dadeby, 2012, p. 97).

The mechanical ventilation system in Passivhaus buildings works by recovering heat from the exhaust air during the heating season. The system can recover over 90% of the heat in exhaust (Mardiana-Idayu and Riffat, 2012, p. 1242, Cotterel and Dadeby, 2012, p. 203). The heat recovery system allows the heat contained in the exhaust air to be used to warm the fresh air coming from the outside (iPHA, 2010). The exhaust air and the supply air go through a heat exchanger without being mixed with each other (Cotterel and Dadeby, 2012). During the cooling season, the mechanical ventilation system works by using summer bypass ventilation, which allows the air to be supplied directly to the living areas without recovering it (Cotterel and Dadeby, 2012).

The Passivhaus design indoor temperature corresponds to 20 °C in winter and it should not exceed 25 °C for more than 10% of the time in summer (Passive House Institute, 2012a, p. 28, 125).

The Passivhaus standard has been revised to make it suitable to the needs of other warmer climates (Ford et al., 2007b, Schnieders et al., 2012). The remarkable difference between the original Passivhaus standard, which was originally designed for cold climates of central Europe, and the Passivhaus standard for warmer climates is the existence and the management of the summer season.

Evidence has suggested that the Passivhaus standard is flexible and it can be achieved cost-effectively in many different climates (Ford et al., 2007b, Passive House Institute, 2012b, Schnieders et al., 2012). The implementation of the Passivhaus standard has also been demonstrated to be feasible even in tropical climates, where the demand is strictly related to cooling and the temperature has a small seasonal fluctuation (Schnieders et al., 2012).

Figure 1-9 shows recommendations in terms of the envelope U-values for delivering cost-optimised Passivhaus dwellings. Figure 1-10 and Figure 1-11 provide an overview of the cost-effective worldwide feasibility of the Passivhaus dwellings in terms of useful cooling and dehumidification demand, respectively. As shown in the Figures, only the equatorial areas present a more demanding situation, which may restrict the use of the Passivhaus standard, although more effort in research should be conducted to verify its cost-effective applicability.

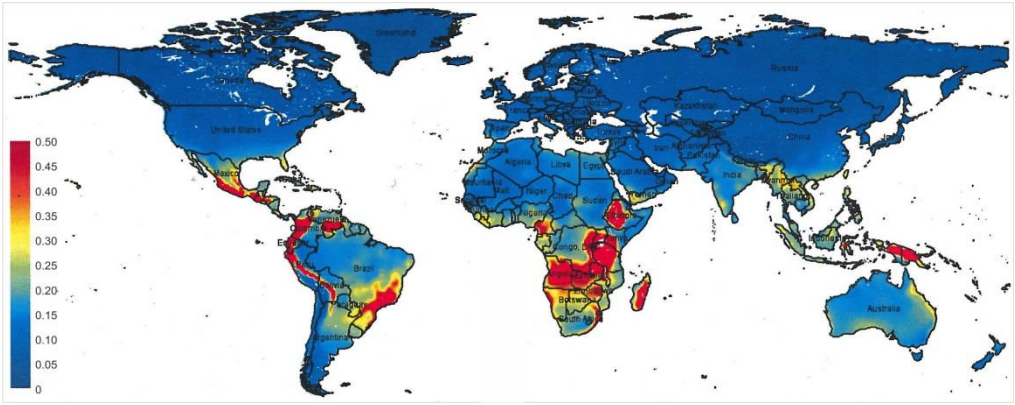


Figure 1-9: Cost-optimised U-value for exterior building components in W/m²K (Schnieders et al., 2012, edited, p. 461)

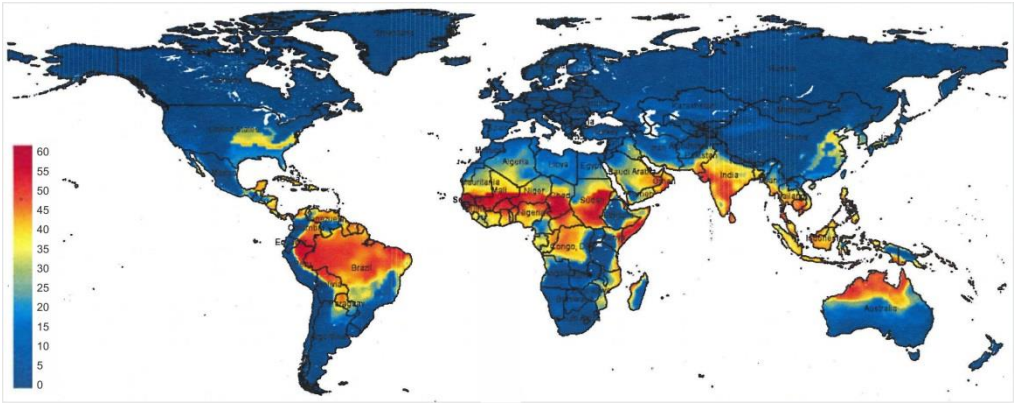


Figure 1-10: Sensible useful cooling demand for cost-optimized houses in kWh/m²a (Schnieders et al., 2012, edited, p. 468)

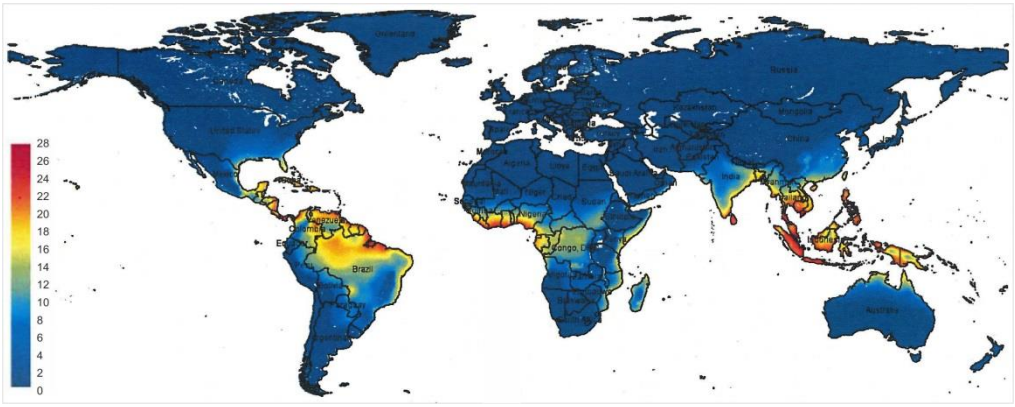


Figure 1-11: Dehumidification demand for cost-optimized houses in kWh/m²a (Schnieders et al., 2012, edited, p. 470)

Research undertaken has shown advances toward the adjustment of the Passivhaus standard requirements for housing in warmer climates. Several studies were revised in the next sections in order to gain understanding of the potential strategies for increasing energy efficiency in dwellings, using the Passivhaus standard requirements as reference. The key points are summarised in Table 1-6.

i. The *Passive-On Project* (Ford et al., 2007b) explored the Passivhaus requirements for typical dwellings in milder European countries;
ii. The *Passivhaus studies for Different Climate zones* (Schnieders et al., 2012) explored the viability of Passivhaus dwellings for a variety of climates around the world;
iii. Study carried out by the Passive House Institute (2012b) in a partnership with Mexican research institutions explored the applicability of the Passivhaus standard concepts to affordable dwellings in Mexico;
iv. Study carried out by Hatt et al. (2012) investigated the potential viability of the Passivhaus houses in Chile.

1.6.1 Passive-On Project

The Passive-On Project (Ford et al., 2007b) explored design guidelines in order to implement the Passivhaus standard in milder European climates, such as those climates in the United Kingdom, Spain, Portugal, Italy and France. Different housing types were investigated to meet the Passivhaus standard for each country involved in the project, making appropriate changes in terms of climate, construction standards, nature of the market, technical and cultural characteristics and life style (Ford et al., 2007b).

The findings of the project suggested that an adjustment of the Passivhaus standard should be more related to building performance rather than a prescriptive approach (Schiano-Pan et al., 2008). Therefore, the findings of the project showed that the criteria proposed for implementing the Passivhaus standard in milder climates might not require the same levels of insulation, infiltration rate and ventilation system compared to those proposed by the original Passivhaus standard.

Thermal comfort was considered between 20-26 °C if an active cooling system was predominantly used. If cooling was provided by passive means, the upper temperature limit was considered as extended (Ford et al., 2007b, p. 5-8).

The Passivhaus dwelling for each city is summarised below and it can be found in Ford et al. (2007a, p. 57-86), Ford et al. (2007b, p. 9-22):

i. The Passivhaus dwelling in the United Kingdom consisted of a two-floor semi-detached house with three bedrooms and north-south orientation. The annual energy demand was estimated to be 13.8 kWh/m^2. The U-Values of 0.2 W/m^{2}K, 0.15 W/m^{2}K and 1.80 W/m^{2}K were adopted for the walls, the roof and the windows (low-e double glazing), respectively. An infiltration rate of 3 ach at 50 Pa was assumed and, consequently, a mechanical ventilation system was not considered. Openings for natural ventilation were considered to be manually and automatically controlled. Venetian blinds for solar control during the summer period were adopted on the south facade of the house. Phase change materials (PCM) were adopted within plasterboard of opaque building elements.

ii. The Passivhaus dwellings in Spain consisted of a two-floor semi-detached house with three bedrooms (100 m²), north-south orientation and located both in Seville and Granada. In Seville, which has a severe summer, the annual energy demand was estimated to be 24.5 kWh/m^2, 2.8 kWh/m^2 for heating and 21.7 kWh/m^2 for cooling. In Granada, which has a severe winter, the annual energy demand was estimated to be 16.6 kWh/m^2, 8.7 kWh/m^2 for heating and 7.9 kWh/m^2 for cooling. In Seville, the U-Values of 0.37 W/m^{2}K and 0.39 W/m^{2}K were adopted for the walls and the roof, whereas in Granada the U-Values of 0.26 W/m^{2}K and 0.28 W/m^{2}K were adopted for the walls and the roof, respectively. Double glazing was adopted for both cities. The infiltration rate was assumed as currently found in Spanish buildings and, consequently, a mechanical ventilation system was not adopted. The thermal comfort strategy considered the optimisation of the glazing areas, enlarging them on the south facade and reducing them on the north facade. About 50% of the total windows were placed on the south facade. Moveable shading was adopted on the south facade of the house. High internal thermal mass was adopted in Seville.

iii. The Passivhaus dwelling in Portugal consisted of a single-floor detached house with two bedrooms (110 m^2), north-south orientation and located in Lisbon. The annual energy demand was estimated to be 9.6 kWh/m^2, 5.9 kWh/m^2 of heating and 3.7 kWh/m^2 of cooling. The U-Values of 0.32 W/m^{2}K, 0.23 W/m^{2}K and 2.90 W/m^{2}K were adopted for the walls, the roof and the windows (low-e double glazing), respectively. An infiltration rate of 0.8 ach at 50 Pa was assumed and a mechanical ventilation system was not adopted. The main strategy proposed was a thermal solar system designed to heat the house through a low power hydraulic heating system during the winter. During

the summer, exterior venetian blinds and eaves on the south facade and also the use of night ventilation were the strategies used for thermal comfort. The thermal comfort strategy also considered the optimisation of the glazing areas and 60% of the total windows were placed on the south facade.

iv. The Passivhaus dwellings in Italy consisted of a basement plus two-floor end of terraced house with two bedrooms (120 m^2), north-south orientation and were located in Milan, Rome and Palermo. The annual energy demand was estimated to be less than 15 kWh/m^2 for all the houses in different locations. In Milan, the U-Values of 0.14 W/m^2K, 0.15 W/m^2K and 0.32 W/m^2K were adopted for the walls, the roof and the ground floor, respectively. In Rome, a U-Value of 0.32 W/m^2K was adopted for the walls, the roof and the ground floor. Finally, in Palermo, a U-Value of 0.23 W/m^2K was adopted for the walls and the roof while a U-Value of 1.7 W/m^2K was adopted for the ground floor. Low-e double glazing was adopted for all the cities. An infiltration rate of up to 2 ach at 50 Pa was assumed in Palermo and an infiltration rate of 1 ach at 50 Pa was assumed in Milan and Rome. A mechanical ventilation system with heat recovery was adopted for all the houses. A low power reversible heat pump and overnight ventilation were used during the summer. High thermal inertia and shading through the use of eaves were considered. The optimisation of the glazing areas counted with 30% of the total windows placed on the south facade.

v. The Passivhaus dwellings in France consisted of a terraced house with basement plus two-floors with three bedrooms (120 m^2), north-south orientation and located in Carpentras and Nice. The annual energy demand was estimated to be 14.8 kWh/m^2 in Capentras and 23.7 kWh/m^2 in Nice. Low-e double glazing was adopted for the cities. An infiltration rate of up to 1 ach at 50 Pa was assumed in both cities. A mechanical ventilation system with heat recovery and heat pump was adopted. Overnight ventilation was also considered.

1.6.2 Passivhaus Studies for Different Climate Zones

The study carried out by Schnieders et al. (2012) investigated the adequacy of the Passivhaus standard in some areas of interest, which includes Tokyo, Shanghai, Las Vegas and Dubai.

These locations were chosen because they are very demanding from the thermal comfort perspective. In addition, these locations are either areas of high population density or areas with huge potential of population growth over the next years.

The simulation model considered a two-floor plus basement end of terraced house, with a total area of 120 m^2 and net dimensions of 6 x 11 m (Schnieders et al., 2012, p. 29-30, 495-498). The window areas on the south and north facade were equivalent to 27% and 21% of the total area of facades (approximately 9.1% and 7.1% of the floor area), respectively (Schnieders et al., 2012, p. 29-30). The dwelling was made out of 115 mm masonry wall and a lightweight roof. The infiltration rate in all the cities was considered to be between 0.3 and 0.5 ach at 50 Pa (Schnieders et al., 2012, p. 30). It should be highlighted, however, that the simulation model did not take into account cultural and architectural differences such as housing typology of each location.

The study considered the dwellings with different levels of thermal comfort. A thermal comfort with the temperatures from 20 °C to 26 °C at 60% of relative humidity were considered as ideal (Schnieders et al., 2012, p. 32). An extended thermal comfort range with temperatures from 19 °C to 27 °C at 60% of relative humidity were considered as acceptable (Schnieders et al., 2012, p. 32).

The Passivhaus dwelling for each city is summarised below and can be found in Schnieders et al. (2012, p. 56-140):

i. The Passivhaus dwelling in Tokyo had an annual heating energy demand, cooling energy demand and dehumidification demand estimated to be 14.5 kWh/m^2, 7.1 kWh/m^2 and 10.3 kWh/m^2, respectively. The U-values of 0.20 W/m^2K, 0.15 W/m^2K and 0.28 W/m^2K were adopted for the walls, the roof and the ground floor, respectively. A U-value of 0.72 W/m^2K was adopted for the window frame and the glazing had a U-value of 1.19 W/m^2K and a g-value of 0.6. For the heating demand, MVHR with 85% efficiency was assumed. For the cooling demand, cooling via supply air was assumed as controlled by both temperature and humidity.

ii. The Passivhaus dwelling in Shanghai had an annual heating energy demand, cooling energy demand and dehumidification demand estimated to be 11 kWh/m^2, 11.4 kWh/m^2 and 11.8 kWh/m^2, respectively. The U-values of opaque and glazing elements were the same values as adopted in Tokyo. For heating demand, MVHR with 85% efficiency was adopted. For cooling demand, cooling via supply air was assumed as controlled by both temperature and humidity and humidity recovery was adopted.

iii. The Passivhaus dwelling in Las Vegas had an annual heating energy demand, cooling energy demand and dehumidification demand estimated to be 14.5 kWh/m^2, 15.2 kWh/m^2 and 1.3 kWh/m^2, respectively. The U-values of 0.12 W/m^2K, 0.20 W/m^2K and 1.66 W/m^2K were adopted for the walls, the roof and

the ground floor, respectively. Insulation on the ground floor was not needed. A U-value of 1.6 W/m^{2}K was adopted for the window frame and the glazing had a U-value of 1.19 W/m^{2}K and a g-value of 0.31. For the heating demand, MVHR with 85% efficiency was assumed as controlled. For cooling demand, cooling via supply air and overnight ventilation were adopted. Also, humidity recovery was used to increase air humidity in the summer and the winter. Reflective coating was used on the walls and the roof.

iv. The Passivhaus dwelling in Dubai had an annual cooling energy demand and dehumidification demand estimated to be 37.7 kWh/m^2 and 21.9 kWh/m^2, respectively. The U-values of 0.12 W/m^{2}K, 0.15 W/m^{2}K and 0.20 W/m^{2}K were adopted for the walls, the roof and the ground floor, respectively. A U-value of 1.6 W/m^{2}K was adopted for the window frame and the glazing had a U-value of 0.70 W/m^{2}K and a g-value of 0.25 (triple glazing with sun protection). MVHR with 85% efficiency was adopted but heat recovery did not present benefits in this case. Overnight ventilation was adopted only for the few colder months. Cooling via supply air was assumed as controlled by humidity levels and the use of humidity recovery helped reduce the energy demand for dehumidification. Reflective coating was used on the walls and the roof. Eaves were adopted to reduce direct solar radiation on the glazing and opaque surfaces.

Despite the advances in adjusting the Passivhaus approach for these locations, the main contribution of this study (Schnieders et al., 2012) was the provisional cooling requirements for Passivhaus buildings, which were incorporated in the standard in 2012.

1.6.3 Passivhaus Study in Mexico

The study was carried out through a partnership between Mexican and German organizations for increasing energy efficiency in affordable housing. The technical report of this study was published by Passive House Institute (2012b).

The study explored three different typical Mexican social housing types and proposed levels of optimisation for each typology, ranging from the baseline case to the Passivhaus Standard. The typologies consisted of a detached house of 38.4 m^2, a terraced/semi-detached house of 81.0m^2 including two housing units and a six-storey building of 79.4 m^2 including two housing units per floor (Passive House Institute, 2012b, p. 3-6).

A total of four locations were selected: Hermosillo (hot and dry climate), Guadalajara (moderate climate), Puebla (cold-moderate climate) and Cancun (hot and humid climate).

Most of the baseline elements of this study were adopted as typically found in social houses in Mexico (Passive House Institute, 2012b, p. 3-8):

i. The windows were made out of approximately 4 cm aluminium frame and 3 mm single glazing.
ii. The walls of the detached and multi-storey houses were built out of reinforced concrete masonry of 10 and 12 cm of thickness, respectively. The walls of the terraced house were made out of reinforced concrete of 8 cm of thickness.
iii. The ground floor and roof were built out of reinforced concrete slab of 10 and 12 cm of thickness, respectively.
iv. Infiltration of 5 ach at 50 Pa was considered.
v. Internal gains: 5.3 W/m^2
vi. Occupation: 20 m^2 per person, equivalent to 2 persons per housing unit was adopted in compliance with the minimum requirement of the Passivhaus standard, although each housing unit tends to have higher occupancy.
vii. Lighting: compact fluorescent light 20 W.
viii. Appliances: current average appliances used for social housing; fridge (2.68 kWh/d), TV (0.19 kWh/d), fan (100 W), washing machine (0.32 kWh/d) and microwave (0.17 kWh/d).
ix. Cooling system: air conditioning split unit of coefficient of performance (COP) of 2.5.
x. DHW and cooking: LP gas.
xi. Comfort criteria: 20-25 ºC and low thermal comfort level of 18-28 ºC.

The study concluded that the typical electrical appliances had a negative impact on electricity demand and they contributed to increase heat gains and cooling demand. Hence, the housing optimisation focused on mitigating this problem, by using efficient electrical appliances, adopting appropriate ventilation system and shading devices and optimising the building envelope.

Another important finding of the study was the importance of the compactness factor. The multi-storey house, which had a high compactness ratio estimated to be 0.3 m, required lower insulation levels when compared to the other housing typologies. The detached and terraced/semi-detached housing typologies had low compactness ratios estimated to be between 0.9 and 1.2 m, respectively, and they required more insulation than the multi-storey typology to achieve the same levels of energy efficiency.

The Passivhaus dwelling for each city is summarised below. The data refers exclusively to the detached house typology, which required more insulation levels due to its spread-out form (Passive House Institute, 2012b, p. 14-24, 36-38):

i. The Passivhaus dwelling in Hermosillo had annual heating and cooling energy demands estimated to be 2.0 kWh/m^2 and 15.0 kWh/m^2, respectively. Insulation of 250 mm, 300 mm 125 mm were adopted for the walls, the roof and the ground floor, respectively. The windows were considered with triple glazing (glazing U-value of 0.6 W/m^{2}K, g-value of 0.33), protected by moveable shading devices. MVHR and a separate recirculation cooling system were assumed. Cool colour or reflective coating was assumed on the walls and roof.

ii. The Passivhaus dwelling in Guadalajara had annual heating and cooling energy demands estimated to be 4.0 kWh/m^2 and 6.0 kWh/m^2, respectively. Insulation of 50 mm, 100 mm and 25 mm were adopted for the walls, the roof and the ground floor, respectively. The windows were considered with low-e double glazing (glazing U-value of 3.0 W/m^{2}K, g-value of 0.78). The use of extract air system instead of MVHR and the use of night ventilation were assumed.

iii. The Passivhaus dwelling in Puebla had annual heating and cooling energy demands estimated to be 15.0 kWh/m^2 and 1.0 kWh/m^2, respectively. Insulation of 150 mm, 275 mm and 125 mm were adopted for the walls, the roof and the ground floor, respectively. The windows were also considered with low-e double glazing (glazing U-value of 3.0 W/m^{2}K, g-value of 0.78). The use of extract air system and natural ventilation were assumed.

iv. The Passivhaus dwelling in Cancun had annual cooling and dehumidification demands estimated to be 39.0 kWh/m^2 and 30.0 kWh/m^2, respectively. Insulation of 250 mm, 200 mm and 225 mm were adopted for the walls, the roof and the ground floor, respectively. The windows were considered with triple glazing (glazing U-value of 0.6 W/m^{2}K, g-value of 0.33), protected by moveable shading devices. MVHR and a separate recirculation cooling system with dehumidification were assumed. Cool colour or reflective coating was assumed on the walls and roof.

1.6.4 Passivhaus Study in Chile

Hatt et al. (2012) investigated which of the Passivhaus standard variables had greater impact on the energy demand in houses for three distinct climates in the central-south region of Chile (Santiago, Concepción and Puerto Montt).

The simulation model consisted of a two floor house of 100 m^2, with occupancy of 20-25 m^2/person, internal gains of 2.9 W/m^2, an infiltration of 0.6 ach at 50 Pa and an operative temperature of 20 ºC during the winter and 26 ºC during the summer.

The Passivhaus dwelling for each city is summarised below and can be found in Hatt et al. (2012, p. 127-132):

i. In Santiago, where the cooling demand was higher than heating demand, the variables of higher impact on the energy demand were the glazing surface size, the ventilation system with heat recovery, the glazing type, the shading and the opaque elements U-value. U-values equal to or less than 0.35 W/m^2K for the walls, 0.28 W/m^2K for the roof and 0.65 W/m^2K for the ground floor were suggested for this location.

ii. In Concepción, where the energy demand was basically for heating, the variables of higher impact on the energy demand were the ventilation system with heat recovery, the U-values of the opaque elements and glazing types. U-values equal to or less than 0.35 W/m^2K for the walls, 0.28 W/m^2K for the roof and 0.65 W/m^2K for the ground floor were suggested. For the windows, a U-value smaller than 1.5 W/m^2K and a g-value higher than 0.6 were recommended.

iii. In Puerto Montt, where heating and cooling demand were both significant, the variables of higher impact on the energy demand were the ventilation system with heat recovery, the U-values of opaque elements and the glazing type. The use of ventilation with heat recovery could reduce the energy demand up to 25 kWh/m^2. U-values equal to or less than 0.2 W/m^2K for the walls, 0.16 W/m^2K for the roof and 0.35 W/m^2K for the ground floor were suggested. For the glazing, a U-value less than 1.5 W/m^2K and a g-value higher than 0.6 were recommended.

Table 1-6: Summary of Passivhaus studies in warmer climates. Based on Ford et al. (2007a, p. 57-86), Ford et al. (2007b, p. 9-22), Schnieders et al. (2012, p. 56-140), Passive House Institute (2012b, p. 3-8) and Hatt et al. (2012, p. 127-132)

Place/ approx. Latitude	Housing typology	Area (m^2)	Orient.	Annual energy demand (kWh/m^2) h: heating c: cooling d: dehumidification	U-Value (W/m^2K) w: wall r: roof s: ground	Insulation (mm) w: wall r: roof s: ground	Infiltration rate (ach 50Pa)	Glazing type	Design strategy	Ventilation	Thermal Comfort Interval	Extra Cost/m^2 & Payback period
Birmingham (United kingdom) 52.4°N	NA 2-floor semi-detached	NA	N-S	13.8	w:0.20 r:0.15 s:NA	200 300 NA	3.0	Double low-e	Glass optimisation Thermal mass PCM Shading Overnight ventilation	Natural ventilation windows manually and automatically controlled	20->26 °C	49 £/m^2 or 73 €/m^2 19 years
Seville (Spain) 37.3°N	2-floor semi-detached	100	N-S	h:2.8 c:21.7	w:0.37 r:0.39 s:NA	NA	Not controlled	Double and Double low-e	Glass optimisation Thermal mass Movable and eaves shading Overnight ventilation	Natural ventilation	20->26 °C	20.5 €/m^2 5 years
Granada (Spain) 37.1°N	2-floor semi-detached	100	N-S	h:8.7 c:7.9	w:0.26 r:0.28 s:NA	NA	Not controlled	Double low-e	Glass optimisation Movable and eaves shading Overnight ventilation	Natural ventilation	20->26 °C	24.1 €/m^2 4 years
Lisbon (Portugal) 38.7°N	Single-floor detached	110	N-S	h:5.9 c:3.7	w:0.32 r:0.23 s:NA	100 150 80	0.8	Double low-e	Glass optimisation Thermal mass Shading (eaves) Overnight ventilation	Thermal solar system, low power heating system	20-26 °C, >26 °C naturally ventilated	57 €/m^2 12 years
Milan (Italy) 45.4°N	Basement plus 2-floor end of terraced	120	N-S	h:10.4 c:3.2	w:0.14 r:0.15 s:0.32	250 250 100	1.0	Double low-e	Thermal mass Shading (eaves) Overnight ventilation	MVRH with low power reversible heat pump 1.5 kW	20-26 °C, >26 °C naturally ventilated	84 €/m^2 12 years
Rome (Italy) 41.9°N	Basement plus 2-floor end of terraced	120	N-S	h:6.2 c:6.6	w:0.32 r:0.32 s:0.32	100 100 100	1.0	Double low-e	Thermal mass Shading (eaves) Overnight ventilation	MVRH with low power reversible heat pump 1.5 kW	20-26 °C, >26 °C naturally ventilated	60 €/m^2 8 years
Palermo (Italy) 38.1°N	Basement plus 2-floor end of terraced	120	N-S	h:2.4 c:9.6	w:0.23 r:0.23 s:1.70	150 150 -	1.0 to 2.0	Double low-e	Thermal mass Shading (eaves) Overnight ventilation	MVRH with low power reversible heat pump 1.5 kW	20-26 °C, >26 °C naturally ventilated	60 €/m^2 8 years
Carpentras (France) 44.0°N	Basement plus 2-floor terraced	120	N-S	h:14.8	NA	150 150 60	< 1.0	Double low-e	Shading Overnight ventilation	MVRH with heat pump	20-26 °C, >26 °C naturally ventilated	103 €/m^2 19.5 years
Nice (France) 43.7°N	Basement plus 2-floor terraced	120	N-S	h:13.1 c:10.6	NA	60 100 20	< 1.0	Double low-e	Shading	MVRH with heat pump, cooling via supply air	20-26 °C, >26 °C naturally ventilated	103 €/m^2 19.5 years

Place/ approx. Latitude	Housing typology	Area (m^2)	Orient.	Annual energy demand (kWh/m^2) h: heating c: cooling d: dehumidification	U-Value (W/m^2K) w: wall r: roof s: ground	Insulation (mm) w: wall r: roof s: ground	Infiltration (ach 50Pa)	Glazing type	Design strategy	Ventilation	Thermal Comfort Interval	Extra Cost/m^2 & Payback period
Tokyo (Japan) 36.2°N	Basement plus 2-floor end of terraced	120	N-S	h:14.5 c:7.1 d:10.3	w:0.20 r:0.15 s:0.28	150 200 100	0.3 to 0.5	Double low-e	Compactness Movable shading	MVRH, cooling via supply air, humidity control	20-26 °C UR 60%	NA
Shanghai (China) 31.4°N	Basement plus 2-floor end of terraced	120	N-S	h:11.0 c:11.4 d:11.8	w:0.20 r:0.15 s:0.28	150 200 100	0.3 to 0.5	Double low-e	Movable shading	MVRH, cooling via supply air, humidity control and recovery	20-26 °C UR 60%	NA
Las Vegas (USA) 35.7°N	Basement plus 2-floor end of terraced	120	N-S	h:14.5 c:15.2 d:1.3	w:0.12 r:0.20 s:1.66	250 150 -	0.3 to 0.5	Double low-e	Glass sun protection Cool colour coating Overnight ventilation	MVRH, cooling via supply air	20-26 °C UR 60%	NA
Dubai (UAE) 24.4°N	Basement plus 2-floor end of terraced	120	N-S	c:37.7 d:21.9	w:0.12 r:0.15 s:0.20	250 200 150	0.3 to 0.5	Triple low-e	Glass sun protection Cool colour coating Shading (eaves) Overnight ventilation	MVRH, cooling via supply air, humidity control	20-26 °C UR 60%	NA
Hermosillo (Mexico) 29.1°N	Single-floor detached	≅38	N-S	h:2.0 c:15.0	NA	250 300 125	5.0	Triple	Thermal mass Movable shading Cool colour coating	MVRH, separate recirculation cooling	20-25 °C 18-28 °C	450 $/$m^2$
Guadalajara (Mexico) 20.6°N	Single-floor detached	≅38	N-S	h:4.0 c:6.0	NA	50 100 25	5.0	Double low-e	Thermal mass Overnight ventilation Cool colour coating	Extract air system	20-25 °C 18-28 °C	191 $/$m^2$
Puebla (Mexico) 19.0°N	Single-floor detached	≅38	N-S	h:15.0 c:1.0	NA	150 275 125	5.0	Double	Cool colour coating	Extract air system Natural ventilation	20-25 °C 18-28 °C	251 $/$m^2$
Cancun (Mexico) 21.1°N	Single-floor detached	≅38	N-S	c:39.0 d:30.0	NA	250 200 225	5.0	Triple	Thermal mass Movable shading Cool colour coating	MVRH, separate recirculation cooling, dehumidification	20-25 °C 18-28 °C	450 $/$m^2$
Santiago (Chile) 33.4°S	2-floor	100	Variable	h:≅15 c:≅5.0	w:0.35 r:0.28 s:0.65	NA	0.6	Double	Shading	MVRH	20-26 °C	NA
Concepción (Chile) 36.8°S	2-floor	100	Variable	h:≅20	w:0.35 r:0.28 s:0.65	NA	0.6	Double	Shading	MVRH	20-26 °C	NA
Puerto Montt (Chile) 41.4°S	2-floor	100	Variable	h:≅25	w:0.20 r:0.16 s:0.35	NA	0.6	Double	Compactness Shading	MVRH	20-26 °C	NA

1.7 Conclusions

Dwellings designed and constructed based on the Fabric First approach used building physics theory for increasing energy efficiency and improving thermal performance.

Dwellings where the Fabric First approach is mostly adopted, tended to be similar in terms of their size, occupancy rate and energy use in the locations evaluated. These houses tended to be large and the areas of dwellings showed to be in an upward rise (except by specific countries as the United Kingdom that showed a downward trend). The areas of dwellings were found mostly between 100 and 120 m^2.

Despite the fact that dwellings' size is being increased, they tend to accommodate small families. The average household size corresponded to less than 3 persons and, consequently, the occupancy rates (m^2/ person) showed to be high, mostly between 35 and 45 m^2 per person. Because fewer people live in each dwelling, the impact on the internal gains might not be same that could be so in highly occupied dwellings.

The Passivhaus standard incorporates these dwelling patterns in its scheme. Most of the Passivhaus dwellings are constructed with an area higher than 100 m^2 and the occupancy rate of the standard is set as 35 m^2 per person. Consequently, the internal gains of Passivhaus dwellings are considered very low and no more than 2.10 W/m^2, ensured by the use of efficient appliances and mechanical ventilation systems.

The typology of dwellings based on the Fabric First approach showed to vary according to cultural and architectural patterns of each location. The Passivhaus dwellings examples showed that all kind of typologies can be optimised for low energy use and thermal comfort, although detached house (mainly those of one-storey) typology might require more insulation and low infiltration rate compared to other typologies to achieve the same levels of efficiency and thermal comfort due to its typical spread-out configuration.

However, a compact building typology (with a form factor smaller than 3) is more important in climates where the energy demand is more significant. The areas of the building exposed should be kept at a minimum in order to be economically feasible for the implementation of the Passivhaus standard, otherwise smaller U-values are required to compensate these exposed surfaces, and consequently, higher costs are needed to implement these measures.

All the reviewed studies of Passivhaus dwellings were fundamental because they offered an insight into potential key areas of exploration for house optimisation, aiming for increasing energy efficiency and thermal comfort. Most of the studies considered

climate, cultural and architectural differences for optimising dwellings to near the Passivhaus standard such as housing typology, materials and ventilation systems.

These studies also showed that a significant reduction of the space heating and cooling demand was achieved and, consequently, a relevant increase of thermal comfort was ensured through the use of a variety of key design strategies in these buildings. Among the strategies, the design optimisation (i.e. shading, orientation), the use of insulation materials and low infiltration rates occurred repeatedly.

The levels of insulation showed to be higher in hotter climates and lower in milder ones. Most of the Passivhaus dwellings examples in warmer climates used less levels of insulation than the Passivhaus standard levels.

Despite the fact of its benefits, low infiltration rate was regarded with a certain criticism from the cultural, market and architectural perspective. This parameter was found to be a difficult target to be met and it might not be commonly adopted and widely accepted in dwellings in a variety of locations around the world.

Similarly, MVHR was also found to be an unconventional ventilation system used in dwellings in milder climates. As in these climates the infiltration rates are not reduced significantly and natural ventilation is mostly used, the system is not needed.

Passivhaus dwellings' upfront additional costs showed to be high but they varied according to the energy efficient reference used. In the United Kingdom, the additional costs represent about 15-20% of the typical costs. These dwellings, however, seem to be cost-effective within their lifespan mainly because their running costs tend to be low. The payback period is likely to be short in large size houses which are heated or cooled. On the contrary, the payback is likely to be higher in small naturally ventilated houses, which do not tend to be heated or cooled. Also, both the cost and the payback period tends to be higher in those locations that might not have yet adopted high energy efficient dwellings as the disparities between the Passivhaus dwellings and the local dwelling used as reference will be high.

Thermal comfort temperature limit was mostly found to be used between 20 °C and 25 °C mainly because of the potential use of hybrid ventilation systems. Nonetheless, an extension of the thermal comfort criterion mainly related to the upper comfort limit was accepted when natural ventilation was taken into account.

The next chapter sets out the research scene for the Brazilian context.

CHAPTER 2: HOUSING AND ENERGY IN BRAZIL

This chapter outlines the housing and household energy trends in Brazil. Additionally, Brazilian building energy regulations and relevant studies for optimising the building envelopes in Brazilian housing are described in detail. The findings helped define the typical affordable Brazilian housing typology and its main features. Also, the outcomes informed the need for revisiting ways of increasing the thermal performance of the Brazilian housing envelope and suggested that there is a great potential for improving thermal comfort and energy efficiency in Brazilian housing through an optimised building envelope.

"In 2010, Brazil had 57.6 million households, 86.5 per cent of its people residing in detached homes (49.8 million) and 10.6 per cent of apartments (6.1 million)."
(UN-Habitat, 2013, p. 18)

"The housing shortage is a problem that mostly affects the urban poor. In Brazil, 85 per cent of the deficit is in cities. Metropolitan areas alone concentrate 28 per cent of the deficit. Regarded per income ranges, the deficit persists as a problem affecting mostly the poor. Between 85 and 90 per cent of the deficit is within families with an income of up to three minimum wages."
(UN-Habitat, 2013, p. 22)

2 HOUSING AND ENERGY IN BRAZIL

This chapter establishes the basis of this research in terms of the housing and energy scenario for the Brazilian context. Thus, an investigation is conducted with the aim of defining the Brazilian housing typology and related patterns regarding these homes, which is used to support this research. Also, the energy consumption in housing is explored as a means of establishing the households' energy use and, consequently, ways of saving energy in housing. It should be noted that this chapter constitutes a new addition to knowledge as differently from the United Kingdom, Brazil does not have easily accessible data regarding homes.

The chapter also showed national building energy regulations and relevant studies for optimising the Brazilian housing envelope. The purpose consisted of exploring envelope benchmarks and ways of optimising the building envelope for increasing indoor thermal comfort and energy efficiency in Brazilian housing.

2.1 Introduction

Brazilian territory covers an area of nearly 35 times the size of the United Kingdom, extending from 5° N latitude to 34° S (Lamberts, 1988, p. 1). The country extends along 4,394.7 km from north to south (IBGE, 2014c). The vast majority of Brazilian territory, which corresponds to about 90% of its territory, is located in the southern hemisphere (IBGE, 2014c). Brazil has a total area of around 8,515,767 km^2 and a population of 190 million (IBGE, 2013, p. 11)[9]. The population is irregularly distributed and 85% of the entire population occupies only 0.6% of the national territory (Bonduki, 2012, UN-Habitat, 2013, p. 5), as shown in Figure 2-1. This concentration is such that 60% of the country's urban population lives in only 230 of the 5,565 countries' municipalities (Bonduki, 2012, UN-Habitat, 2013, p. 5).

Brazil is divided into 26 states and a Federal district, which hosts the country's capital. The states are grouped into regions, which are classified according to the states proximity and other similarities (e.g. economic, social). Figure 2-2 illustrates the Brazilian division by states and regions.

[9] Population estimated to be 204.9 million in 2015. IBGE. 2015. *Projeção da população do Brasil e das Unidades da Federação.* [Online]. Rio de Janeiro, Brazil: Instituto Brasileiro de Geografia e Estatística (IBGE). Available: http://www.ibge.gov.br/apps/populacao/projecao/ [Accessed 23 October 2015.

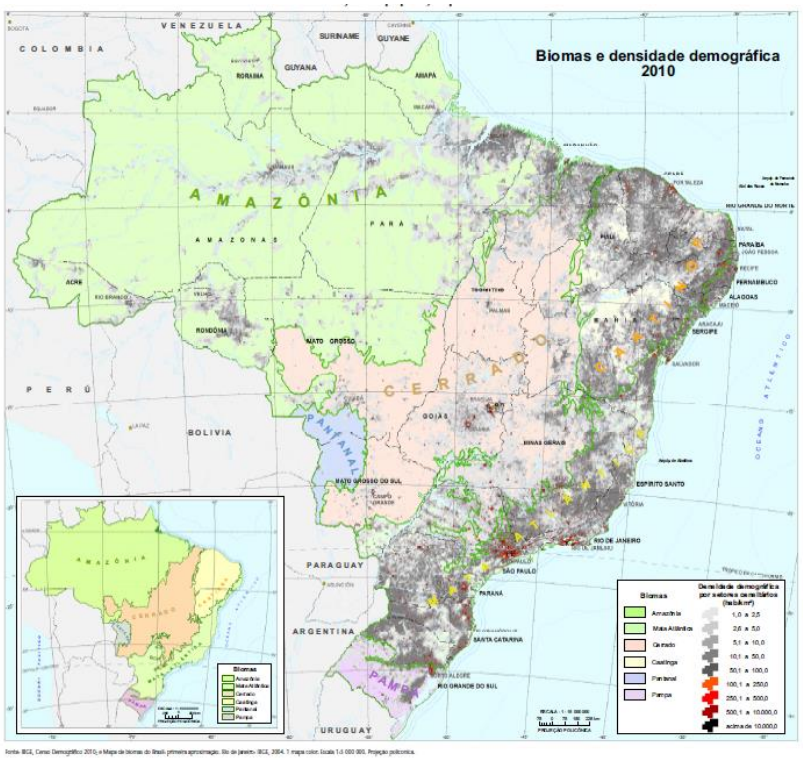


Figure 2-1: Population density (IBGE, 2013, p. 54)

Figure 2-2: Brazil division by states and regions

2.2 Housing in Brazil

Brazil is a county of disparities and, consequently, the housing typology varies hugely across different economic classes, which makes it difficult to characterise. In order to understand the Brazilian housing typology, the household economic classes need to be firstly investigated.

There is a certain criticism regarding the division of Brazilian economic classes mainly because it can differentiate significantly depending on the source but also because many of the available sources tend to interpret the categorisation of middle class differently. For instance, Brazilian economic classes can be classified by monthly household income, minimum wage or household goods. In the present research, the criterion of FGV/CPS (2011), which rates the economic classes according to minimum monthly household income, was adopted as it uses a similar criterion as the national Census research.

Table 2-1 shows Brazilian economic classes from A to E, varying according to the monthly household income. The lowest economic classes D and E have the lowest monthly incomes, whereas the highest economic classes A and B have the highest monthly incomes. Economic class C or middleclass comprehends a monthly income from 3 to 13 minimum wages and it consists of the majority of the Brazilian population, estimated to be 60.20% of the entire population in 2014 (Neri, 2012, p. 17).

Table 2-1: Economic classes in Brazil. Based on FGV/CPS (2011) and Neri (2012, p. 14, 17)

	A	B	C (middle class)	D	E
Monthly income 2011, in R$	Higher than R$ 9,745.00	R$ 7,475.00 - R$ 9,745.00	R$ 1.734 - R$ 7,475.00	R$ 1,085.00 - R$ 1,734.00	Less than R$ 1,085.00
Converted into Minimum wage[10]	Higher than 18x minimum wage	13 -18x minimum wage	3 -13x minimum wage	2 - 3x minimum wage	Less than 2x minimum wage
Monthly income, in 2015, in R$	~Higher than R$ 14,184.00	~R$ 10,244.00 - R$ 14,184.00	~R$ 2,364.00 - R$ 10,244.00	~R$ 1,576.00 - R$ 2,364.00	~Less than R$ 1,576.00
Monthly income, in 2015, in US$[11]	Higher than US$ 4,665.00	US$ 3,369.00 – US$ 4,665.00	US$ 777.00 – US$ 3,369.00	US$ 518.00 - US$ 777.00	Less than US$ 518.00
Percentage of population	14.85%		60.20%	24.95%	

Currently Brazilian monthly income is equivalent to an annual income of approximately US$ 3,369.00 (monthly income plus 13th salary).

The housing sector corresponds to one third of the entire construction sector and nearly 2% of the national gross domestic product (Ministério das Cidades, 2009, p. 60-61). Brazilian housing stock accounted for a remarkable number of 57.3 million units in 2010 (IBGE, 2011a, p. 162). Most of the housing stock, equivalent to more than 49.2 million housing units are located in urban areas, which represents 86% of the housing stock (IBGE, 2010a, p. 107).

[10] Minimum wage of 545 Brazilian reais was considered in 2011. Brazilian minimum wage is equivalent to 788 Brazilian reais in 2015. PORTAL BRASIL. 2015. *Salário Mínimo Brasileiro* [Online]. Available: http://www.portalbrasil.net/salariominimo.htm [Accessed 23 October 2015.

[11] Exchange rate: R$ 3.04 ~ US$ 1.00. BANCO CENTRAL DO BRASIL. 2015. *Dólar americano* [Online]. Available: http://www4.bcb.gov.br/pec/taxas/batch/taxas.asp?id=txdolar [Accessed 08 May 2015.

Despite the remarkable extent of the housing sector, the country has still experienced a housing shortfall estimated to be nearly 5.546 million of housing units and also a large proportion of inadequate homes with poor living conditions, which are estimated to be about 10.948 million (Fundação João Pinheiro, 2011, p. 59, 87). The housing deficit is higher in the southeast and northern regions, where it corresponds to 36.9% and 35.1% of the national housing demand, respectively (Fundação João Pinheiro, 2011, p. 29, 31). The south region ranks third and accounts for 10% of the national deficit (Fundação João Pinheiro, 2011, p. 31).

The highest urban housing shortage is found for households whose income is below 3 minimum wages (economic classes D and E), which corresponds to 89.6% of the total urban housing deficit (Angélil and Hehl, 2014, p. 32). Households whose income is up to 5 minimum wages (up to low-middle class) constitute 96.6% of the total urban housing deficit (Angélil and Hehl, 2014, p. 32).

The government's way to tackle the housing deficit and to provide ways of supporting the construction and financing of new homes is through its housing programme '*Minha Casa, Minha Vida'* (MCMV, 'My house, My life', in English). The MCMV programme was launched in 2009 with the aim of helping construct and purchase new affordable homes for low- and middle-income householders with a monthly income of up to 10 minimum wages (up to economic class C)(Angélil and Hehl, 2014, p. 34). However, the programme mainly focuses on providing a housing unit for households whose monthly income is up to 3 minimum wages (Angélil and Hehl, 2014, p. 34).

The programme invested 361 billion Brazilian reais (approximately 118.7 billion US dollars) between 2011 and 2014 and delivered more than 1.7 million housing units during this period (Ministério do Planejamento, 2014). This investment is part of an ambitious target, which aims to deliver up to 24 million new affordable houses by 2022 (Carbon Trust, 2012a, p. 47).

The majority of the Brazilian housing stock is composed of detached houses and it accounts for 86.9% of the overall housing stock (IBGE, 2010c, p. 14). Only 10.7% of the housing stock corresponds to apartments (IBGE, 2010c, p. 14).

However, the concept of Brazilian detached house typology seems to deviate from the common concept, which established that a detached house is a house isolated on the plot. In fact, detached houses are mostly common because the housing construction in Brazil is mostly based on self-build, which means that the households tend to build on their own plots, independently of houses besides the plots. A vast number of Brazilian houses are built by owners themselves, with the help of a contractor and unskilled workers (Lara, 2010).

The preferences for constructing detached houses were part of the first housing policies in Brazil in the period from 1930 to 1950 when Brazil was under a dictatorial government. The reason for choosing detached dwellings relied on the fact that single-family detached-houses would facilitate the household's moral and behaviour control, instead of the collective house which could 'subvert' the householders as they could have more interaction with other people in other housing typologies (Poleto, 2011).

Figure 2-3 shows the relationship between the housing typology and the monthly household income. According to the Figure, both detached houses and apartments are typologies found in all income ranges. In particular, the flat typology tends to be more representative for medium and high monthly income, which means economic classes A, B and upper C.

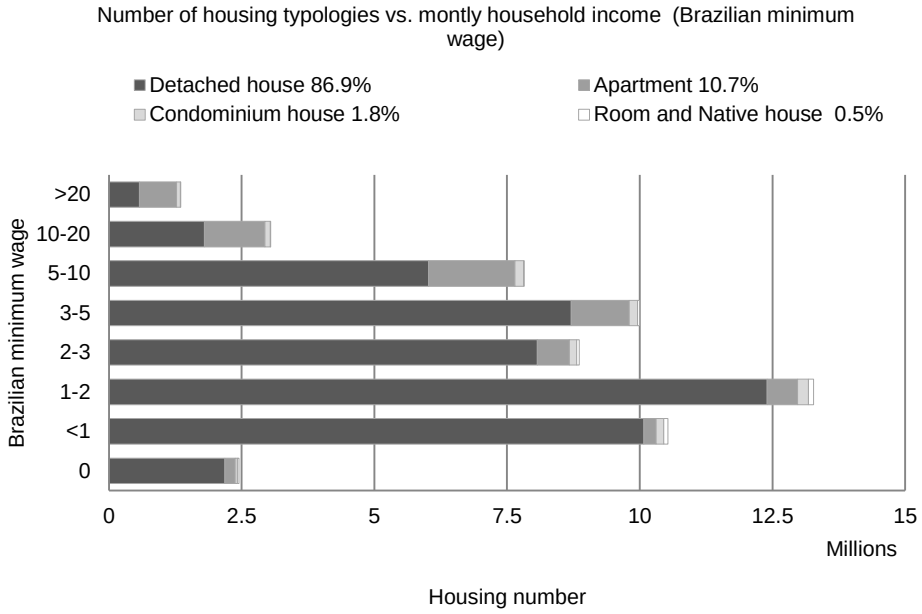


Figure 2-3: Number of housing typologies according to the household incomes. Based on IBGE (2010c, p. 14) [12,13]

[12] Condominium house typology is a group of houses with just one common public access, but with each house considered individually. This kind of typology could have detached or terraced houses. IBGE 2010a. Censo Demográfico 2010: Famílias e domicilios - Resultados da amostra. Rio de Janeiro, Brazil: Instituto Brasileiro de Geografia e Estatística (IBGE).

[13] Rooms Housing (Cortiço) and Native houses are linked with very low incomes and ethnic groups, respectively. Particularly, Cortiço is a building that is subdivided inside of one house or site and is rented or granted by courtesy usually without formal agreement by more than one family. The use of house common areas is shared among the householders. Ibid.

Figure 2-4 reveals the housing wall materials per household incomes range. Housing walls are mostly built out of masonry, which represents more than 90% of the national housing stock (IBGE, 2010a, p.120, 124, 125). Masonry with coating[14] and brick masonry without coating accounts for 80.0% and 10.7% of the entire housing stock, respectively. Housing walls made out of planned timber and coated rammed earth materials correspond to only 6.4% and 0.7% of the housing stock, respectively. The remaining percentage of the housing stock (2.2%) is built out of non-durable materials, which includes houses made out of rammed earth with no coating, recycled wood, straw and other non-specified materials.

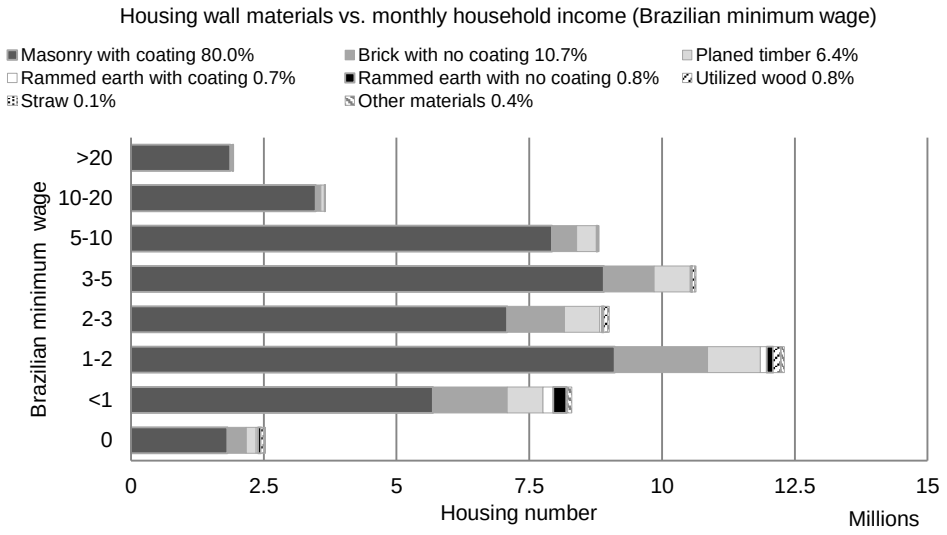


Figure 2-4: Housing wall materials according to the household incomes. Based on IBGE (2010a, p. 124-125)

Housing in Brazil uses conventional materials due to their traditional acceptability in the society and its construction adopts low-innovative techniques because of the lack of skilled labour in the construction sector (Kruger and Laroca, 2010). The housing construction process follows what is known as wet process, in which the materials are mixed on site and very little prefabrication is considered (Lara, 2010). This means that industrialised materials are not carried any further from standard materials such as bricks and blocks, cement, aggregate stones and wood (Lara, 2010).

A study conducted in southern Brazil (Sattler, 2007, p. 75-76) suggested that low-income housing is mostly built with masonry or timber walls, fibre-cement or ceramic roof tiles and aluminium, iron or timber window frames. Low-middle-income housing uses a wide range of materials similar to low-income housing, although the masonry is

[14] This piece of information needs to be handled with care because masonry with coating can correspond to a vast number of different masonry types, such as brick walls with coating, rock walls and concrete walls.

mostly made out of ceramic brick and blocks. Middle-income housing is predominantly built out of ceramic roof tiles, timber window frames and conventional masonry walls. The most typical masonry walls are built out of ceramic bricks covered by mortar (Oliveira et al., 2009).

Figure 2-5 shows the general scheme of the typical Brazilian housing plan, which varies according to the size of the house, its economic level and its construction period of time. Porches or balconies are common architectural elements of Brazilian houses and they are used as a connection space between the inside and outside of the house, mostly providing shading (Lara, 2010). Another peculiarity in Brazilian houses is the employee facilities. These facilities appear to be a housing characteristic remnant from the past, when the householders were likely to have an employee working during the day in their houses. The employee facilities used to comprise a small bedroom and bathroom but these areas are recently being supressed or being reduced even in high standard houses.

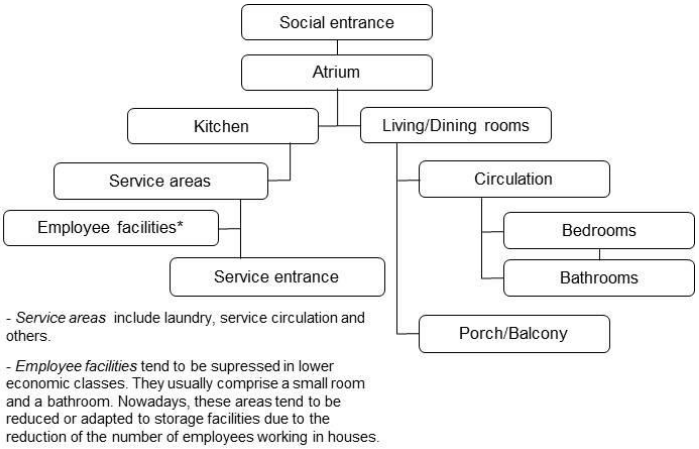


Figure 2-5: General scheme of Brazilian housing plan. Adapted from Anitelli and Tramontano (2011, p. 3)

Figure 2-6 shows the relationship between the number of housing bedrooms and the monthly household income. A 2-bedroom housing typology is mostly found in Brazil and it accounts for 45.2% of overall housing (IBGE, 2010a, p. 120). 1- and 3-bedroom housing typologies are also likely to be found and they account for 29.2% and 21.8% of overall housing, respectively. 1- or 2-bedroom house are more prone to be found for low-middle economic class households, whereas 2- or 3-bedroom houses are more likely to be found for high-middle economic class households.

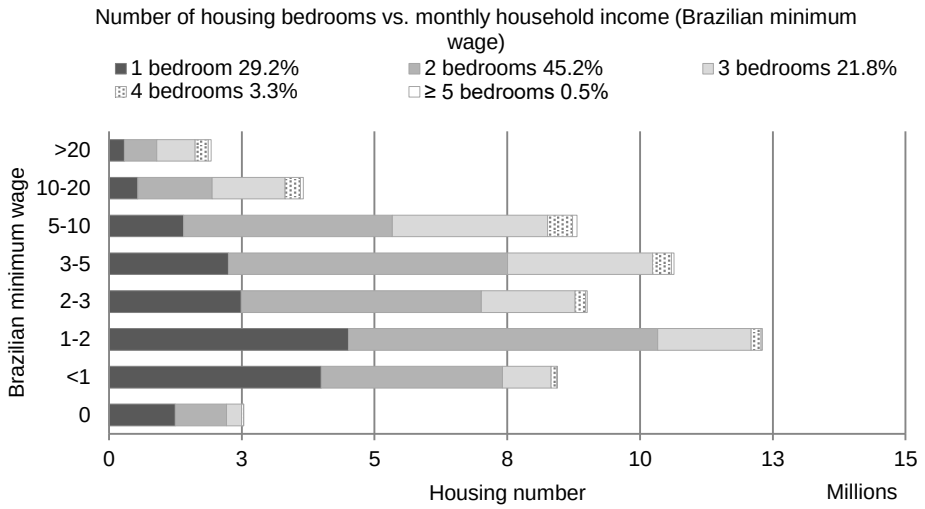


Figure 2-6: Number of bedrooms according to the household income. Based on IBGE (2010a, p.120)

Figure 2-7 illustrates the number of bathrooms for a monthly household income. There is a greater predominance of 1-bathroom house for the lowest economic classes D and E and low-middle class C, whereas there is a significant number of 2-bathroom housing and also a number of 3-bathroom housing for the highest economic classes A and B and upper-middle class C. It should be stressed that to be considered as a bathroom, there is need for only a lavatory.

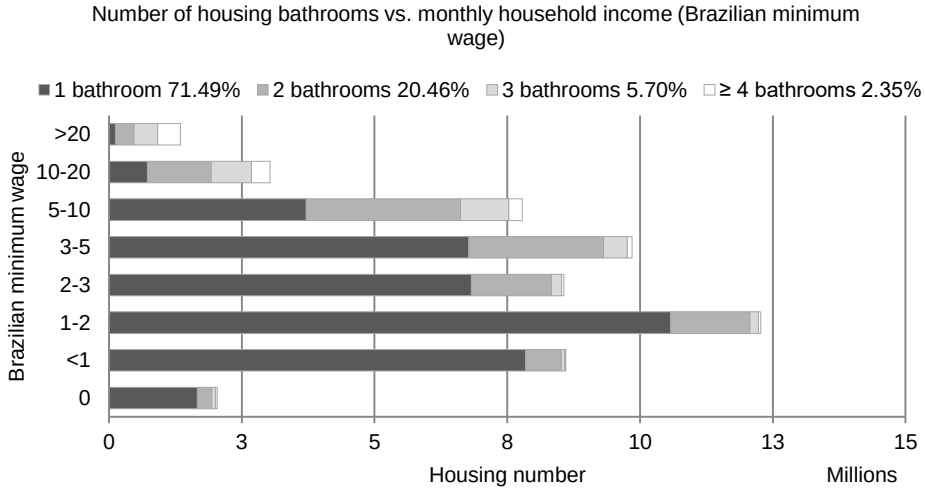


Figure 2-7: Number of bathrooms according to the household income. Based on IBGE (2011a, p. 176, 182)

The average housing size is difficult to estimate in Brazil. The reason for this is because there is a lack of data at national level and also because the available data is conducted for different entities and for different aims at local level and, consequently, the data may not be directly compared against each other. Furthermore, there is no available data of

the average housing size of the overall housing stock and the data focuses only on new housing developments. The housing data focuses on conventional developments, which means the housing units that are built to be sold on the market and, consequently, it does not account for self-build houses and it might not account for affordable houses either. Therefore, it is expected that this housing data would be more related to middle-income housing.

For instance, in São Paulo, which is one of the most important and populous Brazilian cities, the average new housing size was estimated to be 80.78 m^2 in 2013 (Embraesp, 2014, p. 29). This value was bigger than 2012, which reached the average area of 77.49 m^2 but smaller than 2011 and 2010, when the average area was estimated to be 101.86 m^2 and 87.34 m^2, respectively (Embraesp, 2014, p. 29). 2-bedroom housing was mostly built in 2013, followed by 1-bedroom and 3-bedroom housing, respectively. The average area per number of bedrooms was estimated to be 40.52 m^2 for 1-bedroom housing, 57.17 m^2 for 2-bedroom housing, 87.74 m^2 for 3-bedroom housing and 194 m^2 for 4-bedroom housing or bigger (Embraesp, 2014, p. 20). These values are related to the useful area and they tend to be bigger if considering the total area built.

Similarly, in Porto Alegre, which is the capital of the state of Rio Grande do Sul, the average new housing size was estimated to be 78.87 m^2 in 2013 (SINDUSCON-RS, 2013a, p. 2). It was also bigger than 2012, when the average area was estimated to be 76.25 m^2 but smaller than the previous years of 2011 and 2010, with an area of 83.83 m^2 and 82.83 m^2, respectively (SINDUSCON-RS, 2013a, p. 2). In terms of flats, a 2-bedroom flat was found to be the most common housing typology built, followed by a 3-bedroom flat. In terms of houses, a 3-bedroom house was mostly built, followed by a 2-bedroom housing typology.

However, low- and low-middle-income housing tends to have more limited internal areas. Minimum areas of Brazilian housing varies according to the housing room areas, their function and layout (Reis and Lay, 2002, p. 17-21): a master bedroom is estimated to be about 9 to 9.5 m^2; a second bedroom is estimated to be about 8 m^2; a living room is estimated to be 10m^2, mainly when it corresponds to an open space area, combined with a dining room; a kitchen is estimated to be at least 5 m^2 of area but it depends on the household appliances and the space configuration; a bathroom is estimated to be at least 2.5m^2 of area.

The occupancy rate in Brazilian housing heavily depends on the economic level of the household and also on the housing floor area. So far there is no official data regarding to the average occupancy per square metre of housing. However, it should be considered that affordable houses are more likely to be fully occupied than those houses of the high and upper-middle classes.

The average number of households per housing unit is estimated to be 3.3 in Brazil (IBGE, 2010a, p. 92). However, research in affordable housing estimates that an occupancy rate of 13 m^2 of treated floor area per person for a 1-storey 2-bedroom house with an occupancy of 4 people and built area between 41 and 46 m^2 is mostly found (Cruz and Ornstein, 1995, p. 277). Affordable housing in Brazil can reach a maximum occupancy rate of 9 m^2 per person if considering a 2-bedroom detached house for a family of four people, based on a minimum area of 36 m^2 accepted by the affordable housing programme (Ministério das Cidades, 2014b).

As this research looks specifically into affordable housing, it is necessary to describe in detail this housing typology for the Brazilian context. In parallel, for information purposes, middle standard housing is also depicted in order to show the differences between both housing standards.

2.2.1 Affordable Housing

Affordable housing or low standard housing is the housing typology destined for the economic classes D and E and low-middle class C. The definition of this housing typology is straightforward and one of the ways to characterize this typology is to look at the MCMV housing typologies, which make up the lowest income households.

Figure 2-8 and Figure 2-9 show the MCMV housing typologies of a detached house and apartment for a household with income of up to 3 Brazilian minimum wages. The minimum areas for the house and apartment typologies corresponded to 35 m^2 and 42 m^2 for a 2-bedroom housing, respectively (UN-Habitat, 2013, p. 46). More recently, the minimum internal areas were set out to be more than 36 m^2 and 39 m^2 for house and apartment[15], respectively (Ministério das Cidades, 2014a, p.1, Ministério das Cidades, 2014b, p. 1). It should be noted that the area of each room of the MCMV typology is not standardized and it can be varied as long it complies to the local building codes and with the minimum requirements in terms of furniture (Angélil and Hehl, 2014), which is established by the programme and found at Ministério das Cidades (2014b). More information can be found in Chapter 5.

[15] http://www.cidades.gov.br/images/stories/ArquivosSNH/ArquivosPDF/Especificacoes/especificacoes_apartamento_port168.pdf [Accessed 06 January 2015].

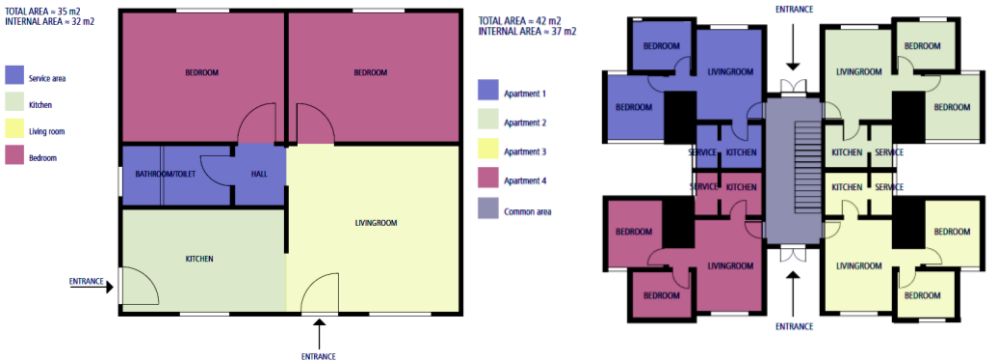


Figure 2-8: MCMV plan typologies of a detached house (left) and apartment (right) for a household with income of up to 3 Brazilian minimum wages (UN-Habitat, 2013, p. 45, edited)

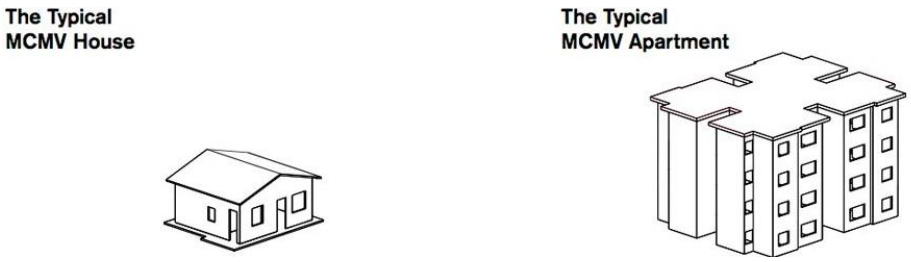


Figure 2-9: MCMV isometric perspective typologies of a detached house (left) and apartment (right) for a household with income of up to 3 Brazilian minimum wages (Angélil and Hehl, 2014, p 40-41).

Figure 2-10 shows an example of the house typology implementation and construction. The cost estimation of each housing unit greatly varies according to the region of the country where the building is located. The estimated cost of the standard house unit is 64 thousand Brazilian reais (approximately 21 thousand US dollars) for the metropolitan areas of the south region and between 60 and 76 thousand Brazilian reais (approximately 20-25 thousand US dollars) for the metropolitan areas of the southeast region (Angélil and Hehl, 2014, p. 39).

Figure 2-10: MCMV detached house example of construction (Angélil and Hehl, 2014, p. 166-167)

Despite the MCMV typology, affordable housing can also be defined based on the Brazilian standard NBR 17221 (ABNT, 2006). The standard defines the housing typologies based on common practices of the Brazilian market, aiming for setting evaluation criteria for costs. According to the standard, a low cost standard housing is

a 2-bedroom house with a built area of 58.64 m^2 and it differs from the MCMV house only by the existence of an indoor area for laundry and more spacious rooms.

2.2.2 Middle Standard Housing

Middle standard housing is the housing typology destined mostly for the economic class C, which comprises more than half of the Brazilian population. However, this typology is very diverse from the architectural point of view due to the economic class income range, the nature of self-build construction and the existing regionalism, which makes it difficult to establish a common house type.

According to the Brazilian standard NBR 17221 (ABNT, 2006), a typical middle standard housing is a 3-bedroom house with a built area of 106 m^2, composed of two bathrooms (one is an ensuite bathroom), living room, kitchen, circulation area, service area for laundry with service bathroom and porch for parking space.

As the built area of the house counts all construction elements (i.e. walls, porches), it is estimated that the useful housing floor area would be smaller, which might be similar to those examples of average dwelling size in São Paulo and Porto Alegre of approximately 80 m^2. Hence, it seems reasonable to consider that houses with areas between 80 and 100 m^2, which have similar rooms according to the aforementioned standard, could be treated as middle standard houses.

In addition to this section that reviewed the main features of Brazilian housing, the next section reveals the energy end-use in Brazilian housing.

2.3 Energy Use in Housing in Brazil

The housing sector energy consumption is estimated to be 9.4% of national energy consumption (EPE, 2013b, p. 28). However, it is believed that the sector is responsible for a much higher percentage of energy consumption since it consumes large amounts of natural resources from the construction activities. Thus, it is estimated that housing construction activities account for 22% of the national energy consumption (Pfeiffer, 2011, p. 8).

The housing sector had an energy consumption growth rate of 4.4% between 2010 and 2011 (EPE, 2012, p. 16) and an additional growth rate of 2.1% in 2012 (EPE, 2013b, p. 16), which might be due to the increased number of households and increase of purchasing power in the last few years in Brazil.

The housing sector's energy consumption is mainly met by electricity. It corresponded to 23.6% of the national electricity consumption in 2012 (EPE, 2013b, p. 32)[16].

Electricity in Brazil is basically met by hydro sources (76.9%); the remaining electricity energy sources are met by biomass (6.8%), natural gas (7.9%), oil products (3.3%), nuclear (2.7%), coal (1.6%) and wind (0.9%) (EPE, 2013b, p. 16). Because hydropower is the major resource to generate electricity and it is considered as a renewable source, it is estimated that Brazil releases 6 times less CO_2 than Europe to produce the same amount of electricity, equivalent to 1TWh of electric energy; the country contributes to emissions equivalent to 82 kgCO_2 per MWh generate of electricity (EPE, 2013a, p. 41). However, although less carbon emissions are produced by hydropower, a significant energy loss exists in the energy transmission system and, consequently, more energy needs to be produced to compensate these energy losses.

Figure 2-11 shows the housing sector's energy consumption according to the main energy resources. Electricity consumption represents about 43% of the housing sector's energy consumption and it appears as an upward trend. The remaining energy consumption in the sector is provided by firewood (27.2%), LP gas (26.9%, usually associated to cooking), charcoal and natural gas (EPE, 2013b, p. 77).

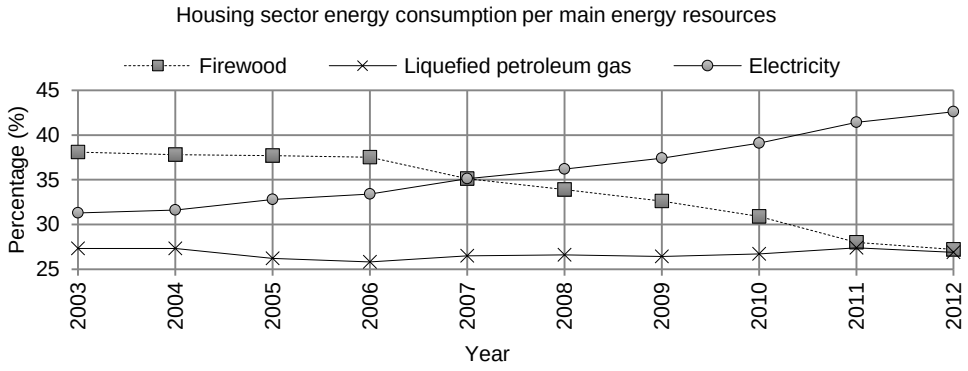


Figure 2-11: Housing sector energy consumption. Based on EPE (2013b, p. 77)

Even though 65% of the housing sector energy consumption is estimated to be derived from renewable energy sources through hydropower (EPE, 2013a, p. 28), the percentage delivered by non-renewable energy sources has increased in recent years. The fossil-fuel-based matrix has risen in a government attempt to increase the country's electricity energy capacity. A growth rate of 5.1% of the housing electricity consumption between 2011 and 2012 was supplied by thermoelectric, which increased its national electricity contribution from 4.4 to 7.9% (EPE, 2013a, p. 11, 28).

[16] Industrial, commercial and public sector accounted for 42.1%, 16.0% and 8.0% of the national electricity consumption, respectively.

The electricity tariffs in Brazil vary considerably across the country and the prices can almost double depending on the location and the energy distributor (ANEEL, 2015). In addition, the tariffs of electricity in Brazil were changed in 2015 by the electricity government agency for all local electricity distributors (AES Eletropaulo, 2015a). The electricity government agency launched 3 different price bands, which should be defined monthly based on the electricity generation. According to the new scheme, if the electricity generation by hydroelectric power should go down due to low river levels, the electricity tariff in that month would go up because thermoelectric power would be used to supplement power generation. Also, households with consumption about 200 kWh (or less depending on the location) must pay higher taxes equivalent to 25% of the energy cost (AES Eletropaulo, 2015a, CEEE, 2015b).

The electricity tariffs in Brazil have been adjusted beyond the typical inflation index of about 6% per annum (Figure 2-12). In 2014, the increase of electricity tariffs represented 18.2% (Banco Central do Brasil, 2014b, p. 74). In 2015, the tariffs were increased on average by 33% (AES Eletropaulo, 2015a).

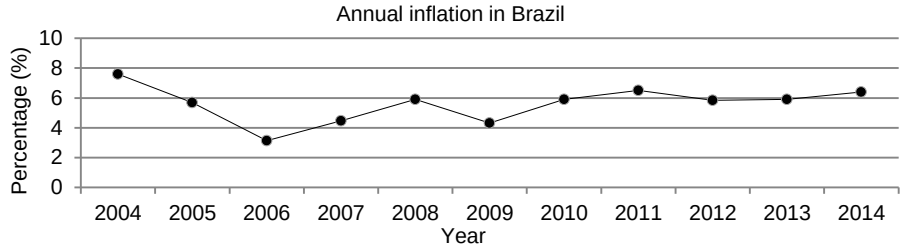


Figure 2-12: History of Brazilian annual inflation. Based on Banco Central do Brasil (2014a)

Figure 2-13 shows the monthly electricity consumption distribution in housing. The monthly mean electricity consumption represents 164 kWh per household but a growth of 2.1% per year predicted by 2023 expects to raise the monthly electricity energy consumption to 202 kWh (EPE, 2013c, p. 56). Most of the monthly energy consumption per household (31%) ranges between 101 and 200 kWh and more than two thirds of Brazilian households consume up to 200 kWh per month (ELETROBRAS and PROCEL, 2007, p. 20, PROCEL INFO, 2005).

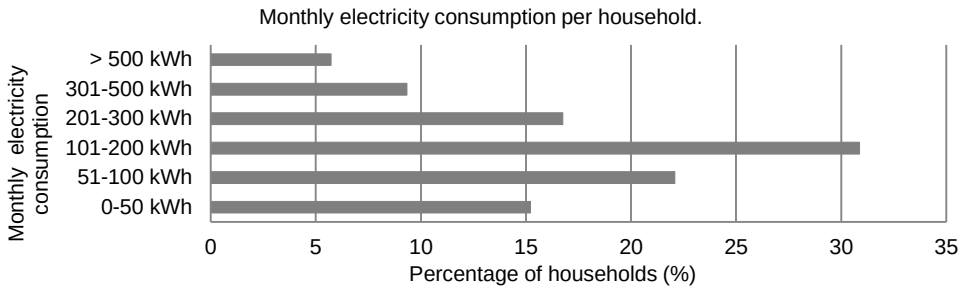


Figure 2-13: Monthly energy consumption in housing. Based on PROCEL INFO (2005).

The housing electricity consumption varies according to the household income, the house size and the number of occupants (Ghisi et al., 2007, Paulsen and Sposto, 2013). Figure 2-14, Figure 2-15 and Figure 2-16 show the housing electricity consumption related to the household income, housing area and number of occupants, respectively.

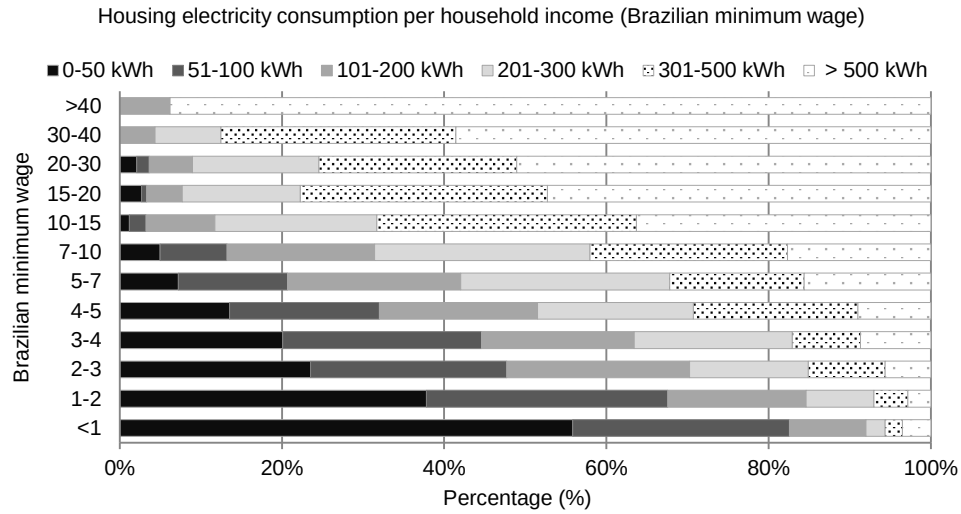


Figure 2-14: Housing electricity consumption according to the household income. Based on PROCEL INFO (2005).

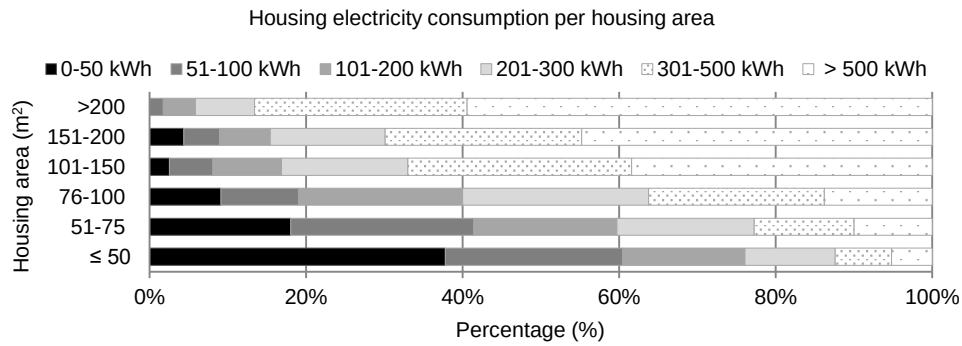


Figure 2-15: Housing energy consumption according to the housing area. Based on PROCEL INFO (2005).

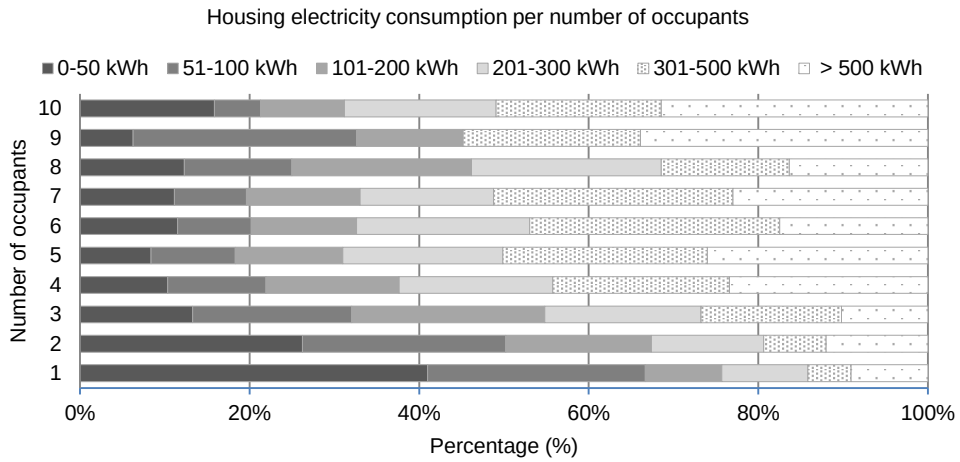


Figure 2-16: Housing electricity consumption according to the number of occupants. Based on PROCEL INFO (2005).

As shown in the Figures, low electricity consumption (< 50 kWh) is usually associated with limited household incomes and, consequently, with a housing area smaller than 50 m^2. High electricity consumption (> 301 kWh) is more likely to be associated with high-income households, with a housing area larger than 101 m^2.

The relationship between occupancy and electricity consumption is difficult to establish mainly due to the existence of both small affordable houses with high occupancy and also with low occupancy, which is a more common trend of very small families in contemporary society.

Figure 2-17 shows the housing electricity consumption for each Brazilian region. The electricity consumption in housing varies widely across the country mainly due to the population and level of development of each region. As the Figure indicates, the southeast consumes a major percentage of electricity compared to the other regions (52.4%) due to its high population density and level of development. The northeast and south regions rank second and third, with 18.2% and 15.9% of the housing national electricity consumption, respectively (EPE, 2013b, p. 147).

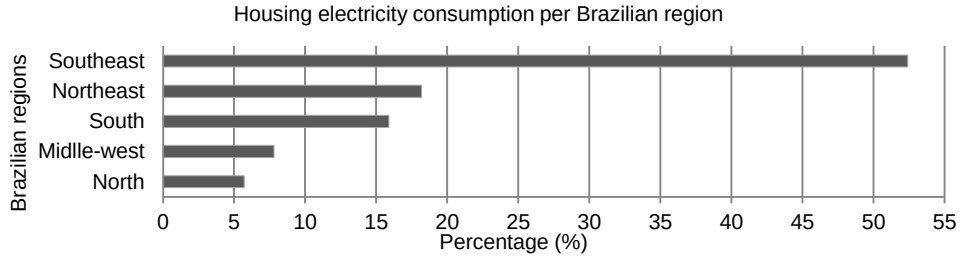


Figure 2-17: Residential electricity consumption per Brazilian region. Based on EPE (2013b, p. 147)

Table 2-2 indicates the breakdown of electricity consumption by appliances per Brazilian region. The main electricity consumption contributors are space conditioning systems, fridges and DHW for electric showers (Pacheco and Lamberts, 2013).

Table 2-2: Breakdown of electricity consumption by appliances, per Brazilian region. Based on ELETROBRAS and PROCEL (2007, p. 53)

	Brazil	Southeast	Northeast	South	Centre-west	North
Cooling/ heating	20.0%	11.0%	27.0%	32.0%	18.0%	40.0%
Freezer	5.0%	5.0%	5.0%	7.0%	4.0%	4.0%
Fridge	22.0%	22.0%	29.0%	16.0%	24.0%	25.0%
Iron	3.0%	3.0%	3.0%	2.0%	3.0%	3.0%
Lighting	14.0%	19.0%	11%	8.0%	12.0%	14.0%
TV	9.0%	10.0%	11.0%	7.0%	7.0%	9.0%
Shower (DHW)	24.0%	26.0%	9.0%	25.0%	28.0%	2.0%
Sound system	3.0%	3.0%	5.0%	3.0%	3.0%	3.0%
Washer	-	1.0%	-	-	1.0%	-

In particular, the use of cooling or heating appliances represents 20% of the overall housing electricity consumption. Northeast and south regions are where there is a predominance of space conditioning systems, due to the hot and seasonal climates, respectively. However, although this energy consumption contribution is already significant, it is achieved by a very small number of appliances. It is estimated that cooling or heating appliances are found in just 16.5% and 16.1% of households in the north and south region, respectively (ELETROBRAS and PROCEL, 2007, p. 40). Even though the majority of households in Brazil do not currently have heating or cooling appliances, the rise in income and standard of living are expected to raise the numbers of households that utilize active means for space conditioning as this will be within economic reach (Ghisi et al., 2007).

Figure 2-18 shows the most common household appliances. Stove, fridge and TV are the most common appliances found in Brazilian houses. Iron was found in most of the households with an estimated use of 1 to 3 times per week. (ELETROBRAS and PROCEL, 2007, p. 44). Other appliances such as sound system, washer and computer appear as a smaller percentage. An estimation of the appliances' energy consumption is shown in Table 2-3, based on an assumed usage.

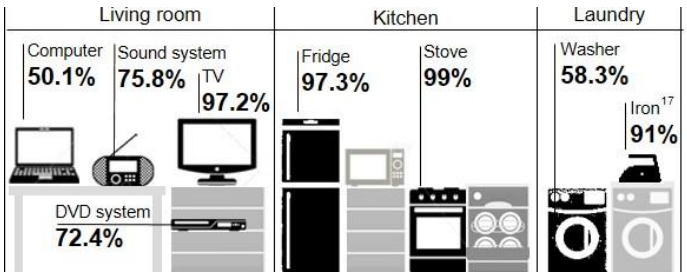


Figure 2-18: Possession of some durable goods in Brazilian houses. Based on IBGE (2014b, p. 68)

[17] Survey conducted by the Data Popular Institute in partnership with Central Única de Favelas (CUFA), based on a projection that crossed PNAD data (National Survey from Home Sampling), POF data (Family Budget Survey), from IBGE census. DATA FAVELA. 2013. *Classe média na favela sobe de 33% para 65%*

Table 2-3: Appliances energy consumption based on a given usage. Calculated according to INMETRO (2014) and PROCEL INFO (2006)

Appliances		Power (kW)	Usage assumed	Daily energy consumption (kW)
Fridge	Per hour	0.032	year	0.790
Fridge + Freezer	Per hour	0.053	year	1.280
Iron	When on	1.200	2.3h/ week	0.40
Microwave, 30l	When on	1.250	30 min/day	0.625
TV, 22''	When on	0.300	4h/ day	1.2
DVD system	When on	0.015	2h/ week	0.0042
Sound system	When on	0.110	1 h/ day	0.11
Washer, 10 kg	1h/ cycle	0.300	2 cycles/ week	0.085
Dishwasher	2.45h/ cycle	1.350	3 cycles/ week	1.417
Computer	When on	0.063	2h/ day	0.126
Shower	When on	4.400	1h/ day	4.4
Heating/Cooling, 7.000 Btu/h; 2.051W	When on	0.639	1h/ day	2.05

The next section explores Brazilian building energy regulations in housing for reducing the energy use in dwellings.

2.4 Energy Regulations in Housing in Brazil

Affordable housing in Brazil is not particularly designed for a specific location, which means that the same typology and envelope are used disregarding the climate and context where the building is. In other words, the same housing type and housing envelope is used across the country, even where very distinct cultural and climatic conditions exist (Kruger and Laroca, 2010). As a result, a high energy consumption and inappropriate indoor thermal environment can be found in these homes (Kruger and Zannin, 2007).

The Brazilian government has set out mandatory and voluntary building energy regulations to deal with the building envelope adequacy for each region in the country. These regulations are certainly a step forward to improving indoor thermal comfort and energy efficiency in housing, but their levels of stringency are still much lower than the building energy regulations in Europe, where great attention has been given on designing and constructing buildings that are highly insulated and airtight (Zero Carbon Hub and NHBC Foundation, 2012). More information regarding the comparison between the national standards and the stringent European standards can be found in the author's publication (Tubelo et al., 2013, Tubelo et al., 2014a).

The standard *NBR 15220: Thermal performance in buildings* (ABNT, 2005a, ABNT, 2005b, ABNT, 2005c, ABNT, 2005d, ABNT, 2005e) came into force in 2005. This standard consists of thermal performance terminology, methods for calculating thermal

em 10 anos [Online]. Data Favela. Available: http://datafavela.com.br/classe-media-na-favela-sobe-de-33-para-65-em-10-anos/ [Accessed 30 October 2015.

properties of building components, Brazilian climatic zoning and methods for calculating thermal resistance and conductivity of building components. Overall, the standard is mandatory, except by its Part 3, which has a character of recommendation. In the *Part 3: Brazilian Bioclimatic Zones and Building Guidelines for Low-Cost Houses* (ABNT, 2005c), the standard establishes the Brazilian climatic zones and recommends design guidelines for affordable houses, as shown in Figure 2-19 and Table 2-4, respectively.

As the Figure shows, Brazil is divided into eight climatic zones, from ZB1 to ZB8. Climatic zone ZB1 is the coldest zone, located in the southernmost areas of the country, while the climatic zone ZB8 is the warmest zone, located in the north region and on the northeast coast of Brazil.

For each climatic zone, specific design guidelines are recommended in terms of fenestration size for ventilation purposes, use of shading on the apertures, thermal properties of wall and roof components and passive design strategies for summer and winter periods.

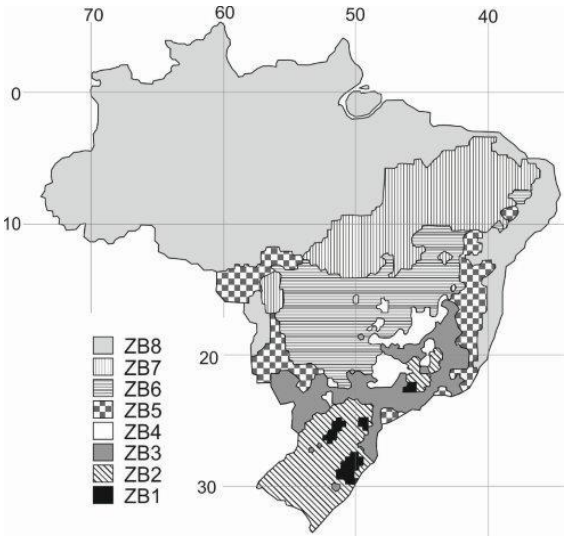


Figure 2-19: Brazilian climatic zones - Brazilian standard NBR 15220. Based on ABNT (2005c).

Table 2-4: Summary of design guidelines - Brazilian standard NBR 15220. Based on ABNT (2005c, p. 3-11, 22)

	Fenestration area (A) (% of floor area)	Building envelope U-value (W/m^2K); time lag[18] (h); solar gain factor[19] (%);		Passive design strategies (S): Summer; (W):Winter
ZB1	Medium 15%<A<25% Allow sun in winter	wall	Light; U≤3.00; φ≤4.3; FS_o ≤ 5;	(S): NA; (W): Direct solar heating gain; Heavy internal walls (thermal inertia);
		roof	Light/insulated; U≤2.00; φ≥3.3; FS_o ≤6.5;	
ZB2		wall	Light; U≤3.00; φ≤4.3; FS_o ≤5%	(S): Cross ventilation; (W): Direct solar heating gain; Heavy internal walls;
		roof	Light/insulated; U≤2.00; φ≥3.3; FS_o ≤6.5;	
ZB3		wall	Light/reflective; U≤3.60; φ≤4.3; FS_o ≤4;	(S): Cross ventilation; (W): Direct solar heating gain; Heavy internal walls;
		roof	Light/insulated; U≤2.00;φ≥3.3; FS_o≤ 6.5;	
ZB4	Medium 15%<A<25% Shade openings	wall	Heavy; U≤2.20;φ≥6.5; FS_o≤ 3.5;	(S): Selective ventilation; Evaporative and thermal mass for cooling; (W): Direct solar heating gain; Heavy internal walls;
		roof	Light/insulated; U≤2.00;φ≥3.3; FS_o≤ 6.5;	
ZB5		wall	Light/reflective; U≤3.60; φ≤4.3; FS_o ≤ 4;	(S): Cross ventilation; (W): Heavy internal walls;
		roof	Light/insulated; U≤2.00; φ≥3.3; FS_o≤ 6.5;	
ZB6		wall	Heavy; U≤2.20; φ≥6.5; FS_o≤ 3.5;	(S): Selective ventilation; Evaporative and thermal mass for cooling; (W): Heavy internal walls;
		roof	Light/insulated; U≤2.00; φ≥3.3; FS_o≤ 6.5;	
ZB7	Small; 10%<A<15% Shade openings	wall	Heavy; U≤2.20; φ≥6.5; FS_o≤ 3.5;	(S): Selective ventilation; Evaporative cooling and thermal mass for cooling; (W): NA;
		roof	Heavy; U≤2.00; φ≥6.5; FS_o ≤6.5;	
ZB8	Large A>40% Shade openings	wall	Light/reflective; U≤3.60; φ≤4.3; FS_o≤4;	(S): Permanent cross ventilation; (W): NA;
		roof	Light/reflective; U≤2.30 (FT);φ≥3.3; FS_o≤6.5	

Floor area applies only for the occupied rooms, whose occupancy is not limited to short periods (for example, bathrooms are not counted).
FT corresponds to a U-value correction related to the height of ventilated attic roof.
The U-values of the roof refers to downward flux.
NA: Not applicable

The other mandatory standard *NBR 15575: Residential buildings - Performance* (ABNT, 2013a, ABNT, 2013b, ABNT, 2013c, ABNT, 2013d, ABNT, 2013e, ABNT, 2013f) came into force only in 2013. It focuses on the performance requirements in many different levels of buildings, including the thermal performance requirements, and it is based on the climatic zones set by the NBR 15220 (ABNT, 2005c). The building envelope requirements proposed by the standard *NBR 15575* (ABNT, 2013a, ABNT, 2013d, ABNT, 2013e) are illustrated in Table 2-5.

[18] As mentioned, time lag (φ, in hours) is the time for a peak temperature difference which happens on the surface of component be noticed on the other surface of the component and it depends on the properties such as thermal conductivity, specific heat capacity, absolute density and the thickness of the material.

[19] Solar gain factor of an opaque element (FS_o, in %) is the ratio between the transmitted radiation by an opaque element and the incident radiation on the external surface of this element. ABNT 2005a. NBR 15220-1: Thermal performance in buildings - Part 1: Terminology, symbols and units. Rio de Janeiro, Brazil: Associação Brasileira de Normas Técnicas (ABNT).

Table 2-5: Summary of envelope requirements – Brazilian standard NBR 15575. Based on ABNT (2013d, p. 27, 28), ABNT (2013e, p. 27)

	Fenestration area (A) (% of floor area)	Building envelope U-value (W/m²K); absorptance (α)[20]	
		wall	roof
ZB1	Medium A≥7% seal in winter	U≤2.5;	U≤2.3;
ZB2			
ZB3		U≤3.7, when α≤0.6; U≤2.5, when α>0.6;	U≤2.3, when α≤0.6; U≤1.5, when α>0.6;
ZB4			
ZB5			
ZB6			
ZB7	Medium A≥7%	U≤3.7, when α≤0.6; U≤2.5, when α>0.6;	U≤2.3 (FT), when α≤0.4; U≤1.5 (FT), when α>0.4;
ZB8	Large A≥12% to N region; A≥8% to NE and SE region;	U≤3.7, when α≤0.6; U≤2.5, when α>0.6;	U≤2.3 (FT), when α≤0.4; U≤1.5 (FT), when α>0.4;

Floor area applies only for the occupied rooms, whose occupancy is not limited to short periods (for example, bathrooms are not counted).
Apart from the walls in ZB8, which has no requirement, all external walls must have heat capacity equal or bigger than 130 KJ/m²K.
FT corresponds to a U-value correction related to the height of ventilated attic roof, established by the NBR15220 (ABNT, 2005c).
The U-values of the roof refers to downward flux.
N, NE and SE refer to north, northeast and southeast Brazilian regions.

Also, a voluntary standard *Energy Labelling Schemes for Residential Buildings* (RTQ-R), launched in 2010 and updated in 2012 (INMETRO, 2012), rates the building according to its energy efficiency level. The level of energy efficiency is rated from level A (most efficient) to E (least efficient), for housing units (houses or apartments), multi-family residential buildings and common areas of multi-family buildings through prescriptive and simulation methods (Scalco et al., 2012). The RTQ-R label thermal performance assessment covers building envelope and DHW.

The RTQ-R label establishes minimum requirements for the building envelope, which varies with the climatic zone where the building is. Table 2-6 summarizes these requirements.

Table 2-6: Summary of envelope requirements - RTQ-R label. Based on INMETRO (2012, p. 23, 26)

	Fenestrations (A) (% of floor area)	Building envelope U-value (W/m²K); absorptance (α)	
		wall	roof
ZB1	A≥8%	U≤2.5	U≤2.3;
ZB2			
ZB3	A≥8%	U≤3.7, when α≤0.6; U≤2.5, when α>0.6;	U≤2.3, when α≤0.6 U≤1.5, when α>0.6
ZB4			
ZB5			
ZB6			
ZB7	A≥5%	U≤3.7, when α≤0.6; U≤2.5, when α>0.6;	U≤2.3,when α≤0.4 U≤1.5, when α>0.4
ZB8	A≥10%;	U≤3.7, when α≤0.6; U≤2.5, when α>0.6;	U≤2.3, when α≤0.4 U≤1.5, when α>0.4

Apart from the walls in ZB8, which has no requirement, all external walls must have heat capacity no smaller than 130 KJ/m²K.
The U-values of the roof refers to downward flux.

[20] Absorptance value of a surface is considered as 0.3, 0.5 and 0.7 for light, medium and dark colors, respectively. p. 25. ABNT 2013a. NBR 15575-1: Residential buildings - Performance - Part 1: General requirements. Rio de Janeiro, Brazil: Associação Brasileira de Normas Técnicas (ABNT).

It should be noted that the Brazilian standard NBR 15220 (ABNT, 2005c) recommends U-values ranging from 2.20 W/m²K to 3.60 W/m²K for the walls and from 2.00 W/m²K to 2.30 W/m²K for the roofs. The Brazilian standard NBR 15575 (ABNT, 2013d, ABNT, 2013e) and the RTQ-R label (INMETRO, 2012) sets out the U-values varying between 2.50 W/m²K and 3.70 W/m²K for the walls and between 1.5W/m²K and 2.3 W/m²K for the roofs. However, the building envelope U-value heavily depends on the absorptance value of the material surface, which means that less strict U-values are used for low absorptance values while stricter U-values are adopted for high absorptance values.

The RTQ-R label is the only Brazilian standard that considers building performance criteria. However, these criteria differ from the common building energy regulations methods, which rate the building performance based on its energy consumption.

The RTQ-R label envelope energy efficiency is calculated by a prescriptive method for both naturally and artificially conditioned buildings through a set of equations, which are compared against a benchmark in order to establish the envelope level of energy efficiency for the climate zone where the building is located. These equations were developed by multiple linear regression models (Scalco et al., 2012) and a detailed calculation method can be found in INMETRO (2012).

For naturally ventilated buildings, through the prescriptive method, the envelope efficiency in summer is obtained by cooling degree-hours[21]. The base temperature of 26 °C was chosen instead of an adaptive comfort temperature in order to show comparatively the difference between better performance solutions if the household had a HVAC system (Scalco et al., 2012). This method seems to be a good thermal performance indicator since it allows setting the indoor operative temperature without using artificial conditioning or promoting its use (Scalco et al., 2012). In winter, the envelope efficiency is obtained only for climatic zones from ZB1 to ZB4 (Scalco et al., 2012) by the heating relative consumption. Heating relative consumption, in kWh/m²a is the annual energy consumption per m² necessary to heat the areas of prolonged permanence between 9 pm and 8 am to keep the temperature at 22 °C (INMETRO, 2012). The heating energy consumption could be used as an indicator even in naturally ventilated buildings because the windows are mostly closed during the winter (Scalco et al., 2012).

For artificially conditioned buildings, through the prescriptive method, the envelope efficiency level is calculated only for comparison purposes. The envelope efficiency in

[21] Degree-hours consist of the summation of temperature difference for an hourly reference. This temperature difference is between a reference temperature and the temperature investigated. The reference temperature, named as base temperature, is a reference thermal comfort limit temperature that does not need any heating or cooling systems to run in order to maintain comfort conditions. CIBSE 2006a. Degree-days: Theory and application. London, United Kingdom: The Chartered Institution of Building Services Engineering (CIBSE).

summer is obtained by cooling energy consumption. Cooling energy consumption, in kWh/m²a, is the annual energy consumption per m² necessary to cool the areas of prolonged permanence between 9 pm and 8 am to keep the temperature at 24 °C (INMETRO, 2012).

As mentioned, the envelope energy efficiency can also be evaluated through the simulation method for both naturally ventilated and artificially conditioned buildings following the same aforementioned criteria. The results from the simulations should be compared against a benchmark, available in PROCEL website (http://www.procelinfo.com.br).

One of the problems of the RTQ-R label method is the complexity of the calculations that need to be handled. Also, the RTQ-R label establishes that heating or cooling would be used only for a specific period of the day and that the remaining period would be naturally ventilated. This might not be able to properly evaluate the building energy performance and certainly this does not mean that the occupant will be in thermal comfort during the day, specifically in the winter period where no other heating system is considered.

To sum up, this section discussed the building energy regulations as the government set of actions to support the design and the construction of more energy efficient homes. The next section explores research undertaken for optimising the building envelope and, consequently, improving indoor thermal comfort and energy efficiency in Brazilian housing.

2.5 Studies for the Optimization of the Envelope in Housing

This section explores in detail studies that have paid attention to optimising the building envelope for increasing thermal comfort in southern Brazilian housing. Despite the fact that these studies show potential alternatives to improve the building envelope in housing, the degree of optimization on the building envelope and the thermal comfort achieved by them was still quite limited. These studies were also referred to in Tubelo et al. (2014b).

The study conducted by Pereira and Ghisi (2011) explored the building envelope of an occupied and naturally ventilated 2-bedroom detached house in the city of Florianópolis, in the state of Santa Catarina (ZB3). The authors assessed different roof and wall combinations through the use of dynamic building simulations. The study did not evaluate the combined envelope strategies, just changed the roofs or the walls each time. The U-values for the walls ranged from 5.04 W/m²K to 1.31 W/m²K and walls of different materials and thickness were considered such as solid ceramic brick,

wood and concrete walls. The U-values for the roofs ranged from 4.55 W/m^{2}K to 0.95 W/m^{2}K and roofs made out of ceramic roof tiles with different ceiling combinations were considered. From all the simulations performed, just one wall and roof were considered with an insulation material. The findings suggested that a wall made out of double solid brick compared with other wall types performed better to the specific climate. Roofs with a concrete slab performed better compared to other evaluated roofs, although insulated roofs with a wooden ceiling also performed well. The ventilation patterns adopted in the simulations considered no use ventilation in winter (only infiltration) and use of daytime ventilation in summer. The results demonstrated a greater thermal discomfort due to the heat by the addition of ventilation, which meant that selective ventilation would be a more appropriate ventilation strategy. The findings were shown against the number of comfort hours and discomfort hours, using Givoni's (1992) psychrometric chart as reference.

Research undertaken by Lamberts et al. (2010a) and Lamberts et al. (2010b) considered the same housing model as the Pereira and Ghisi (2011) study but the authors undertook a broad investigation in terms of suitability of the building envelope for the city of Florianópolis. The simulations aimed to help the design decision of a housing prototype construction and they were conducted by changing one parameter each time. The base case building envelope was considered as typically adopted in local houses, composed of a single layer solid brick wall, fibre-cement roof with wooden ceiling and single glazing window. The optimised building envelope considered the adoption of a double layer solid brick wall filled with 2.5 cm of insulation material (U-value of 1.06 W/m^{2}K), ceramic roof tile with aluminium reflective rock wool insulation and wooden ceiling (0.57 W/m^{2}K) and double glazing window. The optimised envelope showed a reduction of the energy consumption and an increase of thermal comfort when compared to its base case. The results were evaluated in terms of heating and cooling degree-hours, with operative temperature at 18 °C and 26 °C, respectively. The study also evaluated ventilation patterns during the summer and concluded that selective ventilation controlled by temperature was a favourable strategy for that climate.

Research conducted by Kruger and Laroca (2010) assessed the thermal performance of a wooden affordable 3-bedroom housing through dynamic building simulations for three cities: Curitiba, Florianópolis and Porto Alegre. The housing walls were made out of 12 cm of double wall panels of plywood (U-value of 2.17 W/m^{2}K). The roof was made out of fibre-cement roof tiles with a pinewood ceiling. The dynamic building simulations considered three different wall variations: as built, with a thicker wall (U-value of 1.81 W/m^2 K); and with a thicker wall plus the addition of 7.5 rock wool insulation placed between the panels (U-value of 0.42 W/m^2 K). Occupancy and summer ventilation were considered in the simulations. The findings suggested that the original prototype had

good performance during the summer. However, the use of insulation could be beneficial mainly in winter and the use of insulation might be more appropriate in Curitiba rather than Florianópolis and Porto Alegre.

The study undertaken by Kruger and Zannin (2007) investigated 2 affordable 2-bedroom houses, built with different materials for the city of Curitiba, in the state of Paraná (ZB1). One housing building envelope was made out of 1.5 cm of prefabricated single layer wooden boards' walls with the joints between panels covered by wood finish. Windows were built out of 4 mm of single glazing and wooden frame. The roof was made out of 5 mm of fibre-cement tiles with ventilated attic and wooden ceiling. The U-values for walls and roofs corresponded to 3.7 W/m²K and 3.75 W/m²K, respectively. The other housing building envelope was made out of 12 cm of an insulated monolith panel wall, assembled between two steel meshes filled with expanded polystyrene. The windows were built out of 4 mm of single glazing with steel frame. The roof was made out of ceramic tile with non-ventilated attic space and the ceiling was composed of a slab of the same insulation technology. The U-values corresponded to 0.39 W/m²K for the walls and 0.80 W/m²K for the roof. Despite the fact that the sample was limited and very distinct, the findings indicated an inverse strong correlation between the housing thermal performance and its envelope U-value.

The studies on building envelope optimisation showed that there is still room for delivering high thermal performance in Brazilian housing and also there is a huge potential for investigating ways of increasing thermal comfort and energy efficiency in these homes.

2.6 Conclusions

The housing sector corresponds to 2% of the Brazilian national gross domestic product. The sector constitutes one third of the entire construction sector and accounts for 22% of the national energy consumption. The housing stock in Brazil accounts for 57.3 million housing units and 86.9% of the stock is detached housing.

Housing is part of a current agenda in Brazil to tackle a housing deficit of 5.546 million units, in which 96.6% of the lack of housing is related to low-income households up to 5 times the national minimum wage. The government housing programme '*Minha Casa, Minha Vida*' has supported the supply and financing of more than 1.5 million housing units until 2014 and another ambitious target of 24 million housing units is planned to be built until 2022, which will cater to households up to 10 times the minimum wage.

Middle and low economic classes account for approximately 85% of Brazilian households. Between these classes, the findings of the investigation reveal a notorious disparity between their housing patterns, which is shown in Table 2-7 .

Table 2-7: Summary of housing patterns for different economic classes

	Affordable House (Low Standard Housing)	Middle Standard Housing
Typology	Mostly detached houses but also apartments	Detached houses and apartments
Number of rooms	2 bedrooms	3 bedrooms
Room types	Bedrooms, bathroom, living room, kitchen and laundry (external or internal)	Bedrooms, bathrooms, living room, kitchen, circulation area, laundry, service bathroom, porch and parking space
Number of bathrooms	1 bathroom	2 or more bathrooms
Average internal area	No less than 36 m^2 The house should accommodate minimum furniture.	New housing developments tend to have approximately 80 m^2, but it is assumed that a typical area can be found between 80 and 100 m^2. The areas can vary significantly depending on the size of living areas, circulation spaces and layout arrangement.
Average external area	Up to 58 m^2	Up to 106 m^2
Occupation	13 m^2 per person but can reach around 9m^2 per person when each bedroom is occupied by 2 people	Higher occupation rate (m^2/person); Second and third bedrooms tend to be occupied by one person instead of two.
Appliances and patterns	It tends to have a small number of appliances	It tends to have a great number of appliances
Energy consumption	Low; usually less than 200 kWh	High; usually higher than 200 kWh
Envelopes materials	Fibre-cement or ceramic roof tiles; Aluminium, iron or timber windows; Timber or masonry walls (mostly made out of ceramic brick or blocks)	Ceramic roof tiles, timber window frames and conventional masonry walls
Thermal properties of the envelope	It tends to achieve minimum building energy requirements.	The building envelope normally has good quality and usually achieves minimum building energy requirements.

The analyses revealed that the average affordable housing size appears to be up to 58 m^2, but the useful area can achieve a minimum limit of 36 m^2. For illustration purposes, if comparing an affordable 2-bedroom house of 36 m^2 for an occupancy of 3 and 4

people as these homes are more likely to be fully occupied, against the benchmark of minimum housing space standards of London guidance (Mayor of London, 2010) to ensure the occupants feel comfortable and provide minimum living requirements, mentioned in Chapter 1, the minimum area of the affordable Brazilian house should be at least 61 and 70 m^2 for a one-storey housing typology, respectively. This represents more than double the current area found in affordable Brazilian houses.

In parallel, the analyses also showed that the average size of middle-class housing seems to be commonly found up to 106 m^2, but the useful area can vary mostly between 80 and 100 m^2. The average new dwellings have approximately 80 m^2, which is quite similar to the United Kingdom trend of 76 m^2, mentioned in Chapter 1.

The housing in Brazil is mostly manually constructed, made out of conservative material such as masonry. The most typical masonry walls are built out of ceramic bricks covered by mortar. The roofs are mostly built out of ceramic roof tiles. Window frames are found in different materials but mostly in timber.

The housing electricity energy consumption represents 23.6% of the entire electricity energy consumption in the country and it has increased progressively over the years. The sector's electricity consumption grew 5.1% in 2012, but the national renewable electricity production shrank and it had to be supplemented by energy production dependent on fossil fuels, which is believed to be impacting on the energy tariffs.

The use of cooling and heating systems comprises 20% of the housing electricity consumption and it is in an upward trend, stimulated by the rise in income and purchasing power and increase of credit.

Recently launched mandatory and voluntary standards showed that the government has placed more importance on the energy agenda. The Brazilian standard NBR 15575 (ABNT, 2013a) set out for the first time compulsory compliance with minimum requirements for the building envelope for all housing construction buildings, which has been a milestone for the national housing market. However, although a genuine effort has been made to make this standard mandatory, the criteria set by this regulation have not achieved similar levels of indoor thermal comfort and energy efficiency as those achieved in European countries such as the United Kingdom.

Case study evidence suggests that it is feasible to improve indoor thermal comfort and energy efficiency in Brazilian housing through the optimisation of the building envelope. The studies indicated that an improvement on the envelope beyond the levels required by the Brazilian building energy regulations would appear to increase the house's thermal performance. Therefore, there is a clear justification for this current research to focus on optimising the building envelope as a way to achieve higher levels of

thermal comfort and energy efficiency in housing. Also, there is a need for revisiting ways of optimising the building envelope in housing in Brazil.

To sum up, this research focuses on affordable 2-bedroom detached houses as this is the most common typology in Brazil and also the typology that will mostly be built in the forthcoming years due to the housing deficit. Houses are also the typology that has a greater potential to be changed with relative ease when compared to the apartment typology. This is mainly because houses allow more autonomy of the householders to undertake improvements for increasing energy efficiency and thermal comfort in buildings.

One factor that is of importance when considering thermal comfort and energy efficiency in houses is the climate they are built in. Because of that, the next chapter outlines the climate investigated for the present research and seeks to explore environmental design strategies through looking at vernacular housing in order to increase the indoor thermal comfort for the locations under investigation.

CHAPTER 3: CLIMATE AND ARCHITECTURE IN BRAZIL

This chapter leads-in the development of the research, outlining the climate and comfort criteria of the locations under investigation. A new take on the literature of vernacular architecture and climatic design strategies used in dwellings is shown in detail. The outcomes consist of the development of climate responsive design strategies, which were also used to help select the research case studies.

''The first step in any bioclimatic design approach is to examine the given climate and establish the nature of the climatic problem: relate the climate to human requirements.''
(Szokolay, 2008, p. 53).

''Vernacular building traditions [...] display a remarkably sophisticated thermal adaptation. Primitive builders consistently used forms and materials that effectively moderated prevailing climatic conditions.''
(Heschong, 1979, p. 8).

3 CLIMATE AND ARCHITECTURE IN BRAZIL

This chapter sets the scene to the development of the present research and the main purpose is to create the basis to support the present work in terms of climate and architecture.

In order to ensure that the aim is achieved, this chapter focuses on four main key areas: the climate in Brazil is introduced and the areas used for investigation are defined; the thermal comfort criteria adopted in the research are established; climatic analyses are conducted and potential climatic responsive design strategies are identified; the story of traditional housing architecture is discussed in terms of typology, materials and applied environmental design strategies.

3.1 Climate in Brazil

Brazil accounts for three main climates: tropical, semi-arid and subtropical climates (Figure 3-1). The tropical climate is the prevalent one and it covers an area equivalent to 81% of the national territory, mostly located in the north and centre-west regions (Alvares et al., 2014, p. 716). However, these regions also correspond to the locations with the lowest population density, where only 15.7% of the population live (IBGE, 2013, p. 12). The semi-arid climate corresponds to 5% of the Brazilian territory and it is the typical climate of north-eastern Brazil, characterised by scarce annual rainfall (Alvares et al., 2014, p. 722). The subtropical climate covers 14% of the Brazilian territory and it corresponds to areas located immediately above and below the tropic of Capricorn (Alvares et al., 2014, p. 723). These areas are the south and south-east regions of Brazil, where the population density is higher and also where more than 50% of the population live (IBGE, 2013, p. 12).

The subtropical climate is the climate that this research deals with. This climate has often-conflicting solutions for dealing with heating and cooling demands, which makes it difficult to find appropriate architectural design solutions.

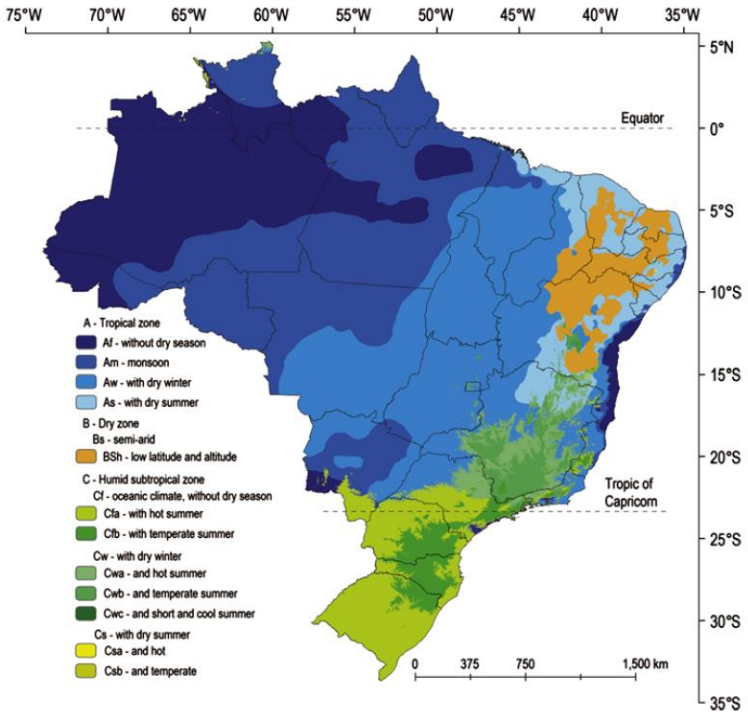


Figure 3-1: Climate classification for Brazil, according to the Köppen criteria (Alvares et al., 2014, p. 717)

For the present work, three cities in the south and southeast Brazilian regions were selected to be assessed: Curitiba (lat.: 25.43°S; long.: 49.27°W; alt.: 924 m), São Paulo (lat.: 23.85°S; long.: 46.64°W; alt.: 792 m) and Porto Alegre (lat.: 30.03°S; long.: 51.23°W; alt.: 47 m). Figure 3-2 and Figure 3-3 show these cities marked by red dots.

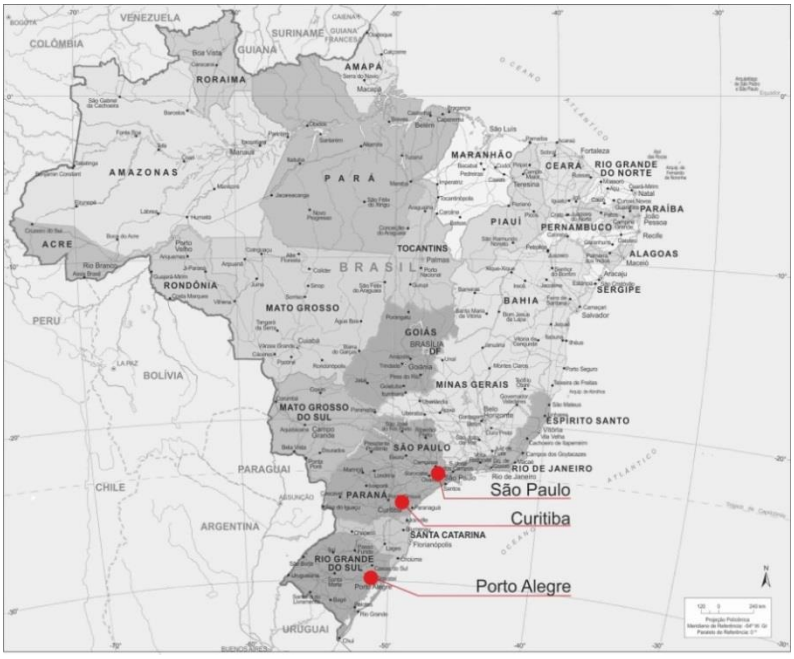


Figure 3-2: Map of Brazil with the investigated locations marked by the red dots. Adapted from IBGE (2014a).

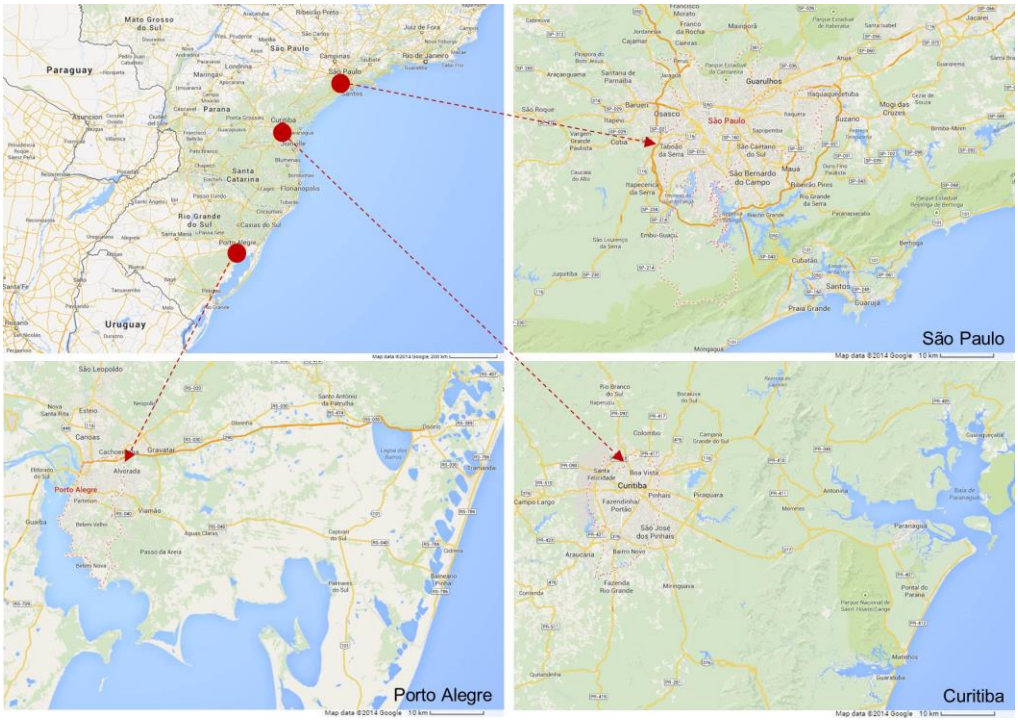


Figure 3-3: Location of Curitiba, São Paulo and Porto Alegre. Adapted from Google (2014)

These cities were selected because they are the main locations in their regions. Also, these cities have high population densities and all of them have surrounding conurbation areas, which can lead to a major impact on this investigation.

From the climatic point of view, these cities were chosen because they seem to be a more appropriate choice to initially investigate the feasibility of the Fabric First approach in Brazil due to its mild climate characteristic. Despite the fact that climatic differences exist between climates in Europe and southern Brazil, the climate of the south part of Brazil has more similarities to the European ones than any other Brazilian climate.

Curitiba in particular was chosen because it is the most representative city of the coldest Brazilian climatic zone ZB1 (Cfb according to Köppen classification). It has a humid subtropical climate with a temperate summer and an annual temperature between 16 °C and 18 °C (Alvares et al., 2014, p. 715, 724). Porto Alegre was also selected because the author is familiar with the climate and with the requirements needed to design buildings there. The city is located in Brazilian climatic zone ZB3 (Cfa according to Köppen classification) and it has a humid subtropical climate, characterised by a hot summer, with annual temperature between 18 °C and 20 °C (Alvares et al., 2014, p. 715, 723-724). It presents great daily and seasonal fluctuations of the air temperature, with hot summers and cold rainy winters (Kruger and Laroca, 2010). São Paulo was selected not only because it is the most populous city in Brazil but also for comparison purposes. As the city is located in the same climatic zone as

Porto Alegre and it has the same climatic classification, it is possible to compare the two cities if the findings from one city can be extended to another city. São Paulo has warm humid summers and cool and drier winters, with annual average of 19.1 °C and average minimum and maximum temperatures ranging from 10.7 to 31.3 °C (Alves et al., 2015, p. 8-9).

Figure 3-4, Figure 3-5 and Figure 3-6 illustrate the climate classification of each city. The climate classification methodology was based on Szokolay (2008), which divides the climate into cool, moderate, hot dry and hot humid. For this classification, the weather data file of each city was plotted against the psychrometric chart, through the use of Ecotect Software (Autodesk, 2010). The cities were classified predominantly as being located in a moderate climate, although Curitiba also showed incidence of a cool climate and Porto Alegre also has incidence of the warm humid climate.

Moderate climates are characterized by seasonal variation between underheating and overheating, but neither is severe (Szokolay, 2008, p. 34). These combined heating and cooling demands require from the designers applied research skills to deal with the often-conflicting summer and winter requirements (Goulart, 2004). Design strategies to deal with this kind of climate consist of solar radiation protection and air movement in summer and direct use of solar radiation and ventilation limitation in winter (Lamberts, 1988).

The next section defines the thermal comfort criteria for the present research.

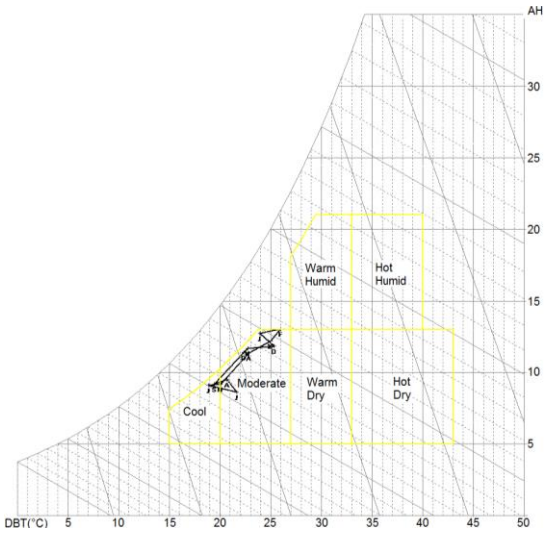


Figure 3-4: Climate classification of Curitiba. From Ecotect (Autodesk, 2010)

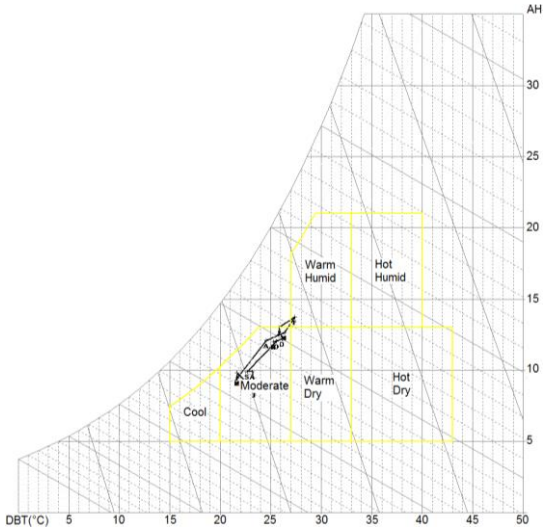


Figure 3-5: Climate classification of São Paulo. From Ecotect (Autodesk, 2010)

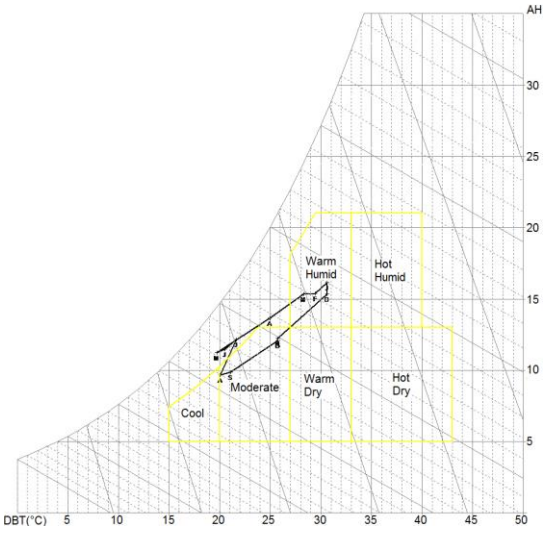


Figure 3-6: Climate classification of Porto Alegre. From Ecotect (Autodesk, 2010)

3.2 Thermal Comfort Criteria for Housing in Brazil

Thermal comfort relies on theoretical rational or adaptive approaches as a core of the knowledge in this field.

The rational approach considers 'the subjective response of people to the thermal environment in terms of the physics and the physiology of heat transfer' (Nicol and Humphreys, 2002, p. 564). The rational approach assumes comfort[22] and environment[23] variables in stable conditions in climate chambers (Peeters et al., 2009). This approach adopts thermal comfort temperature within a narrow range because it mostly relies on conditioned buildings.

The rational approach is based on Fanger's work, which proposed the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indexes. PMV is an index to predict the thermal sensation of people in an arbitrary climate quantified by the ASHRAE[24] scale ranging from -3 (much too cold) to +3 (much too hot) (Peeters et al., 2009, p. 773). PPD is an index to predict people dissatisfaction with the environment quantified by a scale ranging from -1 (cold) to +1 (hot) (Peeters et al., 2009, p. 773). PPD of 5% corresponds to 0 of PMV. A problem associated with the adoption of the rational approach is its overestimation of people response at high temperatures and underestimation at low temperatures (Nicol, 2004).

The adaptive approach considers the thermal acceptability of the occupants to the environment and defines that this acceptability depends on the context, the occupants' behaviour and their expectations (Djongyang et al., 2010). In other words, this means that the occupants are active agents within the indoor environment and can take decisions to enhance their thermal comfort sensation.

Nicol and Humphreys (2002, p. 564) explain that humans have a capacity to adapt to changing conditions in their environment and if a thermal environmental change occurs there is a human reaction to restore their thermal comfort. Humphreys (1996) claims that thermal comfort is more likely to be achieved where people have a more effective control of their environment as in residential buildings. A set of conditions can be changed in residential buildings, such as changing activity, varying clothing, opening windows, closing blinds and drinking cold or warm drinks (Peeters et al., 2009). This is the reason why the adoption of the rational approach might fail for residential buildings,

[22] Metabolic rate and clothing insulation.

[23] Temperature of the air, mean radiant temperature, partial pressure of water vapour in ambient air and relative velocity of the air.

[24] American Society of Heating, Refrigerating and Air-conditioning Engineers.

because it does not take into account the effect of people adaptation, which is relatively high in these kinds of buildings (Humphreys, 1996, Peeters et al., 2009).

The current ANSI/ASHRAE Standard 55 (2010) and the European standard EN 15251 (2007) are standards that establish acceptable thermal comfort temperatures. They adopt the rational approach for artificially ventilated buildings and the adaptive approach for naturally ventilated buildings, in which more flexible indoor operative temperatures are acceptable.

In naturally ventilated buildings, the ANSI/ASHRAE Standard 55 (2010) establishes an acceptable indoor operative temperature range based on the weighted daily mean temperature (Nicol et al., 2012). The acceptable indoor operative temperature ranges according to the level of building occupant's acceptability of 80% (±3.5 K) and 90% (±2.5 K) (Nicol et al., 2012), as shown in Figure 3-7 and Equation 3-1.

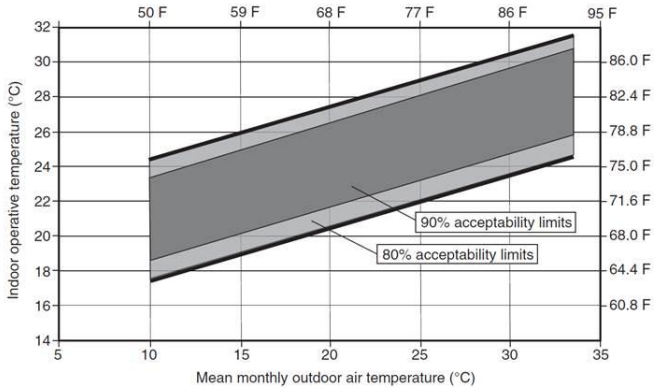


Figure 3-7: Acceptable operative temperature ranges for naturally ventilated buildings according to ANSI/ASHRAE Standard 55 (2010) (Nicol et al., 2012, p. 55)

Equation 3-1: Comfort temperature for naturally ventilated buildings (Nicol et al., 2012, p. 55)

$$T_{comf} = 0.31\,T_o + 17.8$$

Where,
T_{comf} = comfort temperature, in °C
T_o = indoor operative temperature, in °C

Similarly, the European standard EN 15251 (2007) establishes the acceptable indoor operative temperature for naturally ventilated and artificially ventilated buildings. In naturally ventilated buildings, the acceptable indoor operative temperature threshold is divided into three different levels, as shown in Figure 3-8: high level of expectation (I), normal level of expectation (II), and low level of expectation or acceptable level (III), which is associated with acceptability degrees of <6%, <10% PPD and <15% of PPD, respectively. Equation 3-2 and Equation 3-3 depicts the relationship illustrated in Figure 3-8 for upper and low indoor operative temperature limits at normal expectation level.

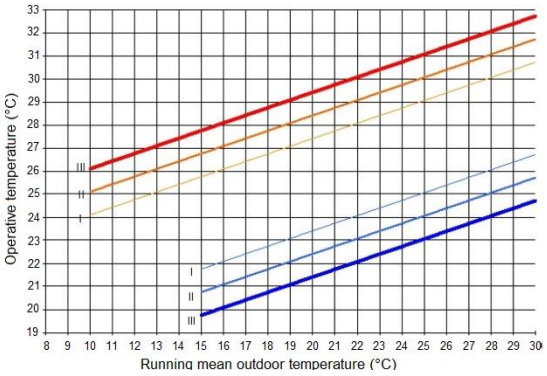


Figure 3-8: Threshold values of indoor operative temperatures (θ_o) in free-running buildings as a function of weighted running mean of outdoor temperature (EN 15251, 2007, edited, p. 27).

Equation 3-2: Upper indoor temperature limit at normal expectation level (EN 15251, 2007, p. 28)

$$\theta_{i\,max} = 0.33\theta_{rm} + 18.8 + 3$$

Equation 3-3: Lower indoor temperature limit at normal expectation level (EN 15251, 2007, p. 28)

$$\theta_{i\,min} = 0.33\theta_{rm} + 18.8 - 3$$

Where,
θ_o = indoor operative temperature, in °C
$\theta_{i\,max}$ = upper limit of indoor operative temperature, in °C
$\theta_{i\,min}$ = lower limit of indoor operative temperature, in °C
θ_{rm} = running mean outdoor temperature, in °C

Particularly in naturally ventilated residential buildings, the operative temperatures at normal level of expectation can vary from 20 to 25 °C in winter and from 23 to 26 °C in summer, whereas the operative temperatures at low level of expectation can vary from 18 to 25 °C in winter and from 22 to 27 °C in summer (EN 15251, 2007, p. 31).

In artificially ventilated residential buildings, the operative temperature ranges from 20 °C to 26 °C at normal level of expectation and can be extended to intervals between 18 and 27 °C with low level of expectation (EN 15251, 2007, p. 26)[25].

It should be stressed that more recently the term ‘running daily mean temperature’ or ‘weight daily mean temperature’ rather than ‘monthly mean temperature’ has been used. Monthly mean temperature seems to be an assertive choice to estimate a given climate but running/weight daily mean temperature is a more useful choice to perform building simulation in order to predict the indoor temperatures (Nicol et al., 2012). The running/weighted mean outdoor temperature is expressed by Equation 3-4.

[25] Clothing insulation varying from 1.0 to 0.5 clo.

Equation 3-4: Weighted running mean of outdoor temperature (Nicol et al., 2012, p. 38)

$$T_{rm} = (1-\propto)\{T_{od-1} + \propto T_{od-2} + \propto^2 T_{od-3} \dots\}$$

Where,
T_{rm} = weighted running mean outdoor temperature, in °C
T_{od-1}; T_{od-2}; T_{od-3}= daily mean outdoor temperature for the previous day; daily mean outdoor temperature for the day before; and successively, in °C.
α = constant between 0 and 1 which express how quickly the running mean responds to the outdoor temperature.

In naturally ventilated buildings, there is a strong correlation between indoor comfort temperature and mean outdoor temperature, where indoor temperature tends to reflect outdoor temperature (Nicol, 2004, Nicol et al., 2012, Humphreys et al., 2013), as shown in Figure 3-9.

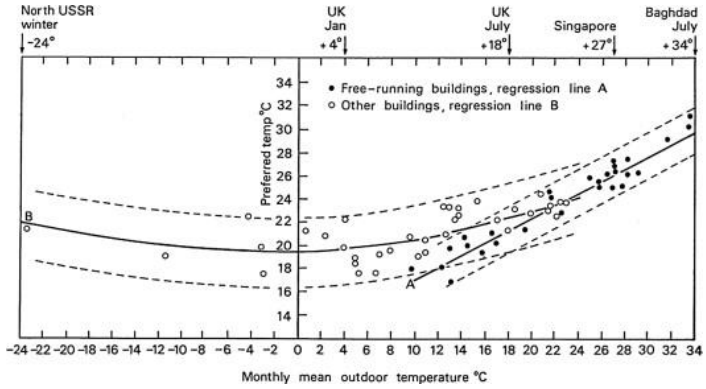


Figure 3-9: Humphreys' diagram for comfort temperature and the mean outdoor temperature (Humphreys et al., 2013, p. 41).

This correlation in fact demonstrates the high adaptation of the occupants to the environment. This would be considered in the current call for designing buildings that uses less energy to heat and cool the buildings. Specifically, developing nations such as Brazil should be conscious of the high energy impacts of unnecessary heating and cooling of buildings, which is seen in many developed countries (Lamberts et al., 2013). Understanding thermal preferences and the degree of acceptability of the occupants regarding the environment can help designers and applied research to save more energy to run the buildings because more adequate comfort levels can be established based on occupants expectations (Lamberts et al., 2013).

For example, in the United Kingdom, the operative temperatures in residential buildings are recommended by CIBSE (2006b, p. 1-8), based on the season, the room type, the occupant's activity and the clothing levels, as shown in Figure 3-1. Overheating in the living room and bedroom would occur when the indoor temperature exceeds benchmark peak temperature of 28 °C and 26 °C in more than 1% of annual occupied hours, respectively (CIBSE, 2006b, p. 1-12).

Table 3-1: Operative temperatures according to CIBSE (2006b, p. 1-8, 1-12)

Temp. (°C)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Winter															
Summer															
Year															
Bathroom															
Kitchen															
Bedroom											O				
Living room													O		

O: overheating > 1% of the time.
Bathroom: 1.2 met, 0.25 clo; kitchen: 1.2 met, 1 clo in winter, 0.65 clo in summer; bedrooms: 0.9 met; 2.5 clo in winter, 1.2 clo in summer; living room: 1.1 met; 1 clo in winter, 0.65 clo in summer.

Similarly, as mentioned in Chapter 1, the Passivhaus standard establishes a narrow thermal comfort range and an upper temperature threshold of 25 °C, which should not be exceeded by more than 10% in a year (Passive House Institute, 2012a, p. 28, 125), as illustrated in Table 3-2.

Table 3-2: Operative temperatures according to Passivhaus standard (Passive House Institute, 2012a, p. 28, 125)

Temp. (°C)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Year										O					

O: overheating > 10% of the time

However, studies have shown that in naturally ventilated buildings it is possible to achieve acceptable levels of indoor thermal comfort within a wide thermal comfort range. Natural ventilation can enhance the sense of coolness and reduce the sense of warmth. In addition, the intense use of ventilation by the use of fans would suggest an acceptability of 2K higher than the predicted indoor comfort temperature threshold (Nicol, 2004).

Lamberts et al. (2013) reported a number of studies conducted in naturally ventilated buildings in Brazil over the years, in which people tend to accept temperature variation during the day and the year and also prefer higher air speed compared to the parameters proposed by current standards. In other words, people may have a higher acceptability to temperature and humidity levels than those limits established by rational models.

However, it should be stressed that people's thermal responses vary according to the climate where they are exposed to. Xavier (2000) developed a study to investigate people thermal sensation in three different Brazilian cities, located in the south, centre-west and northeast of Brazil. The work considered people developing sedentary activities compatible with offices. The results demonstrated that the comfort temperature threshold differs consistently in terms of geographical position and whether the building is naturally or artificially ventilated. In naturally ventilated buildings, the findings estimated that the comfort temperature threshold of a city located in southern Brazil (ZB3) varied from 19.6 °C to 24.9 °C and high levels of relative humidity did not show significant differences in terms of discomfort by heat in ventilated buildings

(Xavier, 2000, p. 170). However, low levels of relative humidity, such as below 45%, presented thermal discomfort sensation due to the cold. In artificially conditioned buildings, a slight narrow comfort temperature threshold was observed to be between 20.5 °C and 24.5 °C and the relative humidity between 49.0% and 85.9% (Xavier, 2000, p. 170-171).

These findings seems to be quite similar to the comfort temperature threshold proposed by the Passivhaus standard (Passive House Institute, 2012a), EN 15251 (2007) and ANSI/ASHRAE Standard 55 (2010) for 90% of acceptability level.

So far in Brazil there is a lack of a thermal comfort standard for buildings. A draft standard, based on ANSI/ASHRAE Standard 55 (2010), has been proposed and more information can be found in Lamberts et al. (2013). The standard introduces acceptable temperatures for artificially ventilated, naturally ventilated and mixed-mode buildings.

In artificially ventilated buildings, the standard proposal relies on the rational approach. The method is adopted for metabolic rate between 1 and 1.3 *met*[26] and establishes two thermal comfort zones, based on the clothing insulation levels of 0.5 clo and 1.0 clo[27] (Lamberts et al., 2013, p. 92). Upper and lower indoor temperature limits are calculated based on Equation 3-5 and Equation 3-6, respectively.

Equation 3-5: Upper indoor temperature limit (Lamberts et al., 2013, p. 92-93)

$$T_{max,Icl} = \frac{\left[(I_{cl} - 0.5\ clo).T_{max,1\ clo} + (1\ clo - I_{cl}).T_{max,0.5\ clo}\right]}{0.5\ clo}$$

Equation 3-6: Lower indoor temperature limit (Lamberts et al., 2013, p. 92-93)

$$T_{min,Icl} = \frac{\left[(I_{cl} - 0.5\ clo).T_{min,1\ clo} + (1\ clo - I_{cl}).T_{min,0.5\ clo}\right]}{0.5\ clo}$$

Where,
$T_{max,\ Icl}$ = upper limit of indoor operative temperature for clothing insulation, in °C
$T_{min,\ Icl}$ = lower limit of indoor operative temperature for clothing insulation, in °C
I_{cl} = specific clothing insulation, in clo

In naturally ventilated buildings, the standard proposal relies on the adaptive approach and suggests 80% of acceptability to the environment. Upper and lower operative temperature limits are calculated through Equation 3-7 and Equation 3-8, respectively.

[26] As reference, sitting still corresponds to 1 met and standing relaxed corresponds to 1.2 met. p. 107. LAMBERTS, R., CANDIDO, C., DE DEAR, R. & DE VECCHI, R. 2013. Toward a Brazilian Standard on Thermal Comfort. Federal University of Santa Catarina & University of Sydney.

[27] As reference, trousers and short-sleeved shirt correspond to 0.57 clo and trousers, long-sleeved shirt and sweater/jacket corresponds to 0.96 clo. p. 110. Ibid.

Equation 3-7: Upper indoor temperature limit - 80% of acceptability (Lamberts et al., 2013, p. 95)

$$t_{o\ upper} = 0.31 t_{pma} + 21.3$$

Equation 3-8: Lower indoor temperature limit - 80% of acceptability (Lamberts et al., 2013, p. 95)

$$t_{o\ lower} = 0.31 t_{pma} + 14.3$$

Where,
$t_{o\ upper}$ = upper limit of indoor operative temperature, in °C
$t_{o\ lower}$ = lower limit of indoor operative temperature, in °C
$t_{\ mpa}$ = weighted mean outdoor temperature of the previous days, in °C.

In mixed-mode buildings, the standard proposal uses both the criteria of artificially and naturally ventilated buildings, varying according to the building's ventilation status.

Some pieces of research carried out in Brazil have found reference in the thermal comfort criteria proposed by Givoni (1992) (Barbosa, 1997, Goulart, 2004, Morello, 2005, Grigoletti, 2007). Givoni defined different boundaries of thermal comfort temperatures in temperate and warm climates, where predominantly developed and developing countries are located, respectively. The proposed thermal comfort in free-running buildings in developed climates considered the temperature varying from 18 °C to 25 °C in winter and from 20 °C to 27 °C in summer, which represented a year thermal comfort of 18-27 °C (Givoni, 1992, p. 15). Moreover, an enlargement of 2 °C in the upper comfort threshold for developing climates was proposed because people in developing and warmer climates tolerate higher temperatures and higher humidity levels due to their acclimatization process, which extended the annual thermal comfort range from 18 °C to 29 °C, (Givoni, 1992, p. 16). Relative humidity levels up to 80% were considered as acceptable (Givoni, 1992, p. 20-21, Lamberts et al., 2014, p. 86). The operative temperatures are summarized in Table 3-3.

Table 3-3: Operative temperatures according to Givoni (1992, p. 15-16)

Temp. (°C)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Winter															
Summer															
Year															

Extended thermal comfort (light colour)

In conclusion, because the present research is dealing with residential buildings and also because most Brazilian houses are naturally ventilated, it seems reasonable that this research relies on the adaptive approach, assuming a wider thermal comfort temperature threshold. The thermal comfort range proposed by Givoni (1992), which considers high adaptation capacity to the environment and an annual wide thermal comfort limit between 18 °C and 29 °C, was considered as this criterion is well established and widely acknowledge in Brazil. This adopted thermal comfort limit will be validate in the next Section 3.3 against ANSI/ASHRAE Standard 55 (2010)/ Nicol et al. (2012) and Lamberts et al. (2013). In addition, a parallel with an annual narrow comfort temperature threshold of 20-25 °C (as adopted by the Passivhaus standard), which corresponds to a higher degree of people acceptability to the environment, also

seems important to be considered as a benchmark. Table 3-4 shows the operative temperatures limits adopted in the present research.

Table 3-4: Operative temperature limits adopted in the present research

Temp. (°C)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Narrow - Year															
Wide - Year															
Extended thermal comfort (light colour)															

The next section shows microclimatic analyses in order to examine the adopted thermal comfort criteria and to define the basis of the design strategies.

3.3 Climate Analysis

The climate analysis was carried out using weather data files of the locations investigated. As the choice for a weather data file has a large influence on the results of the analysis, it is responsibility of the designers and researchers to chose the most appropriate among those set of data available (Rodrigues, 2009).

Weather data available in Brazil is considered to be scarce, which makes it difficult to get complete and reliable weather data (Carlo, 2005). Most complete weather data sources are obtained from the airport weather stations, where the solar radiation is not measured. The vast majority of the solar radiation data is estimated by calculation methods or computational software.

In order to select the most appropriate weather data for this analysis, the available ones were explored. So far there are 5 different types of weather data files and they are discussed as follows:

i. The Solar and Wind Energy Resource Assessment (SWERA): this project developed a data set based on the Typical Meteorological Year (TMY), which consists of a selection of typical and the most representative months within the available period. This data set was elaborated with a large temporal coverage from 1973 to 2002 (SWERA, 2007). The solar radiation was modelled using models and mainly based on cloud cover (SWERA, 2007). This data is available for 20 locations in Brazil but Porto Alegre was not included in those.
ii. The International Weather for Energy Calculations (IWEC2): this database, developed by ASHRAE, corresponds to a data set of weather stations archived for up to 25 years (ASHRAE, 2012). This includes data taken at least four times per day of wind speed, wind direction, sky cover, visibility, ceiling height, dry-bulb temperature, dew-point temperature, atmospheric pressure and precipitation (ASHRAE, 2012). The solar radiation is calculated using empirical

models (ASHRAE, 2012). The 2012 ASHRAE weather data version can be obtained for 32 Brazilian locations.

iii. The Meteonorm Software: this software provides a weather data set through interpolating long term monthly means, resulting in hypothetical years, which statistically represents a typical year (METEOTEST, 2013). The software has different data set sources: by interpolation, by weather stations, by weather stations without global radiation measurement, by design reference year (DRY) and by user-defined. The source used depends on the location to be investigated. For a variety of Brazilian cities, the software provides weather data based on measured and interpolated monthly values. The root mean square error by interpolating monthly radiation data is estimated to be 7% (METEOTEST, 2013). The software offers two climatological periods to be chosen for temperature and radiation: for temperature, between the years 1961-1990 and between the years 2000 and 2009; and for radiation, between 1981-1990 and between 1986 and 2005 (METEOTEST, 2013).

iv. The Laboratory of Energy Efficiency of Buildings (LabEEE) of the Federal University of Santa Catarina (UFSC): the LabEEE reviewed in 2005 the data set of the airport weather stations collected between the decades 1960 and 1970 (Goulart, 1993). The review investigated the adjustment of solar radiation data, through the comparison of solar radiation data collection and the analyses of two different methods to estimate solar radiation. The data was based on the Test Reference Year (TRY), which is obtained by excluding years that present extremes of monthly temperature until a reference year is obtained (Goulart, 1993). TRY tends to be too mild for performance analysis purpose and does not match well with the typical long-term weather pattern (Chow and Chan, 2009). This weather data set is available for 14 Brazilian cities.

v. Roriz (2012a) compiled a database using recent data collection between 2000 and 2010 from different Brazilian weather stations for a variety of 411 Brazilian cities. The collected variables were air temperature, relative air humidity, wet-bulb temperature, atmospheric pressure, wind direction, wind speed, rainfall and horizontal irradiance. The irradiances and the illuminances were calculated and validated by the Munner Model and the Perez Method, respectively (Roriz, 2012a). The data set was based on the Typical Meteorological Year (TMY). The advantage of using more recent data is that they can more closely represent the urbanization process and the climate changes that have happened in the last years. They also seem to be more suitable for simulation comparison purposes with data of recent monitoring. In addition, TMY data set could be advantageous for its better prediction of the energy consumption pattern as well as energy costs (Chow and Chan, 2009).

With that in mind, the weather data set compiled by Roriz (2012a) was selected to be used in this research from now on and this choice considered the following factors: reliability of the weather data set; availability of the weather data set to all the locations investigated; weather data set updating; and handling ability of the weather data (if it could be later on easily used as input for dynamic building simulation software).

The climatic analysis carried out in this section are supported by computer-based tools and they aim to represent in detail the locations investigated. As mentioned in Section 3.1, the cities under investigation are located in the southernmost areas of Brazil, which feature a moderate climate. The extended thermal comfort range was considered as shown in Section 3.2, mostly between 18 °C and 29 °C.

Table 3-5 shows the monthly averages of dry bulb temperature for the cities investigated. Figure 3-10, Figure 3-11 and Figure 3-12 show the annual dry bulb temperature range of Curitiba, São Paulo and Porto Alegre, respectively.

In Curitiba, the difference between maximum and minimum temperature in a year exceeds 30 K. The temperatures are usually below the lower thermal comfort temperature limit of 18 °C during the cold months and temperatures near 0 °C can occur during the coldest periods. During the hottest periods, temperature peaks around 33 °C can occur, but most of the time the temperatures do not exceed the upper comfort temperature of 29 °C. The average daily dry bulb temperature can reach a daily average of down to 5 °C in winter and usually does not exceed 25 °C in summer.

In São Paulo, the difference between maximum and minimum temperature in a year corresponds to approximately 25 K and the temperatures are more uniform during the year when compared to the other cities investigated. The lowest temperatures can reach below 10 °C during the winter period, while the temperature peaks can reach around 35 °C during the summer period. The temperatures are most of the time within the comfort limits. The average daily dry bulb temperature is usually not lower than 10 °C in winter and higher than 29 °C in summer.

Porto Alegre has a higher seasonal dry bulb temperature variation and presents extremes of higher temperatures when compared to the other locations. This city has a broader temperature range, which can almost reach 35 K. Both the temperatures above the upper and below the lower temperature limit are an issue to be dealt with. The average daily dry bulb temperature can vary significantly, from below 8 °C in winter time to more than 30 °C in summer time.

Table 3-5: Monthly averages of dry bulb temperature - Curitiba, São Paulo and Porto Alegre

T (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Curitiba	19.6	20.8	19.9	17.8	15.0	13.6	15.3	15.7	14.6	17.5	18.0	19.4
São Paulo	21.1	22.3	21.6	20.7	17.4	16.7	17.3	18.2	17.6	20.5	20.1	20.8
Porto Alegre	25.3	24.3	23.6	20.3	15.7	15.7	17.4	14.9	15.9	20.3	20.7	24.8

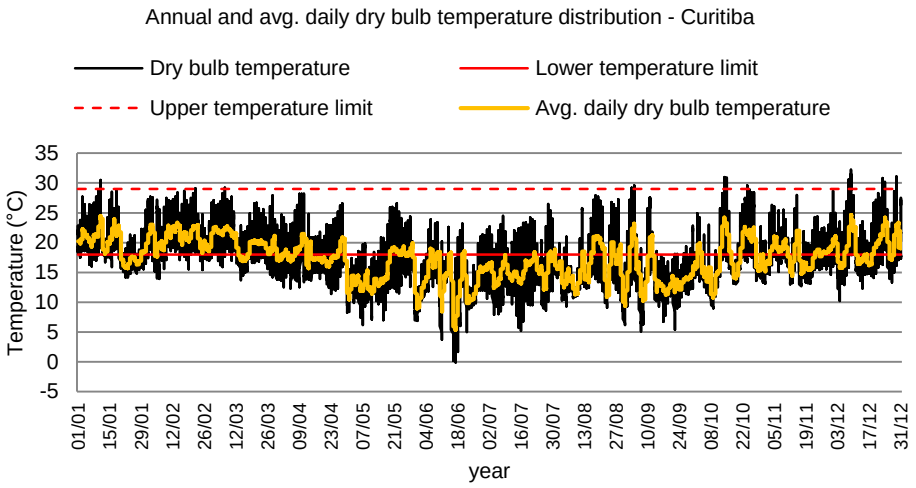


Figure 3-10: Dry bulb temperature against a given thermal comfort benchmark - Curitiba

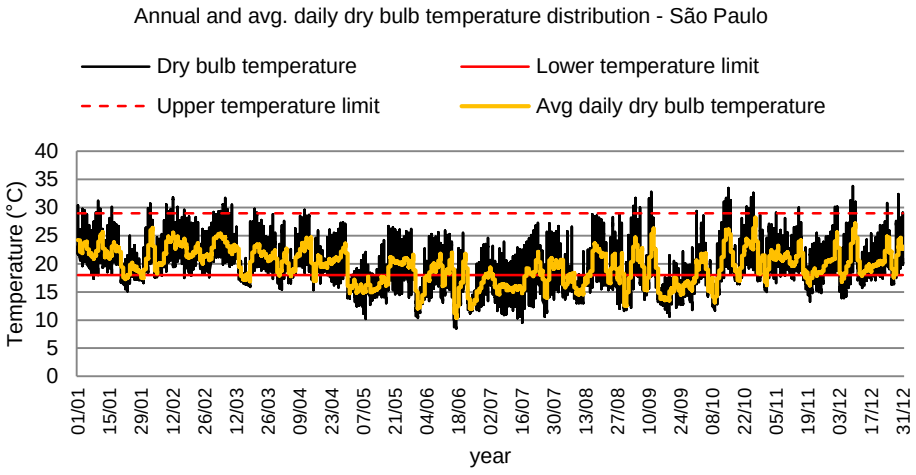


Figure 3-11: Dry bulb temperature against a given thermal comfort benchmark - São Paulo

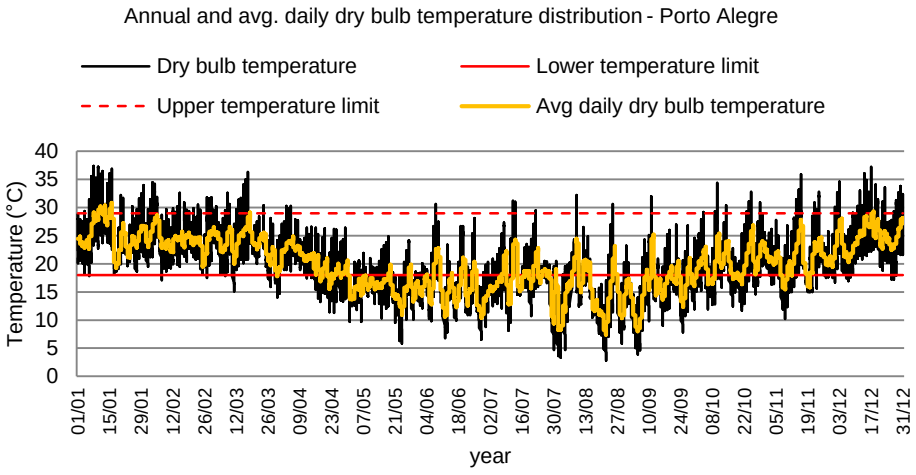


Figure 3-12: Dry bulb temperature against a given thermal comfort benchmark - Porto Alegre

Figure 3-13, Figure 3-14 and Figure 3-15 illustrate the monthly frequencies of temperature in Curitiba, São Paulo and Porto Alegre, based on a thermal comfort zone of 18 °C to 29 °C as defined in the previous section, respectively. The monthly frequencies of temperature are calculated through the sum of all monthly temperature values taking into account a given comfort temperature interval.

In Curitiba, for about 58.8% of the time the temperatures are below the lower comfort limit of temperature. The percentage of the time when the temperature is in thermal comfort corresponds to 40.7% in a year. The period between May and September might be considered as the winter season, as it is the period when the percentage of temperatures below the lower thermal comfort limit occurs in more than 70% of the time. Looking at monthly frequencies of temperature associated with monthly averages of dry bulb temperature, December to March can be considered as summer. In this period, the frequency of temperatures in the comfort zone exceeds the temperatures below the lower comfort limit and this is associated with higher monthly averages of dry bulb temperature. The rest of the year, namely October to November and April, could be treated as mid-season.

In São Paulo, for about 61.5% of the time, the temperatures are within the comfort zone. The percentage of temperature above the upper comfort limit represents only 2% of the time, which demonstrates the mildness of the climate of São Paulo. The winter season is identified as the period when more than 60% of the time the temperatures are below the lower comfort limit of 18 °C, which is considered between May and September. Due to the relative mildness of the hot season, summer period is identified when there is a considerable reduction in the number of hours below the lower thermal comfort limit and, simultaneously, an increase of the number of hours that exceed the upper thermal comfort limit. Also, in order to better define the hottest period, the monthly averages of dry bulb temperature are considered and thus, the summer period is identified as from December to March.

In Porto Alegre, the percentage of temperature above the upper comfort limit in a year is much greater than in other cities, around 5.9% in a year, but the temperatures are still within the set comfort zone most of the time (57.4%). The period from May to September is once again treated as the winter season due to the major occurrence of temperatures below the lower thermal comfort limit for more than 50% of the time. Additionally, the period from December to March is the summer season, since the temperature below 18 °C can be almost negligible and temperatures above 29 °C at least occur for 10% of the time. The periods from October to November and April are considered as mid-season.

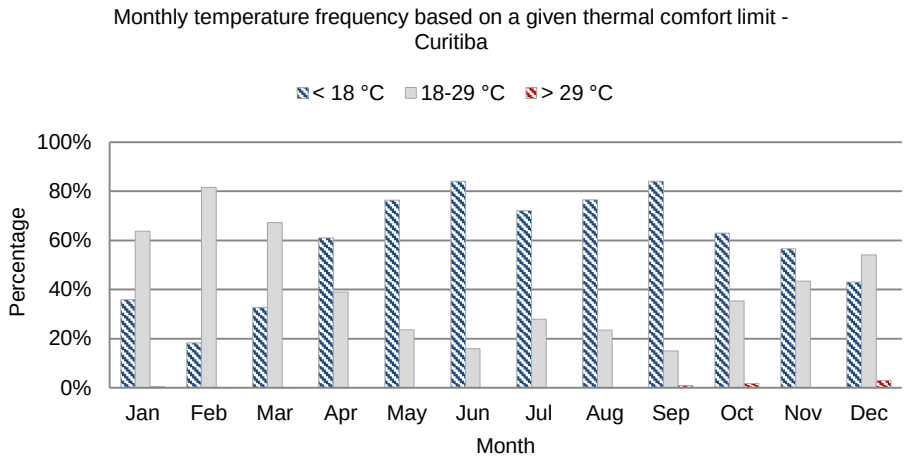


Figure 3-13: Monthly frequencies of temperature for given thermal comfort criteria - Curitiba

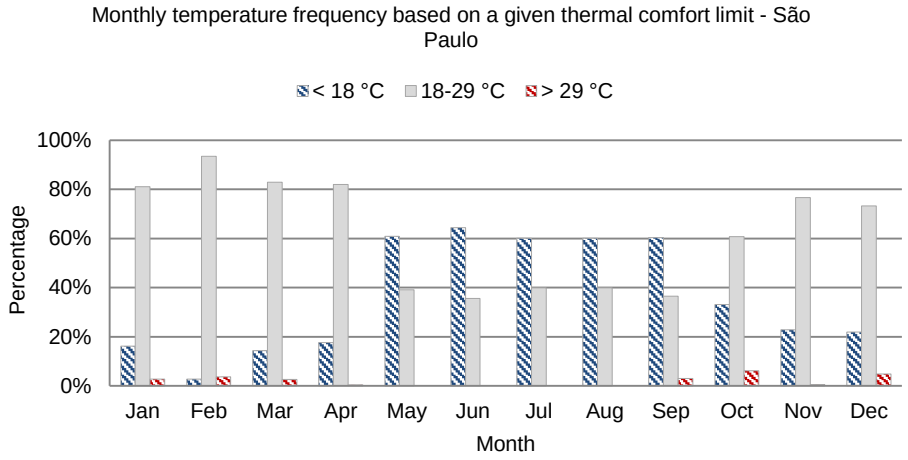


Figure 3-14: Monthly frequencies of temperature for given thermal comfort criteria - São Paulo

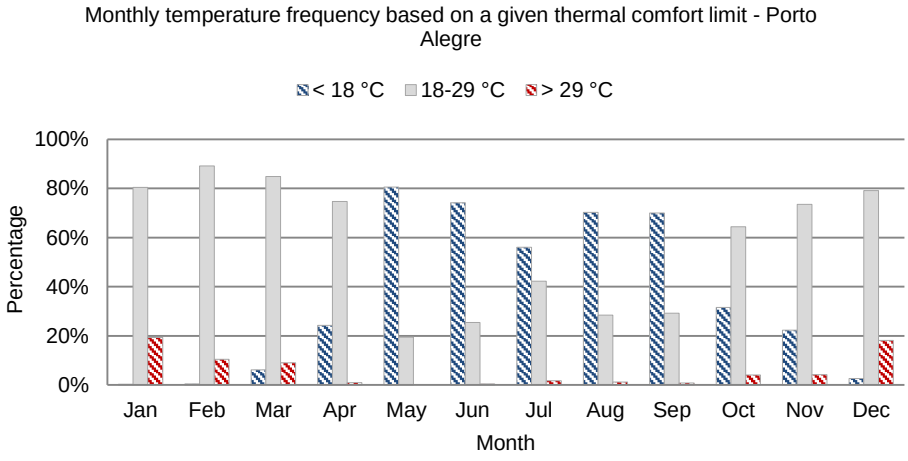


Figure 3-15: Monthly frequencies of temperature for given thermal comfort criteria - Porto Alegre

In order to validate the wide thermal comfort criteria (18-29 °C) proposed by Givoni (1992) and adopted in this research, the comfort temperature limits were calculated based on the adaptive thermal comfort approach. The comfort limits were obtained using monthly average temperatures (T_o). Figure 3-16, Figure 3-17 and Figure 3-18 shows the comfort limits calculated for Curitiba, São Paulo and Porto Alegre, based on the comfort threshold according to ANSI/ASHRAE Standard 55 (2010) and Nicol et al. (2012), which consider the comfort temperature with levels of acceptability of 90% (±2.5 K) and 80% (±3.5 K), respectively. Figure 3-19, Figure 3-20 and Figure 3-21 shows the comfort limits limits calculated for the cities, based on the comfort threshold according to Lamberts et al (2013) for 80% of acceptability.

The results reveal that the calculated comfort limits are entirely within the adopted thermal comfort criteria and these calculated comfort limits are also on the boundary to the comfort zone, which show the appropriateness of the thermal comfort criteria adopted among the three cities investigated. Moreover, because the typology under investigation is residential, it gives the households a higher degree of adaptability to the indoor environment, which ratifies the use of the adopted wide comfort criteria. The calculated comfort limits also support the supposition that the demand for heating is an issue in these locations, mainly because the temperatures in the cold season (May to September) appear below the lowest comfort criteria.

Figure 3-22, Figure 3-23 and Figure 3-24 illustrate the frequency of hours in each temperature interval for a 1-year period and for given seasons in Curitiba, São Paulo and Porto Alegre, respectively.

Despite the fact that Curitiba presents more heating needs, it can be seen that the higher frequency of temperatures occurs between 15 °C and 17 °C, which is, in fact, the boundary to the lower comfort limit. During the coldest season, most of the time the temperatures range from 11 °C to 13 °C. As mentioned before, the hottest season is quite mild and the temperatures are most of the time between 17 °C and 19° C.

The temperature range in São Paulo is smaller compared to Curitiba. In a 1-year period, the temperatures range from 18 °C to 19 °C most of the time. During the winter, the temperatures suffer a slight deviation from the annual distribution and they mostly occur between 14 °C and 16 °C, while during the summer, they appear similar to the annual distribution, mostly varying from 19 °C to 21 °C.

Porto Alegre shows a spread temperature distribution and a more seasonal variation, as mentioned before. The temperatures are mostly found between 15 °C and 23 °C but extremes of temperature could occur more often compared to the other cities. The coldest season most of the time presents temperatures between 15 °C and 16 °C and the hottest season presents temperatures around 22 °C to 24 °C. This suggests that

the indoor temperatures during the hot period could be an issue, as the outdoor temperatures combined with the internal heat gains could increase the indoor temperature, reaching beyond the comfort limits and so, leading to overheating.

Table 3-6 shows the monthly averages of relative humidity in the cities investigated. Figure 3-25, Figure 3-26 and Figure 3-27 reveal the annual and average daily relative humidity of Curitiba, São Paulo and Porto Alegre, respectively.

As a climatic feature of Curitiba, the relative humidity is high most of the time. The relative humidity levels above the upper limit of 80% can occur regularly. The monthly averages of relative humidity are the boundary to the upper limit. The relative humidity is a bit higher during the hottest period and slightly drops during the coldest period. This characteristic increases the importance of ventilation in summer because it is able to remove the moisture inside the building.

The relative humidity levels in São Paulo are lower when compared with Curitiba. Even though the values exceed the upper limit of 80% from time to time, overall the values are kept slightly below this limit.

The relative humidity levels in Porto Alegre increase during the winter and they only occasionally drop to the 60`s%. As a strategy, ventilation should be kept away from the coldest period to avoid the moisture coming into the building.

Table 3-6: Monthly averages of relative humidity - Curitiba, São Paulo and Porto Alegre

RH (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Curitiba	80	76	76	80	77	78	70	76	77	82	81	75
São Paulo	75	73	72	72	68	74	61	69	70	72	72	71
Porto Alegre	71	71	71	73	79	79	79	73	73	71	70	68

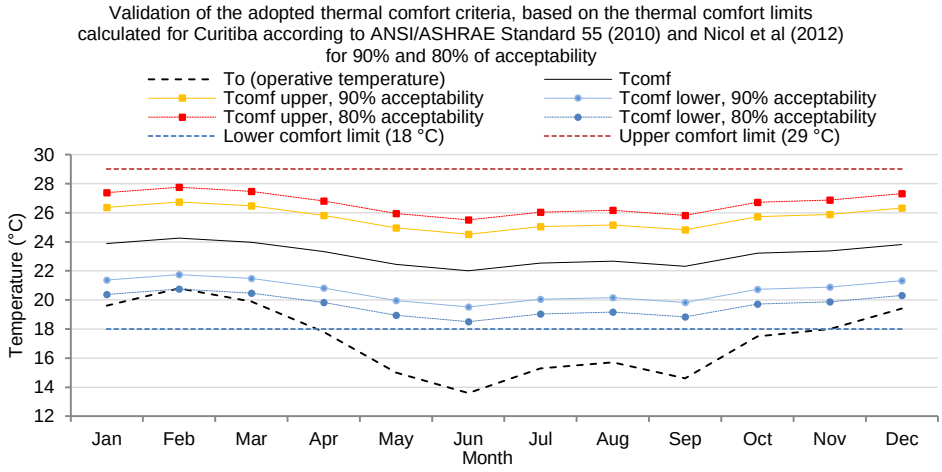


Figure 3-16: Validation of the adopted thermal comfort criteria, based on the thermal comfort limits calculated according to ANSI/ASHRAE Standard 55 (2010) and Nicol et al. (2012) - Curitiba

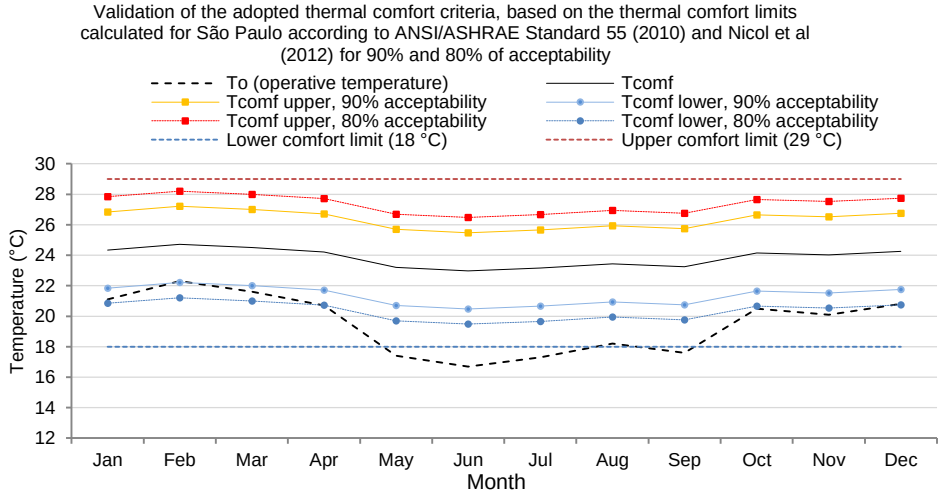


Figure 3-17: Validation of the adopted thermal comfort criteria, based on the thermal comfort limits calculated according to ANSI/ASHRAE Standard 55 (2010) and Nicol et al. (2012) - São Paulo

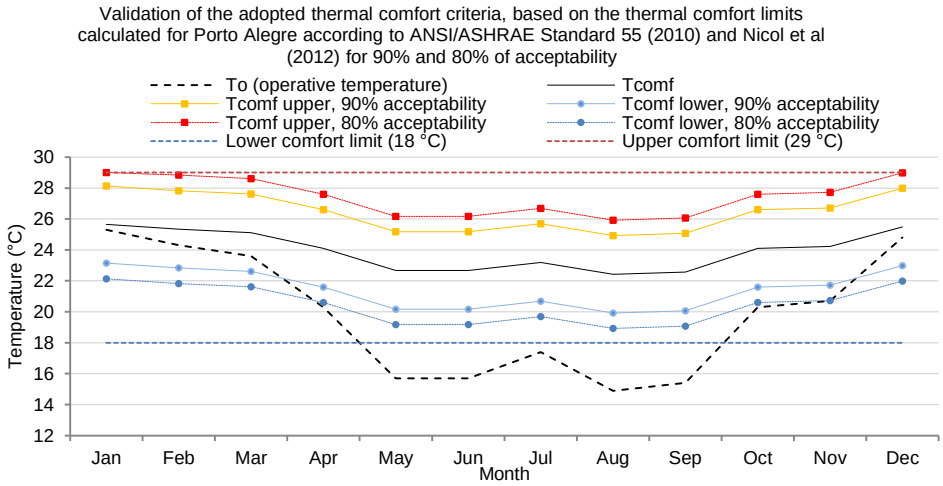


Figure 3-18: Validation of the adopted thermal comfort criteria, based on the thermal comfort limits calculated according to ANSI/ASHRAE Standard 55 (2010) and Nicol et al. (2012) - Porto Alegre

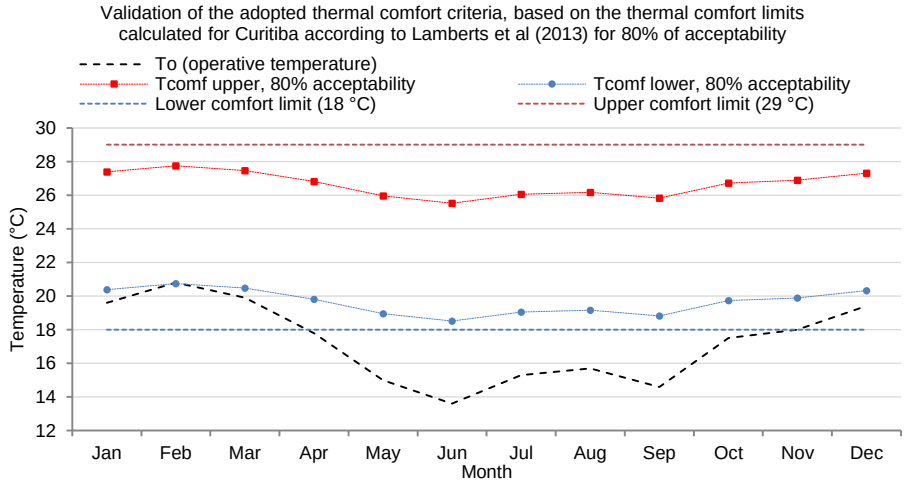


Figure 3-19: Validation of the adopted thermal comfort criteria, based on the thermal comfort limits calculated according to Lamberts et al. (2013) - Curitiba

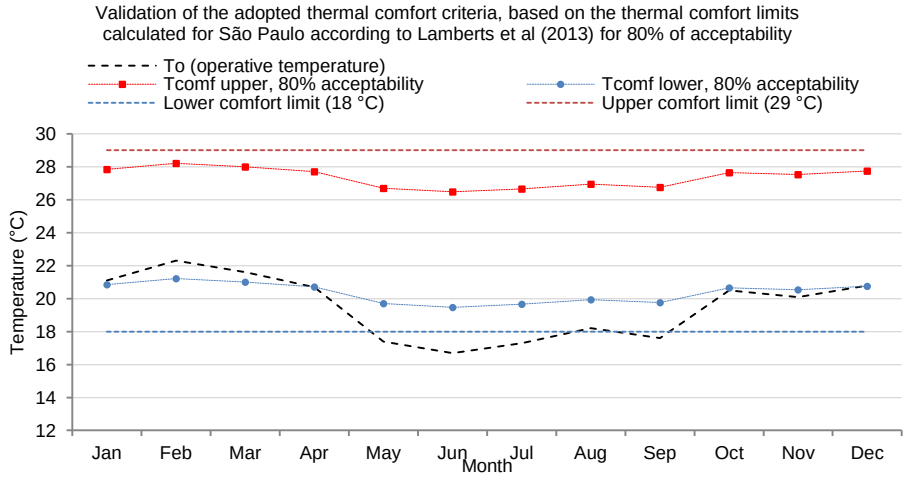


Figure 3-20: Validation of the adopted thermal comfort criteria, based on the thermal comfort limits calculated according to Lamberts et al. (2013) - São Paulo

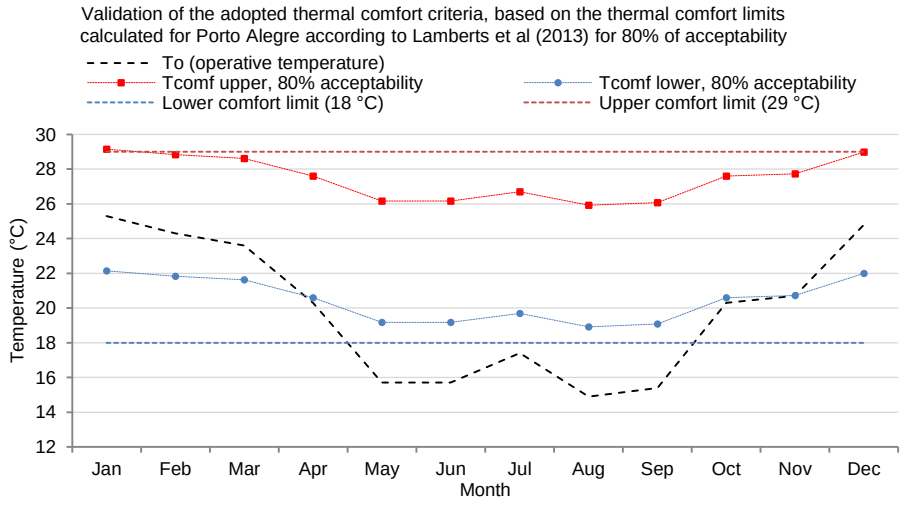


Figure 3-21: Validation of the adopted thermal comfort criteria, based on the thermal comfort limits calculated according to Lamberts et al. (2013) - Porto Alegre

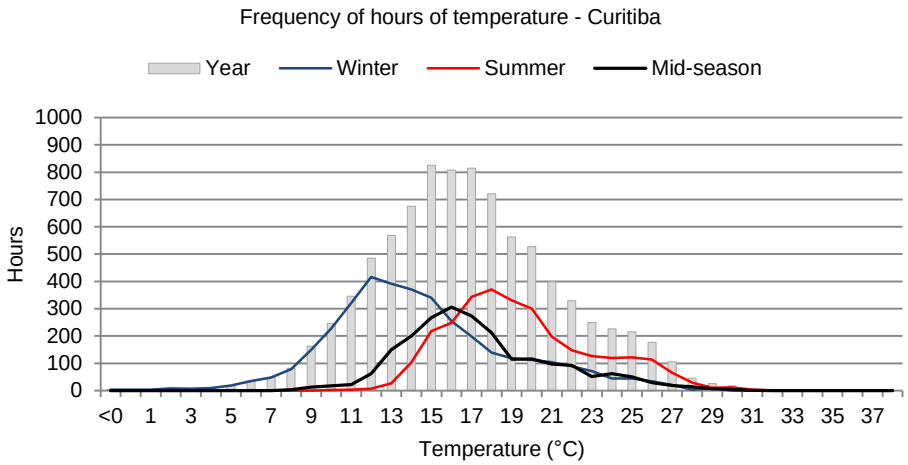


Figure 3-22: Frequency of hours of temperature per year and per seasons - Curitiba

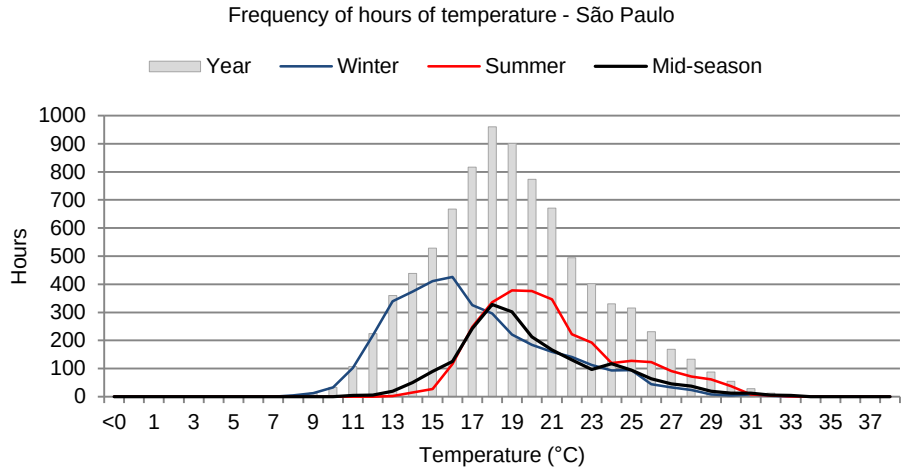


Figure 3-23: Frequency of hours of temperature per year and per seasons - São Paulo

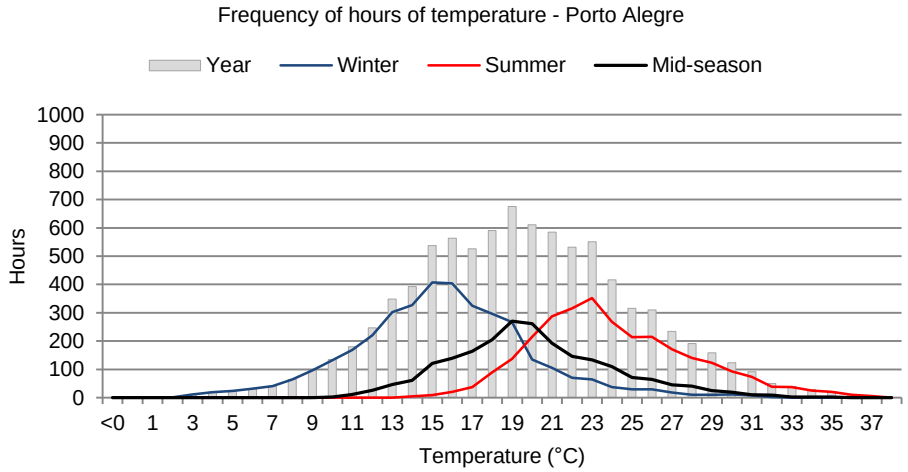


Figure 3-24: Frequency of hours of temperature per year and per seasons - Porto Alegre

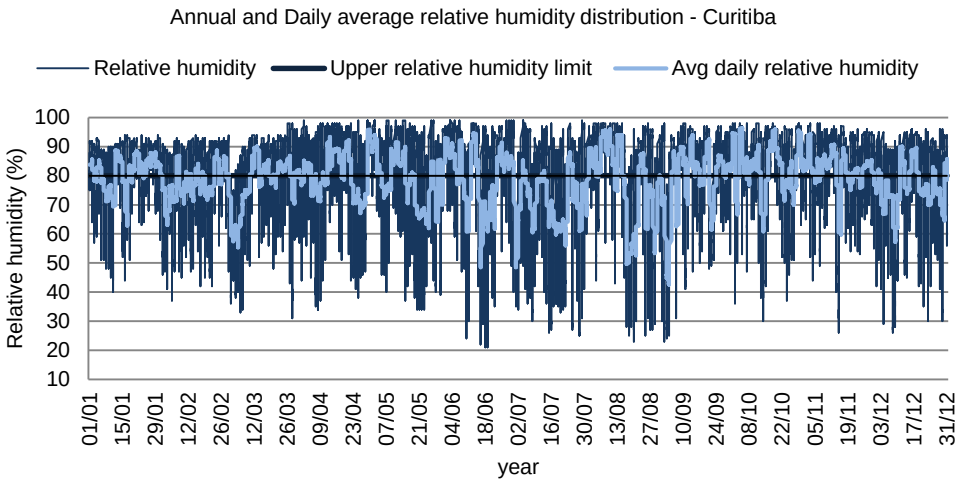


Figure 3-25: Relative humidity - Curitiba

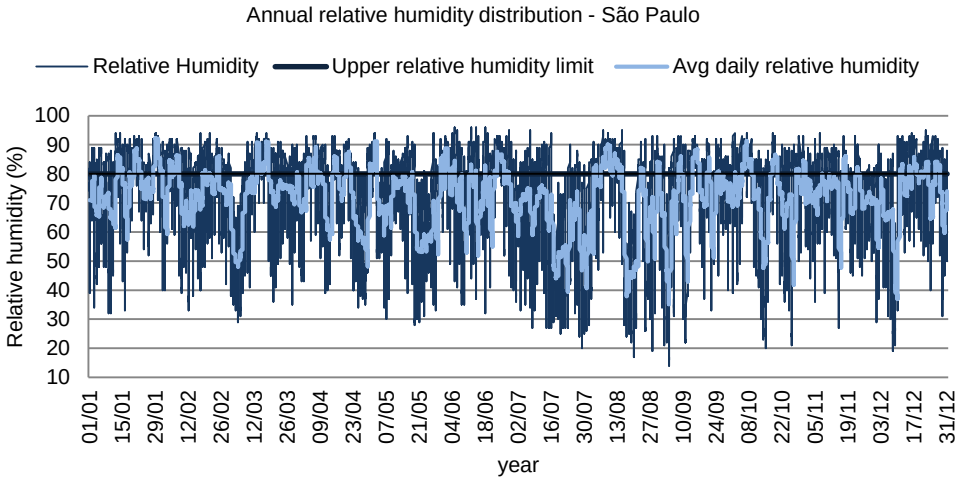


Figure 3-26: Relative humidity - São Paulo

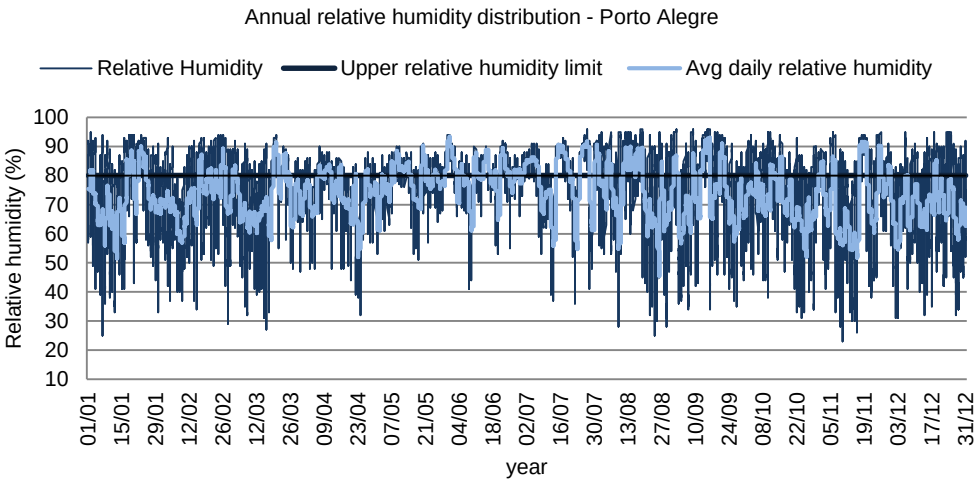


Figure 3-27: Relative humidity - Porto Alegre

Figure 3-28, Figure 3-29 and Figure 3-30 illustrate the monthly diurnal solar radiation average distribution for Curitiba, São Paulo and Porto Alegre, respectively.

The solar radiation availability varies over the year but overall the solar radiation is significant. It shows lower distribution from May to August and higher distribution from November to March. Because the solar radiation levels do not drop considerably during the winter, they moderate the effect of low temperatures. In particular, Porto Alegre has more seasonal solar radiation variation and also presents the highest direct solar radiation during the hottest period among the cities investigated. Therefore, avoiding the penetration of the direct solar radiation in summer and allowing it in winter is important in these cities. In addition, as shown in Figure 3-13 to Figure 3-15, extremes of temperature can occur from time to time in mid-seasons, such as in October and November. In this period, the direct solar radiation already has high levels. Thus, it might be required to equip the buildings with shadings in order to avoid potential indoor overheating in this period.

However, mostly in São Paulo and in specific months in Curitiba and Porto Alegre, the monthly diffuse solar radiation levels have similar levels of the monthly direct solar radiation. This means that there are many days of overcast sky, in which shade will not be as effective and the temperatures will be increased, impacting negatively on thermal comfort. The reason for that is because when the diffuse solar radiation levels are increased, the direct solar radiation levels are reduced and all the facades of the building tend to receive the same amount of diffuse solar radiation (Lamberts et al., 2014). Consequently, in warm days, the building will gain solar heat transferred by convection to nearby spaces, which are inward transmitted by the glazing elements to the interior of the building in all its facades and even pole-facing windows will admit significant heat gain in summer because the diffuse sky light carries heat with it (DeKay and Brown, 2014). Therefore, when the diffuse solar radiation levels are significant, the appropriate windows design assumes greater importance in the delivery of thermal comfort.

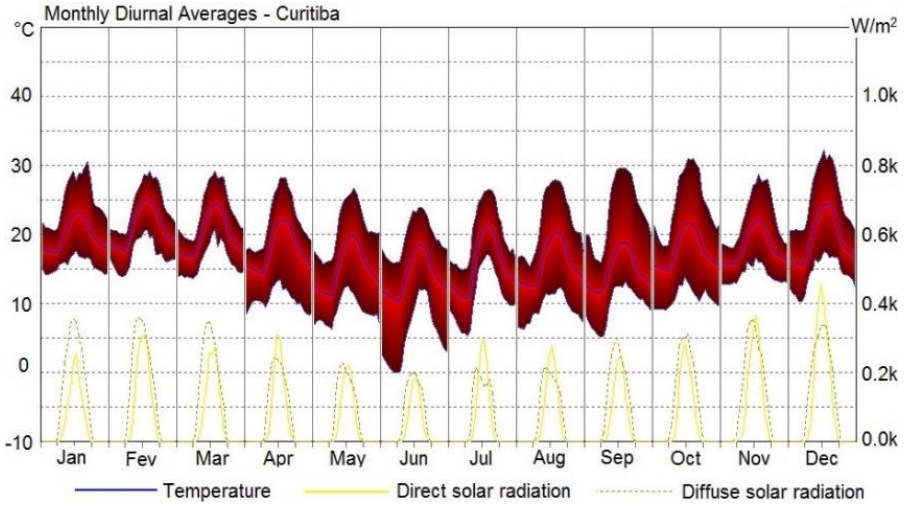


Figure 3-28: Monthly diurnal solar radiation averages - Curitiba. From Ecotect (Autodesk, 2010, edited)

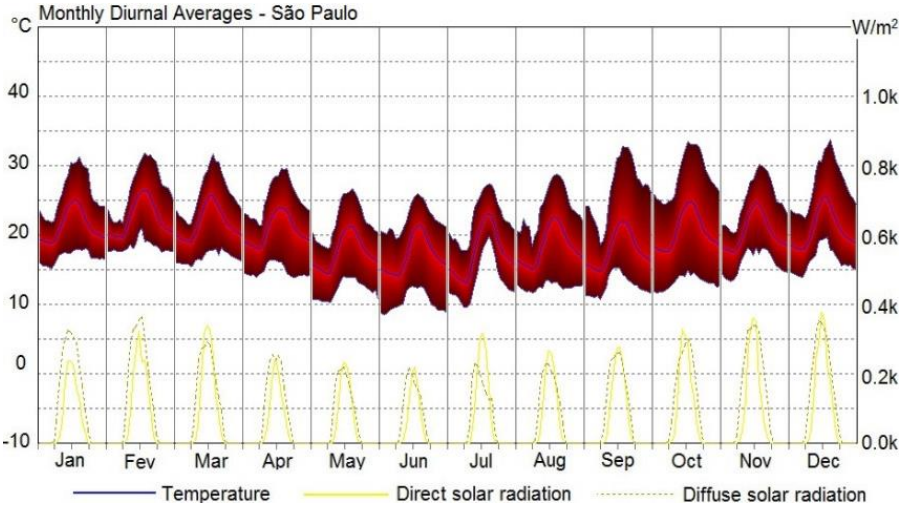


Figure 3-29: Monthly diurnal solar radiation averages - São Paulo. From Ecotect (Autodesk, 2010, edited)

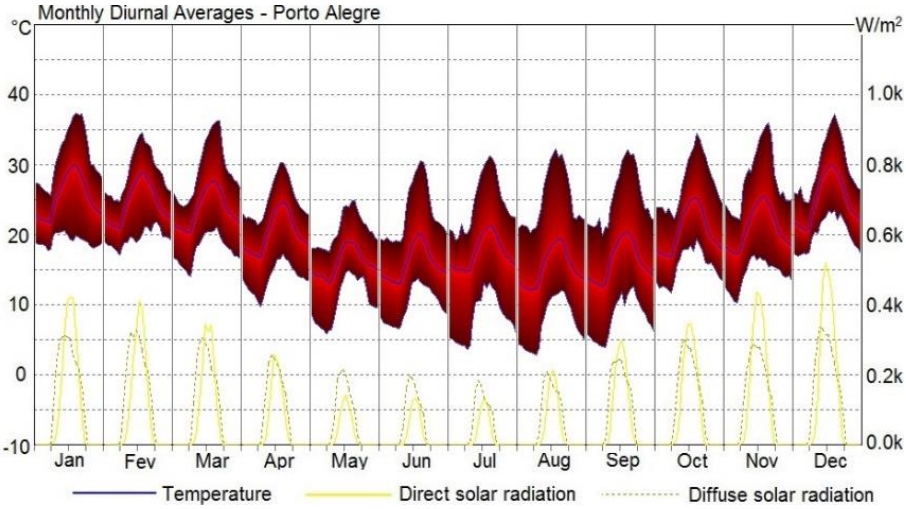


Figure 3-30: Monthly diurnal solar radiation averages - Porto Alegre. From Ecotect (Autodesk, 2010, edited)

The main solar angles of the direct solar radiation are depicted in Table 3-7, Table 3-8 and Table 3-9 in Curitiba, São Paulo and Porto Alegre, respectively. As shown in the Tables, the high solar altitude in summer requires the control of the direct solar radiation.

The design of horizontal shading devices for a window facing the equator with full shading in summer (equinox cut-off) is set by the vertical shadow angles (VSA). VSA can be estimated by the difference of 90° and the corresponding latitude (Szokolay, 2008, p. 37), which results in 64.6°, 66.2° and 60.0° for the cities of Curitiba, São Paulo and Porto Alegre, respectively.

Table 3-7: Main solar angles - Curitiba. Based on Ecotect (Autodesk, 2010)

Date	Time	Azimuth (degrees)	Elevation (degrees)	HSA (degrees)	VSA (degrees)
Summer Solstice 21st December	9h	98.3	45.8	98.3	98.0
	12h	61.5	86.1	61.5	88.1
	15h	-96.0	52.6	-96.0	94.6
	17h	-105.0	25.9	-105.0	118.1
Winter Solstice 21st June	9h	48.7	21.4	48.7	30.8
	12h	5.7	41.0	5.7	41.1
	15h	-42.0	27.5	-42.0	35.0
	17h	-60.3	6.2	-63.7	12.5
Equinox 20th March/ 22nd September	9h	67.9	37.3	67.9	63.7
	12h	5.6	63.9	5.6	64.0
	15h	-64.3	41.4	-64.3	63.8
	17h	-81.8	15.5	-81.8	62.6

Table 3-8: Main solar angles - São Paulo. Based on Ecotect (Autodesk, 2010)

Date	Time	Azimuth (degrees)	Elevation (degrees)	HSA (degrees)	VSA (degrees)
Summer Solstice 21st December	9h	99.1	48.0	99.1	98.1
	12h	66.8	88.9	66.8	89.6
	15h	-98.6	49.9	-98.6	97.2
	17h	-106.5	23.2	-106.5	123.6
Winter Solstice 21st June	9h	47.4	24.3	47.4	33.7
	12h	2.5	42.6	2.5	42.7
	15h	-44.6	26.9	-44.6	35.4
	17h	-61.7	4.8	-61.7	10.1
Equinox 20th March/ 22nd September	9h	67.1	40.1	67.1	65.3
	12h	-0.5	65.5	-0.5	65.5
	15h	-67.4	39.8	-67.4	65.3
	17h	-83.3	13.2	-83.3	63.8

Table 3-9: Main solar angles - Porto Alegre. Based on Ecotect (Autodesk, 2010)

Date	Time	Azimuth (degrees)	Elevation (degrees)	HSA (degrees)	VSA (degrees)
Summer Solstice 21st December	9h	94.4	44.6	94.4	94.4
	12h	39.1	81.7	39.1	83.6
	15h	-89.0	54.5	-89.0	89.3
	17h	-10.2	28.7	-102.0	110.9
Winter Solstice 21st June	9h	-48.8	17.1	48.8	25.1
	12h	7.5	36.2	7.5	36.4
	15h	-39.0	25.1	-39.0	31.1
	17h	-59.0	5.4	-59.0	10.3
Equinox 20th March/ 22nd September	9h	66.2	34.0	66.2	59.1
	12h	8.6	59.1	8.6	59.4
	15h	-59.2	40.7	-59.2	59.2
	17h	-79.5	16.4	-79.5	58.2

Figure 3-31, Figure 3-32 and Figure 3-33 illustrate the prevailing wind direction and speed in different seasons in Curitiba, São Paulo and Porto Alegre, respectively.

Overall, for all cities under investigation, in summer, the prevailing wind comes from the east and south-east direction but there is also minor occurrence of winds from the north-west direction. The north-west wind direction, however, is associated with the land masses and wind coming from this direction generally presents higher temperatures, which can be associated with thermal discomfort during the hot season. In winter, the prevailing wind frequently comes from east and south-east but also turns to north-west. South to east wind directions are the main issue in winter, since they present lower temperatures and potentially increase the thermal discomfort in this season.

To sum up briefly, it seems to be important to control the apertures facing south to east, which correspond to the colder winds direction during the winter for these cities. Also, it is important to control the hot winds in summer, which usually come from a north-west direction.

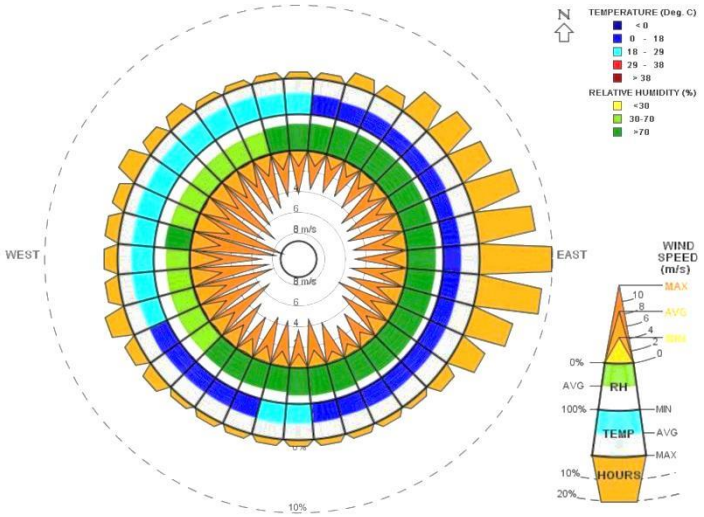


Figure 3-31: Wind direction/ speed in a year- Curitiba. From Climate Consultant (UCLA, 2008)

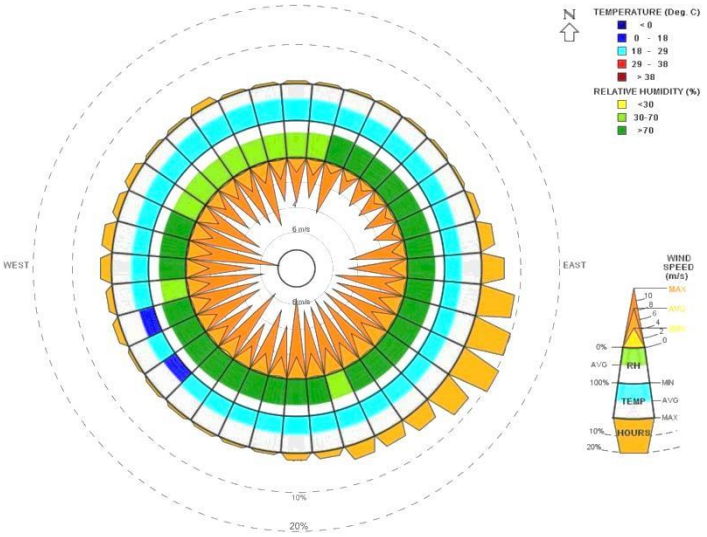


Figure 3-32 : Wind direction/ speed in a year - São Paulo. From Climate Consultant (UCLA, 2008)

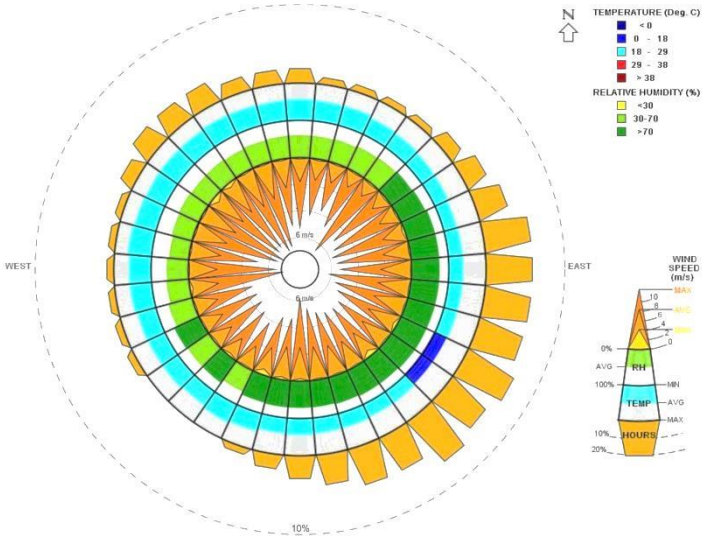


Figure 3-33: Wind direction/ speed in a year - Porto Alegre. From Climate Consultant (UCLA, 2008)

The analyses of the psychrometric charts suggest strategies to extend the thermal comfort conditions. A psychrometric chart elaborated with the use of the Analysis Bio Software (LabEEE, 2010) was adopted in the present research. Analysis Bio Software was designed for the Brazilian context and it adopts the enlarged threshold comfort criteria suggested by Givoni (1992). The use of this psychrometric chart helps establish which strategies are more or less effective in these particular climates and to what extent each strategy or combined strategies should be adopted. Figure 3-34, Figure 3-35 and Figure 3-36 show the psychrometric chart of Curitiba, São Paulo and Porto Alegre, respectively.

The suggested workable environmental strategies for buildings designed in Curitiba, São Paulo and Porto Alegre were zoned on the psychrometric chart and they were divided into: ventilation, evaporative cooling, high thermal mass for cooling, air conditioning, high thermal mass with solar heating, passive solar heating and additional heating. Among the strategies for cooling passively, there are intersections among ventilation, evaporative cooling and high thermal mass strategies, meaning that these strategies could be used individually or concurrently. When these strategies are recommended concurrently, the strategy with more needs or the strategy that is most compatible with the selected winter requirement is the one that must be chosen.

In Curitiba, the thermal comfort condition is found in only 28.8% of the time. The discomfort represents 71.2% of the time, with 67.7% of the time being due to the cold and 3.55% of the time due to the heat. The most suggested passive strategies to deal with low temperatures are high thermal inertia combined with passive solar heating (44.5%) and only passive solar heating (17.5%). The use of high thermal inertia with passive solar heating can compensate the low temperatures by storing solar heat in the walls and releasing to inside the building during the colder hours and this strategy is mostly adopted for temperatures between 14 °C and 20 °C (Lamberts et al., 1997, p. 109). Passive solar heating is used for lower temperatures, between 10.5 °C and 14 °C and for this strategy the need of insulation is higher (Lamberts et al., 1997, p. 110). Also, the building design needs to adopt glazing surfaces facing the sun and reduce the glazing surfaces facing undesirable shading facades, which are generally the strategies also adopted by the Fabric First approach design. Additional heating is only required in 5.6% of the time. For high temperatures, ventilation is the most suggested passive design strategy and it is suggested for 3.41% of the time. Ventilation is used for temperatures between 29 °C and 32 °C and also for high humidities to improve the thermal sensation (Lamberts et al., 1997, p. 106).

São Paulo is the city that is most of the time in thermal comfort when compared with Curitiba and Porto Alegre. In São Paulo, the comfort is found in 44.6% of the time and from the remaining percentage of discomfort of 55.4% of the time, in 47.6% of the time

the discomfort is due to the cold and in 7.82% of the time the discomfort is due to the heat. In terms of design strategies, São Paulo requires overall the same strategies to increase the thermal comfort in buildings when compared to Curitiba. The main difference of the design strategies for São Paulo compared to Curitiba is that there is no need for additional heating; in other words, the comfort can be achieved only with the use of passive design strategies. The most suggested strategies for the discomfort period due to the cold temperatures are high thermal mass with solar heating (39.1%) and passive solar heating (8.15%). The hot temperatures are dealt mostly with ventilation strategy (7.52%) but also with high thermal mass for cooling to a lesser extent (2%). High thermal mass for cooling can be employed to moderate the climate effect inside the building. The heat stored during the day is released to the environment at night and insulated materials can also be used associated with thermal mass.

Porto Alegre ranks second in terms of thermal discomfort (65.5%) but it has the highest thermal discomfort due to heat when compared with the other cities (21.3%). However, the discomfort due to the heat is not the most significant issue, as the thermal discomfort due to the cold occurs in 44.2% of the time. Porto Alegre clearly demonstrates the highest temperature amplitude with the need for both additional heating (4.03%) and cooling (0.81%). The most suggested passive strategies for cold temperatures are high thermal mass with passive solar heating (30.5%) and only passive solar heating (9.68%). The most suggested passive strategies for hot temperatures are ventilation (19.2%), high thermal mass for cooling (5.97%) and evaporative cooling (5.68%). With regard to high thermal mass, due to the relatively large diurnal range of temperature it can work effectively with the use of night-purge ventilation to cool down the indoor warmed air. Evaporative cooling is likely to be the least effective of the cooling strategy because it increases the relative humidity. As an evaporative cooling strategy, the use of deciduous vegetation could be highly recommended; it can help moderate the climate in summer but it does not compromise the levels of relative humidity in winter, which are already very high.

As mentioned, although the cities have most of the time thermal discomfort due to the cold, it is important to highlight that for 47%, 51% and 46% of the time the hours below the lower limit of thermal comfort of 18 °C occur during late night (from 22h to 6h), respectively, which is predominantly the time of the day that people are sleeping under blankets and to do so, the impact of thermal discomfort sensation is reduced.

Thermal comfort: 28.8%/ Thermal discomfort: 71.2%
Discomfort due to the low temperatures: 67.7%/ Discomfort due to the high temperatures: 3.55%

Strategies for dealing with thermal discomfort:

Ventilation:2.89%
Evaporative Cooling: 0.01%
Humidification: 0.1%
High Thermal Mass/ Solar Heating: 44.5%
Passive Solar Heating: 17.5%
Additional Heating: 5.6%
Ventilation/ High Thermal Mass/ Evaporative Cooling: 0.525%
High Thermal Mass/ Evaporative Cooling: 0.01%

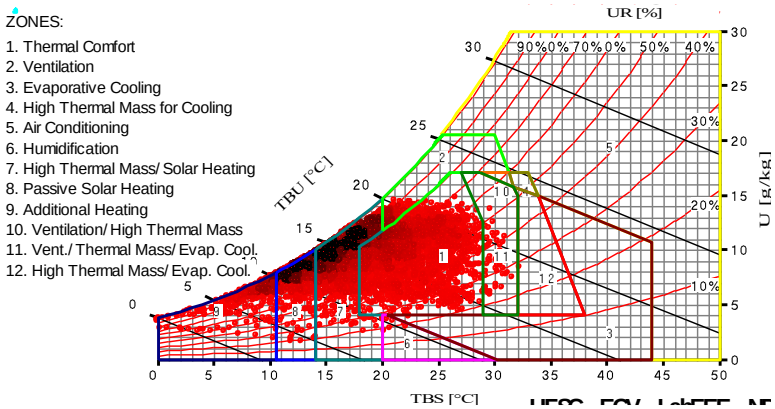


Figure 3-34: Psychrometric chart with zoning of environmental strategies – Curitiba. From Analysis Bio (LabEEE, 2010)

Thermal comfort: 44.6%/ Thermal discomfort: 55.4%
Discomfort due to the low temperatures: 47.6%/ Discomfort due to the high temperatures: 7.82%

Strategies for dealing with thermal discomfort:

Ventilation: 5.73%
Evaporative Cooling: 0.09%
High Thermal Mass/ Solar Heating: 39.1%
Passive Solar heating: 8.15%
Additional Heating: 0.31%
Ventilation/ High Thermal Mass/ Evaporative Cooling: 1.79%
High Thermal Mass/ Evaporative Cooling: 0.21%

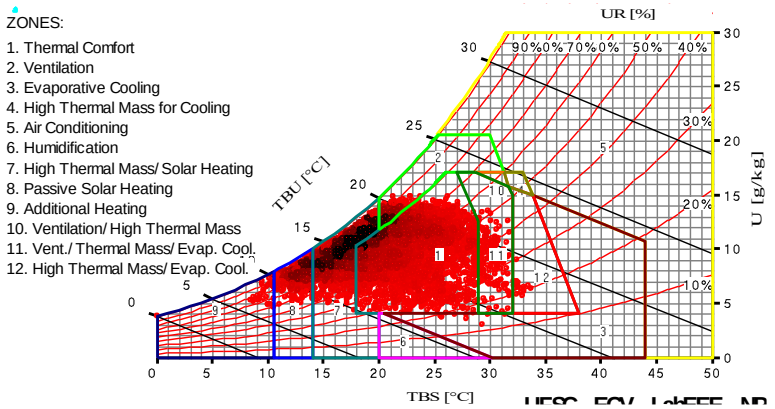


Figure 3-35: Psychrometric chart with zoning of environmental strategies – São Paulo. From Analysis Bio (LabEEE, 2010)

Thermal comfort: 34.5%/ Thermal discomfort: 65.5%
Discomfort due to the low temperatures: 44.2%/ Discomfort due to the high temperatures: 21.3%

Strategies for dealing with thermal discomfort:

Ventilation: 14.3%
Evaporative Cooling: 0.16%
High Thermal Mass for Cooling: 0.24%
Air Conditioning: 0.81%
High Thermal Mass/ Solar Heating: 30.5%
Passive Solar heating: 9.68%
Additional Heating: 4.03%
Ventilation/High Thermal Mass: 0.205%
Ventilation/High Thermal Mass/ Evaporative Cooling: 4.71%
High Thermal Mass/ Evaporative Cooling: 0.81%

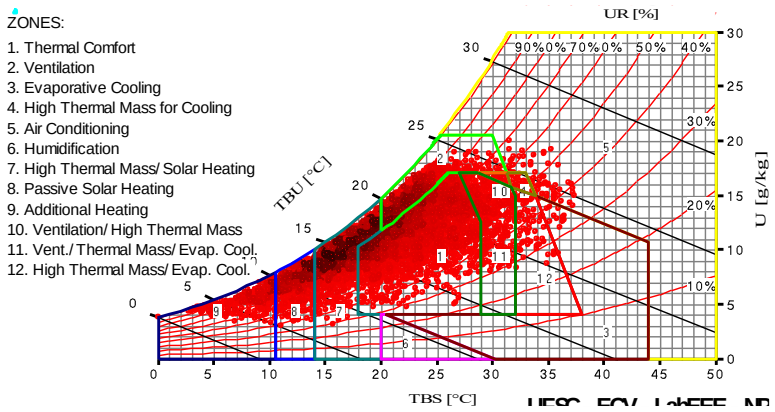
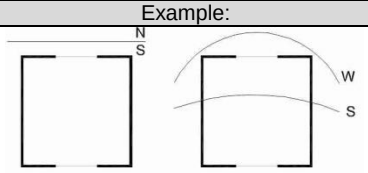
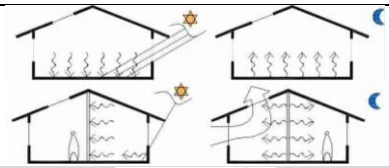
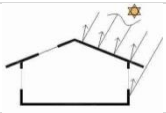
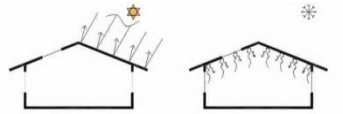
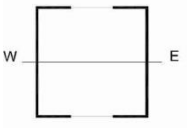
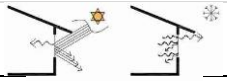
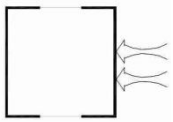
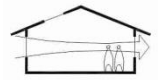
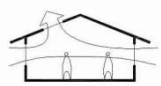
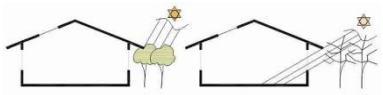
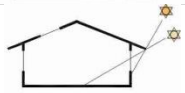


Figure 3-36: Psychrometric chart with zoning of environmental strategies – Porto Alegre. From Analysis Bio (LabEEE, 2010)

Based on the climatic analyses and literature review carried out, potential climate responsive design strategies are explored for the areas investigated and this is shown in Table 3-10. Climate responsive is a fundamental part of the environmental framework to moderate the climate and provide human well-being (Hyde, 2000).

Table 3-10: Summary climate responsive design strategies for Curitiba, São Paulo and Porto Alegre. Based on Szokolay (2008) and Hyde (2000)

	Summer (S)	Winter (W)	Example:
Orientation	Windows preferably facing equator for solar access in winter and solar block in summer.		
Form	Pitched roof works as a buffer space to moderate the indoor temperatures mainly during the summer.		
Fabric	Use of thermal mass. In winter, heat is stored in the walls during the day and it is released during the night, when the temperatures are lower. In summer, it can be used with flushing night ventilation to remove the heat by convection.		
	Roof and walls light coloured to reflect solar radiation	-	
	Use of reflective foil laminate under roof and insulation to reflect the downward radiation and to reduce the heat gain through the fabric.	Use of roof insulation to reduce the upward radiation and the heat loss.	
Windows	Avoid windows to the east and west because it is more difficult to control than north/south	-	
	Shade windows Avoid overuse of glazing to control solar gains	Avoid overuse of openings in south facade to reduce heat losses	
	Use of low-e glazing to reduce heat gain	Use of insulated glazing to reduce the heat loss	
Ventilation	Facing prevailing breezes in summer and block prevailing hot winds	Block prevailing cold winds	
	Maximize cross-ventilation in summer	Seal in winter	
	Maximize stack ventilation in summer	Seal in winter	
Shading	Shade openings to minimize insolation (used associated with deciduous vegetation)	Allow direct solar heat gain	
	Shade walls with the use of porches	Allow direct solar heat gain	
	Use of eaves for shading windows in summer	Allow direct solar heat gain	

With that in mind, it is highly likely that the climate characteristics have influenced how the dwellings have traditionally been built in the southern Brazil. The next section presents the vernacular housing architecture with the aim of helping define case studies of this research and narrowing down the workable design strategies for the chosen locations.

3.4 Vernacular Housing in Brazil

Vernacular buildings are recognised for displaying a remarkably sophisticated thermal adaptation and they were built using forms and materials that effectively moderated prevailing climatic conditions (Heschong, 1979). Studies in these buildings allow understanding of the relationship between culture, climate and building form and they can be examined to inform the architecture (Hyde, 2000).

This section discusses southern vernacular housing architecture and shows a compilation of vernacular housing examples. The aim was to identify housing typologies, materials and environmental design strategies adopted in the vernacular residential architecture in southern Brazil and to also use this knowledge to support the selection of appropriate case studies for the present research.

In Brazil, the vernacular housing architecture is very distinct throughout the country and this is even more evident between the north and the south part of the country. Among other reasons, this architectural difference is mostly due to the climate difference (seasonal climate in south) and the nature of the land occupation.

In particular, southern Brazilian vernacular housing architecture was characterised by its miscegenated culture, which reflected a very singular vernacular architecture. Oliver (1997), in his book, related that such architectural melting is unlikely to be found anywhere else in the world. This architectural multi-culture is initially derived from the miscegenation of Indians, black slaves and Portuguese people (Oliver, 1997). Later, this architectural miscegenation was modified as a result of the intense migratory process which took place in those areas.

The architecture developed in the southernmost areas of the country did not suffer similar influences of the architecture in the northern part mainly because the occupation of the south of Brazil occurred later in the process of colonization. The occupation of southern areas was more related to borders protection to guarantee the Portuguese occupation in Brazilian territory and it relied on the migratory process.

According to Oliver (1997), the first steps of the migratory process in southern Brazil, during the Portuguese dominance, were taken by Portuguese immigrants from the Azores Island. Later, after Brazilian Independence (1822), immigrants arrived from all

over Europe, starting with Germans and followed by Italians, Poles, Ukrainians and others. After Slavery Abolition, from 1888, a new contingent of immigrants came from diverse locations mainly to develop activities of land cultivation, such as the Japanese, who settled in the São Paulo area to work on farms.

The main characteristics of the vernacular housing architecture developed in Brazil were identified by Weimer (2005). In his book, the author stated that vernacular housing architecture was basically characterized by: simplicity, with vast use of local and natural materials; adaptability, seen from the high adaptation of the immigrant's architecture to the different environmental conditions found in Brazil when compared to the climate conditions where the immigrants came from; creativity, with an exploration of local materials; also, plastic and geometrical architectural resulted, which was more related to the technique and material used rather than the form or plastic intention desired.

The adaptability characteristic in Brazilian vernacular housing architecture can be easily observed from the construction techniques employed. Construction techniques such as the *pau-a-pique*, which makes use of wooden stick elements to structure the walls, was originally conceived to have gaps between the elements. The adaptation of this technique to milder Brazilian climates incorporated the use of mud to seal these gaps (Weimer, 2005). This might suggest that some degree of air exchange limit should be appropriate in these locations.

Another characteristic easily observed is that the architectural form would be more a result of the technique used rather than the plastic intention. For example, in the *taipa-de-pilão* technique, which was vastly employed in the São Paulo region, the wall was entirely filled with clay, resulting in a wall thickness of at least 50cm. Due to the intensive use of clay, the walls were quite sensitive to the humidity variation and, consequently, many houses were built with long eaves around the walls' perimeter in order to protect the vertical elements (Weimer, 2005).

This perhaps allows an inference that regardless the plastic architectural effect over the technique adopted may justify the considerable decrease of the walls thickness over the years, as long as the construction techniques allowed the thicknesses of the walls to be reduced. As a consequence of the reduction of the wall thickness, other advantages of thicker walls such as thermal and acoustical properties were also jeopardized.

Apart from the wall thickness, the uses of eaves were continuously being used in southern vernacular housing architecture, despite the development of other envelope materials. The use of eaves seems to become a tradition in dwellings in these areas of the country. They are mostly employed to protect the construction elements from water and sun exposure.

The work of Weimer (2005) presented the most used materials in vernacular housing. According to the author, wood was one of the most important materials employed in Brazilian houses and was also the most representative available material to build houses during the immigration process. The availability of the wood was due to the existence of araucaria forest in the southern areas of the country (from the state of Rio Grande do Sul to the state of Minas Gerais). However, this material was mostly eradicated years later due to its extensive use (Oliver, 1997). A replacement by masonry was gradually happening in those areas where the araucaria forest was extinct, supported by other aesthetics patterns (Oliver, 1997). The wood was employed in many different construction techniques, such as the *enxaimel* style, widely used in the German houses, the board construction, found in the Polish houses and also the old suburban houses, found in Porto Alegre.

Clay was also vastly employed in vernacular residential buildings. As mentioned, the clay was used to build up walls based on the *taipa-de-pilão* technique but also to seal the gaps in the housing construction. For example, in Polish houses, the clay was employed internally and externally to the walls as a plaster between the wooden logs (Oliver, 1997). It should be stressed that the Polish immigrants settled in surroundings of Curitiba city, where sealed constructions seem to be extremely appropriate, since the climate in that area is the coldest one found in Brazil.

Another material employed in the vernacular architecture was stones and the most representative examples can be found in the Italian houses of the immigrants settled in the state of Rio Grande do Sul. The use of stones was supported by the availability of this material in those occupied areas and also by the previous skills of these immigrants. The use of stones was replaced by the use of wood, since plenty of this material was available in the region and also because this material was easier to work with compared to stones (Oliver, 1997). Stones began to appear more frequently just on the ground floor of these dwellings, where the occupants could themselves benefit from the thermal mass of the material. In these ground areas, the apertures were few and these areas were used predominantly to store food (Oliver, 1997).

The use of natural materials was gradually being replaced by the industrialised ones and they are now vastly employed in house construction all over the country. The first and the most consolidated examples of industrial materials were ceramic bricks and ceramic roof tiles (Weimer, 2005).

In terms of roofs, an exclusive adoption of pitched roof and the use of eaves of different length should be noted. In some vernacular examples such as in Native and German architecture, roofs made out of straw were common. However, most of the time the roofs were made out of wood and covered by ceramic roof tiles, which is also the most common roof type being built these days in Brazil.

Figure 3-37 roughly illustrates the map of occupation of each architectural influence in the areas covered by this research. Table 3-11 to Table 3-19 summarize the architectural characteristics of the immigrant dwellings in the areas of investigation, based on the works of Oliver (1997) and Weimer (2005).

Figure 3-37: Map of the vernacular architectural influence in southern Brazil (Oliver, 1997, edited, p. 1681).

Table 3-11: Summary of vernacular architecture influence of *Guarani* Indians. Based on Oliver (1997) and Weimer (2005)

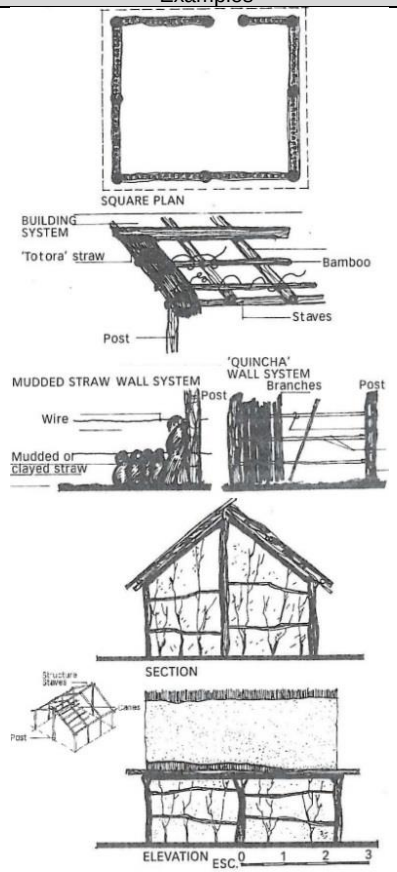
	Characteristics and patterns of the architecture		Examples
Guarani	Location/ General Characteristic	*Guarani* Indians occupied the areas of south and southeast of Brazil, along the coast, from the state of Rio Grande do Sul to the state of Espirito Santo. They settled mostly near the Atlantic forest. Two main types are identified, the Nhandeva and Mbya (nomadic).	 Drawings of *Guarani* house (Oliver, 1997, edited, p. 1693)
	Housing Typology	*Guarani's* house plan is square and the roof is thatched pitched. The house is quite simple and has two openings facing east-west or east-north (but quite often in these faces there are either partial walls or simply no walls). Internal partitions are quite rare. Internally, there are a large communal bed and a circular hearth with space for seating. Cooking area is external to the house. The house structure is made of rounded wooden stakes attached to the roof and intermediate beams with liana; mud may be applied to the vertical wooden structure.	
	Materials	*Guarani's* are located in areas of the forest and they use natural and local materials to build their houses such as slender staves, bamboo, palm-leaf and boards. The walls are constructed with poles or a stave frame inserted at the corners and the doorway, supporting the ridge-poles. 'Four to six vertical bamboo poles are also secured in the ground and three horizontal poles are lashed to them on each side. The space is closed with vertical palm-ribs lashed in place with bark or vines. Woven mats of grass or palm leaves are attached to the framework and the same system is used to clad the roof' (Oliver, 1997, p. 1693). Palm-ribs and woven mats are used for the house door. *Guarani* house solutions are still preserved, although there were some foreign introductions due to contact with the white man such as use of plastics for walls and tiles for the roof.	
	Environmental Design Strategies	- Use of cross-ventilation - Avoidance of openings in south/ wind protection for the cold wind direction - Lightweight construction - Use of hearth for the winter time	

Table 3-12: Summary of vernacular architecture influence of Azores. Based on Oliver (1997) and Weimer (2005)

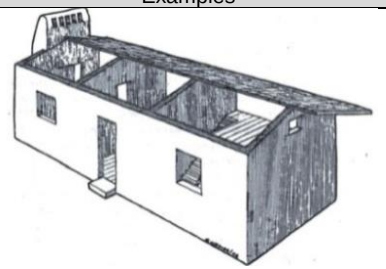
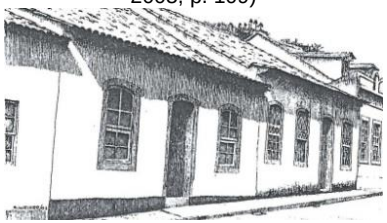
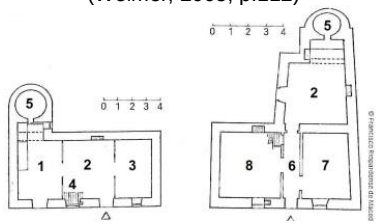
	Characteristics and patterns of the architecture		Examples
Azores	Location/ General Characteristic	The Azores immigrated to Brazil in 1752. In Brazil they were settled in villages, about 145 Km from Porto Alegre, in the state of Rio Grande do Sul.	 Example of original Azorean house (Weimer, 2005, p. 109)  Example of Azorean immigrant house (Weimer, 2005, p.112)  1. Kitchen; 2. Central room; 3. Bedroom; 4. Sewing platform; 5. Oven; 6. Hall; 7.Drawing room; 8. Room with sewing platform. Example of typical rural (on the left) and urban (on the right) Azorean immigrant house plan (Oliver, 1997, p. 1683)
	Housing Typology	The houses were small, quite simple and white coloured. The typology was characterised by 3 rooms built close to the street. The access was in the middle of the building, through the living room and this was directly connected to the kitchen (on the left) and the bedroom (on the right). The Azorean architecture built in Brazil was characterized by thick walls, massive door-jambs, modest roof eaves and small sash windows (which were increased later). In urban areas, a house of two-storey and L-shape plan was adopted.	
	Materials	External walls were made of stone walls. The interior walls were lightweight compared to the external ones, made of adobe produced with horizontal twigs and bamboo tied with liana or rawhide strips, filled with clay. These internal walls were distinct from the original Azorean architecture, which originally used thick partition walls built out of basalt stone.	
	Environmental Design Strategies	- Use of thermal mass - Medium openings - Small eaves - Use of light colours to reflect the solar radiation	

Table 3-13: Summary of vernacular architecture influence of *Bandeiristas.* Based on Oliver (1997) and Weimer (2005)

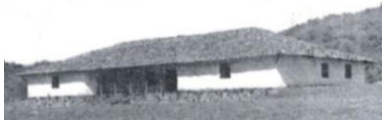
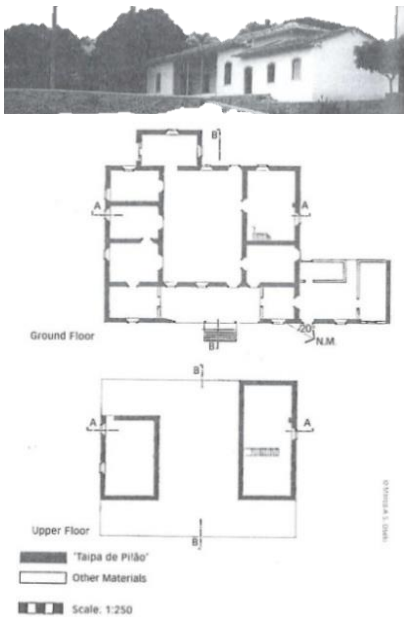
		Characteristics and patterns of the architecture	Examples
Bandeiristas	Location/ General Characteristic	The *Bandeiristas* were constituted by the miscegenation of Indians and Portuguese people. The *Bandeirista* period corresponded to 1580 until the end of the 19th century, and was divided into two main periods. This population was originally settled in the vicinity of São Paulo city and surroundings.	 Example of *Bandeirista* house (Oliver, 1997, p. 1682)
	Housing Typology	Their rural houses were characterized by rectangular plan, white walls, few openings and large pitched roof with upswept eaves. In the first Bandeiristas period (until 1740) all rooms share the same regular rectangle plan and, in the second period (from 1750 until the end of the 19th century), the plan included an extension on the rear side of the rectangle. This was used as kitchen and store room, which were not identified in the earliest period.	
	Materials	The external walls were built out of earth beaten in wooden moulds (*taipa-de-pilão*) and their thickness ranged from 50 cm to 70 cm. The internal walls were made out of *pau-a-pique*, a recognized old Brazilian technique, which is formed by a frame of sticks of vertical timber tied with horizontal wood splinters. It was filled in a mud mixture of clay, sand and water, resulting in a total thickness of 10-15 cm. The roof was simple and consisted of a very light and porous layer of clay tile, structured by great beams directly supported by the walls. The windows had wooden sheets for blinds, opening onto the interior rooms and on the outside had wooden shutters of square section. The walls were painted in white and wooden doors and windows were painted in blue or green.	
	Environmental Design Strategies	- Use of thermal mass - Small openings - Long eaves - Use of light colours to reflect the solar radiation	 Example of *Bandeirista* house: view (far above) and house plan (above) (Oliver, 1997, p. 1684)

Table 3-14: Summary of vernacular architecture influence of *Caiçara.* Based on Oliver (1997) and Weimer (2005)

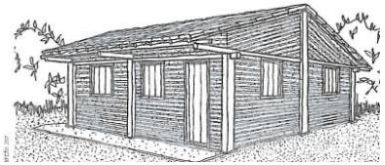
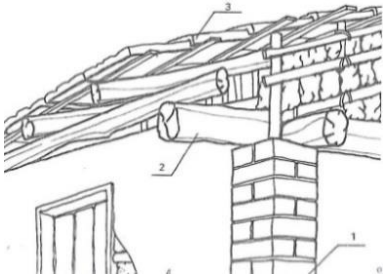
		Characteristics and patterns of the architecture	Examples
Caiçara	Location/ General Characteristic	*Caiçaras* are the result of the miscegenation between Indians and Portuguese people and they appeared in the 16th century. They occupied areas of the southeast of the country, equivalent to the coastal areas of the state of São Paulo, Rio de Janeiro and part of Paraná.	 Example of *Caiçara* house (before final mud application to the walls) (Oliver, 1997, p. 1686)
	Housing Typology	Generally the houses had from one to three bedrooms. Kitchen and toilets were part of a secondary building annexed to the main house or built in the backyards. The house presented a rectangular plan and a pitched roof.	
	Materials	The roof was thatched of palm or tiles, use of tree-trunks in the structure and mud applied over the wood walls. The walls could just meet the roof truss (allowing natural ventilation) and were built out of sawn wood (boards), brick or concrete covered with painted mortar. The internal walls could be plastered with cement and sand and also painted (white, blue, pink or green). *Caiçaras* can still be found in the region but since 1970 their traditional techniques and material have been replaced by new ones, such as ceramic/concrete block walls and iron windows.	 1. Brick pillar; 2. Palm tree trunk beam; 3. Tile roof; 4. Stick structure covered with mud plaster and painted. Construction detail of *Caiçara* house (Oliver, 1997, p. 1686)
	Environmental Design Strategies	- Small openings - Medium eaves - Use of natural ventilation - Use of light colours to reflect the solar radiation	

Table 3-15: Summary of vernacular architecture influence of *Caipira.* Based on Oliver (1997) and Weimer (2005)

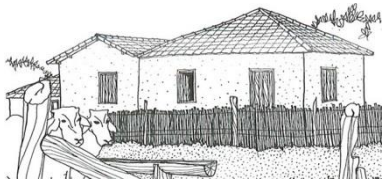
		Characteristics and patterns of the architecture	Examples
Caipira	Location/ General Characteristic	*Caipiras* are the result of early stages of the colonization process in the countryside of São Paulo, Rio de Janeiro and Minas Gerais.	 Example of a *Caipira* house (Oliver, 1997, p. 1687)
	Housing Typology	Mostly rectangular plan and a few rooms.	
	Materials	*Caipira* houses present similar solutions as *Caiçara* ones. They have indigenous influence, as they also use pitched thatched roof of straw or palm, branches and trunks used for roof, enclosing surfaces covered by mud and use of few openings.	
	Environmental Design Strategies	- Small openings - Medium eaves	

Table 3-16: Summary of vernacular architecture influence of Germans. Based on Oliver (1997) and Weimer (2005)

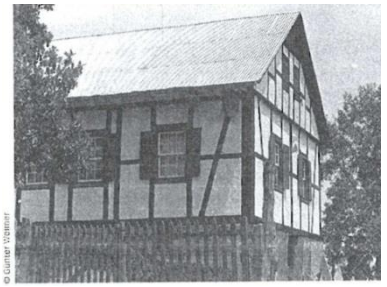
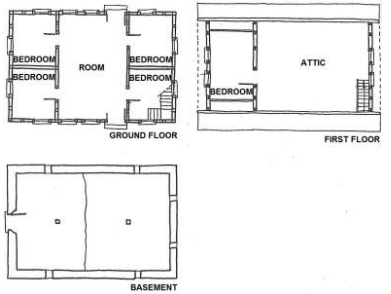
		Characteristics and patterns of the architecture	Examples
Germans	Location/ General Characteristic	The Germans immigrated to remote areas of southern Brazil in the 19th century. They established themselves on the lower hill sides of the coastal of the Rio Grande do Sul state, surrounded by the Araucaria forest.	 Example of an German imigrant house (Oliver, 1997, p. 1691)
	Housing Typology	For a long time, they did not adopt any pre-existent national influence into their architecture and they kept as faithful as possible to their traditions. Originally, the life style of the Germans adapted to the cold winters required to keep the animals and food protected from the weather, inside the house. Initially, there were roofs made by straw with 80cm of thickness to guarantee the weatherproof. The Germans were settled in the mild areas of Brazil and their houses gradually changed from traditional German houses. The most important change was the distinction between living and working functions. The animals and tools were kept apart from the proper house. Other distinction between the original German architecture and changes adopted in Brazil was the division between the house and the kitchen, which was kept apart due to the fear of fire and was integrated into the main house years later.	 Example of a typical German immigrant house plan (Weimer, 2005, edited, p. 166)
	Materials	The material mostly employed was wood.	
	Environmental Design Strategies	- Use of insulation - Medium eaves - Use of shutters	

Table 3-17: Summary of vernacular architecture influence of Italians. Based on Oliver (1997) and Weimer (2005)

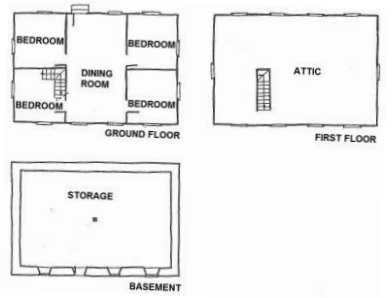
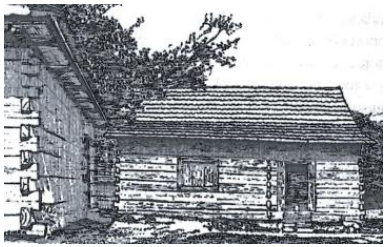
		Characteristics and patterns of the architecture	Examples
Italians	Location/ General Characteristic	The Italians arrived in Brazil in the last quarter of the 19th century and they were settled in the northeast region of the state of Rio Grande do Sul, in a rugged region covered with Araucaria trees.	Example of basalt stone Italian immigrant house (Oliver, 1997)
	Housing Typology	A typical house was a three-storey building made of the combination of stones and wooden materials. The basement (partly underground) was destined to be a wine-cellar and was generally made out of basalt stones with few windows, to create an ideal temperature to develop a storage function. The ground floor contained the general house functions and the top floor contained the male bedrooms and the space to store grains. Typical Italian immigrants plan were similar to the Germans but with a larger width compared to the German ones. Due to the size of the Italian families, which were bigger, the house plan had to accommodate more rooms per housing. In the Italian urban houses, the basement was eliminated.	Example of mix wooden and basalt urban Italian immigrant house (Weimer, 2005, p. 178)
	Materials	Mostly use of wood and basalt stone for the walls. The roof was made out of wooden shingles and later, it was made out of ceramic tiles. The doors and windows were made of wood. The wooden building parts did not receive any protective coating, so the aspect of wooden deterioration was visible resulting in a homogenous dark grey colour.	 Example of a typical Italian immigrant house plan (Weimer, 2005, edited, p. 176)
	Environmental Design Strategies	- Use of thermal mass - Small openings - Medium eaves - Use of shutters	

Table 3-18: Summary of vernacular architecture influence of Japanese. Based on Oliver (1997) and Weimer (2005)

	Characteristics and patterns of the architecture		Examples
Japanese	Location/ General Characteristic	The Japanese came to Brazil at the start of the 20th century, firstly to the São Paulo region and later, seeking land areas to plant, they settled in the area of the Paraná state.	Example of Japanese immigrant house (Oliver, 1997, p. 1695)
	Housing Typology	The original Japanese house erected in Brazil had a huge tiled roof (various roofs), decorative elements and an ornate porch. The house was entirely made of wood, including floors, walls and roof structure. The house plan was L or U-shaped, with defined compartments. The ceiling was high for comfort temperature purposes.	
	Materials	Mostly use of wood. The roof was made out of wooden slivers which were later replaced by ceramic roof tiles.	
	Environmental Design Strategies	- Medium eaves - High internal height for moderating the temperature	

Table 3-19: Summary of vernacular architecture influence of Polish. Based on Oliver (1997) and Weimer (2005)

	Characteristics and patterns of the architecture		Examples
Polish	Location/ General Characteristic	The Polish migrate internally in 1871 from the Santa Catarina to the Paraná state, in the surroundings of Curitiba city.	 Example of a wooden Polish house (Weimer, 2005, p. 184)
	Housing Typology	Compared to the original Polish house, the house in Brazil has the pediments simplified. Their houses were characterized by a one-storey building with an attic, made of wood (hewn logs) and with a rustic appearance. The roof was pitched and covered by plain tiles (or thatched roof of straw), which later were replaced by plain ceramic tiles. The wooden construction used local material and demanded special skills to work on. The gaps remained from the notching process were plastered with mud. The Polish construction started with a log cabin type, which was essentially a storage space, and later become a house. The plan was rectangular, divided into two compartments, bedroom and vestibule. The children's bedroom was located in the attic. The house's entrance was usually placed on the longer side of the building.	
	Materials	Wood and ceramic roof tiles.	
	Environmental Design Strategies	- Sealed walls - Medium eaves - Use of shutters	

As can be seen from the tables, the architectural typology of a rectangular or square plan was dominant in the architecture developed in the south and south-east of Brazil. The simplicity of the architectural examples was evident, mainly because the architecture developed in those areas had a rural character with a very low degree of ornament.

As suggested by Rapoport (1969), form is at least partly independent of the materials and structural means used in vernacular architecture. This means that materials and construction techniques can be treated as modifying factors, rather than form determinists. In fact, in Brazilian southern vernacular architecture, the materials employed were progressively changed over the years, mainly with the use of industrialised elements replacing the natural ones. This apparently did not result either in change of the form or typology adopted.

Another characteristic of vernacular architecture is that they typically respond very well to the climate (Rapoport, 1969). In the architecture developed in southern Brazil, although some environmental design strategies were firstly brought by the immigrants to respond to the climate of origin, a degree of adaptation in the construction could be observed.

Common environmental design strategies were found to be the use of eaves to shade building elements, the use of ventilation, the use of shutters and medium openings to control the solar radiation entering the houses, use of thermal mass to moderate the temperature swing and the use of a pitched roof to moderate the indoor temperature at the occupant's level.

Due to the different cultural influences the variety of typologies found in the southern vernacular architecture gave the region a very particular characteristic. This can also explain the lack of a homogenous traditional housing identity, although some patterns, as mentioned, can still be identified.

3.5 Conclusions

Areas covered in this research consist of three cities in southern Brazil: Curitiba, São Paulo and Porto Alegre. They are located in the subtropical climate area and present a moderate climate, with distinct cool and warm seasons. These cities represent areas of major importance in their regions and occupy areas of potential high population density.

Comfort criteria research in housing in Brazil suggests a high level of adaptation to the indoor environment, which is compatible with the adaptive approach. A wide thermal comfort range is acceptable for naturally ventilated buildings in developing countries because people are able to adapt to the environmental changes and also able to acclimatize themselves to a wide range of temperatures. This research has adopted two different comfort thresholds, one varying from 18 to 29 °C and the other one ranging from 20 to 25 °C. The narrow thermal comfort threshold establishes a comparative with the Passivhaus standard and uses a higher degree of acceptability of the occupants with the environment (about 90%). It should be kept in mind that larger temperature swings can still deliver thermal comfort at acceptable levels and avoid the unnecessary use of air conditioning.

Environmental analyses have shown different climatic characteristics of the locations under investigation. Curitiba has more extremes of low temperatures and presents a very low demand for cooling. São Paulo shows more temperature uniformity with the temperatures distribution more often inside the comfort zone when compared to the other locations. Porto Alegre has the most seasonal temperature variation and the temperatures can reach up to 35 K, with a significant demand for both heating and cooling. The cities have a high solar radiation distribution the levels of which, even with a seasonal variation, do not drop too much in the winter period and, consequently, neither do the temperatures. This characteristic suggests the importance of solar control in residential buildings located in these cities, avoiding solar penetration during the warm period.

The analyses of the psychrometric chart suggest passive design strategies for both underheating and overheating in Curitiba, São Paulo and Porto Alegre. The underheating condition can be mitigated mainly through passive solar heating and thermal mass strategies, while overheating can be mainly moderated by thermal mass and ventilation strategies. Well-shaded and ventilated housing in summer and a sunny and sealed housing in winter are the key climate responsive design strategies.

Vernacular housing architecture developed in the areas under investigation revealed an extensive diversity caused by a variety of cultural influences in the region. The southern Brazilian areas were inhabited by immigrants from many different European

locations, which resulted in this melting of architectural housing typologies. Due to this particular occupation, the identity of the region cannot be well-defined. However, some building patterns could be strongly identified in the architecture of the region such as the use of a rectangular plan, pitched roof, medium openings, eaves, wooden windows with blinds and, more recently, the use of ceramic bricks and blocks.

Based on all the investigation carried out so far, the next Chapter explores the optimization of Brazilian housing envelope through a parametric study, which makes use of sensitivity analysis methodology.

CHAPTER 4: PARAMETRIC STUDY USING THE FABRIC FIRST APPROACH

This chapter consists of a parametric study, which investigates means of increasing Brazilian housing indoor thermal comfort and energy efficiency through the optimization of the building envelope, using the Fabric First approach. The parametric approach adopts a simplified typical affordable housing model. The research method uses sensitivity analysis, varying one parameter at a time, undertaken through daynamic building simulations. The parameters of the sensitivity analysis include a selection of different building envelopes, based on typical Brazilian housing construction. The results are analysed according to thermal comfort criteria, mainly through the degree-hours methodology applied for free-running buildings. The outcomes comparatively show the thermal response of different envelope combinations. The findings reveal that the most typical Brazilian housing envelope underperforms in terms of thermal comfort and its adoption could impact on reducing the thermal comfort of the houses by up to 65% when compared to particular optimised envelopes. Higher levels of thermal comfort are likely to be achieved if particular envelopes are selected. The findings show that lower infiltration rate might be highly beneficial for increasing indoor thermal comfort and it increased the thermal comfort by up to 25% in comparison to the most typical envelope used. The findings also support that a degree of insulation compatible to the Passivhaus standard had one of the best performance envelopes among those explored. However, these envelopes might not be suitable for the investigated locations due to its cost, as it could increase to between 40 and 50% of the typical housing cost and have a high payback period beyond the lifespan of the house.

"Buildings […] can be viewed as a way to modify a landscape to create more favourable microclimates. As soon as a simple square hut is built, at least six new microclimates are created: the south side warmed by a sunny wall, the north side in shade most of the time, an east side with its morning sun and perhaps protected from the prevailing breeze, and a west side warmed in the afternoon but buffered by the wind. […] A building increases the available range of thermal zones so that people can select the microclimate most suitable to their thermal needs."
(Heschong, 1979, p. 8).

"Countries with milder climates have, until recently, shown little, if any, interest in achieving airtight construction. The new motivation for more stringent statutory standards is less to do with comfort and more to do with energy use, but the comfort benefits are already well appreciated."
(Cotterel and Dadeby, 2012, p. 126).

"Ventilation should be provided where and when it is needed – not as a huge continuous background infiltration rate."
(RIBA, 2009, p. 6).

4 PARAMETRIC STUDY USING THE FABRIC FIRST APPROACH

A parametric approach is adopted in this chapter as a means of investigating ways of increasing indoor thermal comfort and consequently energy efficiency in Brazilian housing, through the use of the Fabric First approach. The parametric study focused on optimising the housing envelope in three specific locations - Curitiba, São Paulo and Porto Alegre - as discussed earlier in this thesis.

The study consisted of evaluating different envelope combinations, selected initially by its relevance to the Brazilian housing industry. Typical envelopes were changed sequencently up to levels of thermal transmittance values similar to those considered in the Passivhaus standard. A total of 12 different walls, 3 different roofs and 3 different glazing types were considered in the investigation.

The parametric study was analysed though the sensitivity analysis method, in which one parameter varied each time while the others were kept fixed. Sensitivity analysis outcomes allow a critical understanding about the most sensitive parameter considered. The sensitivity analysis was undertaken through the use of dynamic building simulations, which were performed using a dynamic thermal simulation software and reliable climate data of the cities investigated.

The investigation scope was limited to affordable housing typology, which as described in Chapter 2, corresponded to a compact 1-floor-2-bedroom size with a form factor equivalent to less compact detached houses. The model adopted was simplified in order to reduce the variables involved in the investigation and to better understand the influence of the envelope. The simulation model incorporated specific characteristics of Brazilian housing such as windows, pitched roof, roof eaves and room height.

The dynamic building simulations consisted of 2 different cases - Base Case and Case 1, which vary a degree of envelope infiltration. The cases were investigated under typical patterns of use in affordable Brazilian houses: extensive use of ventilation, significant internal gains due to the high occupancy and shading due to the eaves. For each case, a total of 108 different building envelope combinations were evaluated for each city investigated, which resulted in 648 dynamic building simulations conducted.

The results of the dynamic building simulations were analysed in terms of indoor thermal comfort, mainly using the methodology of degree-hours. The adopted limits of comfort temperature, as explained in Chapter 3, considered the narrow Passivhaus standard comfort limit of 20-25 °C and the wide Brazilian comfort criteria of 18-29 °C.

4.1 Simulation Scope and Method

The parametric study consisted of investigating a combination of different building envelopes for affordable Brazilian houses in 3 main cities of southern Brazil - Curitiba, São Paulo and Porto Alegre. The study used a representative model of an affordable housing typology and also adopted typical patterns and conditions of use in these houses, such as internal gains due to the occupancy and extensive use of natural ventilation. The investigation criterion was determined by indoor thermal comfort, mainly due to the number of degree-hours at a specific comfort temperature range.

The research scope was to examine comparatively the resultant performance of a typical Brazilian housing envelope and a Fabric-First-approach-based envelope, mainly as a result of decreasing thermal transmittance and limiting air permeability rate of the building envelope. The research also investigated the best performing envelope combination among those investigated. Furthermore, the study also explored the technical feasibility of the implementation of the Fabric First approach under typical Brazilian housing patterns.

The parametric study used the method of sensitivity analyses, which was carried out using dynamic building simulations. In order to ensure reliable results from the simulations, the dynamic simulation software and the weather data file was carefully selected, as shown in Sections 1.1.2 and 3.3, respectively.

Sensitivity analysis seems to be a relevant method to understand the development of specific design strategies as it helps identify the influence of each input and its impact on the overall output (Rodrigues, 2009). It assists the designer and the applied researcher in the recognition of the most effective optimization strategy to be adopted to a specific context (Pisello et al., 2012). In the sensitivity analyses carried out, the simulation model had the building envelope components modified each time together with the change in the infiltration rate in order to evaluate the best performing envelope combinations among those investigated in terms of indoor thermal comfort.

The research hypothesis considered that the typical Brazilian envelope may underperform with regard to the delivey of an indoor thermally comfortable environment. As well as this, the increase of the building envelope thermal resistance and reduction of infiltration could increase the indoor thermal comfort and, consequently, the energy efficiency in typical affordable houses, under typical conditions of use. The analyses aimed to address the following questions:

i. Do the typical affordable Brazilian housing envelopes perform satisfactorily in terms of delivering thermal comfort when compared to other envelope combinations of higher thermal resistance properties?

ii. Do the insulated and airtight envelopes, based on the Fabric First concepts, deliver more thermal comfort when compared to the typical envelopes, considering the affordable housing typology and its typical conditions of use?
iii. What is the effect of the reduction of envelope infiltration in the affordable house typology under the typical regime of use?
iv. What is the envelope combination that delivers more indoor thermal comfort, considering the affordable house typology and its typical conditions of use?
v. What is the envelope combination that was shown to be the most cost-benefit?

The envelope combinations investigated in the present research are revealed in detail in the next section.

4.2 Simulation Parameters

The building construction elements used in the simulations were selected because they are mostly used in the affordable houses construction and also widely employed in other housing typology such as medium class standard house.

The methodology adopted consisted of undergoing a degree of improvement to the typical selected envelopes in order to meet similar levels as those achieved by the Passivhaus standard. This improvement corresponded to the reduction of the thermal transmittance values of the building envelope elements, mainly through the addition of thermal insulation products for the opaque elements. For transparent elements, the degree of improvement was ensured by the use of efficient glazing elements, which reduce thermal transmittance.

The use of thermal insulation products reduces the heat transfer through the structure against which, or in which, it is installed (BS EN ISO 9229, 2007). The advantages of using these products are related with reduced cooling or heating need, reduced internal temperature fluctuation, reduced condensation risk and reduced envelope weight when compared with other materials of similar thermal properties (ASHRAE, 2009b).

A considerable variety of thermal insulation products is currently available on the market. Products such as mineral wools (rock and glass wools) and expanded polystyrene (EPS) are examples greatly employed in building envelope components. Both are flexible components as they can be applied externally to the wall envelope or in the wall cavity and also used in roof structures. The selection of a thermal insulation type is related to its suitability, composition, environmental and health aspects (i.e. harmful substance emissions, disposal), installation, maintenance, durability and thermal properties (IBO - Austrian Institute for Healthy and Ecological Building, 2009).

In Brazil, the use of thermal insulation products in residential buildings is still far behind its use in European residential buildings. Only a few residential buildings in Brazil use insulation materials and these materials are mostly placed in the roof areas. Reflective insulation materials are those mostly used, promoted by the new energy building regulation and their low costs. The use of insulation products in wall areas are, however, much more limited when compared to its use in the roof areas. Moreover, the suitability of insulation materials for residential use is more limited than in others such as industrial and commercial use, which may be due to the lack of a strict thermal performance criterion and the lack of concern by the builders and owners with the indoor thermal comfort delivered.

Insulation products such as EPS are the most commonly employed in the Brazilian construction industry due to its characteristics: low thermal conductivity, lightweight, durability, fire resistance and easy handling (ABRAPEX and PINI, undated). EPS can be used as roof insulation and also as an external layer or in cavity walls. Mineral wools are also greatly used in Brazilian construction both internally and externally in the walls and also in roofs and floors, and they can be found in different formats (i.e. quilt, panels).

4.2.1 Wall Construction Types

The most common Brazilian wall construction type in dwellings is ceramic bricks covered by mortar (Oliveira et al., 2009). Ceramic bricks and blocks are vastly employed in the construction and they can be found as part of a load and non-load-bearing masonry. Ceramic bricks are regulated by the national standards NBR 7170 (ABNT, 1983a) and NBR 8041 (ABNT, 1983b), which set ceramic solid brick for masonry and determine its dimension, respectively. Ceramic hollow blocks are regulated by the standards NBR 15270-1 (ABNT, 2005f) and NBR 15270-2 (ABNT, 2005g) which set the requirements for non-load-bearing and for load bearing use, respectively. Table 4-1 shows the brick and block types and dimensions. As can be seen from Table 4-1, ceramic solid bricks and hollow blocks are manufactured in different modular dimensions, which vary with its use (Correa, 2012). However, it should be noted that bricks and blocks that slightly deviate from those dimensions showed in Table 4-1 can be found on the Brazilian market.

Table 4-1: Ceramic brick and block types and dimensions. Based on ABNT (1983a, p. 2), ABNT (1983b, p. 1), ABNT (2005f, p. 6-7), ABNT (2005g, p. 4)

Ceramic brick and block types	Width (cm)	Height (cm)	Length (cm)
Solid ceramic brick	9	5.7	19
		9	
Hollow ceramic block for non-load-bearing masonry	9	9	19
			24
		14	19
			24
			29
		19	19
			24
			29
			39
	11.5	11.5	24
		14	24
		19	19
			24
			29
	14	19	19
			24
			29
			39
	19	19	19
			24
			29
			39
	24	24	24
			29
			39
Structural hollow ceramic block for load-bearing masonry	11.5	11.5	24
		19	24
			29
			39
	14	19	29
			39
	19	19	29
			39

A minimum wall total thickness of 23 cm was considered for this sensitivity analysis, which is a common thickness adopted for robust external walls in Brazil. This is a minimum reference value when the external walls are adopted as a load-bearing masonry (Prefeitura Municipal de Porto Alegre, 2001, p. 25). Both solid and hollow ceramic bricks were considered in the study. The disadvantage of using solid ceramic brick instead of hollow ceramic block is due to the cost and weight but the advantage is related to the thermal mass of the material, which is roughly calculated to be 38% higher than the hollow block, based on ABNT (1980, p. 2). Whilst the solid ceramic brick has a density of 1800 Kg/m^3, the hollow ceramic block has a density around 1300 Kg/m^3 (ABNT, 1980, p. 2).

For the sensitivity analysis, the following walls were considered with different levels of insulation. At first, wall construction types as typically found in Brazil were considered, without the use of insulation materials. These walls have U-values not higher than 2.5 W/m²K, as this value is the limit established by the Brazilian standard NBR 15575 (ABNT, 2013d, p. 27). Insulation was progressively added on the walls until the Passivhaus standard level was met, with U-value equal or less than 0.15 W/m²K. Intermediate insulation levels were also adopted, since they have shown to be a better

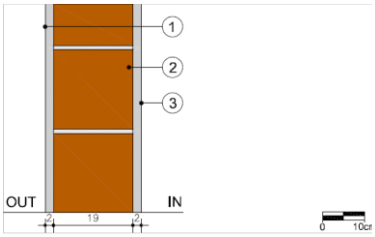
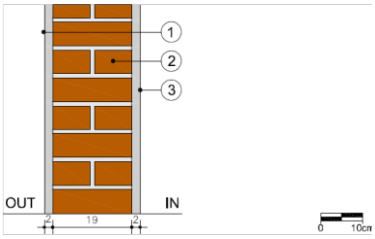
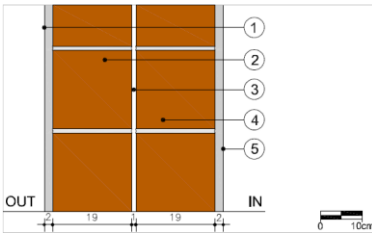
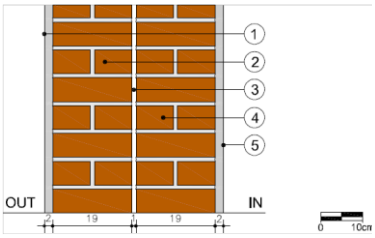
approach for warmer climates such as those climates found in southern Europe, as discussed in Chapter 1.

With that in mind, twelve different wall construction types were selected for the simulations, as can be seen from Table 4-2:

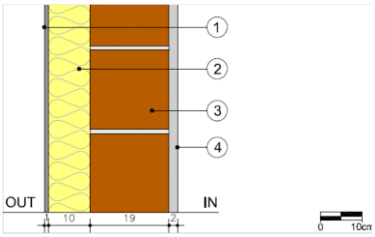
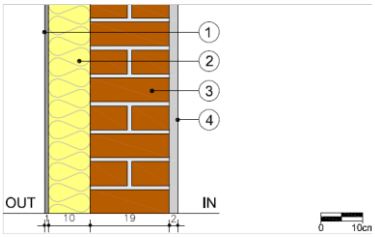
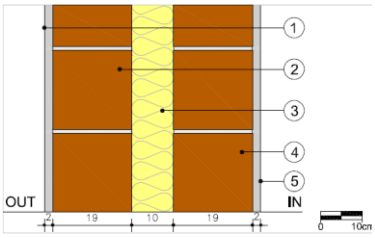
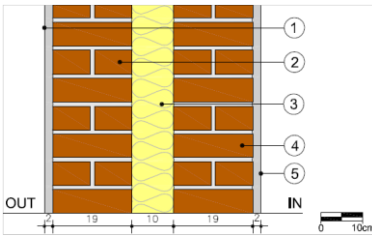
i. Hollow ceramic block wall, uninsulated (HBU);
ii. Solid ceramic brick wall, uninsulated (SBU);
iii. 2-layers hollow ceramic block wall, uninsulated (2HBU);
iv. 2-layers solid ceramic brick wall, uninsulated (2SBU);
v. Hollow ceramic block wall, insulated (HBI);
vi. Solid ceramic brick wall, insulated (SBI);
vii. 2-layers hollow ceramic block wall, insulated (2HBI);
viii. 2-layers solid ceramic brick wall, insulated (2SBI);
ix. Hollow ceramic block wall, extra insulated (HBIE);
x. Solid ceramic brick wall, extra insulated (SBIE);
xi. 2-layers hollow ceramic block wall, extra insulated (2HBIE);
xii. 2-layers solid ceramic brick wall, extra insulated (2SBIE).

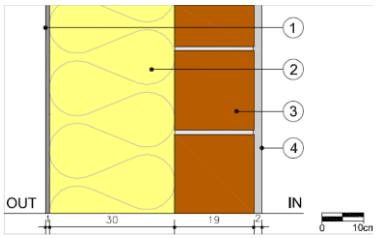
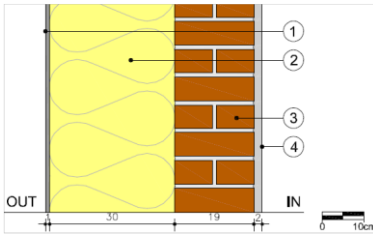
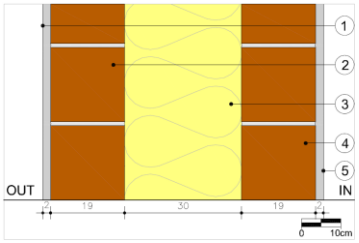
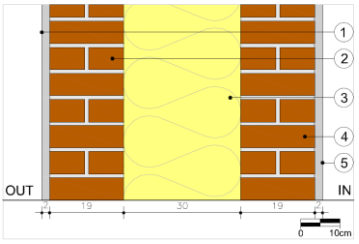
The thermal properties of the constructions elements were calculated wih the use of Dynamic Thermal Properties Calculator tool (Arup, 2010).

Table 4-2: Wall construction types

Wall construction types (thickness and layers)	Thermal properties	Section
i. Hollow ceramic block wall, uninsulated (HBU) Total thickness:230 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Hollow ceramic block (19 x 19 x 29 cm) 20 mm Lime cement plaster	**U-value** (W/m²K): 2.40 **Admittance** (W/m²K): 4.72 **Decrement factor** (0-1): 0.59 **Time Lag** (hours): 5.75	
ii. Solid ceramic brick wall, uninsulated (SBU) Total thickness:230 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Solid ceramic brick (9 x 5.7 x 19 cm) 3. 20 mm Lime cement plaster	**U-value**[28] (W/m²K): 2.50 **Admittance** (W/m²K): 5.02 **Decrement factor** (0-1): 0.49 **Time Lag** (hours): 6.58	
iii. 2-layers hollow ceramic block wall, uninsulated (2HBU) Total thickness: 430 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Hollow ceramic block (19 x 19 x 29 cm) 3. 10 mm air cavity (for building up purposes) 4. 190 mm Hollow ceramic block (19 x 19 x 29 cm) 5. 20 mm Lime cement plaster	**U-value** (W/m²K): 1.29 **Admittance** (W/m²K): 4.88 **Decrement factor** (0-1): 0.19 **Time Lag** (hours): 12.01	
iv. 2-layers solid ceramic brick wall, uninsulated (2SBU) Total thickness: 430 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Solid ceramic brick (9 x 5.7 x 19 cm) 3. 10 mm Air cavity (for building up purposes) 4. 190 mm Solid ceramic brick (9 x 5.7 x 19 cm) 5. 20mm Lime cement plaster	**U-value** (W/m²K): 1.36 **Admittance** (W/m²K): 5.10 **Decrement factor** (0-1): 0.12 **Time Lag** (hours): 13.60	

[28] The U-values refers to homogenous layers of the building components. The effect of thermal bridges was not taken into account in the U-value calculation.

Wall construction types (thickness and layers)	Thermal properties	Section
v. Hollow ceramic block wall, insulated (HBI) Total thickness: 320 mm Layers from outside to inside: 1. 10 mm Silicate plaster 2. 100 mm EPS hard foam 3. 190 mm Hollow ceramic brick (19 x 19 x 29 cm) 4. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.34 **Admittance** (W/m²K): 4.99 **Decrement factor** (0-1): 0.25 **Time Lag** (hours): 7.92	
vi. Solid ceramic brick wall, insulated (SBI) Total thickness: 320 mm Layers from outside to inside: 1. 10 mm Silicate plaster 2. 100 mm EPS hard foam 3. 190 mm Solid ceramic brick (9 x 5.7 x19 cm) 4. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.35 **Admittance** (W/m²K): 5.15 **Decrement factor** (0-1): 0.19 **Time Lag** (hours): 8.61	
vii. 2-layers hollow ceramic block wall, insulated (2HBI) Total thickness: 520 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Hollow ceramic brick (19 x 19 x 29 cm) 3. 100 mm EPS 4. 190 mm Hollow ceramic brick (19 x 19 x 29 cm) 5. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.29 **Admittance** (W/m²K): 4.99 **Decrement factor** (0-1): 0.10 **Time Lag** (hours): 14.33	
viii. 2-layers solid ceramic block wall, insulated (2SBI) Total thickness: 520 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Solid ceramic brick (9 x 5.7 x19 cm) 3. 100 mm EPS 4. 190 mm Solid ceramic brick (9 x 5.7 x19 cm) 5. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.29 **Admittance** (W/m²K): 5.15 **Decrement factor** (0-1): 0.06 **Time Lag** (hours): 15.76	

	Wall construction types (thickness and layers)	Thermal properties	Section
ix.	**Hollow ceramic block wall, extra insulated (HBIE)**, based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 98) Total thickness: 520 mm Layers from outside to inside: 1. 10 mm Silicate plaster 2. 300 mm EPS[29] hard foam 3. 190 mm Hollow ceramic brick (19 x 19 x 29 cm) 4. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.13 **Admittance** (W/m²K): 4.99 **Decrement factor** (0-1): 0.21 **Time Lag** (hours): 10.37	
x.	**Solid ceramic brick wall, extra insulated (SBIE)**, based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 96,98) Total thickness: 520 mm Layers from outside to inside: 1. 10 mm Silicate plaster[30] 2. 300 mm EPS hard foam 3. 190mm Solid ceramic brick (9 x 5.7 x 19 cm) 4. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.13 **Admittance** (W/m²K): 5.14 **Decrement factor** (0-1): 0.16 **Time lag** (hours): 11.03	
xi.	**2-layers hollow ceramic block wall, extra insulated (2HBIE)**, based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 102) Total thickness: 720 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Hollow ceramic brick (19 x 19 x 29 cm) 3. 300 mm EPS 4. 190 mm Hollow ceramic brick (19 x 19 x 29 cm) 5. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.11 **Admittance** (W/m²K): 4.99 **Decrement factor** (0-1): 0.07 **Time Lag** (hours): 18.56	
xii.	**2-layers solid ceramic block wall, extra insulated (2SBIE)**, based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 102) Total thickness: 720 mm Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 190 mm Solid ceramic brick (9 x 5.7 x19 cm) 3. 300 mm EPS 4. 190 mm Solid ceramic brick (9 x 5.7 x19 cm) 5. 20 mm Lime cement plaster	**U-value** (W/m²K): 0.11 **Admittance** (W/m²K): 5.14 **Decrement factor** (0-1): 0.04 **Time Lag** (hours): 19.96	

[29] EPS for facades: density of 18 Kg/m^3, thermal conductivity of 0.04 W/mK, specific heat capacity of 1450 J/kgK and water vapour diffusion of 1. p. 330. IBO - AUSTRIAN INSTITUTE FOR HEALTHY AND ECOLOGICAL BUILDING 2009. *Details for Passive Houses.,* Vienna, Austria, Springer Vienna Architecture.

[30] Silicate plaster is a fire-proof coating applied at external surfaces for protecting thermal insulation layers. The silicate plaster thermal properties are: density of 1800 Kg/m^3, thermal conductivity of 0.8 W/mK, specific heat capacity of 1120 J/kgK and water vapour diffusion of 35. p. 331. Ibid.

Figure 4-1 shows the dynamic thermal properties of the walls. The admittance of solid brick walls was higher than hollow block walls due to its higher ability to store heat. As expected, the addition of insulation material did not impact significantly on the admittance value. The decrement factor showed a reduction of the thermal amplitude peak through the adoption of high thermal mass walls such as those with a double layer. Also, the decrement factor was reduced with the use of insulation materials that retard the heat exchange when compared to the corresponding walls without insulation.

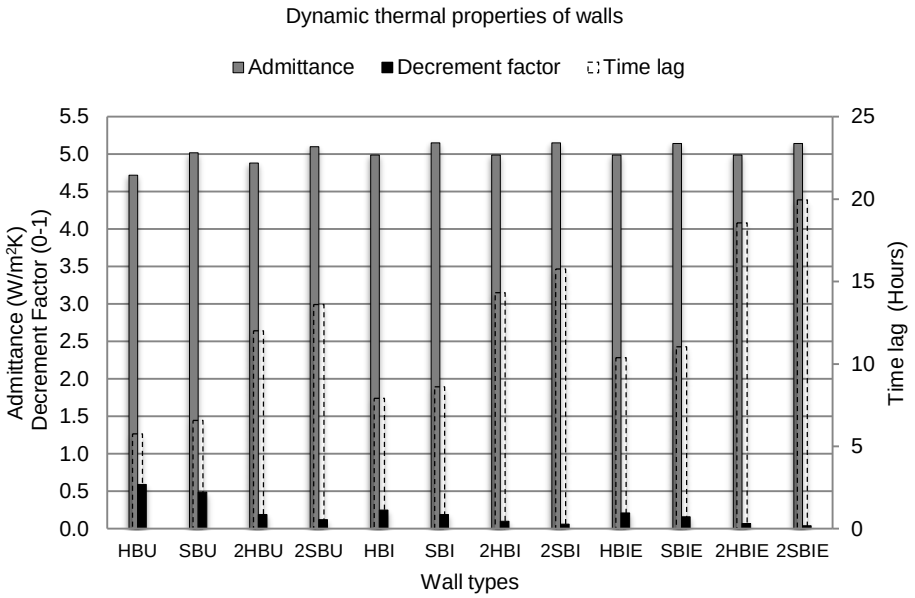


Figure 4-1: Dynamic thermal properties of walls

4.2.2 Roof Construction Types

The most typical roof construction in Brazilian dwellings is made out of ceramic roof tiles with a timber structure, as mentioned in Chapter 2. The roof pitch is based on the main ceramic roof tile types such as Roman, French and Colonial roof tile styles. Their inclinations mostly vary between 30% and 45%[31].

The ceiling can vary significantly according to the architectural solutions desired. A pitched ceiling can create a more interesting architectural effect inside the building and it works as a buffer space, mitigating the temperature extremes at occupant levels. Furthermore, a high ceiling tends to increase the spacious sensation inside the affordable buildings.

[31] More information can be found at http://piniweb.pini.com.br/construcao/noticias/qual-o-caimento-inclinacao-mais-adequado-para-cada-tipo-de-83983-1.aspx [Accessed on 13 July 2015]

For the current research, the roof structure dimensions were considered as typically found in Brazilian houses. Progressively, different degrees of insulation were placed between the roof structures. The insulation materials were placed in the roof areas following the Passivhaus construction component catalogue method, shown in a study called IBO - Austrian Institute for Healthy and Ecological Building (2009). The catalogue is a collection of construction solutions for buildings that meet Passivhaus standard, which were selected from documented and built objects available in central Europe.

The roof was initially built up with a reflective insulation material as it meets the U-value limit of 1.5 W/m²K established by the Brazilian standard NBR 15575 (ABNT, 2013e, p. 27)[32]. Insulation was then added between the roof timber structure to meet the Passivhaus standard level of U-value equal to or smaller than 0.15 W/m²K. An intermediate insulation level was also adopted because this was shown to have better results in warmer climates such as those found in southern Europe, as mentioned in Chapter 1. The ceiling was considered to be pitched as this is also the strategy of the research case studies, shown in Chapters 5 and 6.

It should be noted that reflective insulated roofing is becoming widely employed in Brazil because it meets the Brazilian building energy regulation at a very low cost. It uses aluminium foil, which is a reflective material that is able to reduce the downward thermal radiation transfer due to its low emissivity coefficient.

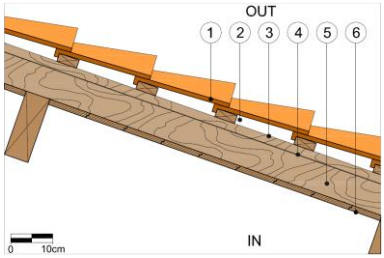
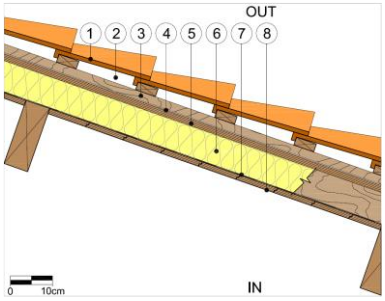
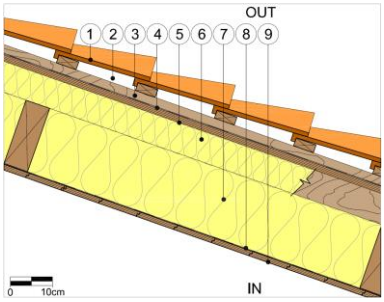
With that in mind, four different roof construction types were selected for the simulations, as can be seen from Table 4-3:

i. Aluminium sheet steeply-pitched roof, reflective insulated (PAI);
ii. Mineral wool steeply-pitched roof, insulated (PMI);
iii. 2-layer Mineral wool steeply-pitched roof, insulated (2PMI).

The thermal properties of the constructions elements were calculated wih the use of Dynamic Thermal Properties Calculator tool (Arup, 2010).

[32] The roof U-value refers to the downward heat flow.

Table 4-3: Roof construction types

Roof construction types (thickness and layers)	Thermal prop. heat flow direction: Up/down(ward)[33]	Section
i. Aluminium foil steeply-pitched roof (PAl) Total thickness: 133.15 mm Layers from outside to inside: 1. 10 mm clay roof tile 2. Lathes 20 x 50mm; ventilation bet cross-lathing 3. Rafters 20 x 50 mm; ventilation bet cross-rafters 4. 0.15 mm Aluminium foil 5. Rafters 70 x 50 mm; air bet cross-rafters 6. 12 mm Timber ceiling	**U-value** (W/m²K): 0.90 **Admittance** (W/m²K): 1.11/ 1.04 **Decrement factor** (0-1): 1.00/ 0.99 **Time Lag** (hours): 0.54/ 0.68	
ii. Mineral wool steeply-pitched roof (PMI), based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 134, 136) Total thickness: 149 mm Layers from outside to inside: 1. 10 mm clay roof tile 2. Lathes 20 x 50 mm; ventilation bet cross-lathing 3. Rafters 20 x 50 mm; ventilation bet cross-rafters 4. Open diffusion roofing sheet (wind tight) 5. 16 mm Wood fibre[34] 6. 70 mm Mineral wool panels[35] bet cross-rafters 7. Vapour barrier 8. 12 mm Timber ceiling; bet horizontal-lathes	**U-value** (W/m²K): 0.41/ 0.39 **Admittance** (W/m²K): 0.85/ 0.83 **Decrement factor** (0-1): 0.97/ 0.96 **Time Lag** (hours): 1.62/ 1.87	
iii. 2-layers mineral wool steeply-pitched roof (2PMI), based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p.134, 136) Total thickness: 309 mm Layers from outside to inside: 1. 10 mm clay roof tile 2. Lathes 20 X 50 mm; ventilation bet cross-lathing 3. Rafters 20 x 50 mm; ventilation bet cross-rafters 4. Open diffusion roofing sheet (wind tight) 5. 16 mm Wood fibre 6. 70 mm Mineral wool panels bet cross-rafters 7. 160 mm Mineral wool panels bet horiz-lathes 8. Vapour barrier 9. 12 mm Timber ceiling	**U-value** (W/m²K): 0.15 **Admittance** (W/m²K): 0.88/ 0.87 **Decrement factor** (0-1): 0.88/ 0.86 **Time Lag** (hours): 3.84/ 4.16	

[33] Upward heat flow direction is considered for winter, while downward is considered for summer. ABNT 2005c. NBR 15220-3: Thermal performance in buildings - Part 3: Brazilian bioclimatic zones and building guidelines for low-cost houses. Rio de Janeiro, Brazil: Associação Brasileira de Normas Técnicas (ABNT).

[34] Wood fibre: density of 270 kg/m³, thermal conductivity of 0.05 W/mK, specific heat capacity of 2000 J/kgK, water vapor diffusion of 5. p. 330. IBO - AUSTRIAN INSTITUTE FOR HEALTHY AND ECOLOGICAL BUILDING 2009. *Details for Passive Houses.,* Vienna, Austria, Springer Vienna Architecture.

[35] Mineral wool (clamping felt between rafters): density of 33 kg/m³, thermal conductivity of 0.04 W/mK, specific heat capacity of 1030 J/kgK, water vapour diffusion of 1. p. 331. Ibid.

Figure 4-2 shows the dynamic thermal properties of the roofs. The thermal admittance of the roof elements is relatively uniform, only slightly higher for the roof with reflective insulation. This is certainly due to the surface resistance of the aluminium foil element, which reduces the rate of heat flow through the element.

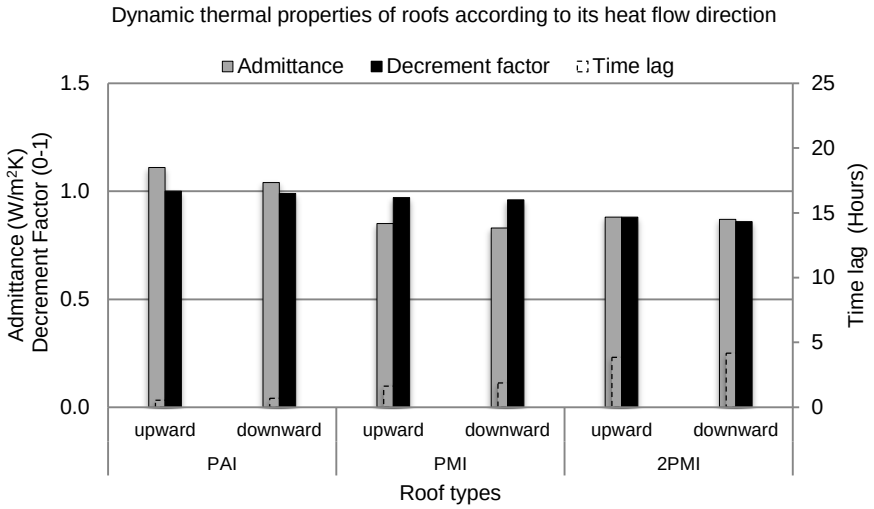


Figure 4-2: Dynamic thermal properties of roofs

4.2.3 Glazing and Window Frame Construction Types

The glazing and window frame type mostly used in Brazilian dwellings seem to be single glazing with timber frame. Timber is one of the most traditional materials used in frames in dwellings and it is responsible for 36% of the overall national windows market (Dos Reis, 2011).

Window frames for low- and lower-middle-income properties are made of steel, aluminium and timber, whereas house window frames for middle-income properties are built predominantly with timber (Sattler, 2007, p. 75-76). Although the aluminium window frame is widely adopted in affordable houses, its frame is narrow and has high conductance due to the inefficient use of frame spacers and so this frame type is less efficient thermally than those built out of wood. The PVC window frame that is generally more airtight and uses efficient frame spacers, still has limited use due to its cost and it is mostly adopted for high-income households (Tachinardi, 2001).

For the current research, because the Brazilian building energy regulations do not recommend any glazing and frame construction type in buildings, the starting point was to consider the use of the most typical glazing – single glazing. The glazing variation consisted of the use of double glazing with and without coating. Double coated glazing (or glazing of low emissivity) was recommended by the Passivhaus study (Schnieders et al., 2012, p. 463, Hopfe and McLeod, 2015, p. 81-82) as an appropriate transparent

element solution for southern Brazil. The benefit of this glazing type is related to its visual transparency and also to its reflectivity to the solar radiation wave (CIBSE, 2006b).

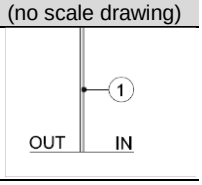
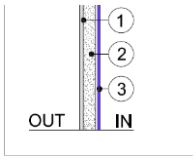
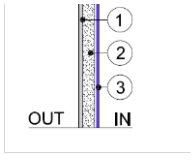
It should be stressed that the use of double glazing in Brazil is more related to acoustics issues than thermal issues, and its use is limited to residential buildings of middle and high income.

For the frame, timber frame was adopted because it has lower heat conductivity[36] than other metal frames used in affordable dwellings such as aluminium and steel. Timber frame is also widely employed for middle-class windows housing, which extends the spectrum of the current research investigation.

With that in mind, three different glazing and frames types were investigated. These glazing and frame type combinations are shown in Table 4-4. The glazing thermal properties were defined according to the glazing construction based on TAS dabase (EDSL, 2013a) and CIBSE (2006b, p. 3-21).

i. Single transparent glazing + wooden frame (SGU);
ii. Double uncoated glazing, air filled + PVC frame (DGU);
iii. Double coated glazing, argon filled + PVC frame (DGC).

Table 4-4: Glazing and frame types

Glazing and frame type[37] (thickness and layers)	**Thermal properties**	**Section** (no scale drawing)
i. Single transparent glazing + timber frame (SGU) Total thickness: 4 mm Layers from outside to inside: 1. 4mm single glazing	**U-value** (W/m^2K) 5.75 **g-value** (W/m^2K) 0.84	
ii. Double uncoated glazing, air filled + PVC frame (DGU) Total thickness: 20 mm Layers from outside to inside: 1. 4mm single glazing 2. 12mm air filled spacing 3. 4mm single glazing	**U-value** (W/m^2K) 2.85 **g-value** (W/m^2K) 0.73	
iii. Double coated glazing, argon filled + PVC frame(DGC) Total thickness: 20 mm Layers from outside to inside: 1. 4mm coated glazing (e-low) 2. 12mm argon filled spacing 3. 4mm single glazing	**U-value** (W/m^2K) 1.42 **g-value** (W/m^2K) 0.58	

[36] The thermal conductivity of wood varies between 0.12 to 0.29 W/mK. p. 15. ABNT 2005b. NBR 15220-2: Thermal performance in buildings - Part 2: Calculation methods of thermal transmittance, thermal capacity, thermal delay and solar heat factor of elements and components of buildings. Rio de Janeiro, Brazil: Associação Brasileira de Normas Técnicas (ABNT).

[37] Linear thermal transmittance of wood and PVC frames are estimated to be around 0.06 W/mK for double or triple uncoated glazing and 0.08 W/mK for double or triple low-emissivity glazing. The thermal conductivity of the glazing is estimated to be around 1.0 W/mK. p. 3-22 CIBSE 2006b. Environmental Design: Guide A. London, United Kingdom: The Chartered Institution of Building Services Engineers (CIBSE).

4.2.4 Ground Floor Construction Type

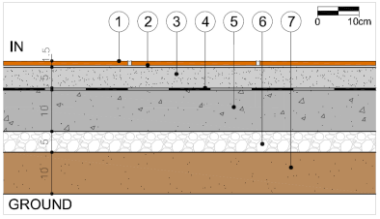
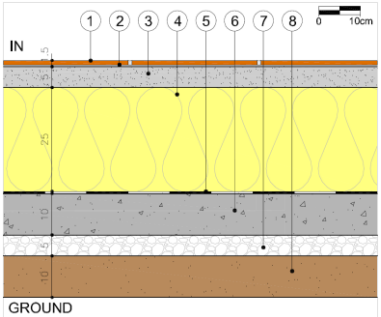
The most typical ground floor construction element in Brazilian dwellings is solid and its base is made out of concrete. The ground floor layer structure system is established by the Brazilian standard NBR 15575 (ABNT, 2013c, p. 4). This standard, however, does not define the minimum thickness of the components nor the minimum U-values requirements. Most affordable houses' ground floors are built as minimal, which means reduced concrete slab thickness and supressed cement screed for floor regularization.

For the present analysis, two ground floor construction types were considered: a typical Brazilian houses' ground floor (with standard dimensions as typically found) and an insulated ground floor. The insulated ground floor followed the same Brazilian ground floor structure but it uses insulation. The construction of the insulated ground floor was based on IBO - Austrian Institute for Healthy and Ecological Building (2009) and aimed to achieve U-values according to the Passivhaus standard level. The ground floor construction types considered are shown in Table 4-5.

i. Solid ground floor, uninsulated;
ii. Solid ground floor, insulated.

The ground floor construction types were tested for all the cities investigated and the best performance floor was adopted in the simulations.

Table 4-5: Ground floor construction types

Ground floor (thickness and layers)	**Thermal Properties** Up/down(ward)	**Section**
i. Solid ground floor, uninsulated, based on (ABNT, 2013c, p. 4) Total thickness: 315 mm Layers from inner to ground: 1. 10 mm Ceramic tile 2. 5 mm Adhesive mortar for sticking ceramic tiles 3. 50 mm Cement screed 4. Waterproof layer 5. 100 mm Concrete slab 6. 50 mm Stone chipping (drainage layer) 7. 100 mm Soil	**U-value** (W/m²K): 2.90/ 2.41 **Admittance** (W/m²K): 6.12/ 4.33 **Decrement factor** (0-1): 0.29/ 0.25 **Time Lag** (hours): 8.97/ 9.31	
ii. Solid ground floor, insulated, based on IBO - Austrian Institute for Healthy and Ecological Building (2009, p. 40,42) Total thickness: 565 mm Layers from inner to ground: 1. 10 mm Ceramic tile 2. 5 mm Adhesive mortar for sticking ceramic tiles 3. 50 mm Cement screed 4. 250mm EPS 5. Waterproof layer 6. 100 mm Concrete slab 7. 50 mm Stone chipping 8. 100 mm Soil	**U-value** (W/m²K): 0.13 **Admittance** (W/m²K): 6.18/ 4.56 **Decrement factor** (0-1): 0.12/ 0.09 **Time Lag** (hours): 15.22/16.03	

4.3 Simulation Parameters Matrix

Based on the construction elements investigated, the simulation parameters matrix was defined in Table 4-6. Please note that each simulation was named as shown in the table and its numbering (1 to 108) will be used to show the results. A detailed description of each building envelope combination can be found in Appendix A.

Table 4-6: Simulation parameters matrix (codes based on Table 4-2,Table 4-3 and Table 4-4)

	Walls/Roof	PAI		PMI		2PMI
SGU glazing	HBU	001	SGU/HBU/PAI*	013	SGU/HBU/PMI	025	SGU/HBU/2PMI
	SBU	002	SGU/SBU/PAI	014	SGU/SBU/PMI	026	SGU/SBU/2PMI
	2HBU	003	SGU/2HBU/PAI	015	SGU/2HBU/PMI	027	SGU/2HBU/2PMI
	2SBU	004	SGU/2SBU/PAI	016	SGU/2SBU/PMI	028	SGU/2SBU/2PMI
	HBI	005	SGU/HBI/PAI	017	SGU/HBI/PMI	029	SGU/HBI/2PMI
	SBI	006	SGU/SBI/PAI	018	SGU/SBI/PMI	030	SGU/SBI/2PMI
	2HBI	007	SGU/2HBI/PAI	019	SGU/2HBI/PMI	031	SGU/2HBI/2PMI
	2SBI	008	SGU/2SBI/PAI	020	SGU/2SBI/PMI	032	SGU/2SBI/2PMI
	HBIE	009	SGU/HBIE/PAI	021	SGU/HBIE/PMI	033	SGU/HBIE/2PMI
	SBIE	010	SGU/SBIE/PAI	022	SGU/SBIE/PMI	034	SGU/SBIE/2PMI
	2HBIE	011	SGU/2HBIE/PAI	023	SGU/2HBIE/PMI	035	SGU/2HBIE/2PMI
	2SBIE	012	SGU/2SBIE/PAI	024	SGU/2SBIE/PMI	036	SGU/2SBIE/2PMI**

	Walls/Roof	PAI		PMI		2PMI
DGU glazing	HBU	037	DGU/HBU/PAI*	049	DGU/HBU/PMI	061	DGU/HBU/2PMI
	SBU	038	DGU/SBU/PAI	050	DGU/SBU/PMI	062	DGU/SBU/2PMI
	2HBU	039	DGU/2HBU/PAI	051	DGU/2HBU/PMI	063	DGU/2HBU/2PMI
	2SBU	040	DGU/2SBU/PAI	052	DGU/2SBU/PMI	064	DGU/2SBU/2PMI
	HBI	041	DGU/HBI/PAI	053	DGU/HBI/PMI	065	DGU/HBI/2PMI
	SBI	042	DGU/SBI/PAI	054	DGU/SBI/PMI	066	DGU/SBI/2PMI
	2HBI	043	DGU/2HBI/PAI	055	DGU/2HBI/PMI	067	DGU/2HBI/2PMI
	2SBI	044	DGU/2SBI/PAI	056	DGU/2SBI/PMI	068	DGU/2SBI/2PMI
	HBIE	045	DGU/HBIE/PAI	057	DGU/HBIE/PMI	069	DGU/HBIE/2PMI
	SBIE	046	DGU/SBIE/PAI	058	DGU/SBIE/PMI	070	DGU/SBIE/2PMI
	2HBIE	047	DGU/2HBIE/PAI	059	DGU/2HBIE/PMI	071	DGU/2HBIE/2PMI
	2SBIE	048	DGU/2SBIE/PAI	060	DGU/2SBIE/PMI	072	DGU/2SBIE/2PMI**

	Walls/Roof	PAI		PMI		2PMI
DGC glazing	HBU	073	DGC/HBU/PAI*	085	DGC/HBU/PMI	097	DGC/HBU/2PMI
	SBU	074	DGC/SBU/PAI	086	DGC/SBU/PMI	098	DGC/SBU/2PMI
	2HBU	075	DGC/2HBU/PAI	087	DGC/2HBU/PMI	099	DGC/2HBU/2PMI
	2SBU	076	DGC/2SBU/PAI	088	DGC/2SBU/PMI	100	DGC/2SBU/2PMI
	HBI	077	DGC/HBI/PAI	089	DGC/HBI/PMI	101	DGC/HBI/2PMI
	SBI	078	DGC/SBI/PAI	090	DGC/SBI/PMI	102	DGC/SBI/2PMI
	2HBI	079	DGC/2HBI/PAI	091	DGC/2HBI/PMI	103	DGC/2HBI/2PMI
	2SBI	080	DGC/2SBI/PAI	092	DGC/2SBI/PMI	104	DGC/2SBI/2PMI
	HBIE	081	DGC/HBIE/PAI	093	DGC/HBIE/PMI	105	DGC/HBIE/2PMI
	SBIE	082	DGC/SBIE/PAI	094	DGC/SBIE/PMI	106	DGC/SBIE/2PMI
	2HBIE	083	DGC/2HBIE/PAI	095	DGC/2HBIE/PMI	107	DGC/2HBIE/2PMI
	2SBIE	084	DGC/2SBIE/PAI	096	DGC/2SBIE/PMI	108	DGC/2SBIE/2PMI**

* refers to the highest U-value in the matrix.
** refers to the lowest U-value in the matrix.

The next section shows the simulation model adopted in the simulations conducted.

4.4 Base Case Simulation Model

The simulation model was built with the aim of being as representative as possible of the affordable Brazilian houses. The dimensions of the model were defined based on the literature review, discussed in Chapter 2.

The literature review in affordable houses showed that their areas can vary a little. For a 2-bedroom house, the national standard NBR 12721 (ABNT, 2006) estimated a typical built area of 58.64 m^2 for a low standard house (R1-B, Low Standard Single-family House, in English). However, the affordable housing typology for the lowest income population such as the MCMV typology is found with a smaller area than those of typical affordable houses. The requirements of the MCMV programme, updated in 2014, regulated minimum liveable conditions in these residential buildings. The programme established that the minimum useful internal areas of the affordable houses must be bigger than 36 m^2 (Ministério das Cidades, 2014b). For this useful internal area of 36 m^2, the internal floor area including the typical internal walls was estimated to be approximately 39.19 m^2. Moreover, the built area including the external walls was calculated to be approximately 45.15 m^2. As this research deals mostly with affordable houses for low-income households, the MCMV house area was adopted in the current research as the reference value for affordable house in Brazil. The optimum reference value was considered as being the typical built area of low standard house of 58.64 m^2, with an internal area estimated to be approximately 51.70 m^2.

Table 4-7 shows specific areas of affordable houses and their dimensions for a square plan reference.

Table 4-7: Areas and dimensions of affordable houses

House typology	Built area (m^2)	Internal area (m^2)	External square plan dimensions (m)	Internal square plan dimensions (m)
Low standard house	58.64	51.70	7.65x7.65	7.19x7.19
MCMV house	45.15	39.19	6.72x6.72	6.26x6.26

The walls were estimated to be 23 cm, which is a value established for walls that are more likely to achieve U-values within the limits set by the regulation NBR 15575 (ABNT, 2013d).

The simulation model was defined with a pitched roof with an inclination of 35%, which is compatible with most roof tiles (e.g. Roman, Portuguese, French roof tiles) available on the Brazilian market The minimum internal height of the house was defined to be not lower than 2.50 m, based on the national standard NBR 15575 (ABNT, 2013a, p. 35).

The minimum dimensions of the MCMV house plan combined with the minimum internal height of the roof as described above were calculated to have a form factor of approximately 4.3. This form factor turned out to be representative of a typical affordable Brazilian house and it is equivalent to a less compact detached house. If the

dimensions of the typical low standard house were adopted with the minimum internal height requirement, the form factor would still be similar with a value around 4.1. This shows that there is a certain similarity in the form factors of affordable Brazilian houses. The uniformity of the form factor might suggest that the results from the minimum house dimensions of the MCMV typology would be applicable for other low standard houses of the same typology (1-floor-2-bedroom house) and similar characteristics, given the small range of the form factors.

The fenestration areas of the simulation model were defined based on typical fenestration areas of affordable houses. Fenestrations in affordable houses tend to be small to medium size and comply with the minimum requirements of local the building codes. This is mainly due to the cost that a window can add to the construction. For example, the cost of a masonry wall built out of 19 cm of hollow block was estimated to be about 55 Brazilian reais per square metre in 2015 and the cost of a sliding timber window was estimated to be 515 Brazilian reais per square metre (564 Brazilian reais for a sliding aluminium window)[38], which is about 10 times more than masonry (PINI, 2015b). Typical window areas of affordable houses that can be found in the market mainly vary from approximately 1.0 to 2.00 m^2 [39].

The fenestration areas of the simulation model met the minimum glazing percentage requirement of the building codes for the cities investigated (Curitiba, São Paulo and Porto Alegre), which corresponded to 1/6 (16.66%) of the internal areas of the housing (Prefeitura Municipal de São Paulo, 1992, p. 52, Prefeitura Municipal de Porto Alegre, 2001, p. 74, Prefeitura Municipal de Curitiba, 2013, p. 209). Hence, the fenestration areas were calculated to be 6.54 m^2 for a reference internal area of 39.19 m^2.

The fenestration areas of the simulation model were optimised as much as possible, considering common practices and existing regulations. The fenestrations were placed along the north and south facade in order to better control the solar radiation. The regulation of the affordable houses in Brazil – MCMV regulation (Ministério das Cidades, 2014b) - sets out that the windows of the bedrooms must not be smaller than 1.50 m^2 while the living room windows cannot be smaller than 2.00 m^2. Hence, lower window requirements were assumed to be south oriented, resulting in a total area of 3.00 m^2 in this direction. The remaining window area of 3.54 m^2 was assumed to be north-oriented in order to maximise the passive solar benefit.

[38] Prices based on the city of São Paulo.

[39] Typical dimensions are (in cm): 120x100, 120x120, 150x100, 150x120, 200x100 and 200x120. Dimensions obtained on the retail market in stores in Porto Alegre, Curitiba and São Paulo. More information can be found at http://www.leroymerlin.com.br/isolamento-de-teto [Accessed on 20th May 2015]. https://www.leroymerlin.com.br/janelas-de-correr [Accessed on 20th May 2015].

In order to be more realistic, all the glazing areas were distributed according to the number of windows and dimensions commonly found in the affordable houses. The north windows had their dimensions slightly adjusted to typical trading standard window dimensions for affordable house standards found in the Brazilian market.

The simulation model is shown in Figure 4-3.

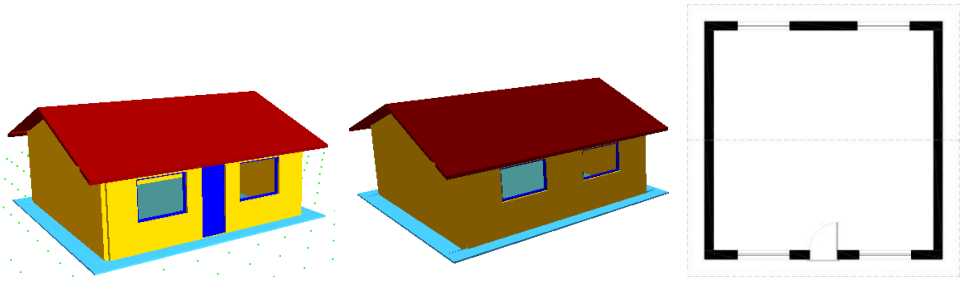


Figure 4-3: 3D TAS simulation model: north facade (left), south facade (middle) and plan (right)

The ventilation areas were also defined complying with the local building codes. The building codes set out that ventilation areas must correspond to at least half of the glazing area, which meant 1/12 (8.33%) of the internal floor area (Prefeitura Municipal de São Paulo, 1992, p. 52, Prefeitura Municipal de Porto Alegre, 2001, p. 74, Prefeitura Municipal de Curitiba, 2013, p. 209). However, the Brazilian standard NBR 15220 (ABNT, 2005c) suggests that the ventilation areas for the cities investigated should be between 15% and 25% of the floor area. Based on this recommendation, all the windows of the simulation model were assumed as capable of opening to all their dimensions in order to meet the thermal comfort recommendation of the standard NBR 15220 (ABNT, 2005c). Window ventilation was assumed as a function of the indoor temperature. It was limited for summer and mid-season, while in winter the windows were assumed closed at all times.

As mentioned in Chapter 3, eaves are common and recognised building elements in the southern Brazilian housing architecture. They protect the walls from rain and sun, resulting in some shading on the glazing elements. The regulation of the most affordable house requires that the eaves have to have at least 50 cm salience (Ministério das Cidades, 2014b).

Combining the minimum eaves dimension required and the window designed for the north facade, the resultant shading for the window would correspond to a VSA (vertical shadow angle) of 71° in Curitiba. It should be stressed that this relationship is only applicable for this specific window with its window height. The eaves' shading, however, is not sufficient to provide the required shading. The shading for temperate climates is recommended to cut-off at the equinox period (Szokolay, 2008, p. 68). Because of that, an additional horizontal shading element was used on the north facade

to complement the amount of shading required. The VSA angles were calculated to be 64.57°, 66.15° and 59.97º for Curitiba, São Paulo and Porto Alegre to equinox cut-off.

It was believed, however, that Curitiba would not need the same amount of shading as the other cities because of its having a cool-moderate climate, with temperatures lower than São Paulo and Porto Alegre. However, looking at the environmental analysis, as shown in Chapter 3, the shading would be at least required for January and February, which are the months with higher temperatures, although March also has considerably high temperatures. Limiting the shading for these months would mean a VSA angle of 77.35°, which is already addressed by the eaves. In other words, this suggests that for the city of Curitiba, the eaves shading would cut-off between 1st March and 20th March. Therefore, in order to have more control of the shading all the cases were adopted to equinox cut-off.

Figure 4-4 shows the shading effect due to the eaves. Figure 4-5 illustrates the additional horizontal shading element to have shading adjusted to equinox cut-off. Figure 4-6 shows in detail the effect of the shading device on blocking the solar radiation at the equinox. Please note that the corresponding shading coefficients are indicated in the Figures.

The simulation model is summarised in Table 4-8.

Table 4-8: Simulation model summary

Assumptions	Description
Typology	Equivalent to 1-floor 2-bedroom house size.
Internal Dimensions	6.26x6.26 m
Internal area	39.19 m^2
Internal height	Variable, ≥ 2.50 m
Form factor	approximately 4.3, compatible with less compact detached house.
Fenestrations	16.66% of internal floor area of the house, calculated to be 6.54 m^2. 3.00 m^2 on the south facade and 3.54 m^2 on the north facade. Fenestration areas were adjusted according to the traded dimensions.
Ventilation	Windows can fully open.
Shading	Shading is provided by the eaves of minimum mandatory length of 50 cm, with a minimum VSA angle of 71°. Additional horizontal shading devices are placed on the north windows for a cut-off at the equinox. The resultant VSA angles correspond to 64.57°, 66.15° and 59.97° for Curitiba, São Paulo and Porto Alegre, respectively.

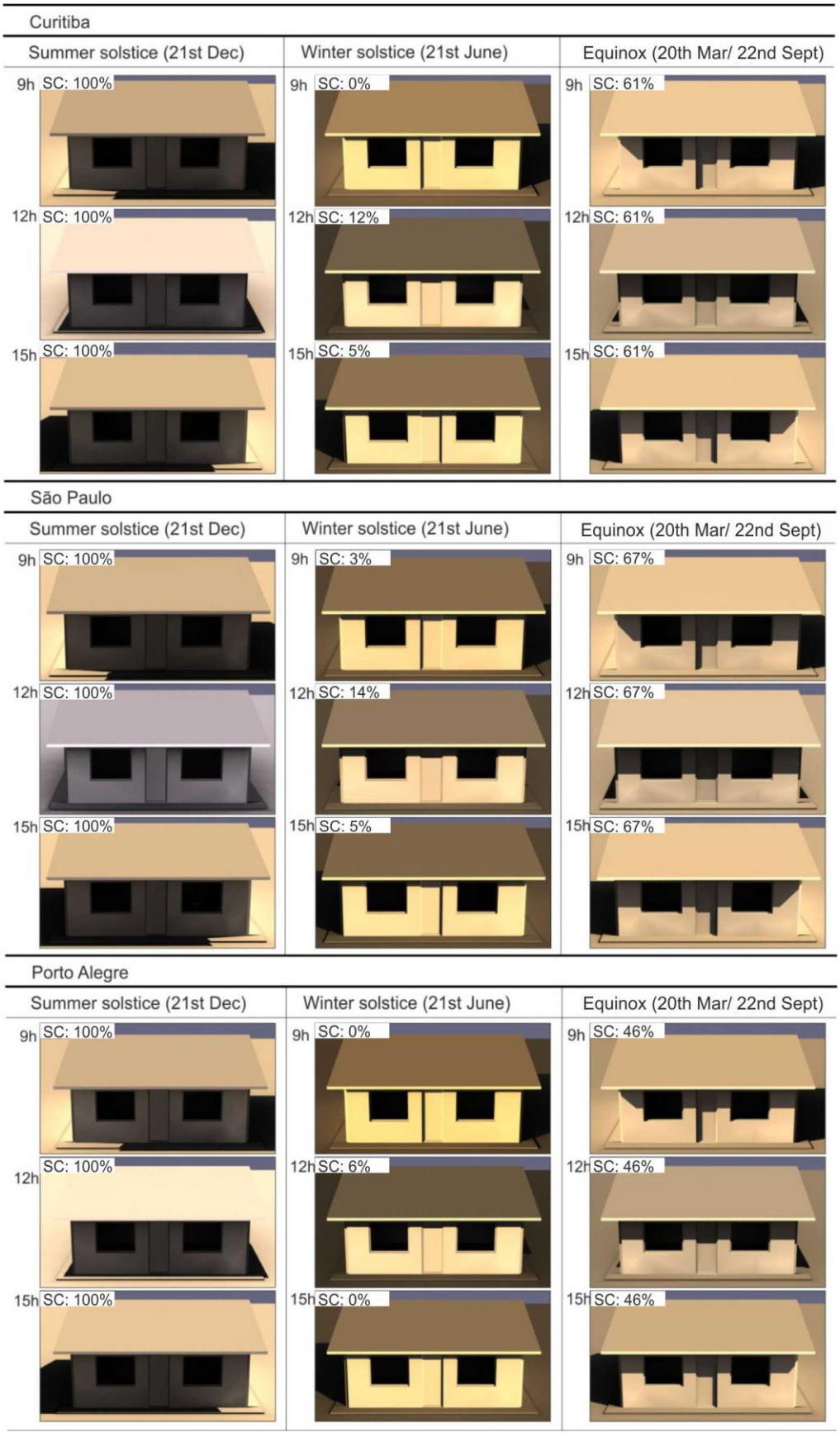


Figure 4-4: Shading effect due to the eaves

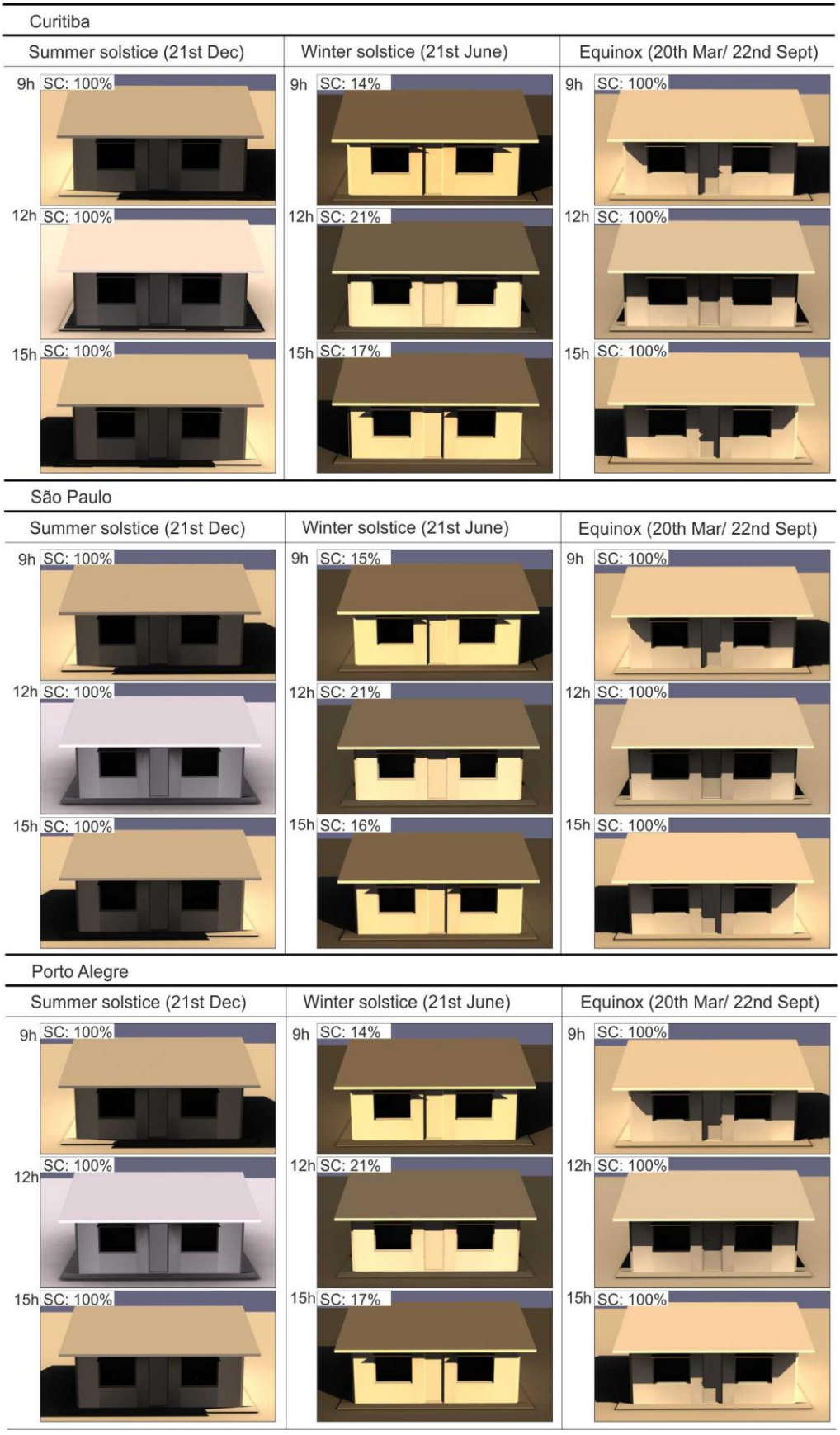


Figure 4-5: Shading adjusted to cut-off at the equinox

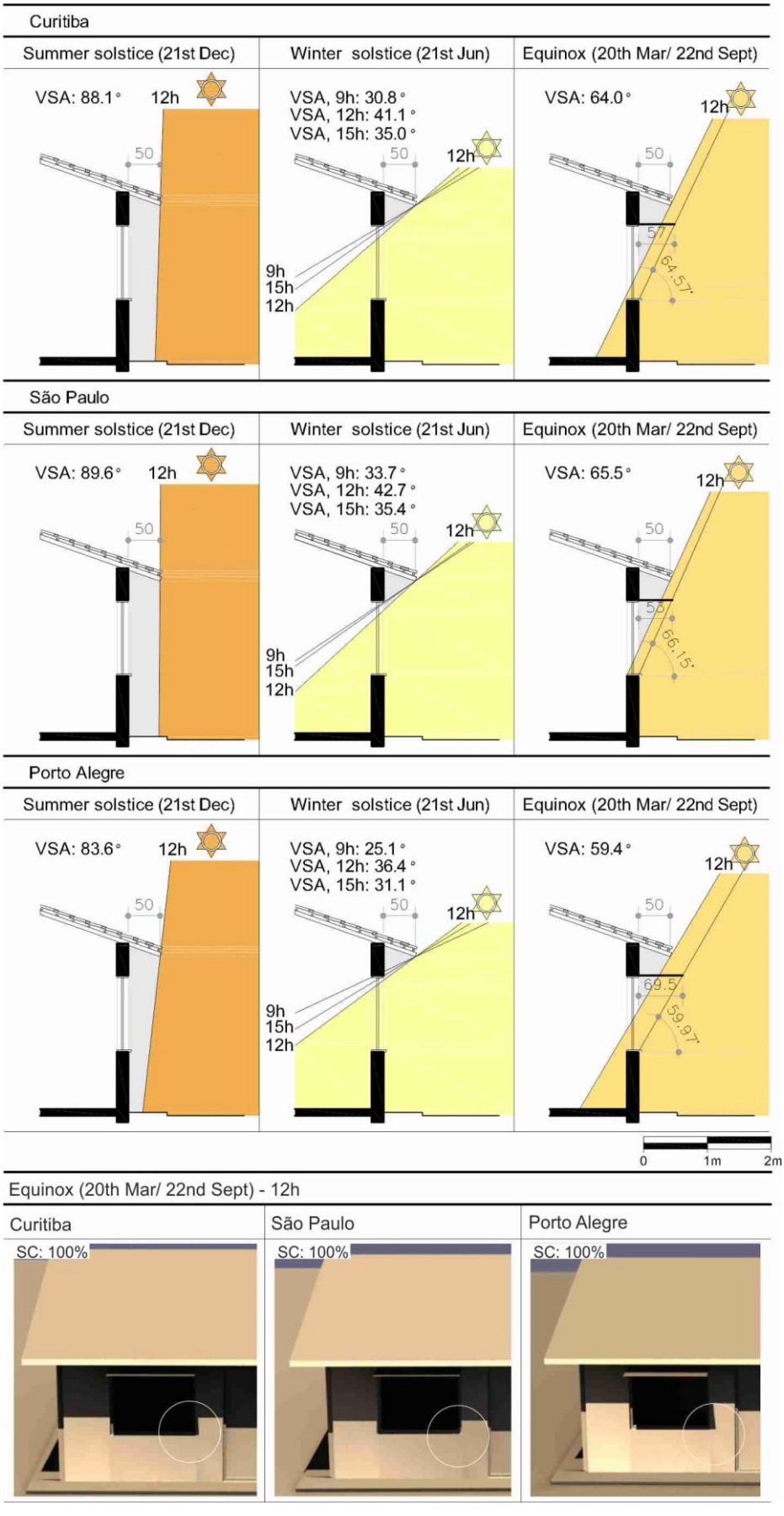


Figure 4-6: Shading device effect due to cut-off at the equinox

4.4.1 Assumptions

The assumptions considered the building model as much as possible to real operation of the affordable Brazilian houses. The main aspects considered in the simulations were the intense use of natural ventilation, high internal gains due to the full occupancy of the house and the lack of active heating or cooling systems.

Many input parameters in dynamic simulation represent quantities that are difficult to be defined because they vary widely with the lifestyle of the house occupants and so assumptions were adopted:

i. Ventilation: All windows were assumed to be opened 100% when the indoor temperatures are higher than external temperatures and closed when the external temperatures exceed the internal ones. The windows started to be opened at 23 ºC and are fully opened when the temperature achieve the upper comfort limit of 25 °C. The ventilation was designed exclusively for summer and mid-season. In winter, when the temperatures are low, the windows were assumed closed at all times.

ii. Internal gains: The house was assumed with a full occupancy as this is the way that affordable houses are commonly occupied. As the affordable house represents a 2-bedroom typology, 4 people were estimated to live in the house. The activity was assumed to vary between seated at rest (95W) and sedentary work (130W) (ASHRAE, 2009a, p. 18.4). The schedule adopted for occupancy considered different routines in weekdays and at the weekend and this is detailed in Appendix A. Lighting was assumed to be 5 W/m^2 for a specific schedule (INMETRO, 2012, p. 71). Kitchen appliances were assumed with a daily energy consumption of 1.9 kWh, compatible with the use of limited Brazilian housing appliances – fridge, microwave, iron and washing machine (INMETRO, 2014, PROCEL INFO, 2006). A TV (30W) was assumed to be turned on for a specific schedule (INMETRO, 2014). The internal gains due to occupancy, lighting and equipment were calculated to be 11.7 W/m^2.

iii. Infiltration: An infiltration of 1 air change per hour at atmospheric pressure was assumed in the simulation as suggested by the Brazilian standard NBR 15575 (ABNT, 2013d, p. 26).

iv. Thermal zones: The simulation model was built with two thermal zones, as shown by Figure 4-7. Thermal zone at occupant level was placed up to 2.5 m. Thermal zone at ceiling level was placed above 2.5 m of height and under the ceiling and it consisted of a buffer space. The division of the model into two thermal zones allowed identifying in detail the temperatures at liveable levels and also explore the difference of the temperatures between the zones due to a specific envelope adoption. In particular, although the thermal zone at

occupant level have a temperature variation across the volume, which might offer a certain margin of error, this variation is deemed acceptable and so, one zone was adopted as it would facilitate the tabulation of the data analysis.

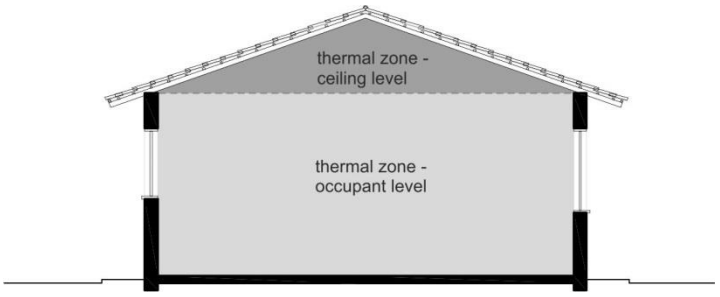


Figure 4-7: Base Case thermal zones

v. Heating or Cooling: No active space conditioning was assumed in the simulations, as affordable houses are mostly naturally ventilated.

vi. Comfort temperature: As indicated in Chapter 3, two thermal comfort intervals were considered - a narrow thermal comfort range of 20-25 °C and a wide thermal comfort range of 18-29 °C.

vii. Calendar: According to the climate analyses of Chapter 3, summer was considered to be from December to March and winter was considered to be from May to September. Mid-season was assumed to be the months of April, October and November.

viii. Weather data: The weather data was based on the weather dataset compiled by Roriz (2012b)

Table 4-9 summarizes the Base Case simulation model assumptions.

Table 4-9: Summary of Base Case simulation model assumptions

Assumptions	Description
Ventilation	The ventilation was designed for summer and mid-season. All windows were assumed to be fully opened when the indoor temperatures achieved the upper comfort limit of 25 °C. Windows were closed when the external temperatures exceeded the internal ones.
Internal gains	The internal gains due to the occupancy, lighting and equipment were calculated to be 11.7 W/m^2. This value was calculated for a 2-bedroom typology and based on the assumptions of a family routine and lifestyle of 4 people.
Infiltration	Infiltration of 1 air change per hour at atmospheric pressure was assumed in the simulation (ABNT, 2013d, p.26).
Thermal zones	Two thermal zones were assumed: one placed at occupant level and the other placed at ceiling level.
Heating or Cooling	No active space conditioning was assumed in the simulations.
Calendar	Summer: from December to March; Winter: from May to September. Mid-season was assumed to be the months of April, October and November.
Comfort temperature	Thermal comfort range of 20-25 °C and 18-29 °C were considered.
Weather data	Weather dataset compiled by Roriz (2012b).

4.4.2 Results

The analyses of the variation of the floor component are discussed first, following which the results across different building envelopes are examined in terms of average, minimum and maximum temperature, degree-hours and annual temperature distribution and frequency of temperatures.

Ground Floor

In the first set of simulations, the analysis of the ground floor construction element suggested that the use of a non-insulated ground floor showed better results when compared to the use of an insulated ground floor for all the cities investigated. A non-insulated ground floor construction was responsible for both more uniformity of indoor temperatures and reduction of extremes of temperatures when compared to an insulated ground floor construction.

Figure 4-8, Figure 4-9 and Figure 4-10 depict comparatively the annual temperature distribution of non-insulated and insulated ground floors for the non-insulated envelope, which is also the most typical Brazilian envelope (n° 1). Figure 4-11, Figure 4-12 and Figure 4-13 show the annual temperature distribution of non-insulated and insulated ground floors for the most insulated envelope (n° 108), which has the lowest overall U-value envelope. Figure 4-14, Figure 4-15 and Figure 4-16 illustrate the extreme temperatures across the whole year in Curitiba, São Paulo and Porto Alegre, respectively.

For the non-insulated envelope (n° 1), the temperature distributions between non- and insulated ground floors were similar for all the cities. However, the insulated ground floor showed higher indoor temperature amplitude and it also had the highest and lowest overall temperatures when compared to the typical non-insulated ground floor. In Curitiba, the minimum and maximum temperature of the insulated ground floor were 7.27 °C and 30.56 °C, around 2 K less and more than the non-insulated ground floor, respectively. In São Paulo and Porto Alegre, the maximum temperatures of insulated ground floors were more evident than the minimum temperatures and they reached 31.15 °C and 34.80 °C, compared to 29.84 °C and 32.31 °C of the non-insulated ground floor, respectively.

For the insulated envelope (n° 108), the insulated ground floor caused a significant increase of the indoor temperatures during the summer period beyond the upper comfort temperature limit of 25 °C in São Paulo and Porto Alegre and to a lesser extent in Curitiba. During the winter period, the indoor temperatures of insulated ground floors were similar of those temperatures of non-insulated ground floors, just slightly higher. The minimum temperatures were similar for both ground floor types for each of the

cities. The maximum peak temperatures of insulated ground floors reached 27.11 °C, 28.4 °C and 32.17 °C and were about 3 K, 2 K and 4 K higher than non-insulated ground floors for Curitiba, São Paulo and Porto Alegre, respectively.

In summary, the insulated ground floor construction element created larger indoor temperature amplitude over the year for both insulated and non-insulated envelopes when compared to the other floor type. This higher indoor temperature amplitude was because the ground floor has a large thermal mass but adding insulation causes a barrier to the heat transfer between the house and the ground. For the non-insulated ground floor, however, the high thermal inertia of the construction element allowed the heat to be stored in its structure and to be released to inside the building when the indoor temperature went down, reducing the indoor temperature variation.

Figure 4-17, Figure 4-18 and Figure 4-19 show the degree-hours for each ground floor construction element for both non- and insulated envelopes. As mentioned in Chapter 2, degree-hours consist of the hourly summation of temperature difference between a reference temperature and the temperature investigated, in which the reference temperature named as base temperature, is a reference thermal comfort limit temperature that does not need any heating or cooling systems in order to maintain comfort conditions (CIBSE, 2006a). Degree-hours are shown in detail throughout this chapter. As shown in the Figures, the insulated ground floor increased the indoor thermal discomfort in both non- and insulated envelopes in São Paulo and Porto Alegre. In Curitiba, although the insulated ground floor showed a reduction of the heating degree-hours, it increased the cooling demand for a city that has almost no cooling demand. In addition, the maximum temperatures of the insulated ground floor were much higher than the non-insulated ground floor and it achieved an indoor temperature of up 30° C, which was significantly high for the context of the city of Curitiba.

It should be highlighted that TAS (EDSL, 2013b) calculates the heat flows of the component through the temperatures between surfaces of the component and updates it each time-step to establish linear relationship between current temperature and heat fluxes at the components surfaces. These values are incorporated in a matrix representing the overall heat balance of each zone. The matrix considers the thermal capacitance and resistance of the component layers and it also includes response factor to ensure that thermal mass is fully considered. In the case of the ground floor component, the external surface temperature of the ground floor is assumed to be equal to the groundwater temperature, which is supplied by the weather data.

Uninsulated ground floor construction element performed better for these cities because the ground temperature does not drop significantly in the cities investigated. The yearly average ground temperature in Curitiba, São Paulo and Porto Alegre

corresponds to 17.3 °C, 19.6 °C and 20.0 °C, respectively (Roriz, 2012b). The seasonal variation of ground heat transfer combined with the thermal inertia of the floor element enhances the performance of the earth coupling to the house, minimizing both summer and winter loads.

Therefore, given the results of the ground floor investigation, all the simulations to investigate the rest of the building envelope combination were performed using non-insulated ground floor type. This ground floor, as typically found in Brazilian houses, performed satisfactorily and did not represent any additional cost or change to the Brazilian construction practices.

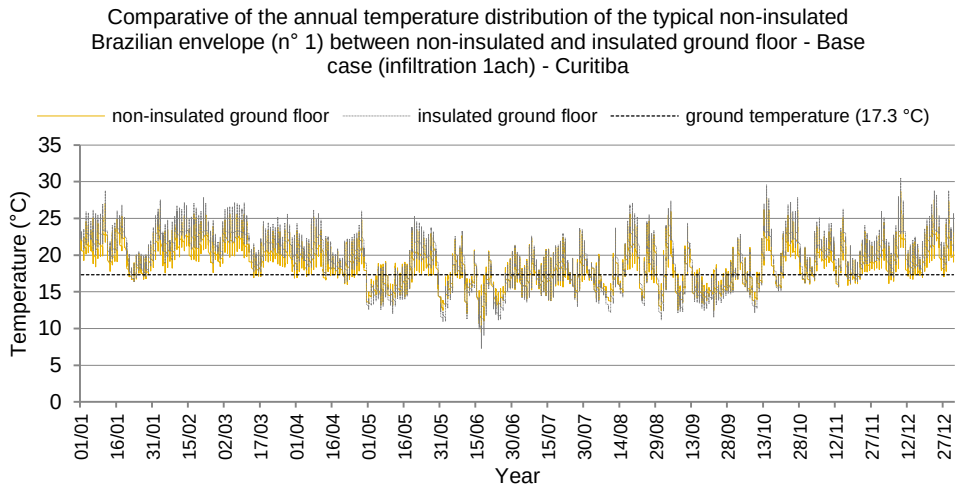


Figure 4-8: Annual internal temperature distribution of the typical non-insulated Brazilian envelope (n° 1) for different ground floor construction types, Base Case, Curitiba

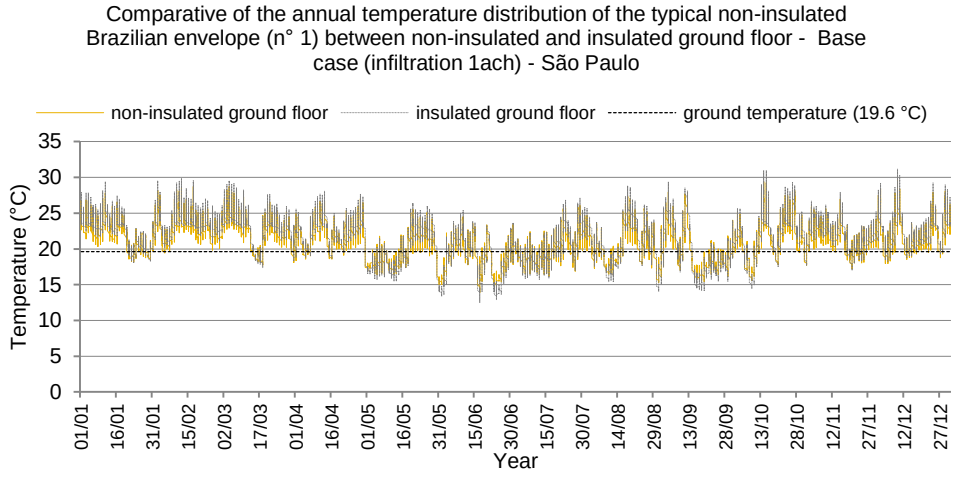


Figure 4-9: Annual internal temperature distribution of the typical non-insulated Brazilian envelope (n° 1) for different ground floor construction types, Base Case, São Paulo

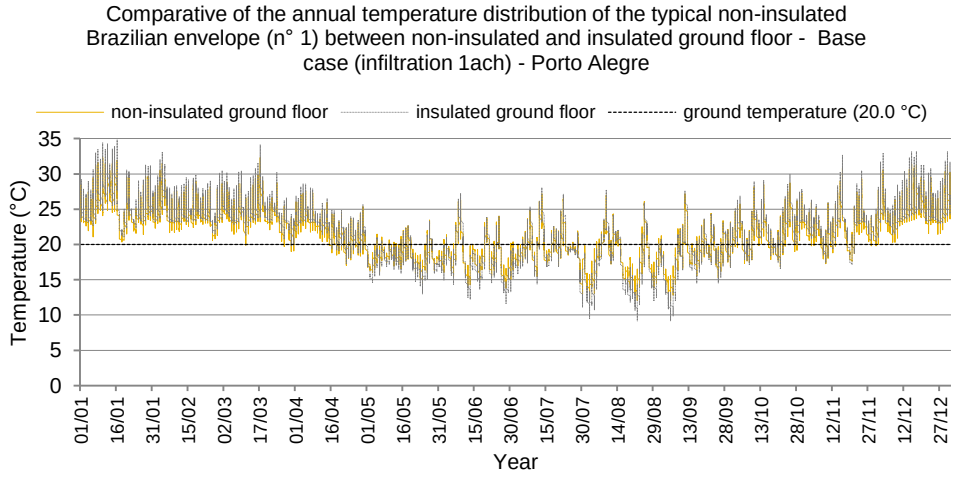


Figure 4-10: Annual internal temperature distribution of the typical non-insulated Brazilian envelope (n° 1) for different ground floor construction types, Base Case, Porto Alegre

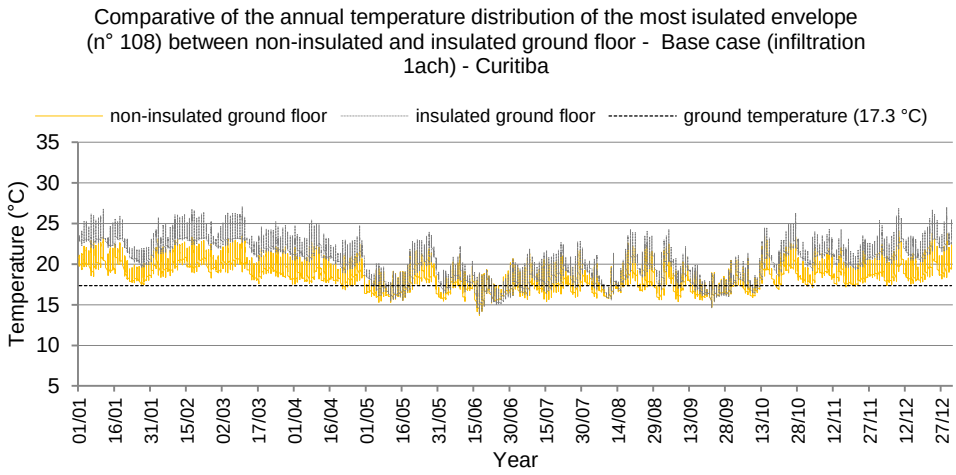


Figure 4-11: Annual internal temperature distribution of the most insulated envelope (n° 108) for different ground floor construction types, Base Case, Curitiba

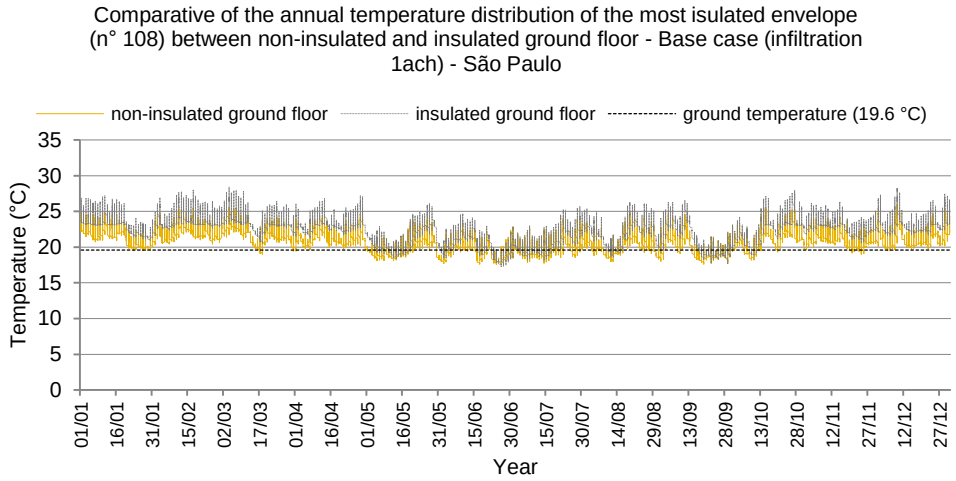


Figure 4-12: Annual internal temperature distribution of the most insulated envelope (n° 108) for different ground floor construction types, Base Case, São Paulo

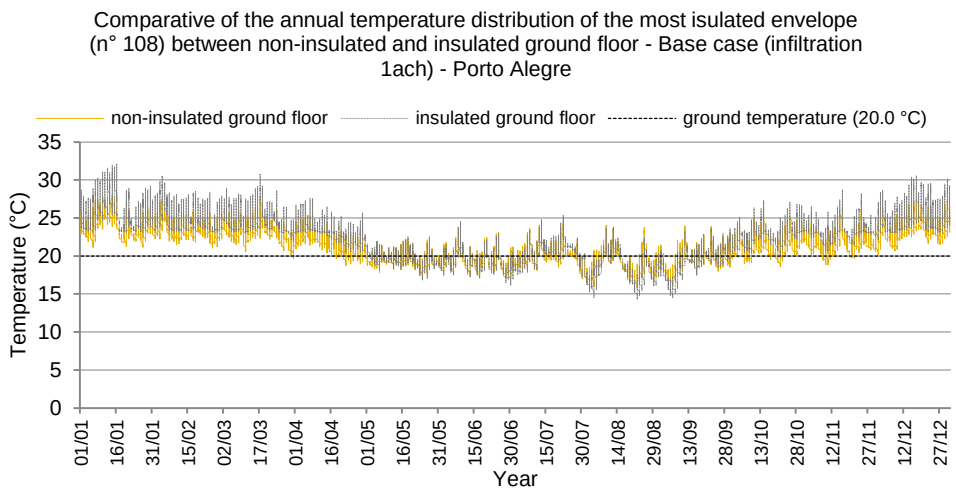


Figure 4-13: Annual internal temperature distribution of the most insulated envelope (n° 108) for different ground floor construction types, Base Case, Porto Alegre

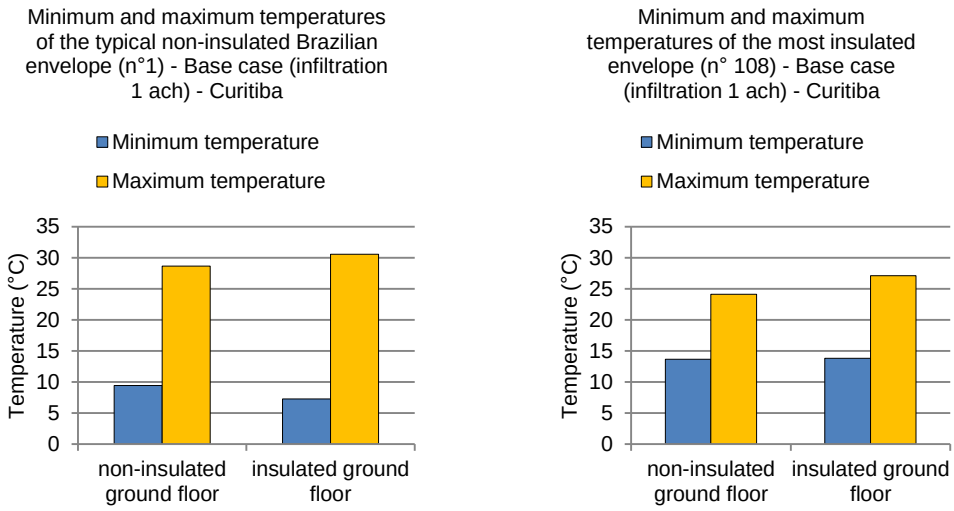


Figure 4-14: Maximum and minimum internal temperatures of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Base Case, Curitiba

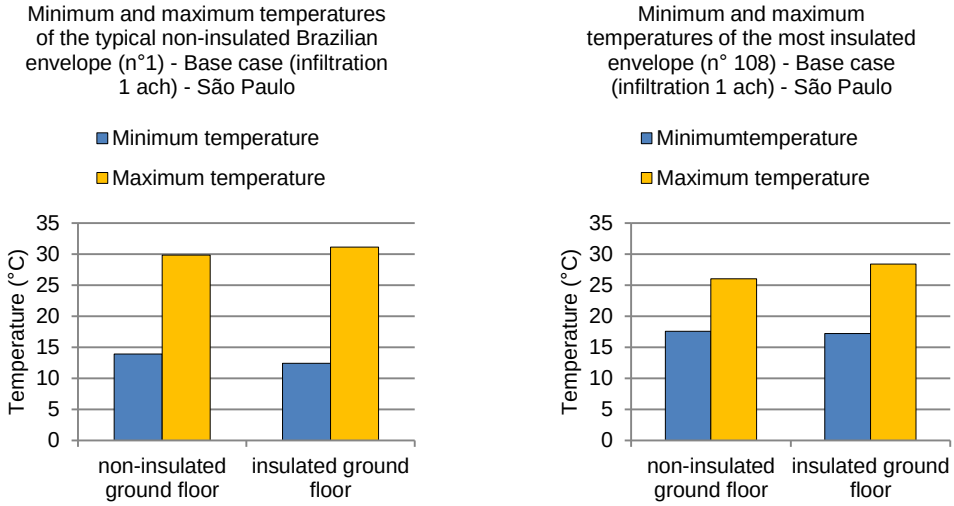


Figure 4-15: Maximum and minimum internal temperatures of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Base Case, São Paulo

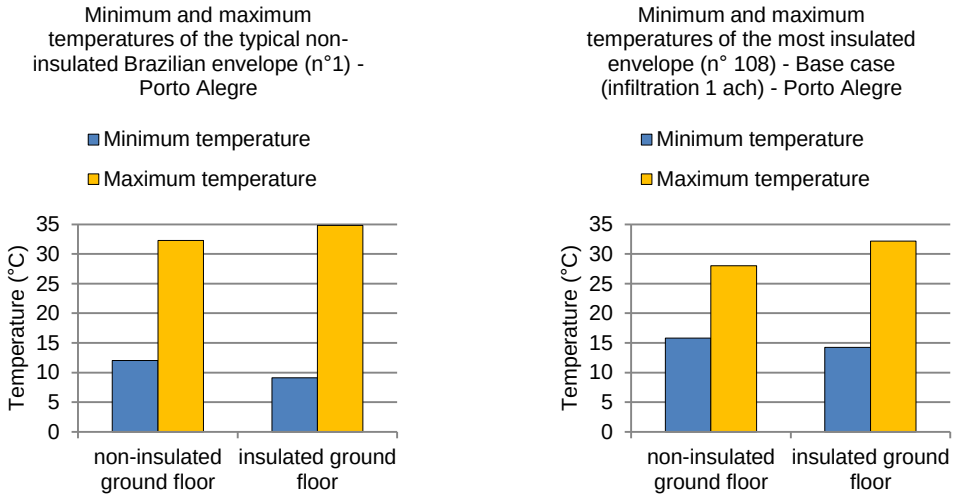


Figure 4-16: Maximum and minimum internal temperatures of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Base Case, Porto Alegre

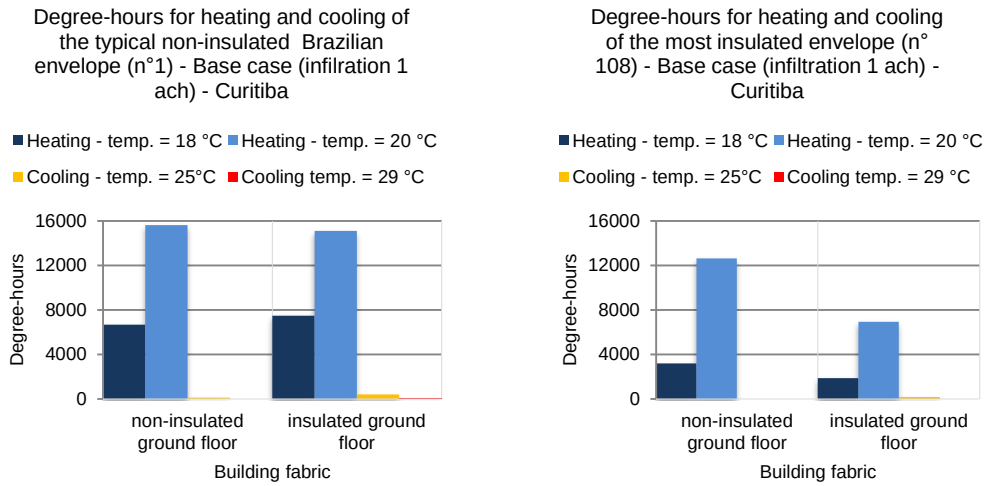


Figure 4-17: Degree-hours of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Base Case, Curitiba

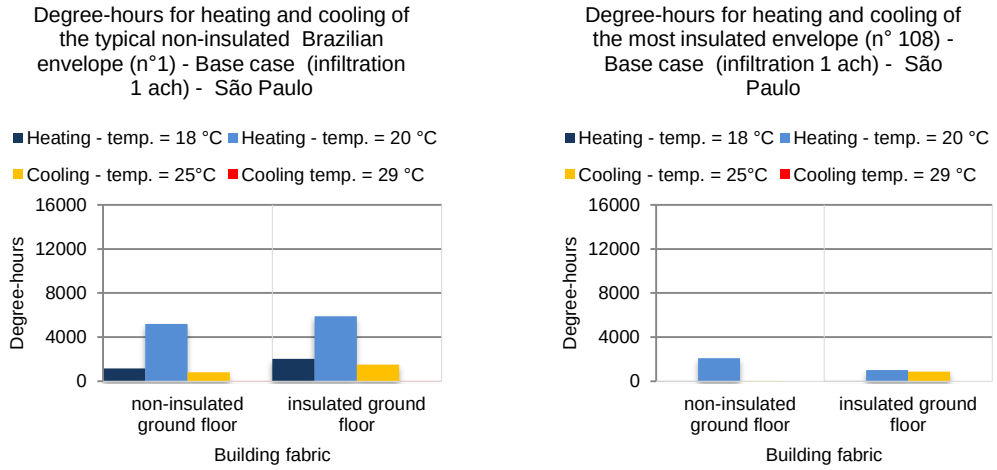


Figure 4-18: Degree-hours of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Base Case, São Paulo

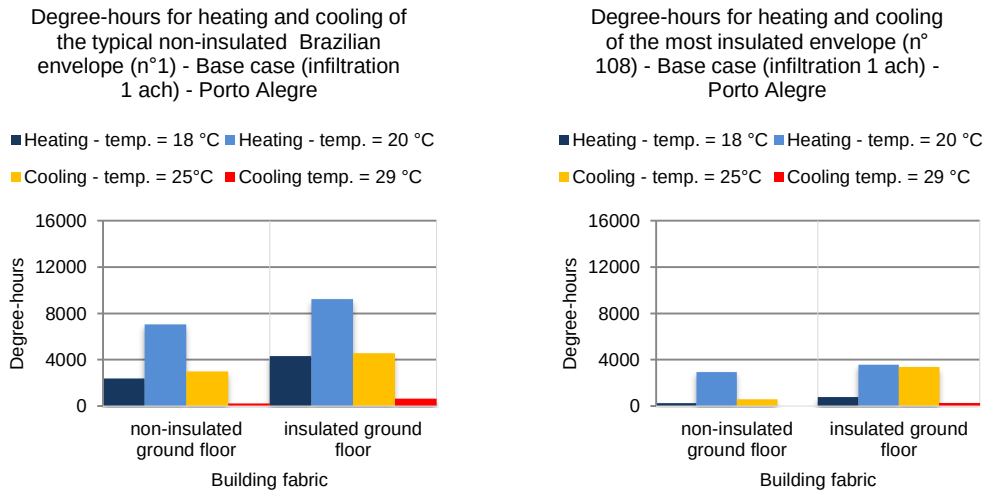


Figure 4-19: Degree-hours of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Base Case, Porto Alegre

Average, Minimum and Maximum Temperature

The results of the simulations showed that the envelopes with a higher degree of insulation, such as those used to meet the Passivhaus standard, had the lowest temperature variations and performed better than the non-insulated typical Brazilian envelope from the perspective of thermal comfort.

Figure 4-20, Figure 4-21 and Figure 4-22 show in detail the annual distribution of the average, minimum and maximum temperatures for all the investigated envelopes. Please note that in these graphs, the data representing the external temperatures were highlighted in a different size to facilitate viewing and to differentiate from the envelopes. The envelopes were organised and numbered according to Table 4-6, varying firstly the walls, followed by the roofs and the glazing and so on successively. As mentioned, a detailed description of each envelope combination and its corresponding number can be found in Appendix A. Table 4-10 summarizes the annual average, minimum and maximum temperatures for the best and the worst performance envelopes for the cities investigated, at occupant level.

Table 4-10: Annual average, minimum and maximum temperatures for Curitiba, São Paulo and Porto Alegre at occupant´s level – Base Case

	Curitiba	São Paulo	Porto Alegre
External avg. temperature	17.29 °C	19.57 °C	19.40 °C
Internal highest. avg. temperature	19.00 °C	21.25 °C	21.69 °C
Internal lowest. avg. temperature	18.85 °C	21.11 °C	21.53 °C
Δt internal avg. temperature	0.15 K	0.14 K	0.16 K
External minimum temperature	- 0.1 °C	8.50 °C	2.80 °C
Internal lowest minimum temperature	9.42 °C	13.87 °C	11.98 °C
Internal highest minimum temperature	13.69 °C	17.60 °C	15.81 °C
Δt Internal min. temperature	4.27 K	3.73 K	3.83 K
External maximum temperature	32.2 °C	33.80 °C	37.40 °C
Internal lowest maximum temperature	24.11 °C	26.04 °C	28.00 °C
Internal highest maximum temperature	28.83 °C	30.05 °C	32.32 °C
Δt Internal max. temperature	4.72 K	4.01 K	4.32 K

Curitiba, São Paulo and Porto Alegre: Envelope with the highest maximum temperature and the lowest minimum temperature: n° 13, followed by n° 1 (typical Brazilian envelope); Envelope with the highest minimum temperature and the lowest maximum temperature: n° 108, followed by n° 106 (insulated envelopes).

The locations investigated had similar thermal responses for each building envelope combination but their thermal comfort levels varied according to the external condition of each city. Curitiba had the lowest temperatures and also had the lowest average temperature both externally and internally (almost 2 °C lower than the other cities, externally). São Paulo had more uniformity of temperatures and the lowest amplitude of temperatures. Porto Alegre had the highest temperature amplitude and also the highest peak temperature among the cities investigated.

In Curitiba, the minimum and maximum external temperatures were -0.1 °C and 32.20 °C, respectively. Internally, the minimum temperature varied from 9.42 °C to 13.69 °C, a difference of 4.27 K of temperature. The maximum temperature varied from 24.11 °C to 28.83 °C, a difference of 4.72 K. A closer look at the envelopes revealed that the

worst performer (n° 13, followed by n° 1, typical Brazilian envelope) was responsible for the highest maximum temperatures and lowest minimum temperatures, whereas the best envelope (n° 108, the most insulated envelope) had the lowest temperature amplitude. The annual temperature amplitude of the worst performance envelope was 19.41 K, almost double the annual temperature amplitude of 10.42 K of the best performance envelope.

In São Paulo, the minimum and maximum external temperatures were 8.50 °C and 33.80 °C, respectively. The poorest performance envelope (n° 13) had a very close behaviour of the typical Brazilian envelope (n° 1) and was responsible for the lowest minimum and highest maximum temperatures of 13.87 °C and 30.05 °C, respectively. The best performance envelope (n° 108, the most insulated envelope) had the lowest temperature amplitude, which varied from 17.60 °C to 26.04 °C for the minimum and maximum temperatures, respectively. Whilst the best performance envelope showed the annual temperature amplitude of 8.44 K, the worst performance envelope had double the annual temperature amplitude of 16.18 K.

In Porto Alegre, the minimum and maximum external temperatures were 2.8 °C and 37.4 °C, respectively. Inside the building, the poorest performance envelope (n° 13, followed by n° 1, typical Brazilian envelope) had minimum and maximum temperatures of 11.98 °C and 32.32 °C, respectively, and an annual temperature amplitude of 20 K. The best performance envelope (n° 108, the most insulated envelope) had minimum and maximum temperatures of 15.81 °C and 28.00 °C, respectively, and an annual temperature amplitude of 12 K. The minimum and maximum temperature amplitude between the best and poorest performance envelopes corresponded to 3.83 K and 4.32 K, respectively. Combining data, the worst performance envelope's temperature amplitude (20 K) was almost double that of the best performance envelope (12 K).

For all the cities investigated, the graphs show that the envelopes made out of uninsulated single layer walls (both hollow and solid brick), as mostly used in Brazil, had the highest temperature amplitudes for any type of roof or glazing combination. The maximum and minimum temperatures swing of these single layer walls were at least 2 K higher and lower each than the envelopes with other wall combinations, respectively. This might be to the square metre of wall surface that is much larger than other elements (i.e. roof) for this housing typology.

The asymmetries of temperatures between the occupant and ceiling levels were reduced by the adoption of highly insulated roofs, as shown in Figure 4-20, Figure 4-21 and Figure 4-22. The thermal zone at ceiling level had maximum temperatures considerably higher when compared to the maximum temperatures found in the thermal zone at occupant level. These areas close to the ceiling acted as a buffer space, reducing the high temperatures at occupant level.

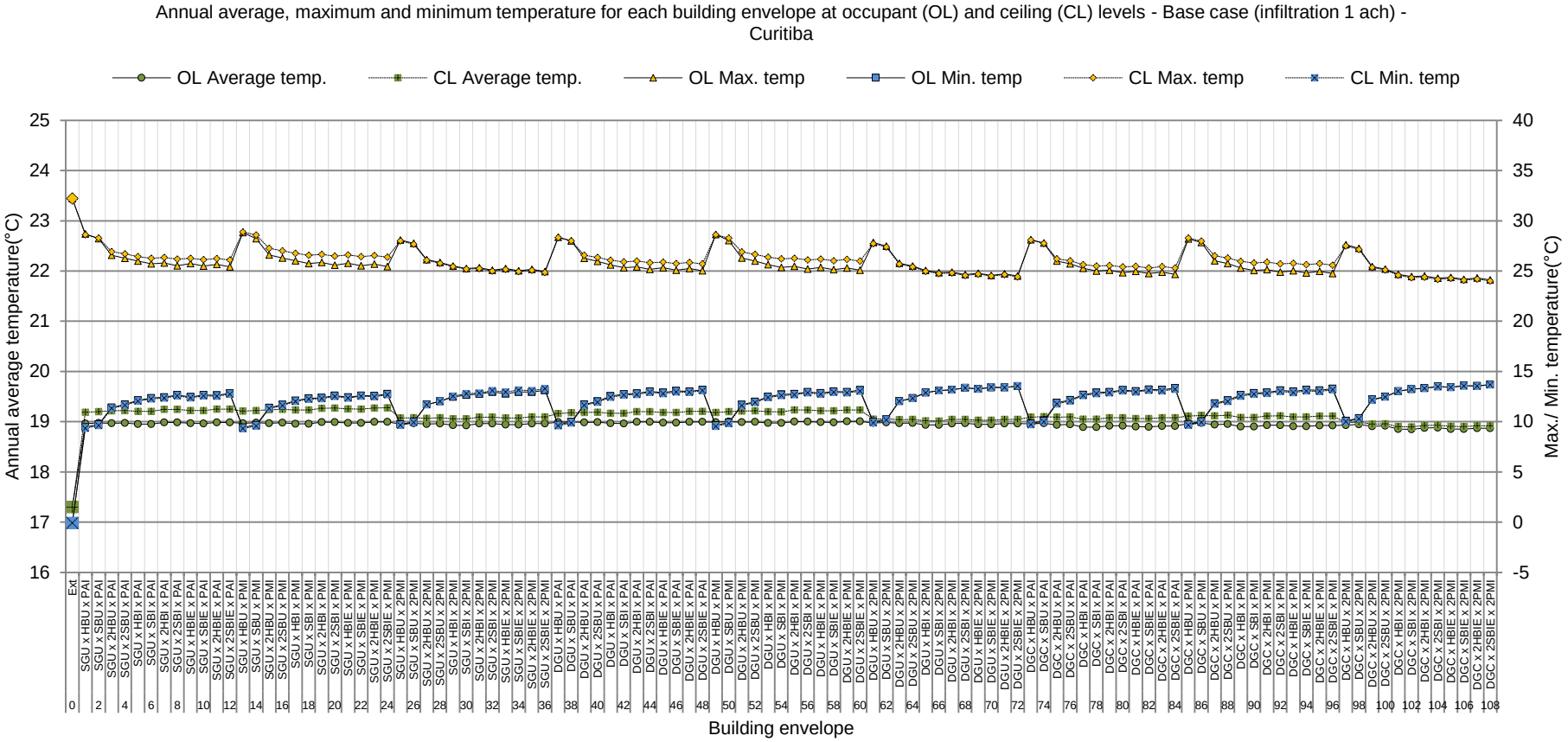


Figure 4-20: Annual average, maximum and minimum temperatures for different building envelopes, Base Case, Curitiba

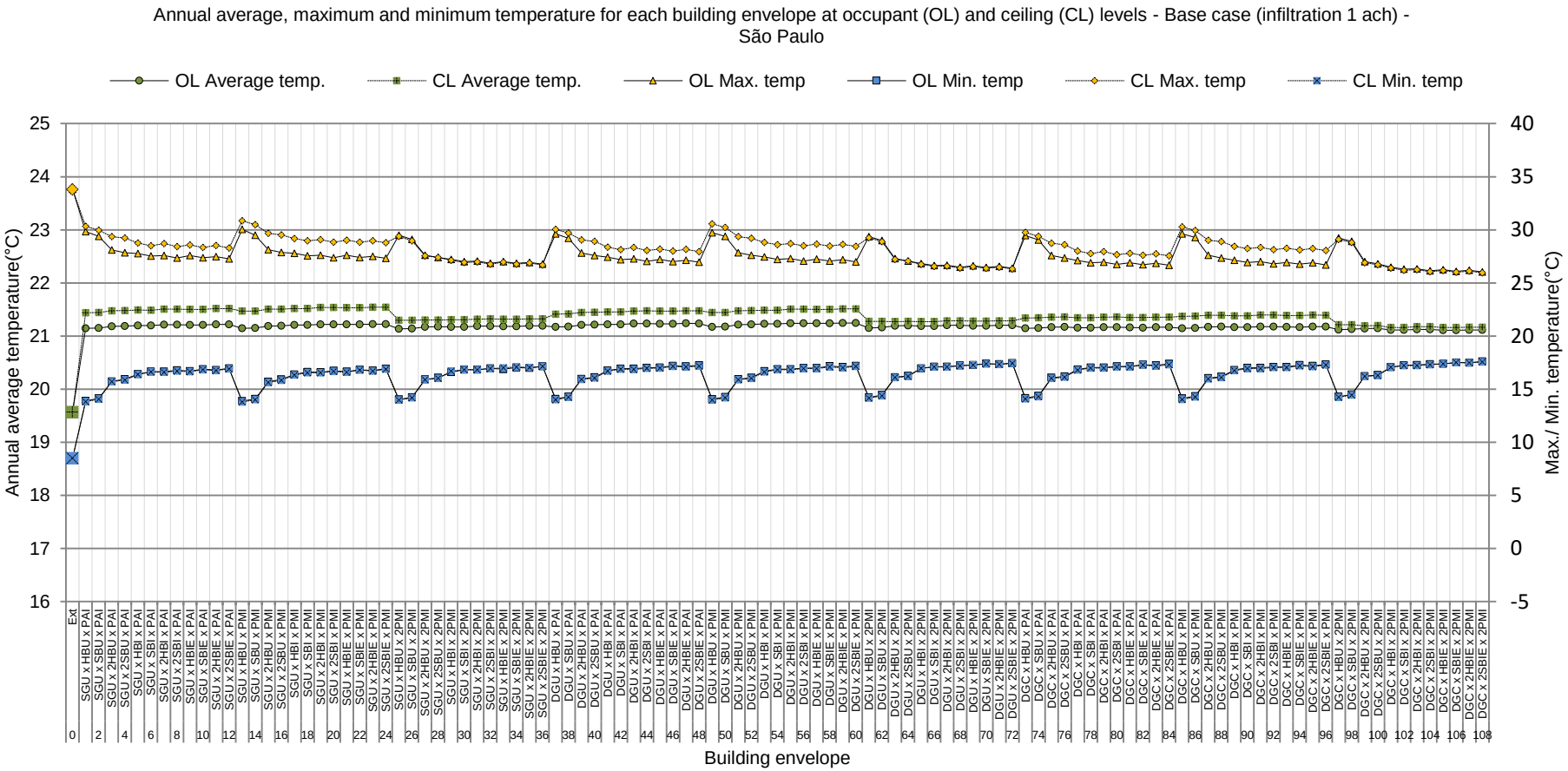


Figure 4-21: Annual average, maximum and minimum temperatures for different building envelopes, Base Case, São Paulo

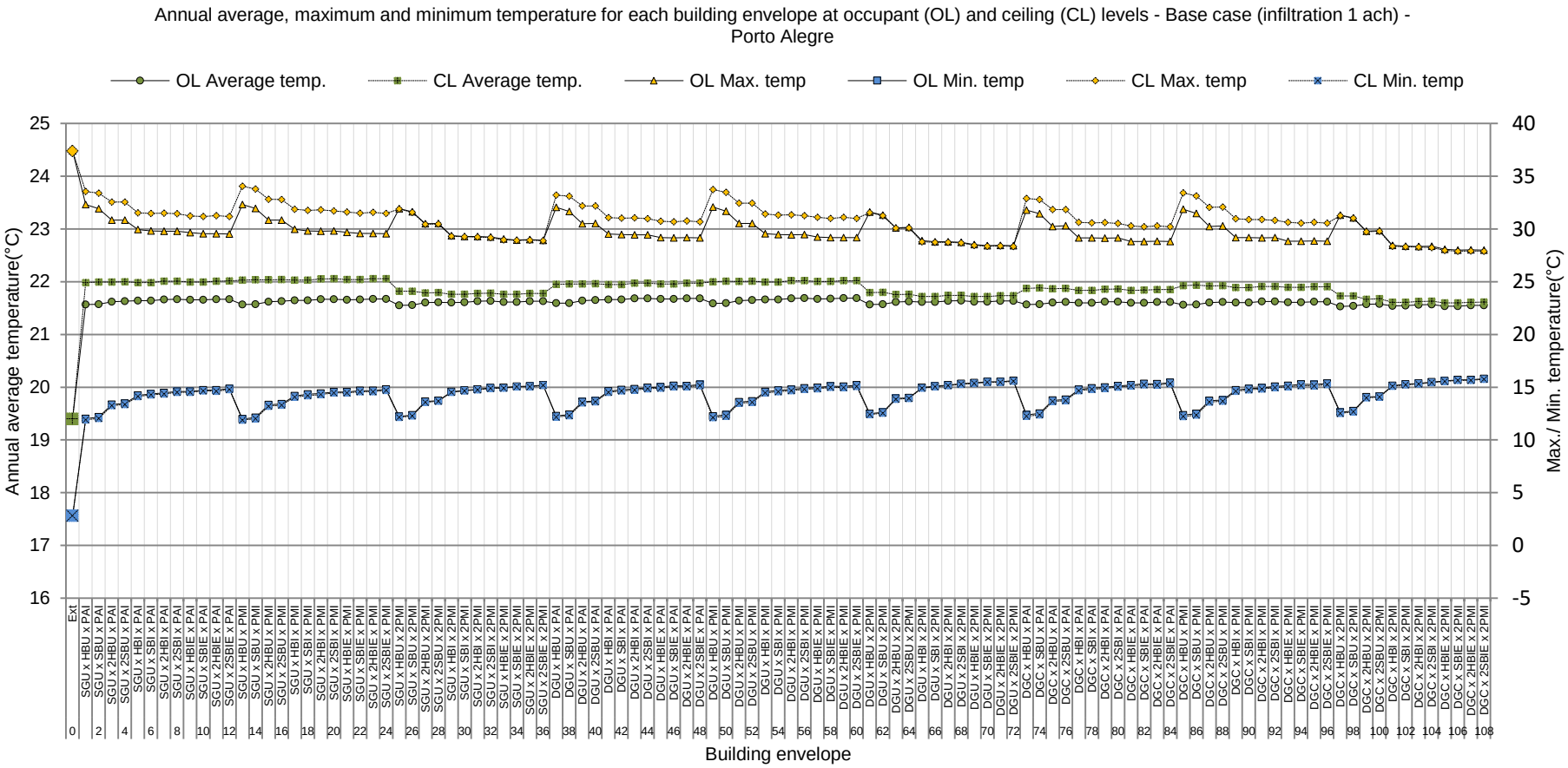


Figure 4-22: Annual average, maximum and minimum temperatures for different building envelopes, Base Case, Porto Alegre

Degree-hours

Figure 4-23, Figure 4-24 and Figure 4-25 show the degree-hours combination for a base temperature of 20 °C (lower thermal comfort limit) and for a base temperature of 25° C (upper thermal comfort limit) for the cities of Curitiba, São Paulo and Porto Alegre, respectively. The main degree-hours results are summarized in Table 4-11. Please note that the external degree-hours were removed from the graphs in order to reduce the interval covered by the graph and, so facilitate viewing of the performance difference among these envelopes investigated.

As mentioned, the methodology of degree-hours accounts for temperature fluctuations and eliminates those periods when heating or cooling systems do not need to operate; consequently, the method can capture both the magnitude and duration of an event of both mild and extreme temperatures (CIBSE, 2006a). The advantage of degree-hours use methodology lies in its relative ease and speed of use and also its reliability in estimating energy consumption that can provide a good approximation of the building response for specific building conditions of use (CIBSE, 2006a). Degree-hours are a suitable methodology for estimating the energy demand and the magnitude of the thermal discomfort in free-running buildings.

Table 4-11: Degree-hours for the narrow thermal comfort interval of 20 °C and 25 °C – Base case

Degree-hours		Curitiba	São Paulo	Porto Alegre
Base temperature of 20 °C	External	31139.70	16667.60	19725.50
	Int. lowest	12331.58	2099.68	2939.56
	Int. highest	15645.66	5217.33	7071.79
Base temperature of 25 °C	External	996.00	2332.00	5164.70
	Int. lowest	0	22.95	588.43
	Int. highest	110.94	816.51	2977.68
Base temperature of 20 °C and 25 °C	External	32135.70	18999.60	24890.20
	Int. lowest	12331.58	2122.63	3527.99
	Int. highest	15756.60	6034.24	10045.72

Lowest degree-hours envelope: in Curitiba, nº 72, followed by n° 71; in São Paulo and Porto Alegre, nº 108, followed by nº 106 (followed eventually by nº 72 in São Paulo and nº 107 in Porto Alegre).
Highest degree-hours envelopes: In all cities, nº 13, followed by the nº 1 (typical Brazilian envelope).

The building envelopes performed in the same manner for both low and high temperatures. In other words, the envelopes that performed best for cold temperatures were also those envelopes that performed best for warm temperatures. The worse performance envelopes were those envelopes that showed more degree-hours for heating and cooling such as those typically used in Brazil (with low degree of insulation material). The best envelope performances were those with the lowest degree-hours for both cooling and heating and so, consequently, those that had more indoor thermal comfort, such as the most insulated envelopes. It should be highlighted, however, that these results relied on the fact that the simulations assumed basic passive design principles to mitigate overheating such as shading and natural ventilation from the beginning.

As can be seen from the figures, all the building envelopes among those investigated showed that heating rather than cooling was the major concern. Cooling was more significant only in Porto Alegre.

In Curitiba, the sum of the external degree-hours for a thermal comfort interval of 20-25 °C corresponded to 32135.70. The best performance envelope in Curitiba was that with the most insulated walls and roof and double uncoated glazing (n° 72). This envelope reduced the degree-hours to 12331.58 and increased the thermal comfort by 21.61% when compared to the typical Brazilian envelope (n° 1) with 15731.37 degree-hours.

In São Paulo, the sum of the external degree-hours for the given thermal comfort interval was 18999.60. The best performance envelope in this city was the most insulated envelope (n° 108). It had degree-hours of 2122.63 and increased the thermal comfort by 64.61% when compared to the typical Brazilian envelope (n° 1) with 5997.67 degree-hours.

In Porto Alegre, the sum of the external degree-hours for the thermal comfort zone between 20-25 °C was 24890.22. The best performance envelope was also the most insulated envelope (n° 108). It was able to reduce the degree-hours to 3527.99 and increased the thermal comfort by 64.76% when compared to the typical Brazilian envelope (n° 1) with 10012.83 degree-hours.

It should be highlighted that for all cities the typical Brazilian envelope (n° 1) had a very similar behaviour pattern of the worst performance envelope (n° 13) and so, the conclusion of one can be extended to the other one[40].

In free-running buildings, the thermal comfort adaptive approach shows that the wider thermal comfort interval is very acceptable to the occupants, especially in the summer season when ventilation is mostly used. There is a high correlation between the acceptability of internal and external temperatures. This correlation suggests that wider temperature intervals, beyond the narrow comfort limits, can be well tolerated by the occupants.

Adopting the wide thermal comfort interval of 18 and 29 °C, as defined in Chapter 3, the results were similar to those obtained through the narrow comfort limit evaluation. The resultant degree-hours are shown in Figure 4-26 and Figure 4-27 and Figure 4-28 for the cities of Curitiba, São Paulo and Porto Alegre, respectively. These main results are summarised in Table 4-12.

[40] The best performance envelopes had an improvement of 21.74%, 64.82% and 64.88% relative to the worst performance envelope (n° 13) in Curitiba, São Paulo and Porto Alegre, respectively.

Table 4-12: Degree-hours for the wide thermal comfort interval of 18 °C and 29 °C – Base case

Degree-hours		Curitiba	São Paulo	Porto Alegre
Base temperature of 18 °C	External	19405.40	8314.10	12006.6
	Int. lowest	3192.92	17.29	266.58
	Int. highest	6687.76	1189.42	2415.96
Base temperature of 29 °C	External	47.60	246.2	1240.00
	Int. lowest	0	0	0
	Int. highest	0	6	243.87
Base temperature of 18 °C and 29 °C	External	19453.00	8560.3	13246.60
	Int. lowest	3192.92	17.29	266.58
	Int. highest	6687.76	1195.42	2659.83

Lowest degree-hours envelope: in Curitiba, nº 108, followed by n° 72; in São Paulo and Porto Alegre, nº 108, followed by nº 106.
Highest degree-hours envelopes: In all cities, nº 13, followed by the nº 1 (typical Brazilian envelope).

As expected, the degree-hours for a wide thermal comfort limit were much lower than the degree-hours for a narrow thermal comfort interval. In all the cities, the major reduction was related to the heating degree-hours change from 20 to 18 °C, which seems a quite reasonable lower thermal comfort temperature limit to be tolerated in a free-running building. This seems to suggest that in fact the indoor thermal comfort condition could be much higher if people considered it acceptable to the environment.

The results of best and worst performance envelopes for the wide thermal comfort interval were consistent with those results for the narrow thermal comfort interval. Examining the degree-hours results for all the cities investigated for the wide thermal comfort interval, the corresponding best performance envelopes in Curitiba, São Paulo and Porto Alegre increased the thermal comfort by 52.06%, 98.53% and 89.86% relative to the typical Brazilian envelope (n° 1) [41,42].

[41] The degree-hours of the typical Brazilian envelope (n° 1) corresponded to 6660.67, 1176.82 and 2630.16 in Curitiba, São Paulo and Porto Alegre, respectively.

[42] The best performance envelopes had an improvement of 52.26%, 98.55% and 89.98% relative to the worst performance envelope (n° 13) in Curitiba, São Paulo and Porto Alegre, respectively.

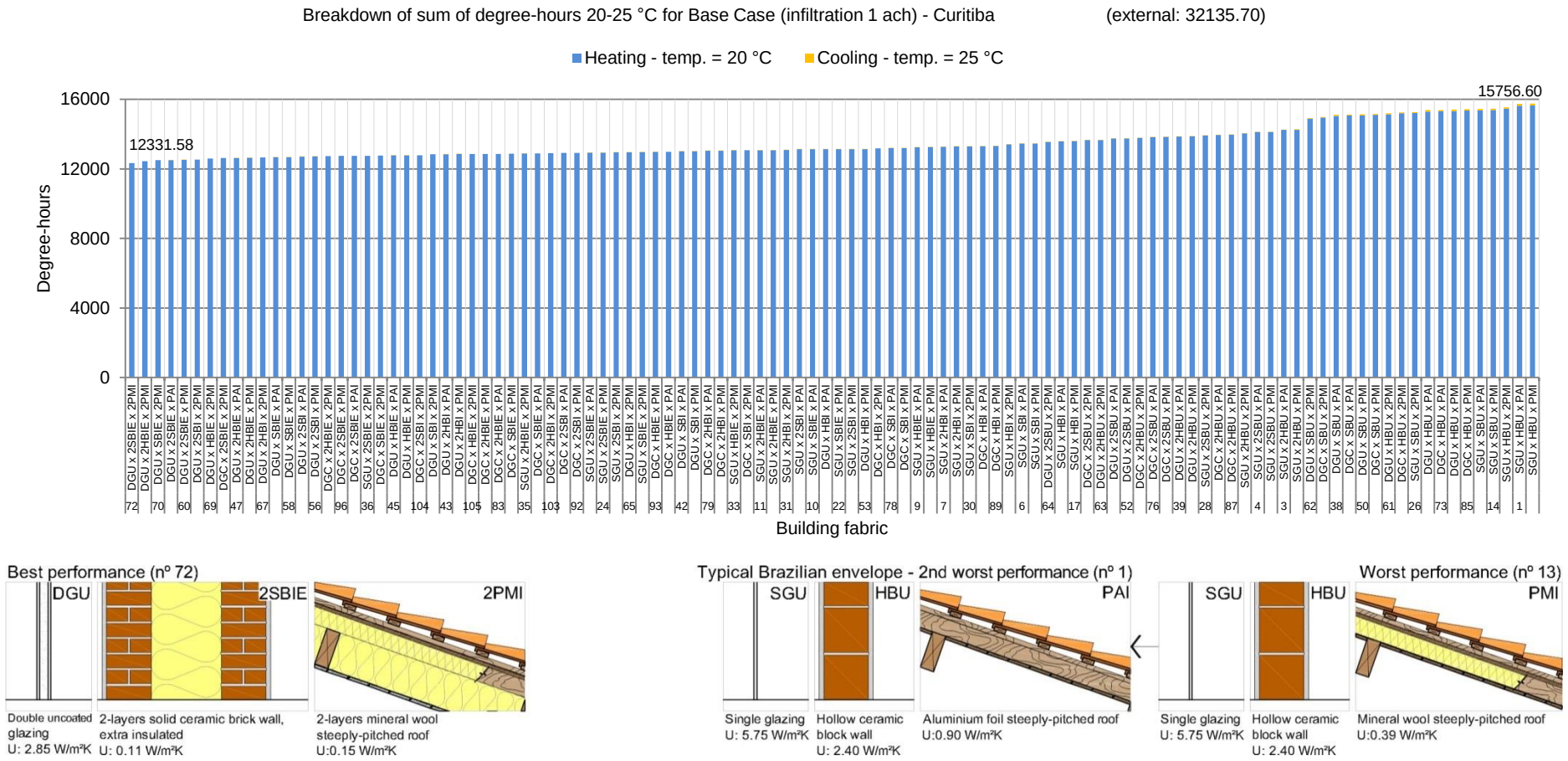


Figure 4-23: Degree-hours 20-25 °C – thermal discomfort, Base Case, Curitiba (organised from the worst to the best)

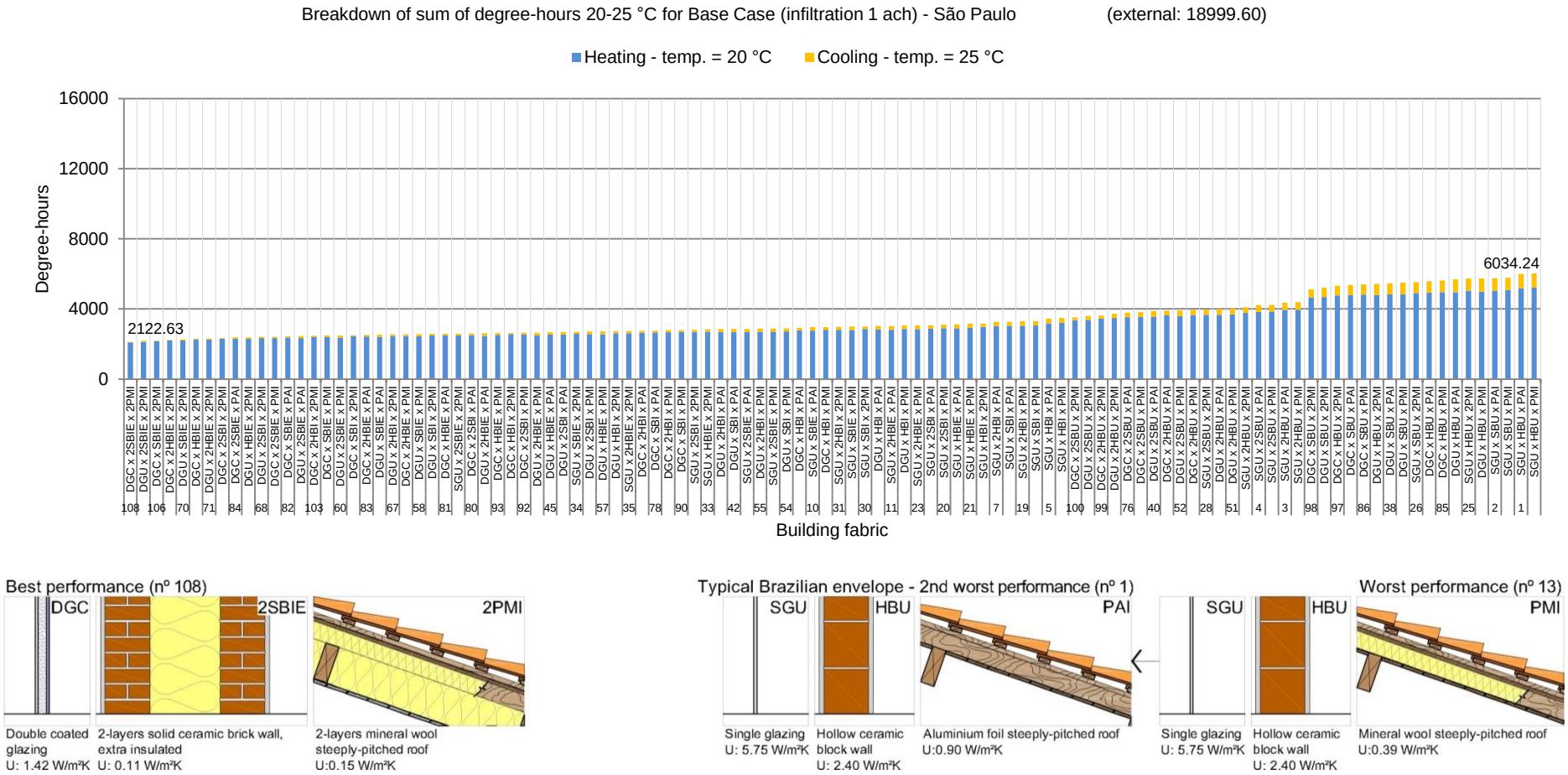


Figure 4-24: Degree-hours 20-25 °C – thermal discomfort, Base Case, São Paulo (organised from the worst to the best)

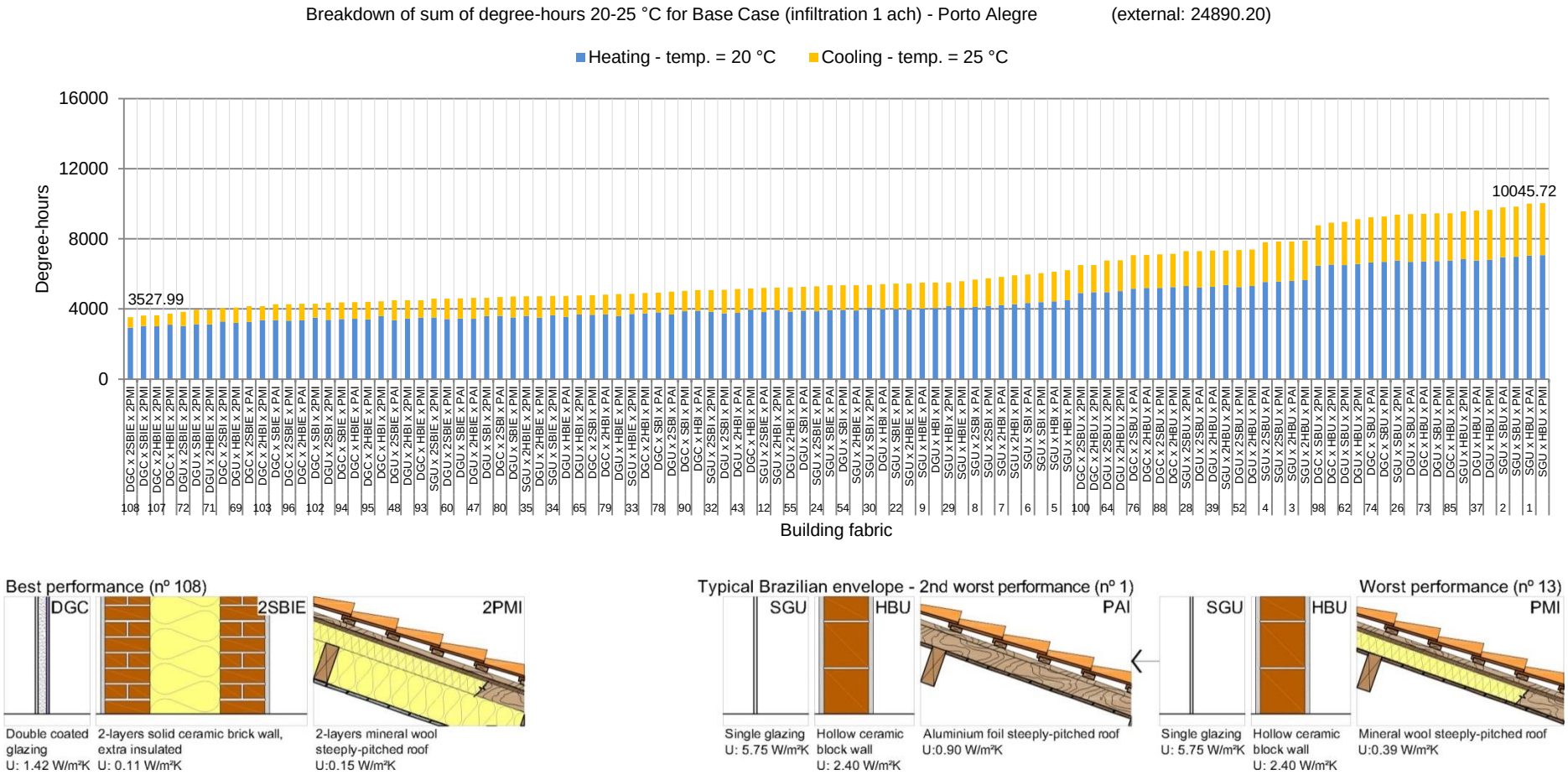


Figure 4-25: Degree-hours 20-25 °C – thermal discomfort, Base Case, Porto Alegre (organised from the worst to the best)

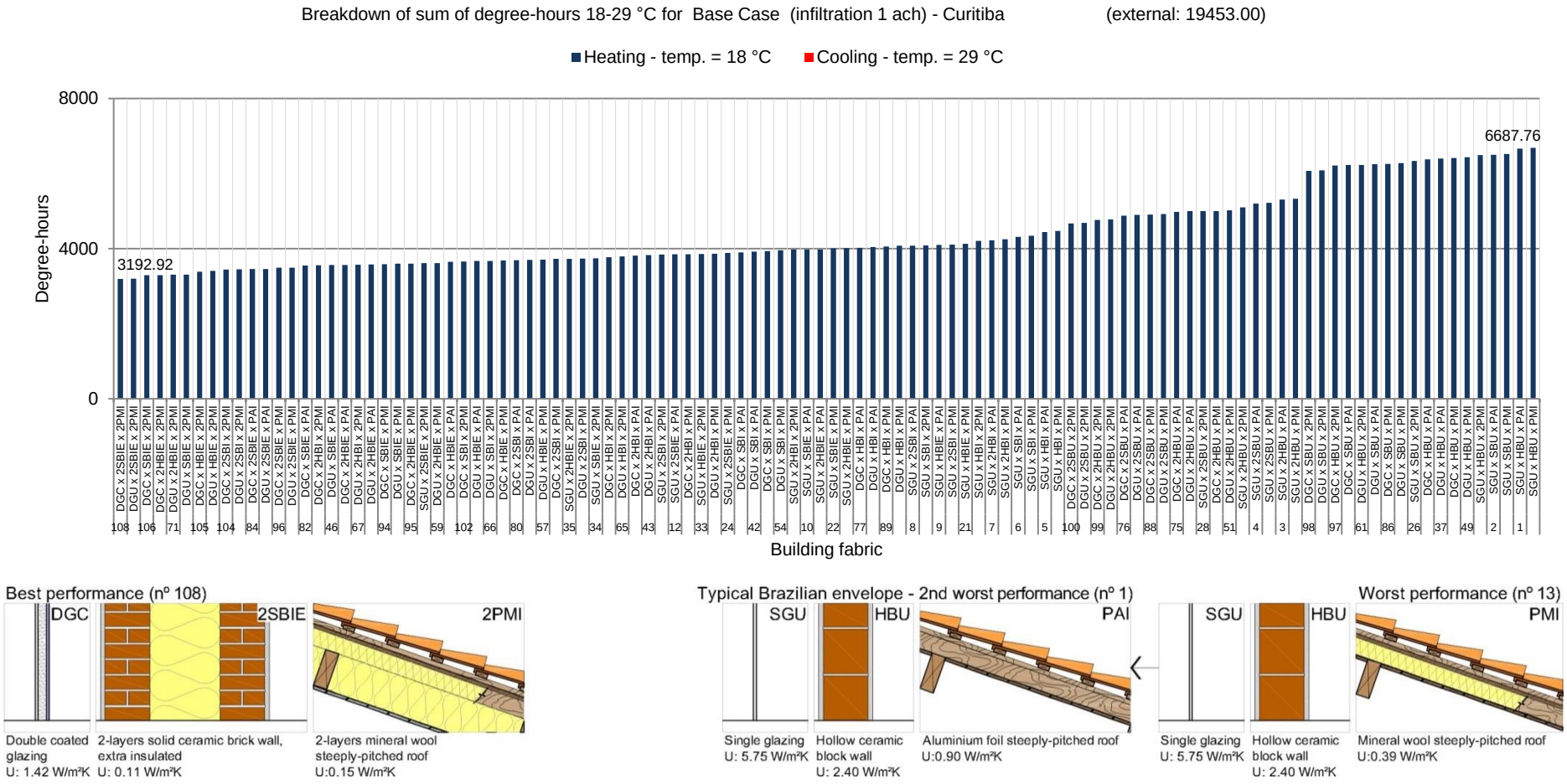


Figure 4-26: Degree-hours 18-29 °C – thermal discomfort, Base Case, Curitiba (organised from the worst to the best)

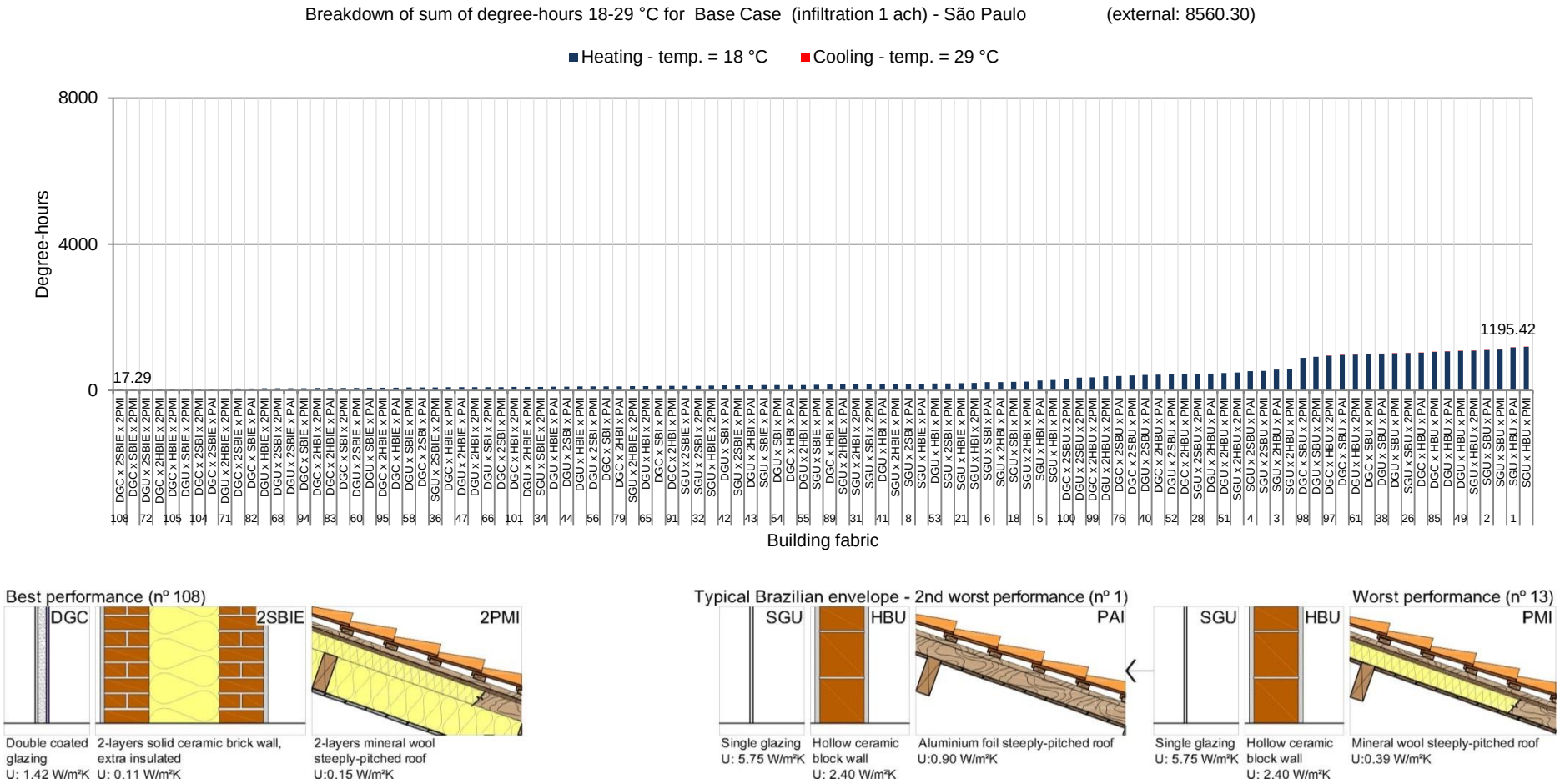


Figure 4-27: Degree-hours 18-29 °C – thermal discomfort, Base Case, São Paulo (organised from the worst to the best)

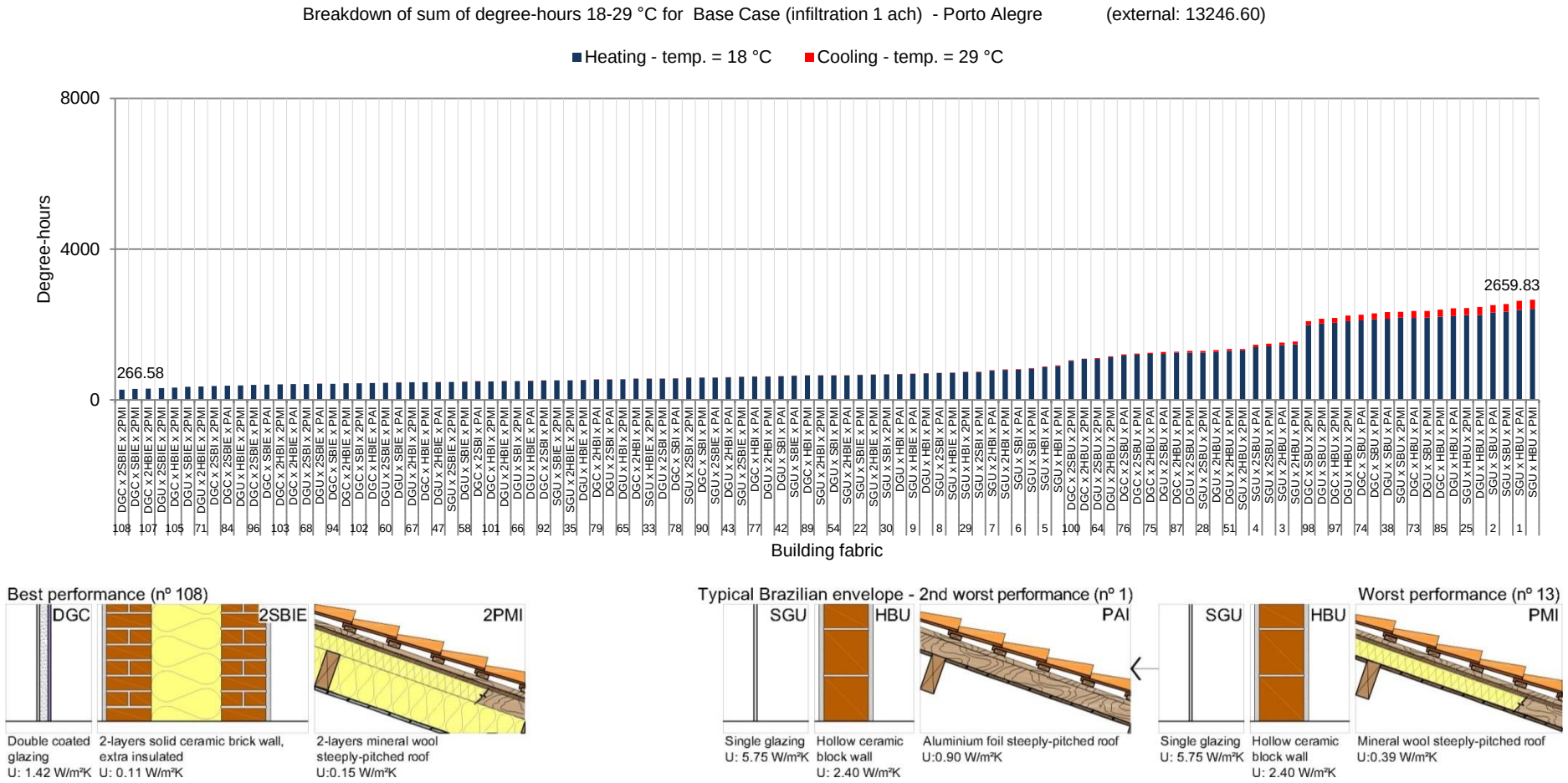


Figure 4-28: Degree-hours 18-29 °C – thermal discomfort, Base Case, Porto Alegre (organised from the worst to the best)

Figure 4-29, Figure 4-30 and Figure 4-31 show the correlation between fabric heat loss and degree-hours for heating and cooling for the cities investigated. Cooling degree-hours for a base temperature of 29 °C is only shown in Porto Alegre, as it was negligible in the other locations. Fabric heat loss is a coefficient that considers the U-value of the envelope and the corresponding surface area of each building element. A very strong correlation was found between degree-hours and fabric heat loss. This corroborates that low U-values, through insulated fabric elements, are indeed appropriate in climates with both heating and cooling requirements. In other words, indoor thermal comfort was increased as moving towards insulated envelopes.

The correlation became weaker as the demand decreased, such as in the case of cooling demand in Curitiba. This is because the insulated envelopes are more suitable for both cold and hot temperatures and are not suitable for envelopes that have mostly indoor temperatures within the thermal comfort zone. In other words, if thermal discomfort is limited, there is no need for using insulated envelopes. However, it should be remembered that the simulation assumptions considered the building as already optimised for reducing its cooling demand. Both selective ventilation and shading were issues addressed in the very beginning of the current work. Disregarding them would result in different findings in terms of the effect of the envelope in providing indoor thermal comfort.

In order to measure the impact of the envelope decision in the lifespan of the house, the heating energy demand, which is the major cause of thermal discomfort for the cities investigated, was estimated through the use of degree-hours method. The estimation of the heating energy demand was calculated by the fabric heat loss coefficient times the heating degree-hours (CIBSE, 2006a, p. 7). Cooling energy demand was not calculated because it was mostly mitigated by passive design strategies and also because it requires more detailed calculations.

The estimated annual heating energy demand for a temperature of 20 °C varied according to each envelope (see Appendix A): from 46.95 to 146.24 kWh/m^2 in Curitiba; from 7.81 to 48.24 kWh/m^2 in São Paulo; and from 10.93 to 66.14 kWh/m^2 in Porto Alegre. Non-insulated envelopes had the highest heating energy demand and insulated envelopes had the lowest heating energy demands. The most insulated envelopes had a heating energy demand 3 times smaller than the typical Brazilian envelope in Curitiba and 6 times smaller in São Paulo and Porto Alegre. In São Paulo and Porto Alegre, the highest performance envelopes had similar levels of heating energy demand to those levels achieved by the Passivhaus standard (15 kWh/m^2). However, these results cannot be directly compared to the Passivhaus standard as the buildings in Brazil do not use mechanical ventilation and heat recovery systems, which are the basic ventilation requirements for a Passivhaus standard building.

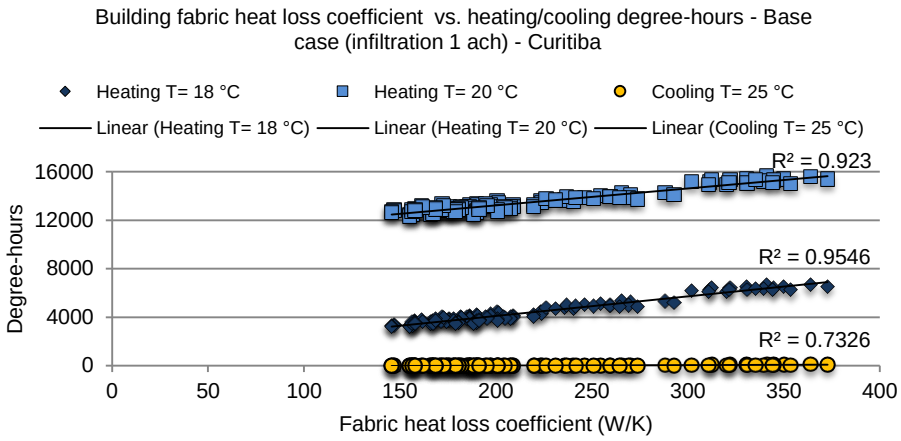


Figure 4-29: Correlation between fabric heat loss coefficient and heating/cooling degree-hours, Base Case, Curitiba

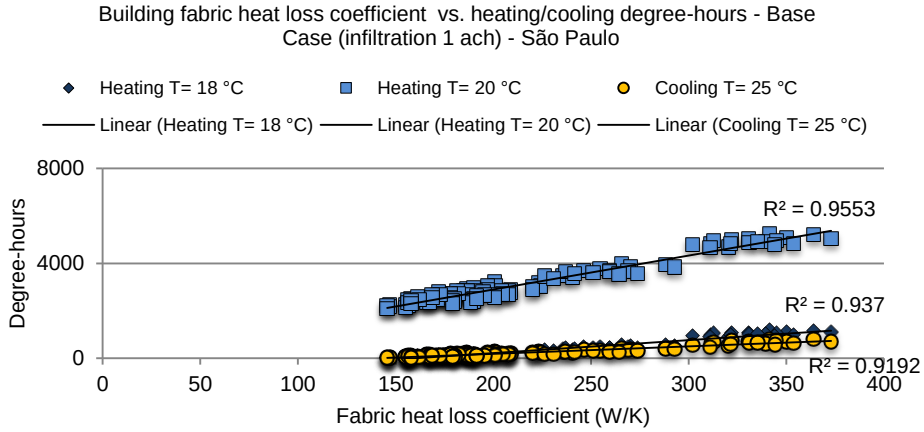


Figure 4-30: Correlation between fabric heat loss coefficient and heating/cooling degree-hours, Base Case, São Paulo

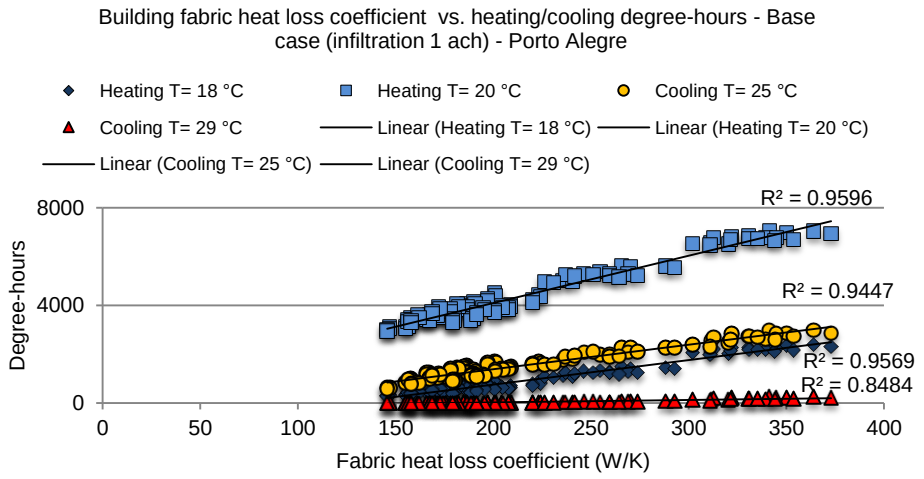


Figure 4-31: Correlation between fabric heat loss coefficient and heating/cooling degree-hours, Base Case, Porto Alegre

Annual Temperature and Frequency

Figure 4-32, Figure 4-33 and Figure 4-34 compare the typical Brazilian envelope and the best performance envelope for the thermal comfort interval of 20-25 °C in different manners under the perspective of thermal comfort for each of the cities. The figures show the annual temperature distribution between the typical and the best performance envelope, the frequency of temperatures and the percentage of temperatures within the thermal comfort intervals and also the maximum and minimum temperatures between those envelopes. The main aim was to highlight the difference in their performance. For all the cities, the typical Brazilian envelope (n° 1) ranked second worst thermal performance among those envelopes investigated and had a similar behavioural pattern to the worst performance envelope (n° 13).

In Curitiba, the best performance envelope (n° 72) had more uniformity of the indoor temperatures over the year with lower amplitude of the temperatures when compared to the typical Brazilian envelope (n° 1). The annual temperature amplitude of the insulated envelope was 10.97 K, almost half of the annual temperature amplitude of the typical Brazilian envelope of 19.22 K.

Externally, for almost 60% of the time the temperatures were below 18 °C. Internally, the typical Brazilian envelope (n° 1) reduced the temperatures below 18 °C to about 40% of the time and the best performance envelope dropped it to 33% of the time. Whilst for 7% of the time the external temperature was above 25 °C, the typical Brazilian envelope almost reduced it to null levels and the best performance envelope fully mitigated it. Based on that, the best performance envelope was within the thermal comfort zone of 18-29 °C for 67% of the time, 6% more than the typical Brazilian envelope thermal comfort. While these differences might seem small in the long run the best performance envelope means a lot more thermal comfort and a lot less energy would be consumed if hybrid ventilation was adopted to address the thermal discomfort portion.

Even though the best performance envelope contribution did not impact considerably on the increase of frequency of temperature within the thermal comfort, it had a significant improvement on the extreme of temperatures. The typical Brazilian envelope (n° 1) had the minimum and maximum temperatures of 9.46 °C and 28.68 °C, which swung 4 K less and more than the best performance envelope (n° 72), respectively.

In São Paulo, the indoor temperatures of the best performance envelope (n° 108) were within the wide thermal comfort zone for most of the year. The temperatures in summer did not exceed beyond 25 °C and the lowest temperatures did not drop below 18 °C. The internal temperature amplitude of the best envelope was only 8.44 K, which was

equivalent to almost half of the annual temperature amplitude of the typical Brazilian envelope (n° 1), estimated to be 15.89 K.

Whilst for more than 35% of the time the external temperatures were below 18 °C, the typical Brazilian envelope (n° 1) greatly reduced it to 13% of the time but it was the best performance envelope (n° 108) that almost mitigated it, reducing the frequency to 1% of the time. The same behaviour was observed for temperatures above 25 °C. Whilst externally this exceeded 10% of the time, the typical Brazilian envelope reduced it internally to 7% of the time and the best performance envelope reduced it to less than 1% of the time. The insulated envelope was within the wide thermal comfort zone for 99% of the time and this was 12% more than in the typical Brazilian envelope, which was within the thermal comfort zone for 87% of the time.

The typical Brazilian envelope (n° 1) had the minimum and maximum temperatures equivalent to 13.91 °C and 29.84 °C, which swung around 3.8 K less and more than the best performance envelope (n° 108), respectively.

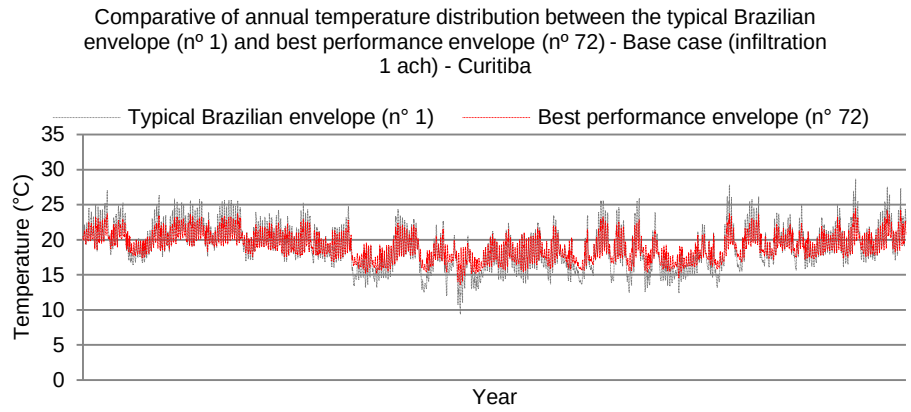
In Porto Alegre, the difference in the annual temperature distribution between the best performance envelope (n° 108) and the typical Brazilian envelope (n° 1) was more significant than in the other cities. The best performance envelope had a temperature amplitude of 12.19 K over the year while the typical Brazilian envelope had its annual temperature variation of 20.30 K.

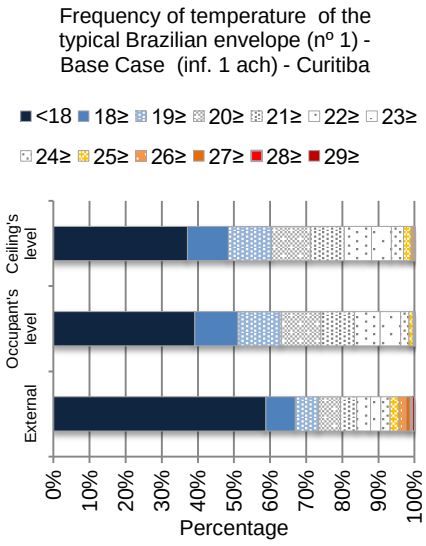
Externally, the temperatures were for more than 35% of the time below the lower thermal comfort of 18 °C and for more than 5% of the time above the upper comfort limit of 29 °C. Internally, the typical Brazilian envelope reduced the temperatures below 18 °C for 17% of the time, whereas the best performance envelope reduced it to about 5% of the time. The typical Brazilian envelope reduced the overheating to more than half when compared to the external levels, while the best performance envelope fully mitigated the overheating. The best performance envelope was within the wide thermal comfort zone for 95% of the time and this was 14% bigger than the thermal comfort achieved by the typical Brazilian envelopes.

The typical Brazilian envelope (n° 1) had the minimum and maximum temperatures of 12.01 °C and 32.31 °C, which was 3.80 K lower and 4.31 K higher than the values of the best performance envelope (n°108), respectively.

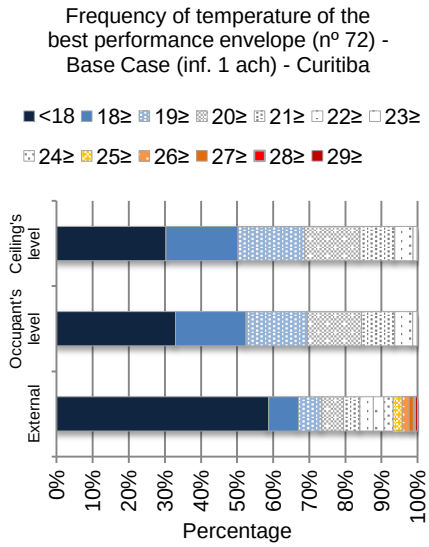
It should be noted that the thermal comfort percentages at ceiling level overall had the same behavioural pattern as at occupant level and this can be seen in the Figures.

The next section investigates the contribution of infiltration reduction on the indoor thermal comfort of affordable Brazilian houses.

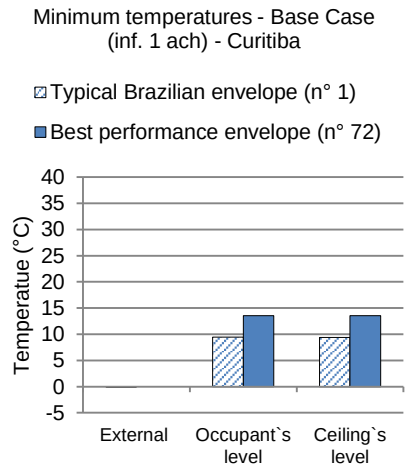




Typical Brazilian envelope (nº 1)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	37%	63%
Occupant level	35%	61%
External	20%	41%



Best performance envelope (nº 72)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	31%	70%
Occupant level	30%	67%
External	20%	41%



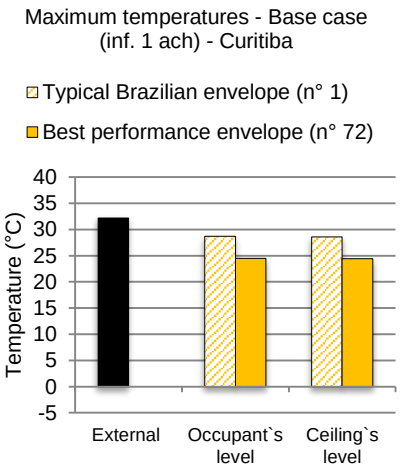
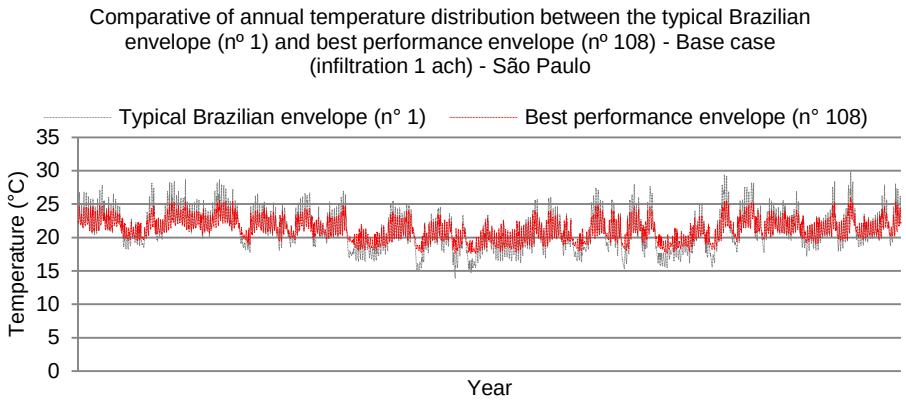
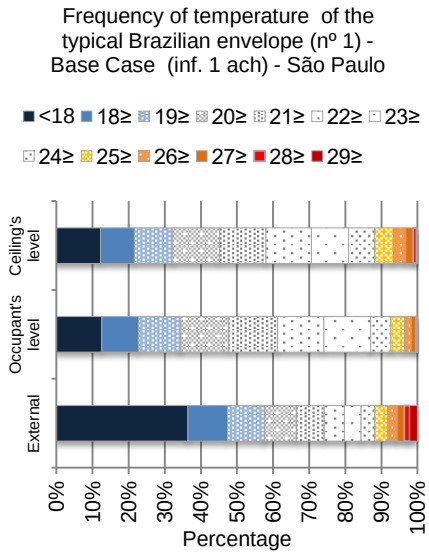
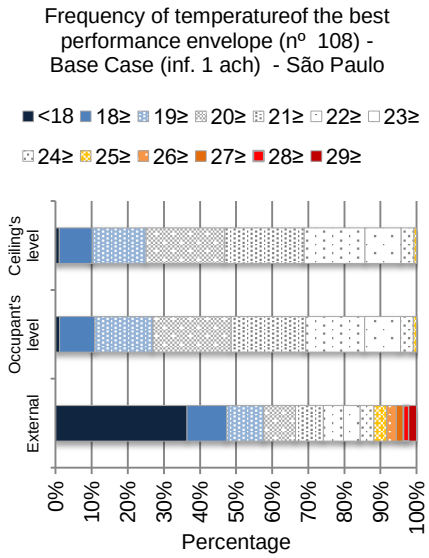


Figure 4-32: Comparative of annual temperature distribution, percentage of comfort and minimum and maximum temperatures between the typical Brazilian envelope (n° 1) and the best performance envelope (n° 72), Base Case, Curitiba

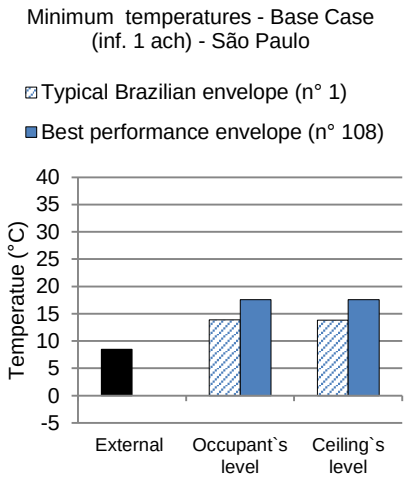




Typical Brazilian envelope (nº 1)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	56%	88%
Occupant level	58%	87%
External	30%	61%



Best performance envelope (nº 108)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	74%	99%
Occupant level	72%	99%
External	30%	61%



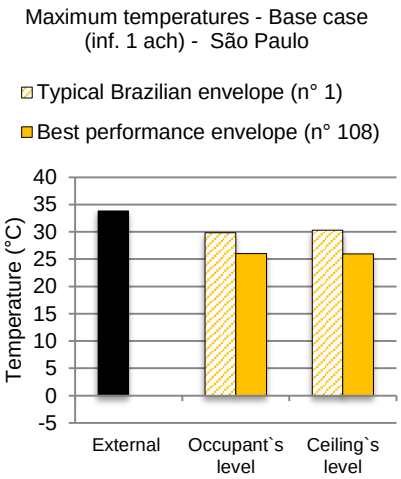
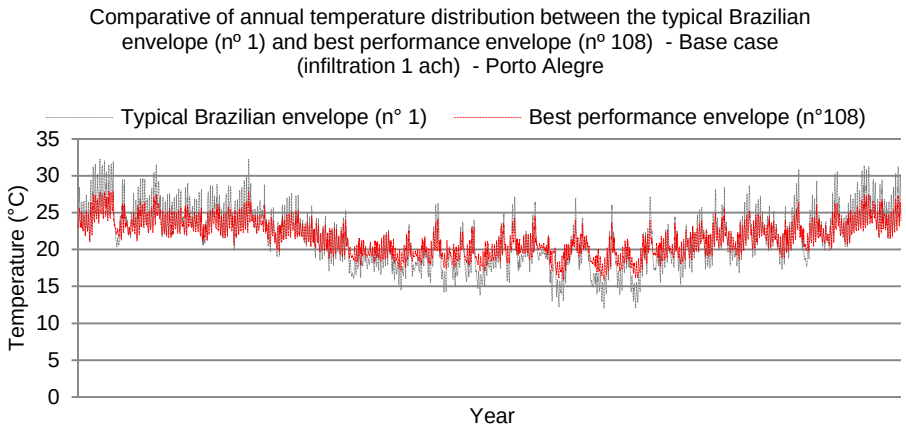
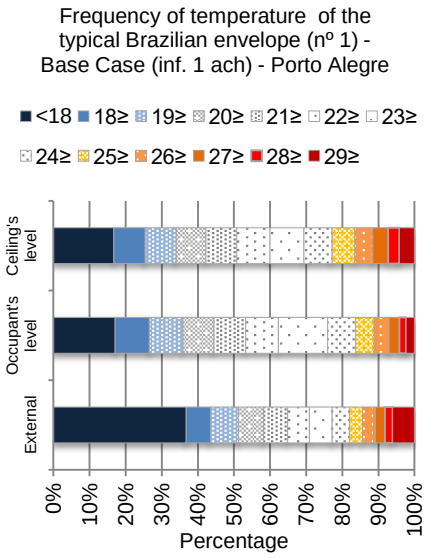
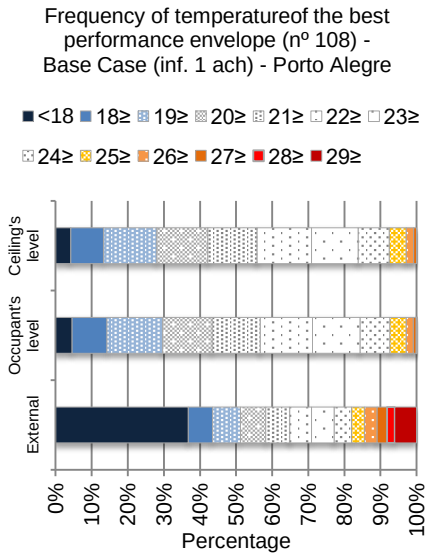


Figure 4-33: Comparative of annual temperature distribution, percentage of comfort and minimum and maximum temperatures between the typical Brazilian envelope (n° 1) and the best performance envelope (n° 108), Base Case, São Paulo

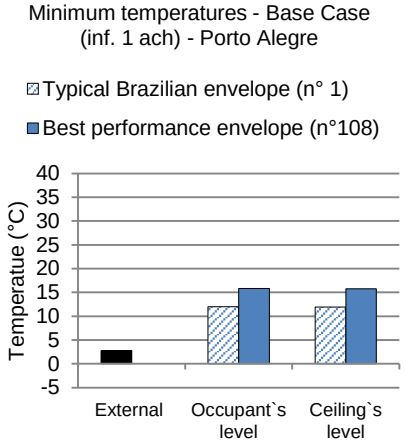




Typical Brazilian envelope (nº 1)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	43%	79%
Occupant level	48%	81%
External	31%	57%



Best performance envelope (nº 108)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	64%	96%
Occupant level	63%	95%
External	31%	57%



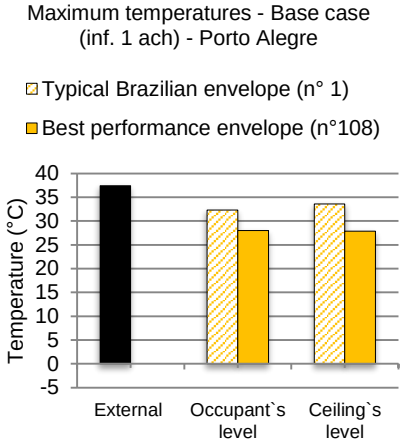


Figure 4-34: Comparative of annual temperature distribution, percentage of comfort and minimum and maximum temperatures between the typical Brazilian envelope (n° 1) and the best performance envelope (n° 108), Base Case, Porto Alegre

4.5 Variation of the Simulation Model

This section investigated the envelope performances under a regime of limited air permeability rate. The purpose of this investigation was to explore the potential benefit of low infiltration rate in the typical affordable Brazilian housing, keeping all the other conditions of use the same as Base Case.

The infiltration rate was assumed to be equivalent to 0.15 ach (roughly converted from 3 $m^3/hr/m^2$ at 50 Pa), which is the limit where non-mechanical ventilation solutions can still be used, according to current best practices in the United Kingdom for naturally ventilated buildings (Cotterel and Dadeby, 2012, p. 126).

4.5.1 Assumptions

Table 4-13 summarizes the Case 1 simulation model assumptions.

Table 4-13: Summary of Case 1 simulation model assumptions

Assumptions	Description
Ventilation/ Internal gains/ Thermal zones/ Calendar/ Comfort temperature/ Weather data	As Base Case (see Table 4-9)
Infiltration	Reduction of infiltration to 0.15 ach at atmospheric pressure, which is the minimum infiltration value for naturally ventilated buildings without using any additional mechanical ventilation system.

4.5.2 Results

Similarly, as in Base Case, the analyses of the variation of the floor component are discussed first, following which the results for a limited infiltration across different building envelopes are examined.

Ground Floor

Figure 4-35, Figure 4-36 and Figure 4-37 show the annual internal temperature distribution of non-insulated and insulated ground floors for the typical Brazilian envelope (n° 1) in Curitiba, São Paulo and Porto Alegre, respectively. Figure 4-38, Figure 4-39 and Figure 4-40 illustrate the annual internal temperature distribution of different ground floors for the most insulated envelopes (n° 108). Figure 4-41, Figure 4-42 and Figure 4-43 illustrate the minimum and maximum temperatures.

As can be seen from the Figures, the use of an insulated ground floor showed the same behavioural pattern for infiltration of 1 ach and 0.15 ach for both non- and insulated envelopes. As mentioned, the insulated ground floor caused more extremes of

temperatures and had higher annual temperature amplitude than the non-insulated floor.

For the typical non-insulated Brazilian envelope (n° 1), in Curitiba, the minimum and maximum temperatures of an insulated ground floor were 9.04 °C and 30.44 °C, around 2 K lower and higher than a non-insulated ground floor, respectively. In São Paulo, the minimum and maximum temperature difference between the insulated and non-insulated floor was just above 1 K each and this was more favourable for the non-insulated ground floor than the insulated ground floor type. In Porto Alegre, the minimum and maximum temperatures of an insulated ground floor reached 10.41 °C and 34.68 °C, around 3 K lower and higher than a non-insulated ground floor, respectively.

The minimum temperature of the typical Brazilian envelope with non-insulated ground floor was 11.03 °C, 14.71 °C and 13.34 °C, which was about 1 K higher than in Base case scenario (infiltration of 1 ach) in Curitiba, São Paulo and Porto Alegre, respectively.

For the insulated envelope (n° 108), the insulated ground floor construction element considerably increased the temperatures to beyond the upper thermal comfort of 25 °C. Even Curitiba, which did not have cooling demand at all, suffered an elevation of its temperatures. The temperatures of the insulated envelopes exceeded 25 °C even in winter time, when used combined with insulated ground floor element. Moreover, during the winter, the indoor temperatures of the insulated envelope when used combined with insulated ground floor construction element were less stable when compared to its use with non-insulated ground floor.

A closer look at the degree-hours (Figure 4-44, Figure 4-45, and Figure 4-46) revealed an increase of the temperatures below 18 °C for the non-insulated envelope when used combined with insulated ground floor component rather than its use combined with non-insulated ground floor component. The use of insulated envelope combined with insulated ground floor construction element also showed an increase of the cooling demand.

For all these reasons, and given that a negative effect in increasing temperature extremes was observed in the typical Brazilian envelope when it included an insulated ground floor, all the simulations in Case 1 also considered the use of a non-insulated floor. Thus, the results seem to suggest that independently of the adopted infiltration rate, the beneficial use of the typical Brazilian ground floor construction remained constant.

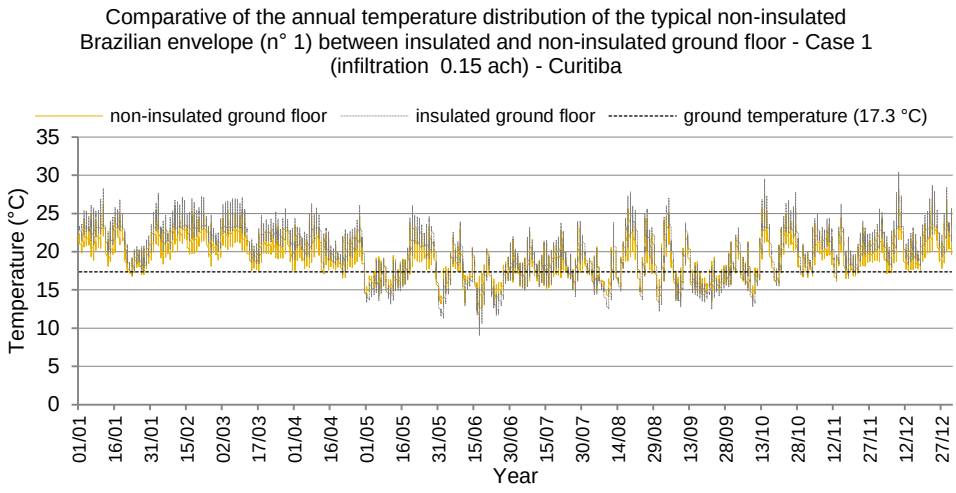


Figure 4-35: Annual internal temperature distribution of the typical non-insulated Brazilian envelope (n° 1) for different ground floor construction types, Case 1, Curitiba

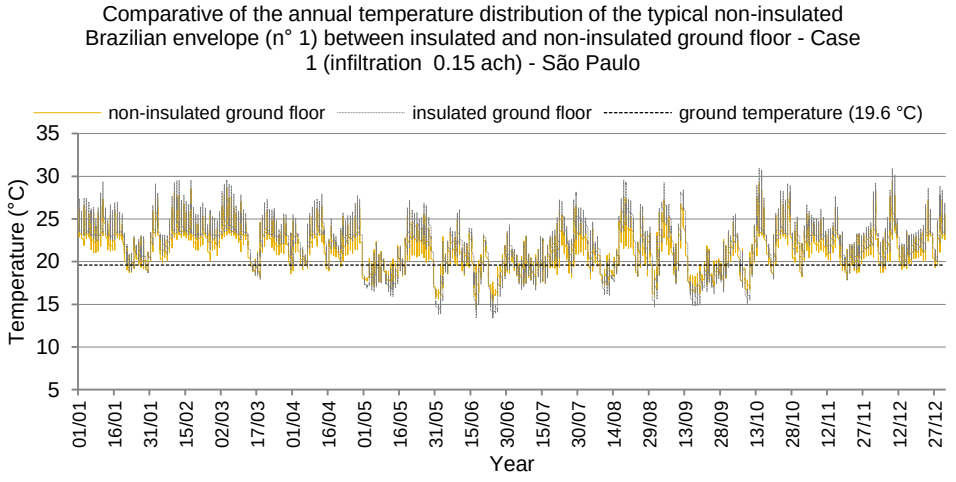


Figure 4-36: Annual internal temperature distribution of the typical non-insulated Brazilian envelope (n° 1) for different ground floor construction types, Case 1, São Paulo

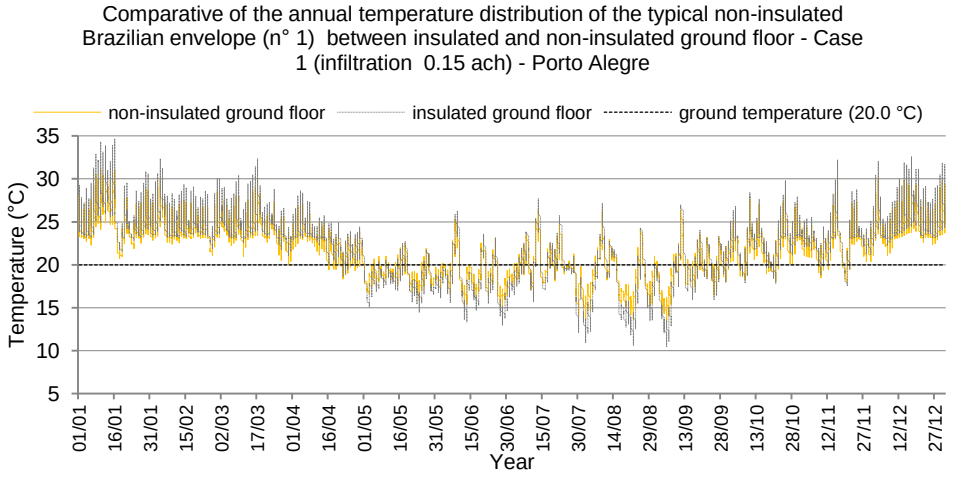


Figure 4-37: Annual internal temperature distribution of the typical non-insulated Brazilian envelope (n° 1) for different ground floor construction types, Case 1, Porto Alegre

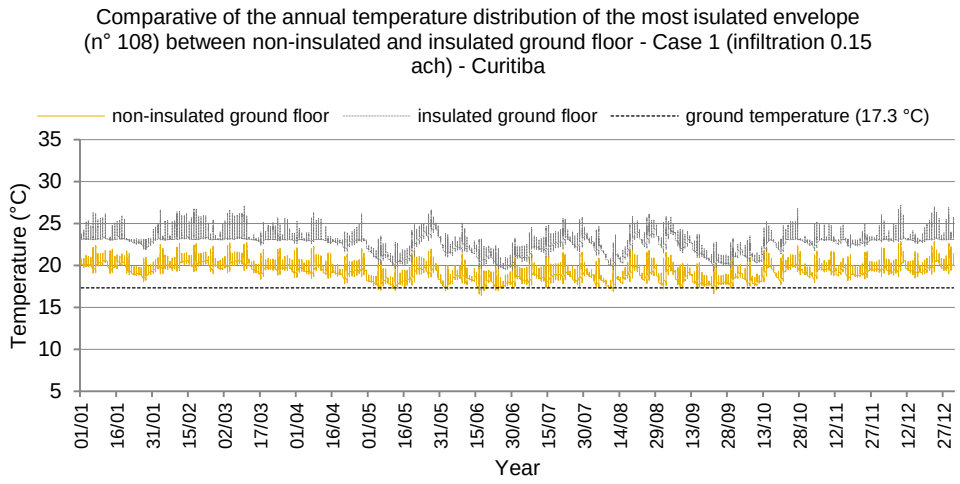


Figure 4-38: Annual internal temperature distribution of the most insulated envelope (n° 108) for different ground floor construction types, Case 1, Curitiba

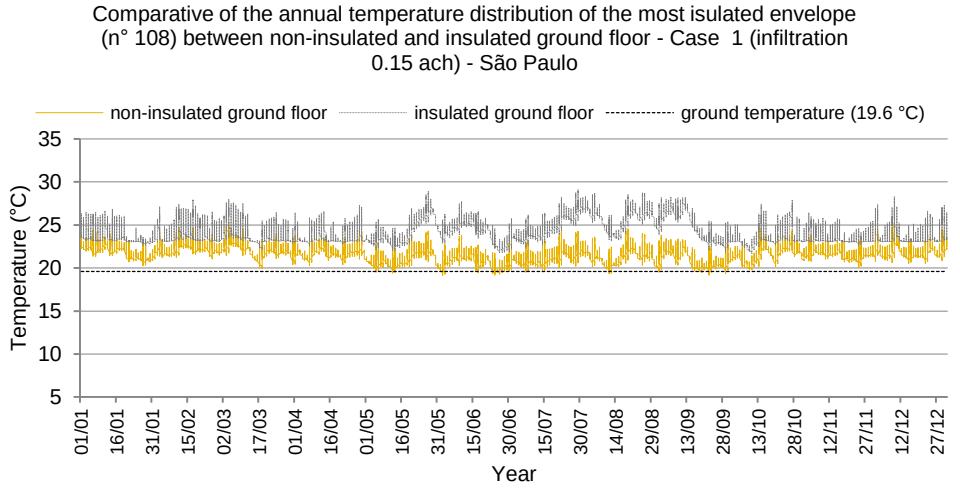


Figure 4-39: Annual internal temperature distribution of the most insulated envelope (n° 108) for different ground floor construction types, Case 1, São Paulo

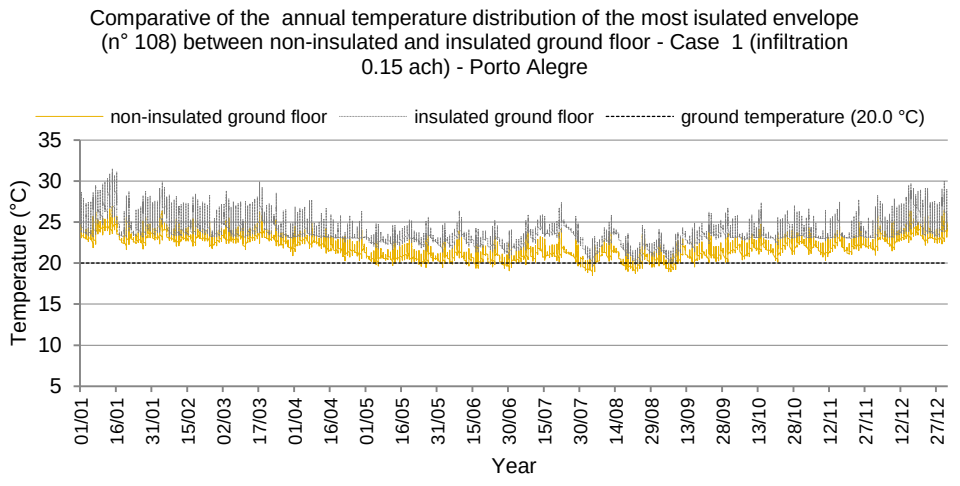


Figure 4-40: Annual internal temperature distribution of the most insulated envelope (n° 108) for different ground floor construction types, Case 1, Porto Alegre

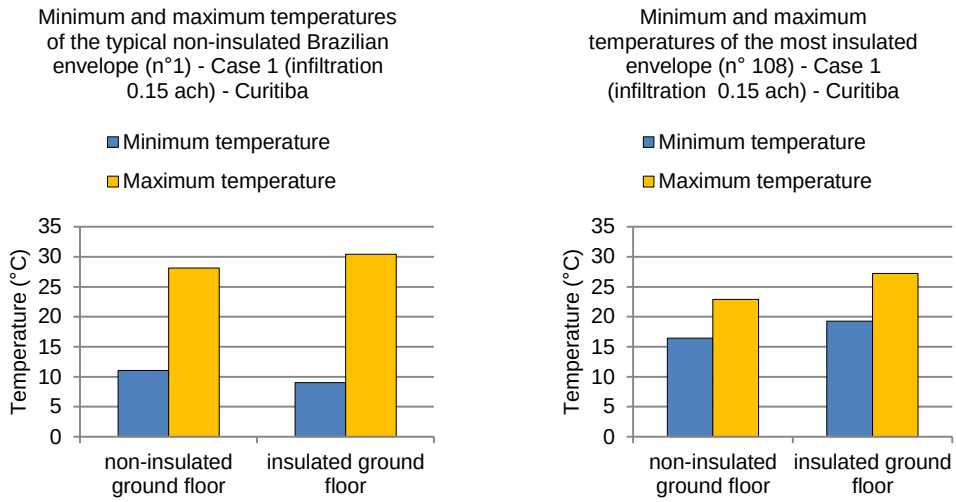


Figure 4-41: Maximum and minimum internal temperatures of different ground floors for non-insulated (n°1) and insulated (n°108) envelopes, Case 1, Curitiba

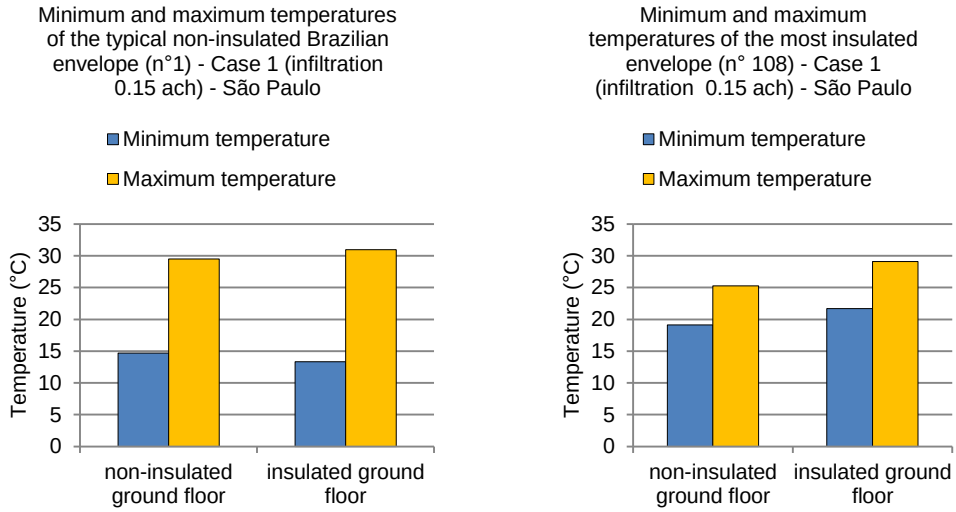


Figure 4-42: Maximum and minimum internal temperatures of different ground floors for non-insulated (n°1) and insulated (n°108) envelopes, Case 1, São Paulo

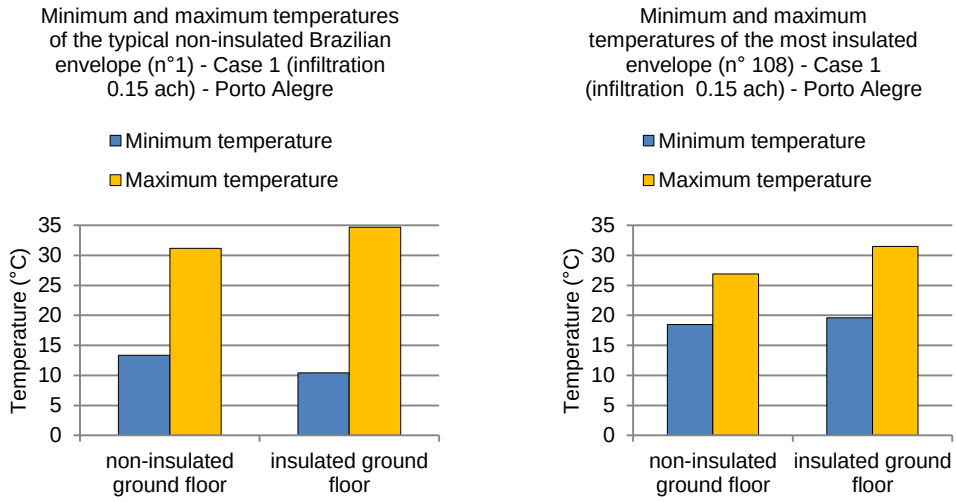


Figure 4-43: Maximum and minimum internal temperatures of different ground floors for non-insulated (n°1) and insulated (n°108) envelopes, Case 1, Porto Alegre

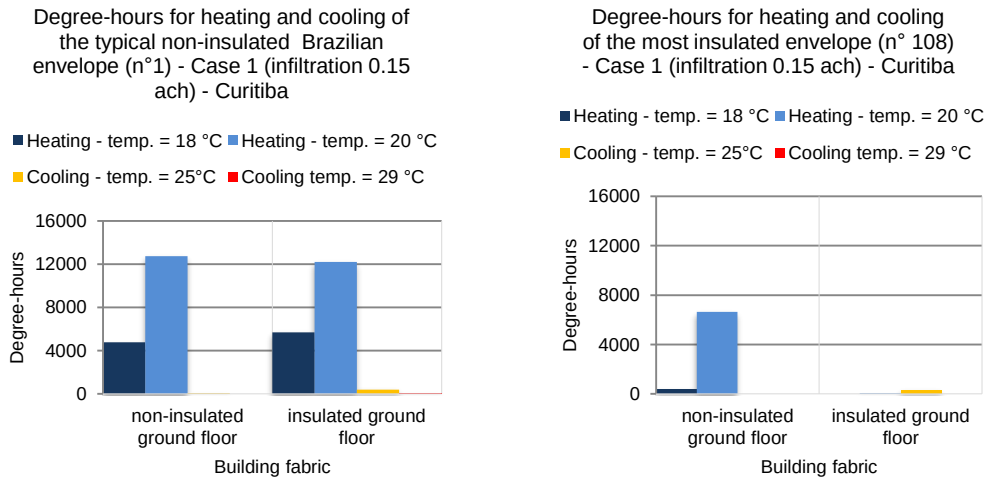


Figure 4-44: Degree-hours of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Case 1, Curitiba

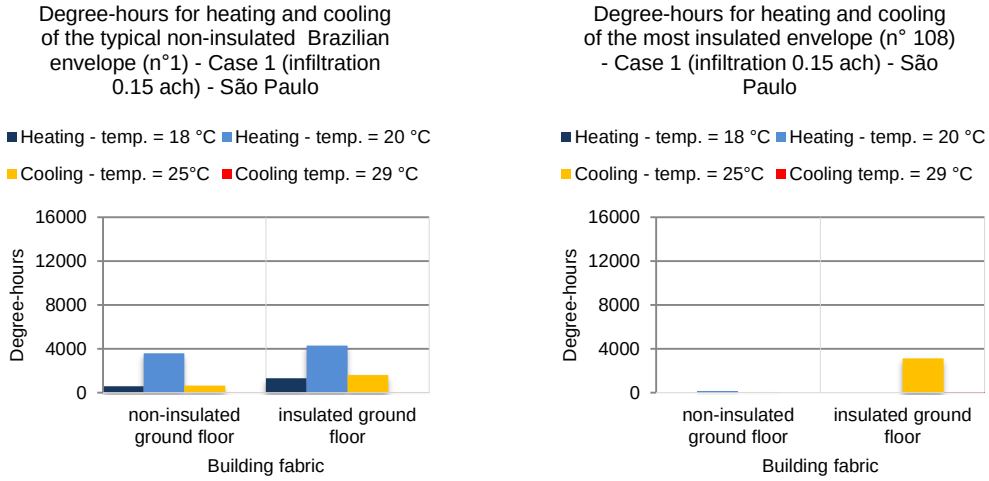


Figure 4-45: Degree-hours of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Case 1, São Paulo

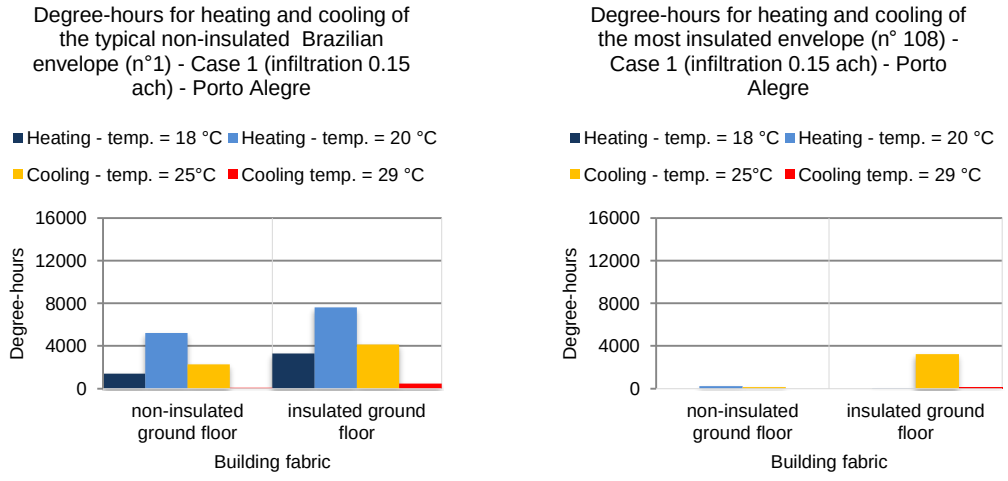


Figure 4-46: Degree-hours of different ground floors for non-insulated (n° 1) and insulated (n° 108) envelopes, Case 1, Porto Alegre

Average, Minimum and Maximum Temperature

Figure 4-47, Figure 4-48 and Figure 4-49 show the average, maximum and minimum temperatures for each envelope combination for the cities investigated. Table 4-14 summarizes the annual average, minimum and maximum temperatures among those envelopes investigated.

Table 4-14: Annual average, minimum and maximum temperatures for Curitiba, São Paulo and Porto Alegre at occupant level – Case 1

	Curitiba	São Paulo	Porto Alegre
External avg. temperature	17.29 °C	19.57 °C	19.40 °C
Internal highest. avg. temperature	19.61 °C	21.82 °C	22.23 °C
Internal lowest. avg. temperature	19.24 °C	21.39 °C	21.77 °C
Δt avg. temperature	0.37 K	0.44 K	0.46 K
External minimum temperature	-0.10 °C	8.50 °C	2.80 °C
Internal lowest minimum temperature	10.98 °C	14.67 °C	13.30 °C
Internal highest minimum temperature	16.48 °C	19.14 °C	18.48 °C
Δt min. temperature	5.50 K	4.47 K	5.18 K
External maximum temperature	32.20 °C	33.80 °C	37.40 °C
Internal lowest maximum temperature	21.76 °C	25.29 °C	26.25 °C
Internal highest maximum temperature	28.21 °C	29.73 °C	31.66 °C
Δt max. temperature	6.45 K	4.44 K	5.41 K

The envelopes with maximum and minimum temperatures differed slightly from those identified at infiltration of 1 ach.
Envelope with the highest minimum temperature and the lowest maximum temperature: n°106 in Curitiba; n° 108 and 106 in São Paulo, respectively; n° 108 and 71 in Porto Alegre, respectively
Envelope with the highest maximum temperature and the lowest minimum temperature: for all the cities was n°13, followed by the typical Brazilian envelope (n° 1) or eventually by n° 49 in the case of maximum temperature in São Paulo and Porto Alegre.

The reduction of the infiltration rate had a very positive effect inside the building in terms of the temperatures. The effect was mostly the increase of the lowest temperatures and decrease of the highest temperatures. Also, the infiltration reduction was responsible for increasing the indoor mean average temperatures by approximately 0.5 °C in all the cities when compared to Base Case scenario.

In Curitiba, the minimum temperatures were uniformly increased by about 3 °C due to the infiltration reduction and the majority of the envelopes were around 15 °C, the only exception being those made out of uninsulated walls that had lower minimum temperatures. Infiltration reduction also decreased slightly the maximum temperatures at occupant level for the envelopes made out of uninsulated walls but it had a major impact on reducing the temperatures to below 25 °C for the envelopes made out of insulated walls. In other words, infiltration had a small positive impact on non-insulated envelopes but it caused a significant positive impact on insulated envelopes.

In São Paulo, the lower infiltration increased the minimum temperatures by 1 °C. The minimum temperatures of the envelopes made out of insulated walls were increased closer to 20 °C while the minimum temperature of the envelopes without insulated walls increased slightly to about 15 °C. The maximum temperatures were slightly reduced at occupant level when compared to Base Case levels.

In Porto Alegre, the minimum temperatures were increased by about 3 °C across the envelopes due to the reduction of infiltration. The maximum temperatures were decreased modestly mainly at occupant level when compared to Base Case scenario.

The main reason for this positive effect of the low infiltration rate relied on the fact that the lowest and highest temperatures occurred mainly when the building was closed (without ventilation). It should be remembered that the assumptions presuppose that no ventilation was considered in winter season and also no ventilation was considered in summer and mid-season when the external temperatures were higher than the indoor temperatures. When infiltration was kept low, this offered a higher resistance barrier to the heat exchange by convection when compared to the building with standard level of infiltration.

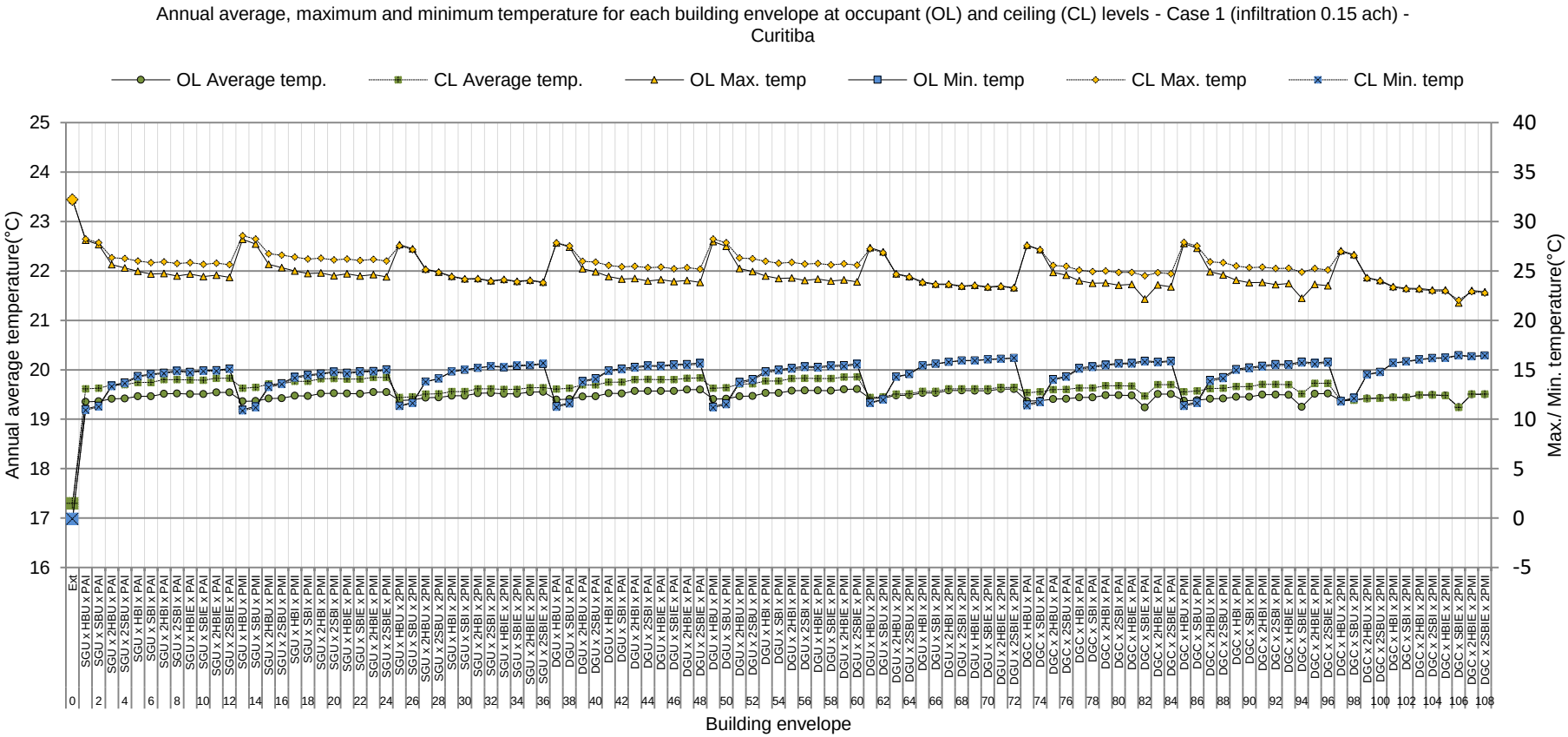


Figure 4-47: Annual average, maximum and minimum temperatures for different building envelopes in Curitiba, Case 1

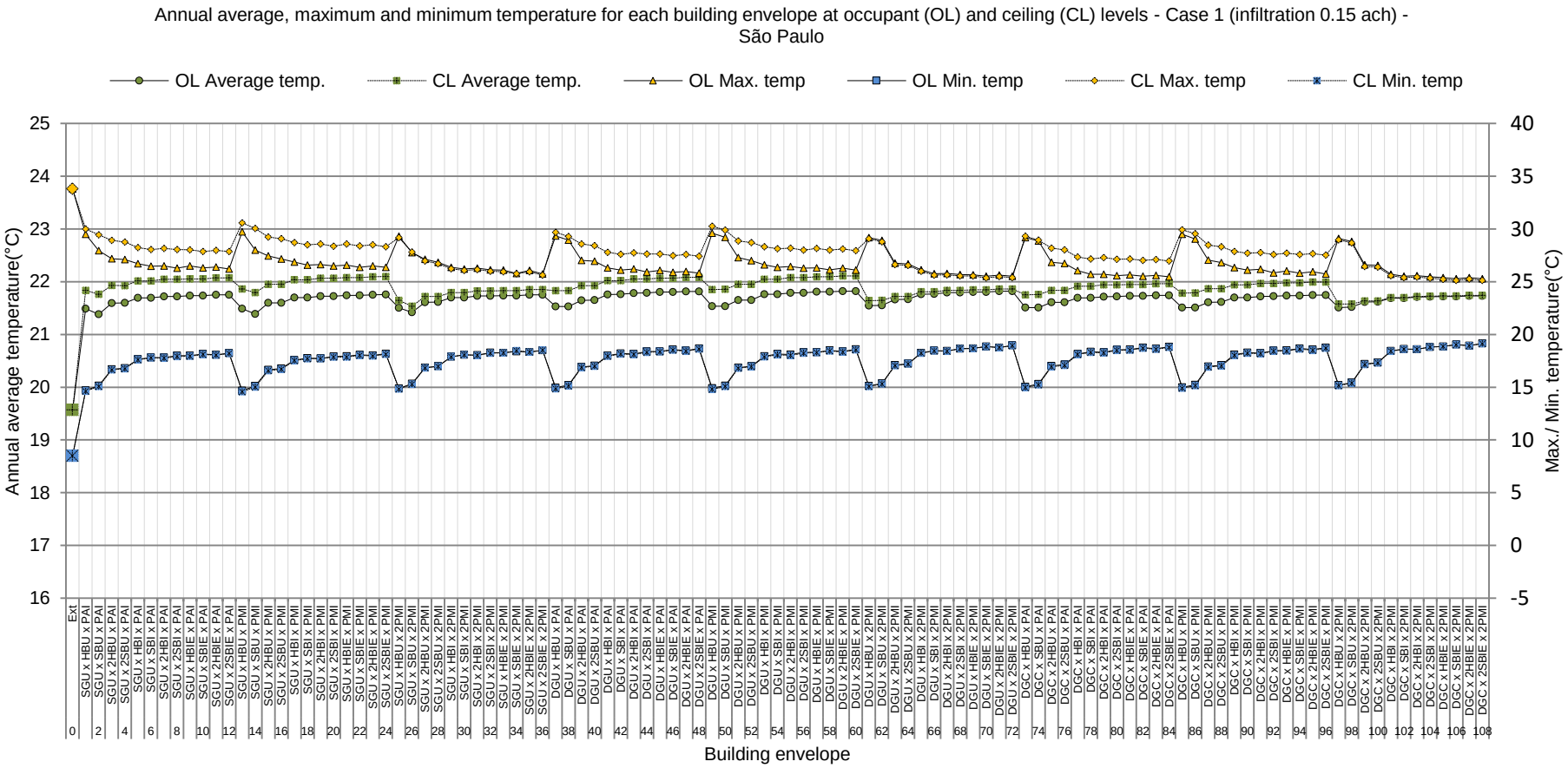


Figure 4-48: Annual average, maximum and minimum temperatures for different building envelopes in São Paulo, Case 1

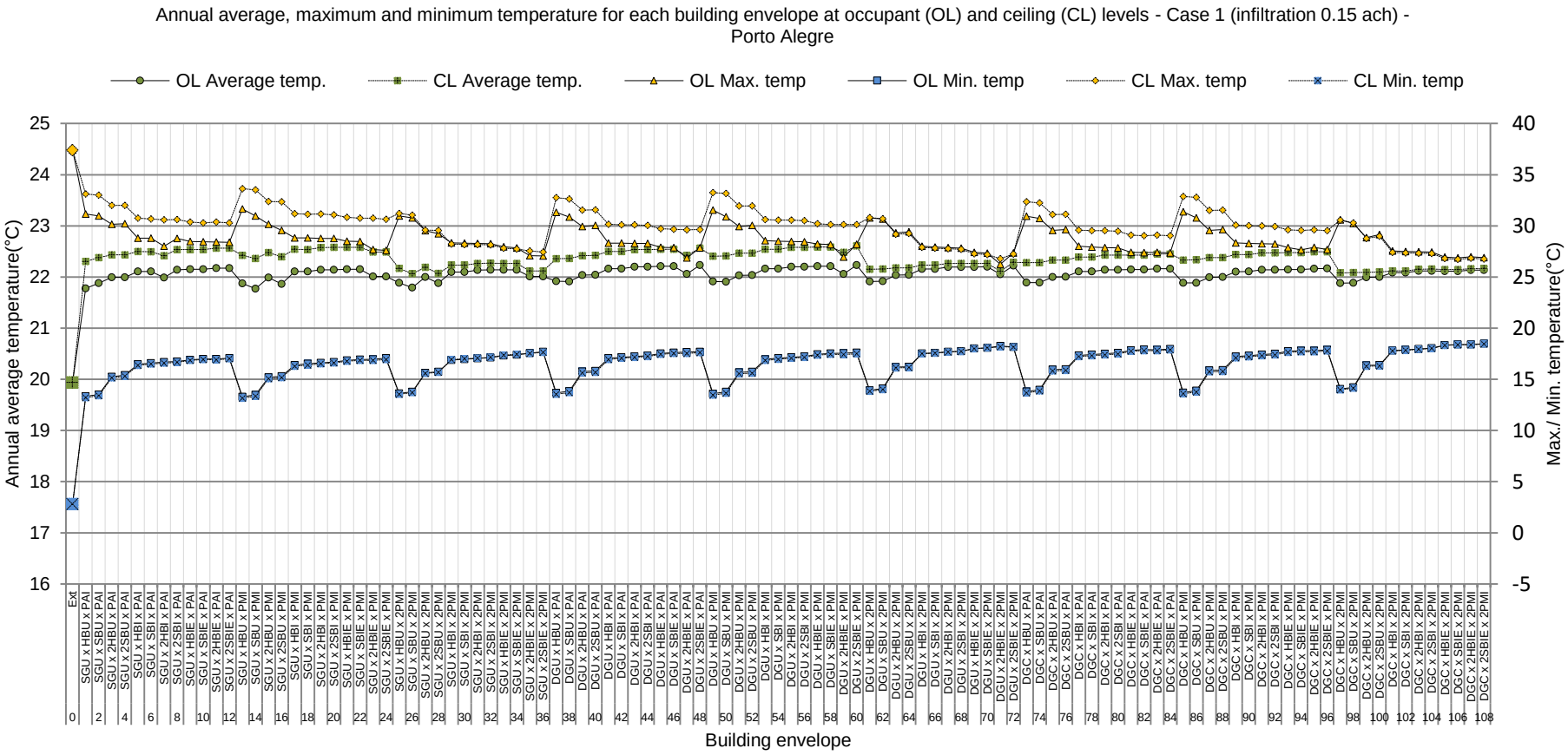


Figure 4-49: Annual average, maximum and minimum temperatures for different building envelopes in Porto Alegre, Case 1

Degree-hours

Figure 4-50, Figure 4-51 and Figure 4-52 show the degree-hours for the thermal comfort limits of 20-25 °C. Table 4-11 summarises these values.

Table 4-15: Degree-hours for thermal comfort interval of 20 °C and 25 °C - Case 1

Degree-hours		Curitiba	São Paulo	Porto Alegre
Base temperature of 20 °C	External	31139.70	16667.60	19725.50
	Int. lowest	6492.10	125.87	230.47
	Int. highest	12755.96	3632.20	5219.86
Base temperature of 25 °C	External	996.00	2332.00	5164.70
	Int. lowest	0	0.90	74.64
	Int. highest	68.66	673.37	2546.35
Base temperature of 20 °C and 25 °C	External	32135.70	18999.60	24890.20
	Int. lowest	6492.10	126.77	360.90
	Int. highest	12824.62	4305.57	7664.69
Lowest degree-hours envelope: in Curitiba, nº 72, followed by n° 71; in São Paulo and Porto Alegre, nº 108, followed by nº 107 in São Paulo and nº 106 in Porto Alegre. Highest degree-hours envelopes: In all cities, nº 13, followed by the nº 1 (typical Brazilian envelope).				

As can be seen from the Figures, the behavioural pattern of the envelopes identified in Base Case was kept similar in Case 1. Once again, the typical Brazilian envelope (n° 1) had a very close behaviour to the worst performance envelope, named as n° 13. The best performance envelopes of each city were consistently kept the same as those mentioned in Base Case.

For all the cities, a substantial reduction of the heating degree-hours was observed due to the adoption of a low infiltration rate of 0.15 ach. The reduction of the infiltration rate resulted in a considerable rise in indoor temperatures during the winter and a reduction of the peak temperatures in summer when the external conditions were not favourable to the use of natural ventilation.

In Curitiba, the external degree-hours for thermal comfort interval of 20-25 °C corresponded to 32135.70. The typical Brazilian envelope (n° 1) had internal degree-hours of 12782.96. The best performance envelopes (n° 72) reduced the degree-hours to 6492.10, which was almost half (49.21%) of the typical Brazilian envelope.

In São Paulo, the external degree-hours for thermal comfort interval of 20-25 °C were 18999.60. The typical Brazilian envelope (n° 1) had degree-hours of 4241.81. The best performance envelope (n° 108) reduced the degree-hours to 126.77. The thermal comfort of the best performance envelope was increased by 97.01% when compared to the levels delivered by the typical Brazilian envelope.

In Porto Alegre, the external degree-hours corresponded to 24890.20. The typical Brazilian envelope (n° 1) had degree-hours of 7482.41. The best performance

envelope (n° 108) reduced the degree-hours to 360.90, which meant a reduction of 95.18%[43] of the thermal discomfort when compared to the typical Brazilian envelope.

A closer look at the demands of the typical Brazilian and best performance envelopes for both infiltrations of 1 ach (Base Case) and 0.15 ach (Case 1) revealed that the positive contribution of infiltration reduction was higher in the most insulated envelopes rather than in the non-insulated typical Brazilian envelope. In order to show this difference, black lines in the Figures show the degree-hours at standard infiltration rate of 1 ach for comparison purposes.

By only reducing the infiltration, the demands for heating and cooling of the best performance envelopes (n° 72 in Curitiba and 108 in São Paulo and Porto Alegre) were reduced by 47.35%, 94% and 89.77% in Curitiba, São Paulo and Porto Alegre, respectively. For the typical Brazilian envelope (n° 1), the demands were overall reduced by 18.74%, 29.27% and 25.27% when a limited infiltration was considered for the cities of Curitiba, São Paulo and Porto Alegre, respectively.

Figure 4-53, Figure 4-54 and Figure 4-55 show the degree-hours for the thermal comfort interval of 18-29 °C. Table 4-12 summarises the main values.

Table 4-16: Degree-hours for thermal comfort interval of 18 °C and 29 °C - Case 1

Degree-hours		Curitiba	São Paulo	Porto Alegre
Base temperature of 18 °C	External	19405.40	8314.10	12006.60
	Int. lowest	341.44	0	0
	Int. highest	4825.95	614.74	1404.60
Base temperature of 29 °C	External	47.60	246.2	1240.00
	Int. lowest	0	0	0
	Int. highest	0	2.43	149.27
Base temperature of 18 °C and 29 °C	External	19453.00	8560.30	13246.60
	Int. lowest	341.44	0	0
	Int. highest	4825.95	617.17	1553.87
Lowest degree-hours envelope: in Curitiba, nº 108, followed by n° 107; in São Paulo and Porto Alegre, many different envelopes were able to reduce the thermal discomfort at negligible levels (see graph) Highest degree-hours envelopes: In all cities, nº 13, followed by the nº 1 (typical Brazilian envelope).				

The degree-hours for a comfort interval of 18-29 °C showed a considerable reduction on their demands for all the cities.

In Curitiba, the best performance envelope (n° 108) was able to reduce the degree-hours to 341.44 and this corresponded to an increase of the thermal comfort by 92.86% when compared to the typical Brazilian envelope (n° 1), which had 4782.83 degree-hours[44].

[43] The best performance envelopes had an improvement of 49.38%, 97.06% and 95.29% relative to the worst performance envelope (n°13) in Curitiba, São Paulo and Porto Alegre, respectively.

[44] This meant an improvement of 92.93% relative to the worst performance envelope (n° 13).

In São Paulo and Porto Alegre, the degree-hours of the typical Brazilian envelope corresponded to 596.84 and 1481.90, respectively. In both cases, the demands for cooling and heating were mitigated for a variety of different envelopes. All those envelopes that were able to mitigate or almost mitigated the demands were those with insulated walls.

The positive effect of the infiltration was more evident at the wide thermal comfort interval of 18-29 °C than the narrow interval of 20-25 °C. This mainly because the reduction in infiltration raised the lower temperatures, which were previously beyond the lower comfort limits, and kept them within the thermal comfort interval. The typical Brazilian envelope had its thermal comfort increased by 28.19%, 49.28% and 43.65% for only limiting the infiltration rate from 1 to 0.15 ach for the cities of Curitiba, São Paulo and Porto Alegre, respectively.

It should be highlighted that these values included ventilation strategies when appropriate (summer/mid-season) and so this seems to demystify the idea that low infiltration cannot be effectively used with natural ventilation. On the contrary, these strategies seem to be complementary for climates that have both heating and cooling as the moderate climates.

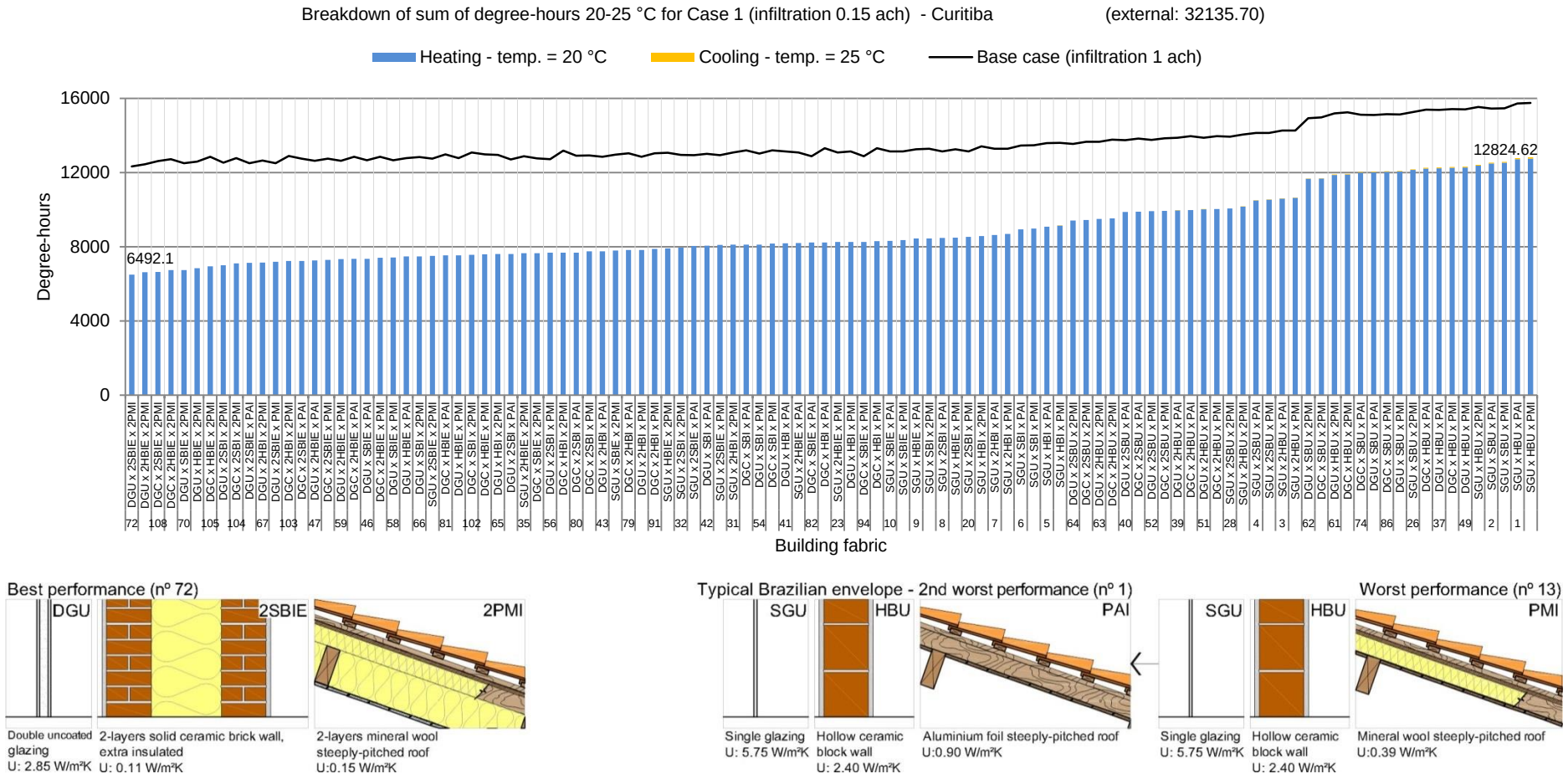


Figure 4-50: Degree-hours 20-25 °C – thermal discomfort, Case 1, Curitiba (organised from the worst to the best)

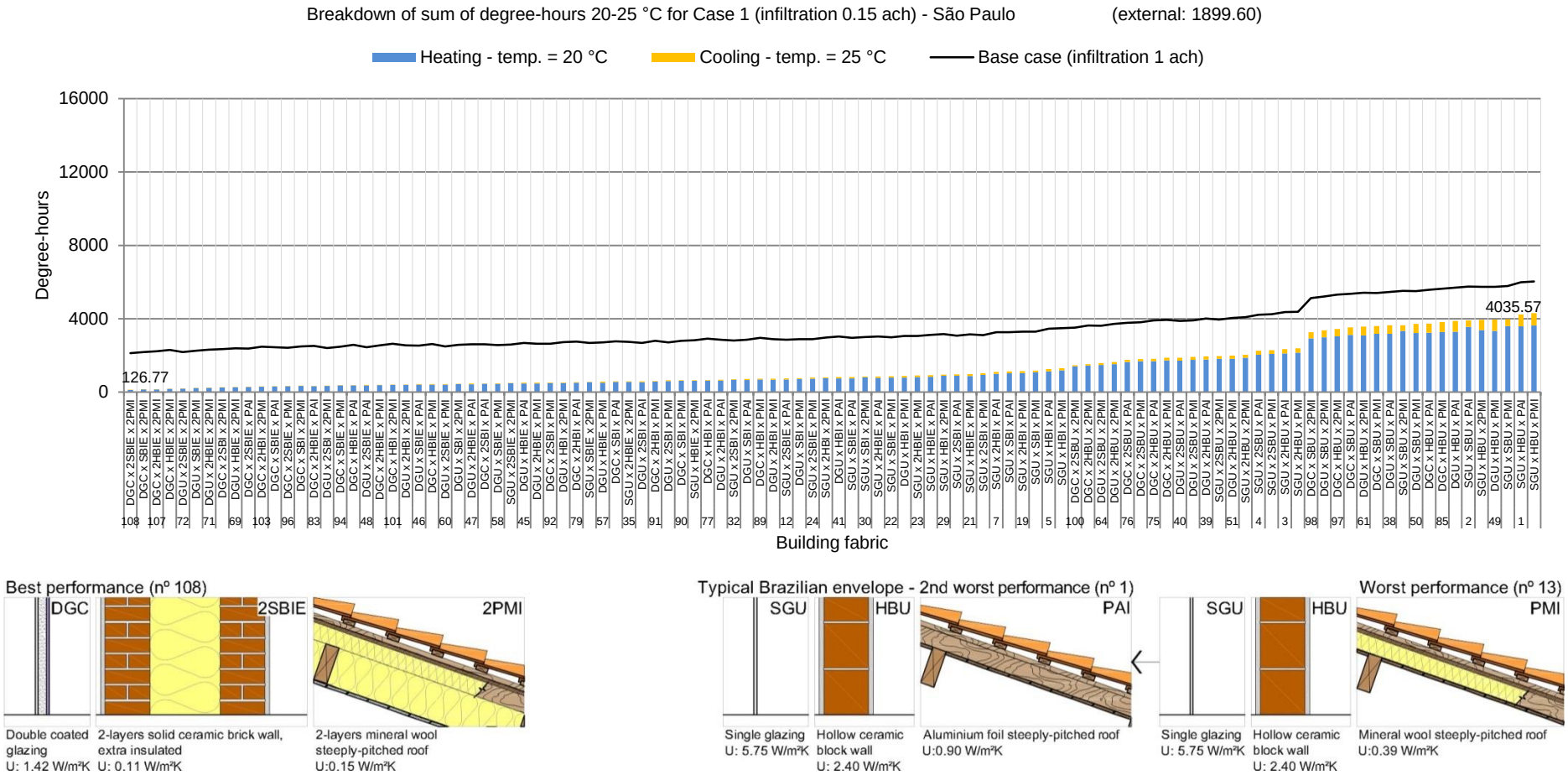


Figure 4-51: Degree-hours 20-25 °C – thermal discomfort, Case 1, São Paulo (organised from the worst to the best)

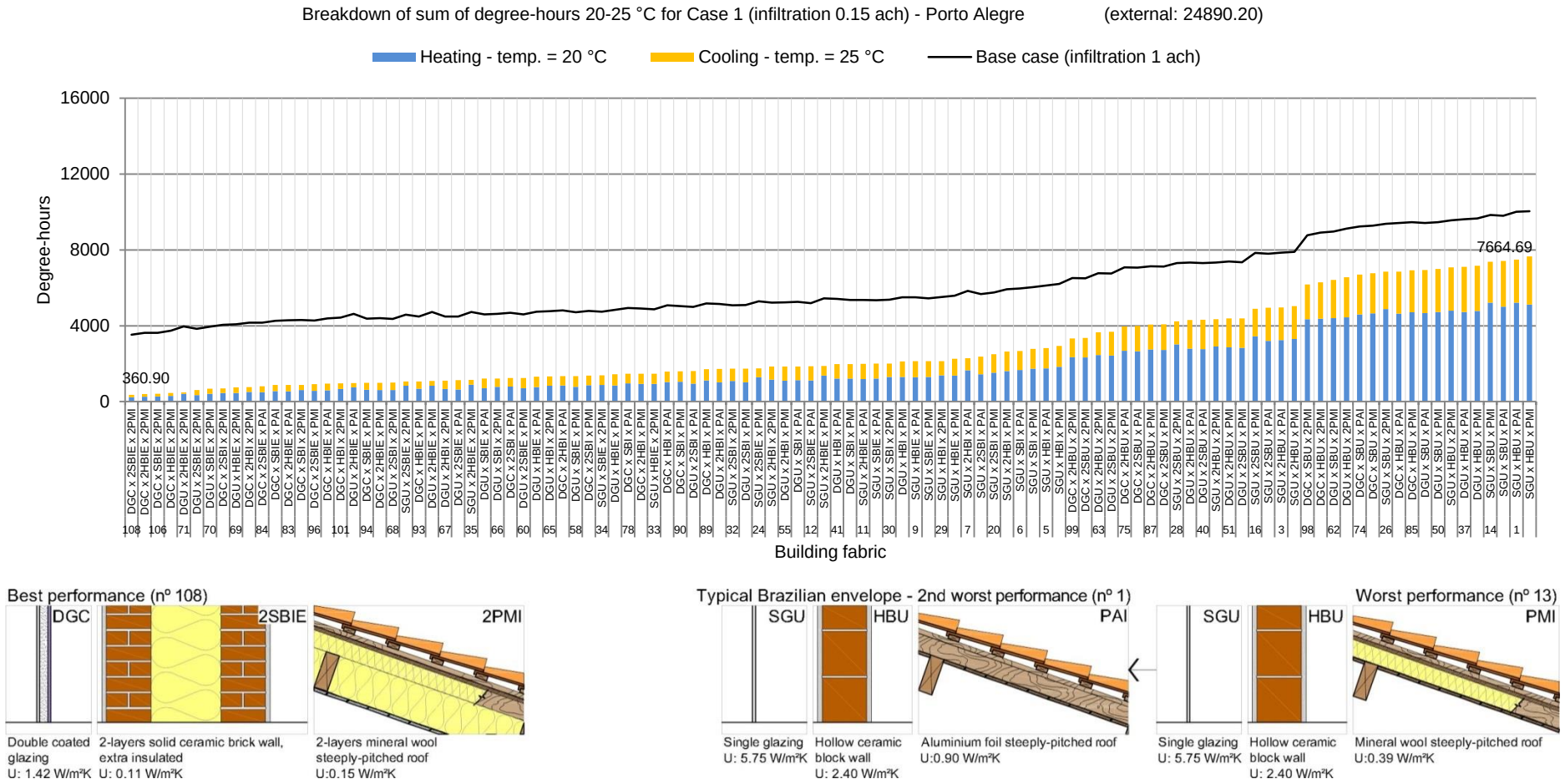


Figure 4-52: Degree-hours 20-25 °C – thermal discomfort, Case 1, Porto Alegre (organised from the worst to the best)

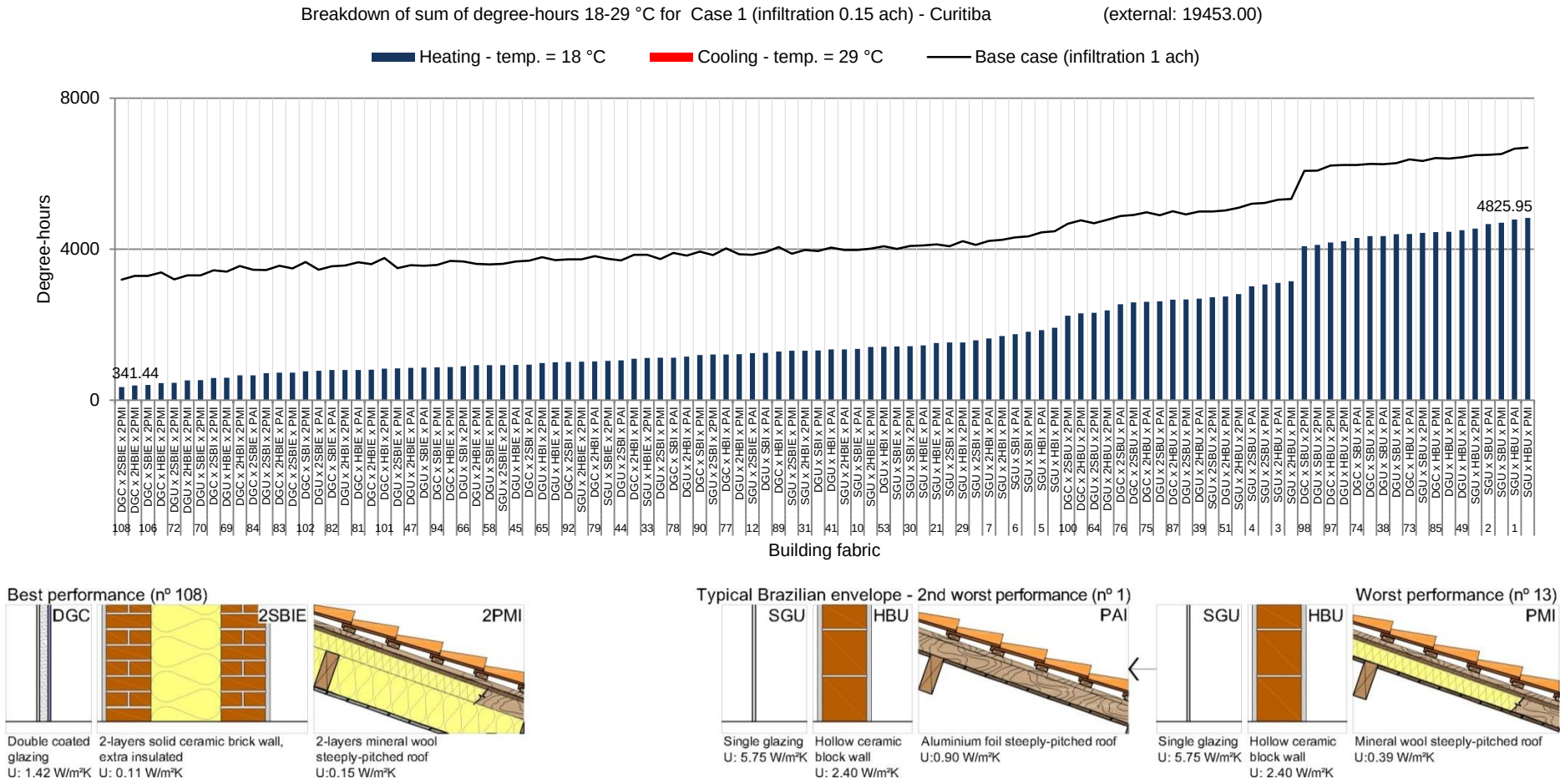


Figure 4-53: Degree-hours 18-29 °C – thermal discomfort, Case 1, Curitiba (organised from the worst to the best)

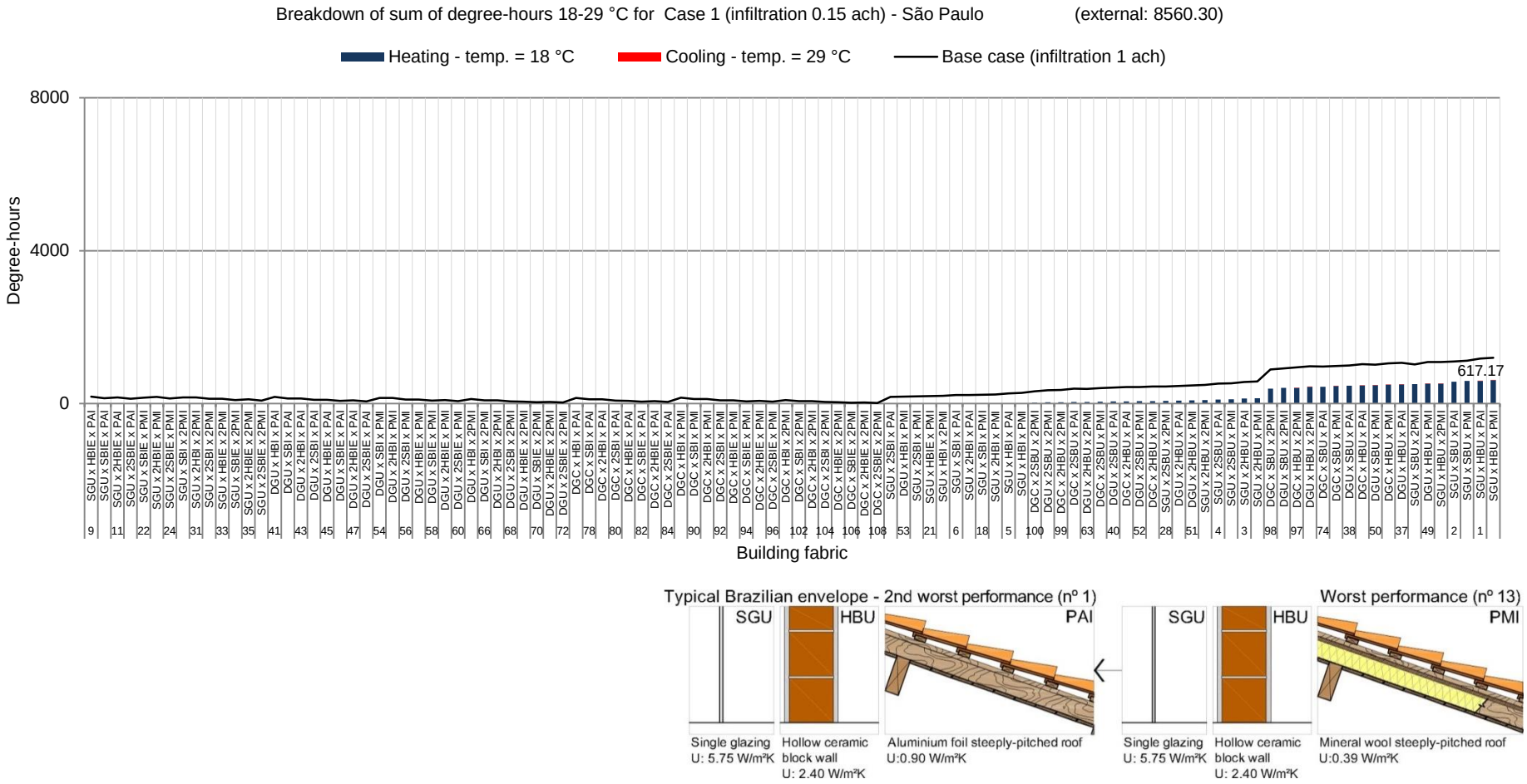


Figure 4-54: Degree-hours 18-29 °C – thermal discomfort, Case 1, São Paulo (organised from the worst to the best)

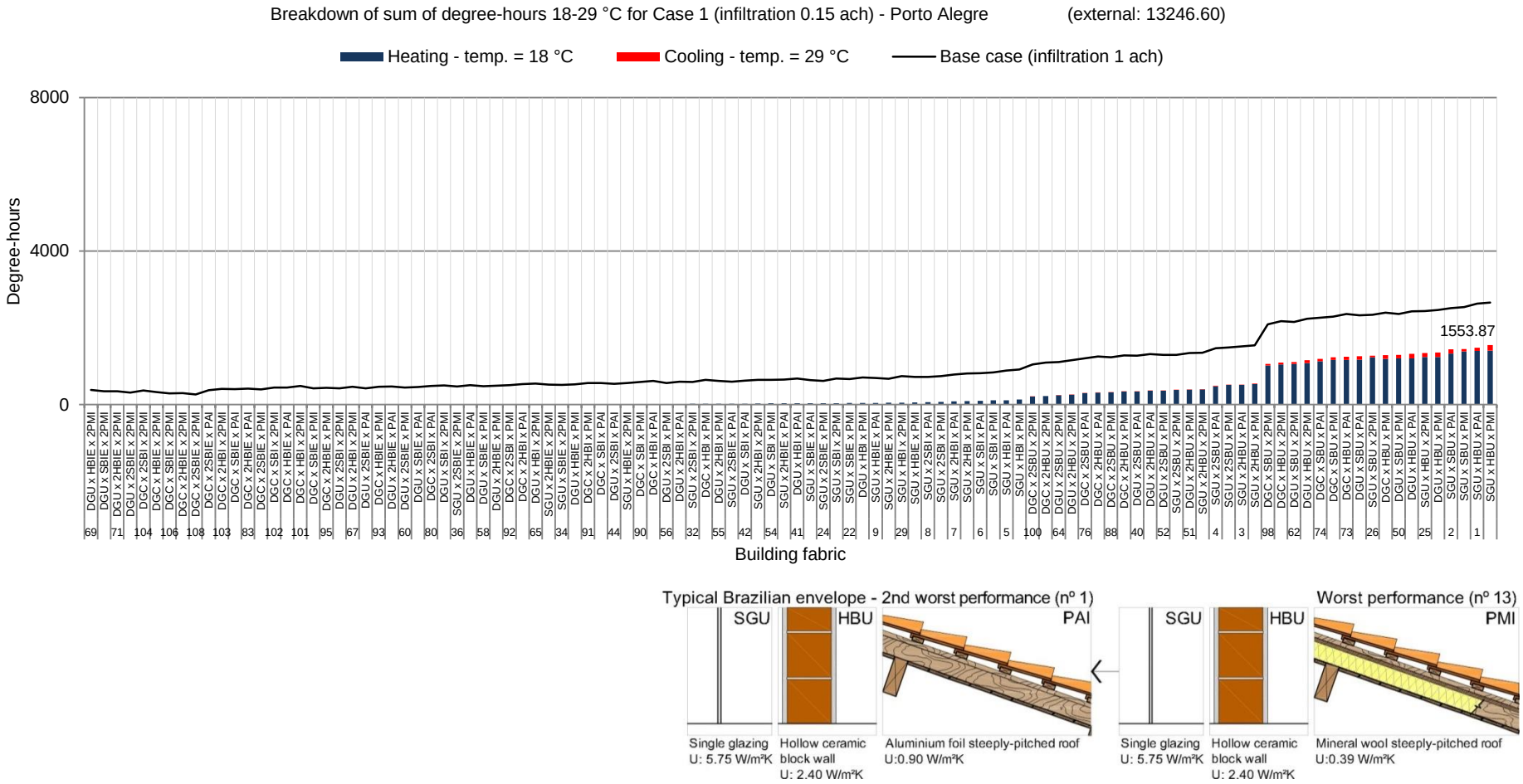


Figure 4-55: Degree-hours 18-29 °C – thermal discomfort, Case 1, Porto Alegre (organised from the worst to the best)

Figure 4-56, Figure 4-57 and Figure 4-58 show the correlation of the fabric heat loss coefficient and the degree-hours for different base temperatures.

As can be seen from the figures, as long as the demands were still representative in the cities, the correlation in terms of heating demand became slightly stronger in the case of infiltration reduction than in the case of infiltration with a standard infiltration rate. This is due to the decrease of the influence of the heat by convection that happens in airtight buildings and, consequently, the increase of the influence of the exchange by conduction, which increases the importance of the envelope U-values and the areas of the envelope exposed.

In order to measure the impact of the reduced infiltration rate of the envelope in the long term, the heating energy demand, which is the major cause of thermal discomfort for the cities investigated, was estimated for informative purposes through the use of degree-hours methodology. The estimated annual heating energy demand for the temperature of 20 °C varied: from 24.67 to 118.85 kWh/m^2 in Curitiba; from 0.47 to 33.89 kWh/m^2 in São Paulo; and from 0.86 to 48.48 kWh/m^2 in Porto Alegre. The most insulated envelopes had the lowest heating energy demands and they had a heating energy demand almost 5 times smaller than the typical Brazilian envelope in Curitiba. In São Paulo and Porto Alegre the most insulated envelopes had the demand reduced to negligible levels. The calculated heating energy for each envelope can be found in Appendix A.

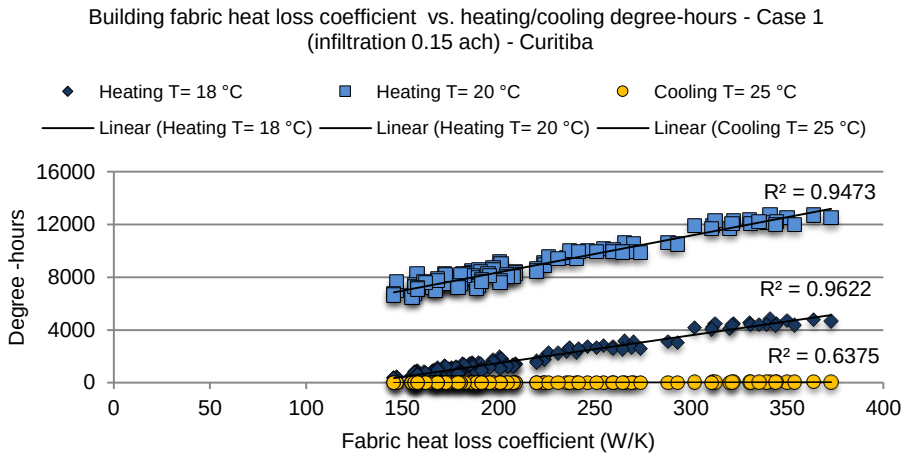


Figure 4-56: Correlation between fabric heat loss coefficient and heating/cooling degree-hours, Case 1, Curitiba

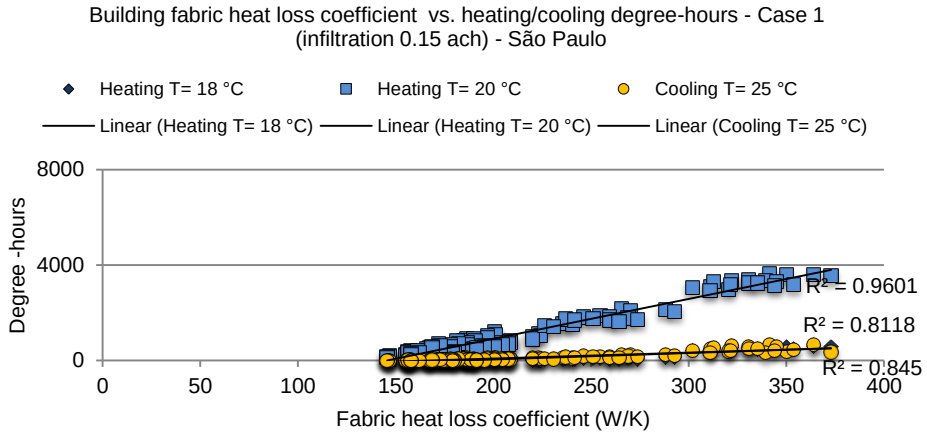


Figure 4-57: Correlation between fabric heat loss coefficient and heating/cooling degree-hours, Case 1, São Paulo

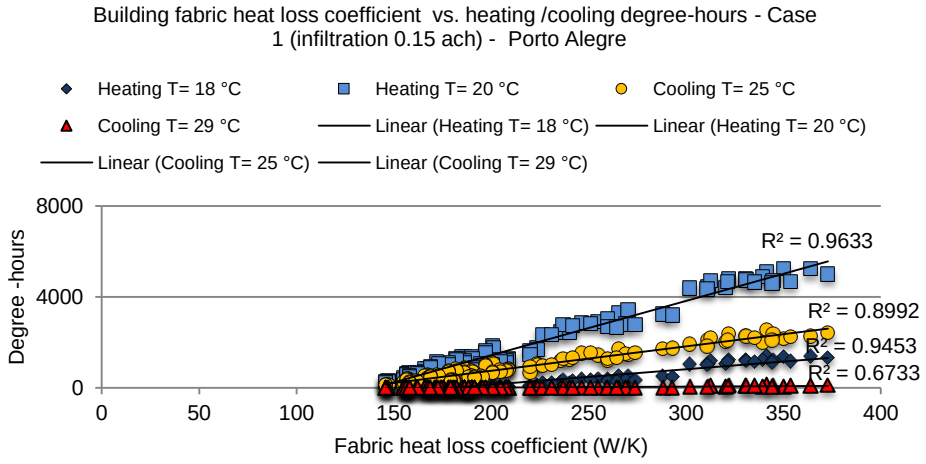


Figure 4-58: Correlation between fabric heat loss coefficient and heating/cooling degree-hours, Case 1, Porto Alegre

Annual Temperature and Frequency

Figure 4-59, Figure 4-60 and Figure 4-61 show comparative thermal comfort data between the best performance envelope and the typical Brazilian envelope (n° 1), which was classified as the second worst performance envelope. The best performance envelope for each city was selected based on the lowest degree-hours at the thermal comfort interval of 20-25 °C and it corresponded to envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre

In Curitiba, the annual temperature variation of the best performance envelope (n° 72) corresponded to 7.10 K, whereas the temperature variation of the typical Brazilian envelope (n° 1) corresponded to 17.10 K and it more than doubled when compared to the best performance envelope.

Externally, for almost 60% of the time the temperatures were below 18 °C. Internally, the typical Brazilian envelope (n° 1) reduced the temperatures below 18 °C to about 32% of the time and the best performance envelope (n° 72) greatly reduced it to 12% of the time. Thermal comfort of 18-29 °C increased from 41% relative to the external temperatures to 68% for the typical Brazilian envelope (n° 1) and to 88% for the best performance envelope (n° 108). Most of the temperatures of the best performance envelope were within the 19 °C and 20 °C range.

The minimum and maximum temperatures of the typical Brazilian envelope (n° 1) corresponded to 11.03 °C and 28.13 °C and they were about 5.18 K lower and 4.82 K higher than the best performance envelope (n° 72), respectively.

In São Paulo, the best performance envelope (n° 108) had an annual indoor temperature amplitude of only 6.15 K. This corresponded to more than half of the annual indoor temperature variation of the typical Brazilian envelope (n° 1), which was estimated to be 14.78 K.

Whilst 36% of the time the external temperatures were below 18 °C, the typical Brazilian envelope (n° 1) greatly reduced it to 8% of the time internally and the best performance envelope (n° 108) totally mitigated the indoor temperatures below the comfort limit of 18 °C. The best performance and the typical Brazilian envelope achieved 100% and 92% of the time within the thermal comfort of 18-29 °C, respectively. For the narrow comfort interval of 20-25 °C, the best performance envelope was within the comfort range for 95% of the time, while the typical Brazilian envelope had only 65%, which was 30% less.

Minimum and maximum temperatures of the typical Brazilian envelope (n° 1) corresponded to 14.71 °C and 29.49 °C, while the best performance envelope (n° 108) swung beyond 4 K more and less, respectively.

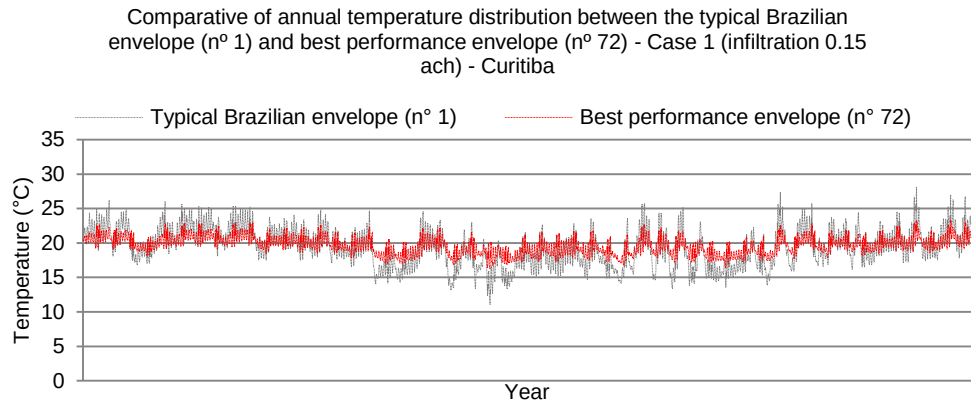
In Porto Alegre, the annual internal temperature amplitude of the best performance envelope was only 8.43 K, more than half the annual amplitude of the typical Brazilian envelope, which was calculated to be 17.82 K.

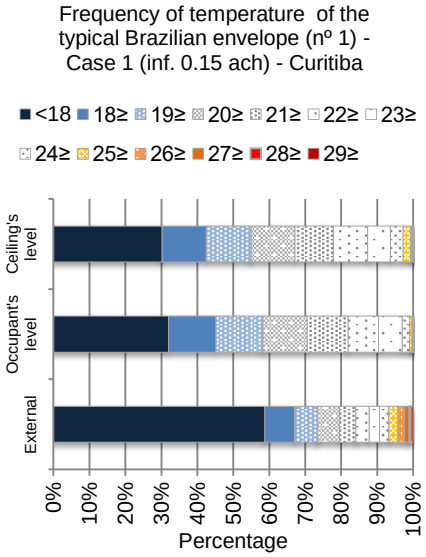
Externally, for more than 35% of the time and for more than 5% of the time the temperatures were below the lower thermal comfort of 18 °C and above the upper thermal comfort of 29 °C, respectively. The typical Brazilian envelope reduced the indoor temperatures below the lower and above the upper thermal comfort limit to 12% and 6% of the year, respectively. The best performance envelope fully mitigated the indoor thermal discomfort for the wide thermal comfort interval of 18-29 °C and had 91% of the time within the narrow thermal comfort interval of 20-25 °C.

Minimum and maximum temperatures of the typical Brazilian envelope (n° 1) corresponded to 13.34 °C and 31.16 °C. They were about 5.14 K lower and 4.25 K higher than the extreme temperatures of the best performance envelope (n° 108).

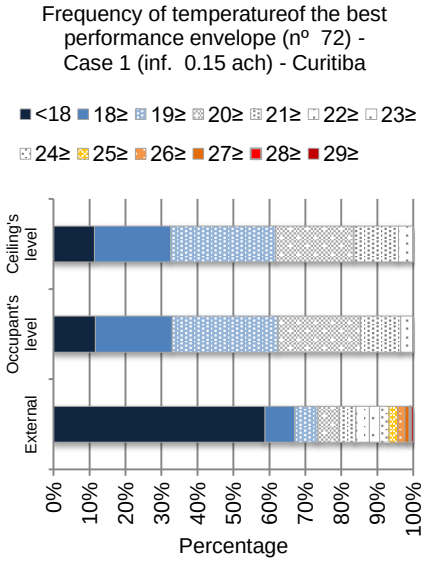
To sum up, the findings demonstrated that typical affordable Brazilian envelopes performed poorly in delivering indoor thermal comfort among those envelopes investigated in typical affordable free-running houses under a specific regime of internal gains, summer and mid-season ventilation and use of shading. Overall, insulated envelope combinations such as those similar to the Passivhaus standard levels were able to maximize the indoor thermal comfort when compared to the building envelope currently adopted in Brazil.

However, all the results from Base Case and Case 1 discussed here should be handled with care as they are the outcome of thermal performance analyses and rely on the assumptions used and the typology adopted. The results showed the best performance envelopes from the thermal comfort point of view, which does not mean that they correspond to the most cost-effective envelopes. The costs of the envelopes under investigation are explored in the next section.

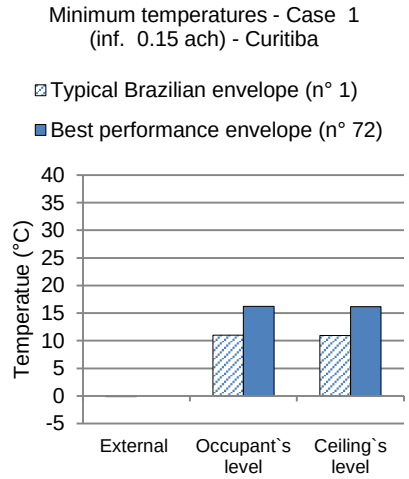




Typical Brazilian envelope (nº 1)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	42%	70%
Occupant level	41%	68%
External	20%	41%



Best performance envelope (nº 72)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	38%	89%
Occupant level	38%	88%
External	20%	41%



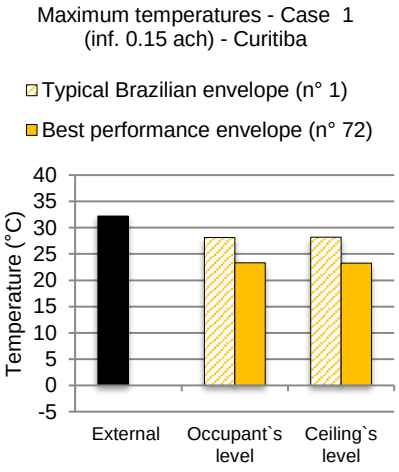
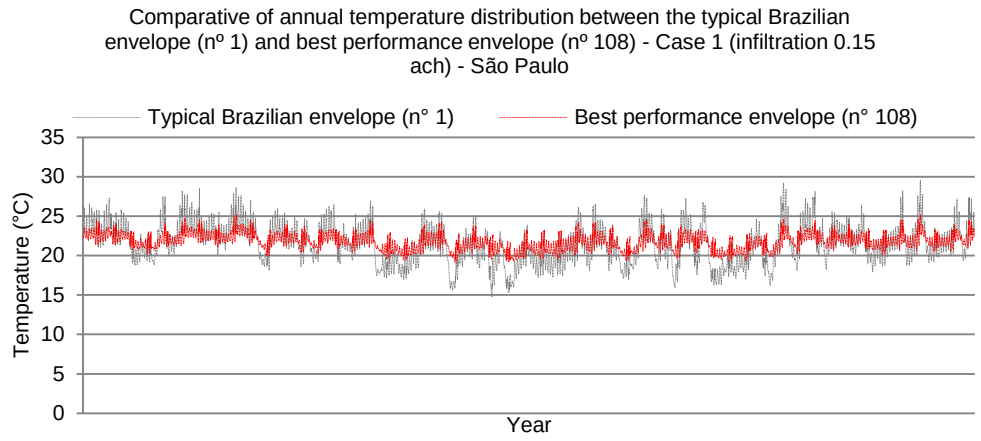
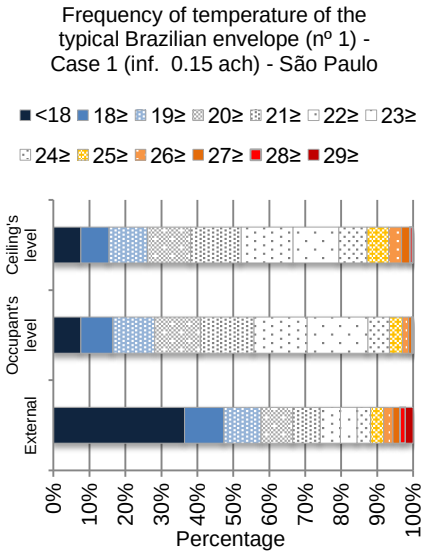
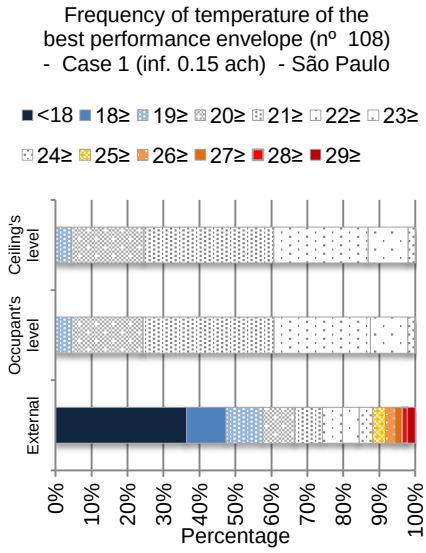


Figure 4-59: Comparative of annual temperature distribution, percentage of comfort and minimum and maximum temperatures between the typical Brazilian envelope (n° 1) and the best performance envelope (n° 72), Case 1, Curitiba

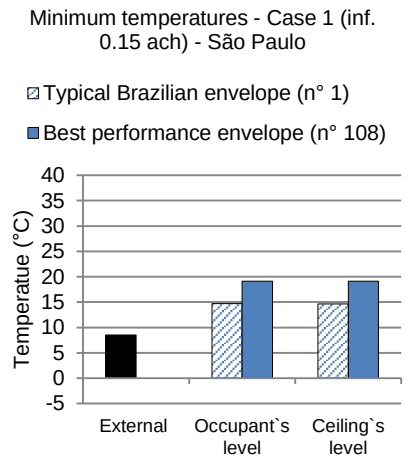






Typical Brazilian envelope (nº 1)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	61%	92%
Occupant level	65%	92%
External	30%	61%

Best performance envelope (nº 108)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	96%	100%
Occupant level	95%	100%
External	30%	61%



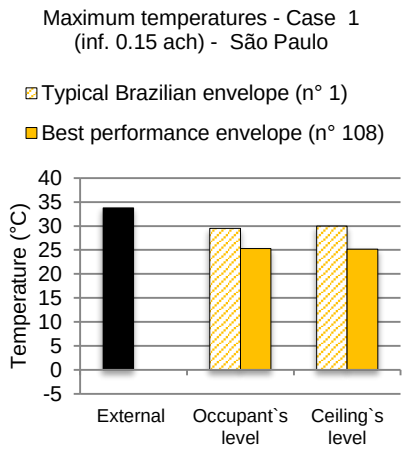
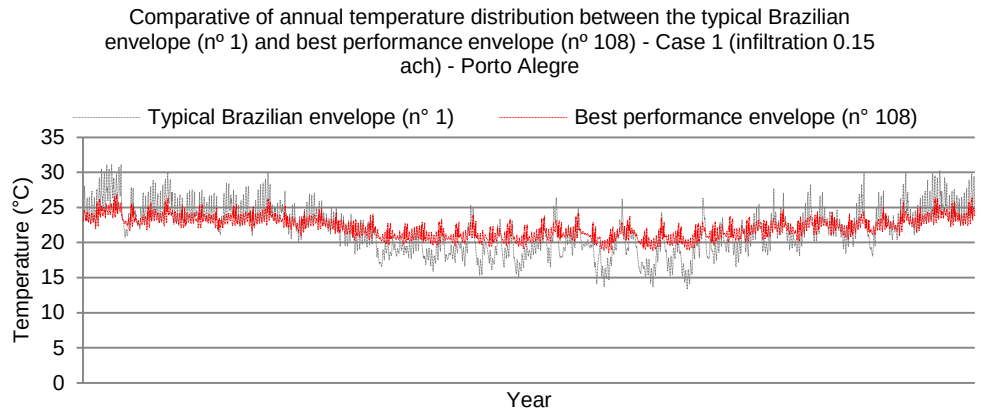
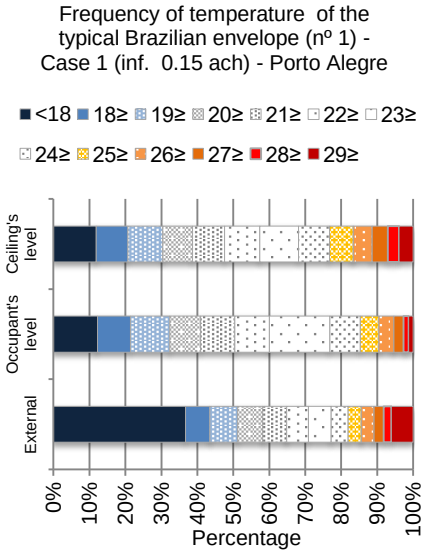
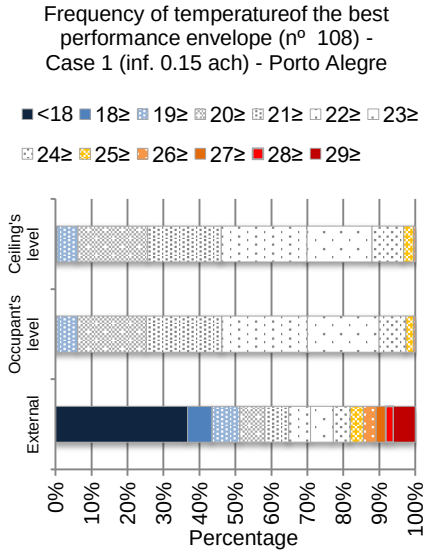


Figure 4-60: Comparative of annual temperature distribution, percentage of comfort and minimum and maximum temperatures between the typical Brazilian envelope (n° 1) and the best performance envelope (n° 108), Case 1, São Paulo

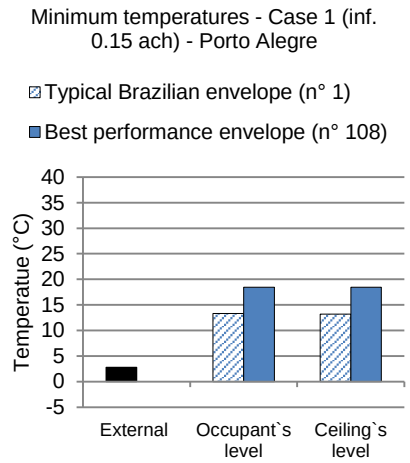




Typical Brazilian envelope (nº 1)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	46%	84%
Occupant level	53%	87%
External	31%	57%



Best performance envelope (nº 108)	Thermal comfort 20-25 °C	Thermal comfort 18-29 °C
Ceiling level	91%	100%
Occupant level	91%	100%
External	31%	57%



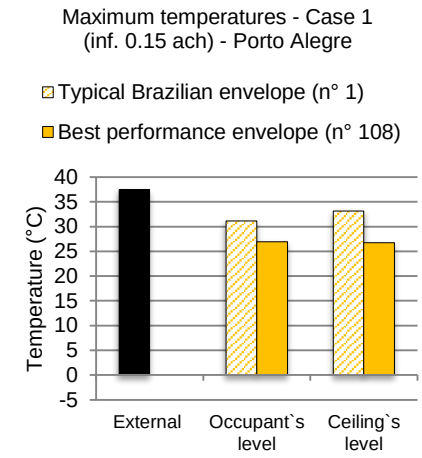


Figure 4-61: Comparative of annual temperature distribution, percentage of comfort and minimum and maximum temperatures between the typical Brazilian envelope (n° 1) and the best performance envelope (n° 108), Case 1, Porto Alegre

4.6 Cost Analysis

The prices used in this cost analysis were estimated through the TCPO's (Price Table Compositions for Quotes, in English) web database (PINI, 2015b). TCPO is a database of more than 5 thousand typical Brazilian construction composition prices that estimates reasonable quantities of labour and materials needed[45]. The TCPO's database is developed by PINI publishing and it has been on the market for more than 50 years, where it has established credibility within the Brazilian civil construction industry (PINI, 2015a).

The TCPO's database adopts the most typical Brazilian construction price compositions, but it does not include innovative products that still have very limited use in the national construction sector, such as high performance glazing and specific insulation materials. For these innovative and high performance products, their prices were set out based on the leading suppliers at national level.

The main focus of this cost assessment was not to establish the costs of an affordable house in detail but the aim was to understand the impact on the costs due to the envelope optimisation. The cost of the affordable house typology varies according to the location where it is built. According to Angélil and Hehl (2014, p. 39), as mentioned in Chapter 2, for the metropolitan areas of the south region, which includes the cities of Curitiba and Porto Alegre, the cost of the house is estimated to be 64 thousand Brazilian reais (approximately 21 thousands US dollars[46]). For the metropolitan areas of the southeast region, which includes the city of São Paulo, the house cost is estimated to be between 60 and 76 thousand Brazilian reais (approximately 20-25 thousands US dollars).

The results of the cost analysis were based on the assumptions that the building envelope that differs from that typically used in Brazil (nº 1) will add extra cost to the housing construction, since the typical Brazilian envelope is a non-insulated envelope and this is the most basic envelope among those investigated in the current research.

At this point of the current research, the same building envelope costs for both a standard infiltration rate of 1 ach (Base case) and a limited infiltration rate of 0.15 ach

[45] TCPO database also contains SINAPI database, which is the database for affordable houses in Brazil. CAIXA & IBGE 2015. Relatórios de Insumo e Composição após Julho/2014 - Não Desonerado. *SINAPI - Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil.* 13 May 2015 ed.: Caixa Econômica Federal (CAIXA) & Instituto Brasileiro de Geografia e Estatística (IBGE).

[46] Exchange rate: R$ 3.04 ~ US$ 1.00. BANCO CENTRAL DO BRASIL. 2015. *Dólar americano* [Online]. Available: http://www4.bcb.gov.br/pec/taxas/batch/taxas.asp?id=txdolar [Accessed 08 May 2015.

(Case 1) was assumed. It should be noted that the cost for delivering low infiltration rate is difficult to measure and this is discussed in detail in the next chapters. It is known, however, that the adoption of low infiltration rates may impact greatly on the design, labour and management costs.

It is believed, however, that the adoption of low infiltration rates in buildings includes a commitment of not just the construction industry, but the market, government, policy-makers, suppliers and stakeholders. Low infiltration rates can be difficult to deliver initially but as long as the whole of construction industry are familiarized and committed to comply with it, the costs will tend to be reduced in the long term. At this stage, it is only presumed that low infiltration rates can be delivered with no extra cost.

Figure 4-62, Figure 4-63 and Figure 4-64 show the calculated extra cost for each building envelope combination at the standard infiltration rate and its relationship with degree-hours 20-25 °C in Curitiba, São Paulo and Porto Alegre, respectively.

In Curitiba, the best performance envelope (n° 72) had the lowest degree-hours but also the second highest cost among those envelopes investigated. Whilst the degree-hours were reduced by only 21.61%, the extra cost was increased by approximately 50% of the original housing cost. This corresponded to an extra cost of 30.50 thousand Brazilian reais (approximately 10 thousand US dollars).

In São Paulo and Porto Alegre, the most insulated envelope (n° 108) at Passivhaus standard levels had the lowest degree-hours but also the highest cost. Whilst the degree-hours were reduced by 64.61% in São Paulo and by 64.76% in Porto Alegre, the extra costs were increased by approximately 40% and 45% of the house cost, respectively. This was equivalent to an extra cost of 30.80 and 29.20 thousand Brazilian reais, respectively.

A closer look at the extra costs of the envelopes revealed that highly insulated envelopes such as those compatible with the Passivhaus standard levels might not be a cost-effective solution as they have impacted significantly in the costs. Although these envelopes had the best performances, their costs were immensely high. Other envelopes were able to deliver similar comfort levels as those delivered by the best performance envelopes but with a much lower extra cost.

As can be seen from the Figures, in Curitiba the envelope n° 71 delivered almost the same level of thermal comfort with a cost 16% less than the best performance envelope (n° 72). In São Paulo, the envelopes n° 107, 104 and 105 had similar degree-hours with an extra cost of approximately 15%, 14% and 22% less than the best performance envelope (n° 108), respectively. In Porto Alegre, the envelopes n° 107, 106 and 105 also achieved degree-hours similar to those achieved by the best performance

envelope (n° 108) but they had an extra cost of approximately 14%, 15% and 22% less than that envelope. This shows that there is a huge potential for exploring greater reductions of energy demand at different range of costs.

Figure 4-65, Figure 4-66 and Figure 4-67 show the cost in Brazilian reais per potential of degree-hour reduction of each envelope, at a standard infiltration rate. This gives an indication of the cost-benefit of each envelope. Please note that the typical Brazilian envelope (n° 1) is located on the '0' position and it is used as a reference.

As shown by the Figures, the best performance envelope had an enormous additional cost when compared to the typical Brazilian envelope but its benefits were also quite significant. This suggests that its cost-benefit is average among those envelopes investigated.

Other envelopes show a small cost when compared to the potential thermal comfort improvement delivered by them. Note that for all the cities the envelopes in white represented in Figure 4-62, Figure 4-63 and Figure 4-64 were those that were more cost-effective (n° 5, 17, 29, 41, 53, 65, 77, 89, 101). What all these envelopes have in common is the adoption of hollow block insulated walls (U: 0.34 W/m^2K).

In order to estimate the potential cost if the house was heated up, the calculated heating energy demand was used. As mentioned before, considering air conditioning as a heating device, as this is mostly found in mixed-mode ventilated houses in Brazil, the annual energy consumption would vary: from 46.95 to 146.24 kWh/m^2 in Curitiba; from 7.81 to 48.24 kWh/m^2 in São Paulo; and from 10.93 to 66.14 kWh/m^2 in Porto Alegre. The heating energy demands for each envelope investigated can be found in Appendix A.

Air conditioner equipment in Brazil has on average a COP (Coefficient of Performance) of 2.84 (McNeil and Letschert, 2007). This means that the equipment roughly generates 2.84 kW of heating for each 1 kW electrical input.

The national electricity tariffs in 2015 varied from 0.289 to 0.589 Brazilian reais per kWh, excluding taxes (ANEEL, 2015). For Curitiba, São Paulo and Porto Alegre, the price of the kWh excluding taxes correspond to 0.49231, 0.43611 and 0.45662 Brazilian reais (ANEEL, 2015). Including taxes, the price of the kWh reaches R$

0.74592 in Curitiba (Copel, 2015) R$ 0.50305 in São Paulo[47,48] and R$ 0.63570 in Porto Alegre[49,50]. As mentioned, these values correspond to the cheapest band and they could be increased in case of functioning of thermoelectric to complement energy generation.

A closer look at the income of the householders and the potential electricity expenditure for heating up the house at 20 °C reveals that the typical Brazilian envelope would correspond to an annual electricity cost of 15% in Curitiba, 3% in São Paulo and 6% in Porto Alegre of the minimum annual gross wage. The best performance envelopes (n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre) would have an annual electricity cost equivalent to only 5% in Curitiba, 0.5% in São Paulo and almost 1% Porto Alegre of the minimum annual gross wage.

As mentioned in Chapter 2, minimum annual wage corresponds to 10,244 Brazilian reais (788 Brazilian reais monthly plus 13th salary). It should be remembered that householders in these houses usually do not earn more than 3 times the minimum Brazilian wage, although some earn up to 10 times the minimum wage.

Even though the best performance envelope would have the lowest electricity costs, the payback period would be high. In Curitiba, the payback period of the best performance envelope (n° 72) would correspond to 30.8 years. In São Paulo and Porto Alegre, because the heating energy demands are not as high as in Curitiba, the payback period of the best performance envelopes (n° 108) would go beyond the estimated house lifespan of 50 years (ABNT, 2013a, p. 53). The estimated payback period of each envelope can be found in Appendix A. The calculations of the payback period considered a simple payback process as the purpose of the analysis was only for comparison between the cases analysed. It should be noted that for the purpose of

[47] Taxes estimated for electricity consumption between 91 kWh and 200 kWh - ICMS: 12%. AES ELETROPAULO. 2015a. *Entenda o aumento na conta de energia (Março/2015)* [Online]. São Paulo, Brazil: Eletropaulo Metropolitana Eletricidade de São Paulo S/A (AES Eletropaulo). Available: https://www.aeseletropaulo.com.br/para-sua-casa/prazos-e-tarifas/conteudo/entenda-o-aumento-na-conta-de-energia-(mar%C3%A7o2015) [Accessed 19 August 2015.

[48] Taxes for August 2015 – PIS: 0.60% COFINS: 2.75%. AES ELETROPAULO. 2015b. *Impostos e outros encargos* [Online]. São Paulo, Brazil: Eletropaulo Metropolitana Eletricidade de São Paulo S/A (AES Eletropaulo). Available: https://www.aeseletropaulo.com.br/para-seu-negocio/prazos-e-tarifas/conteudo/impostos-e-outros-encargos [Accessed 20 August 2015.

[49] Energy price calculated with taxes - ICMS 25%. CEEE. 2015b. *Tabela de Tarifas de Energia Elétrica Baixa Tensão* [Online]. Porto Alegre, Brazil: Companhia Estadual de Energia Elétrica (CEEE). Available: http://www.ceee.com.br/pportal/ceee/archives/Tabela%20Grupo%20B%20marco%202015.pdf [Accessed 18 August 2015.

[50] Taxes for August 2015 – PIS: 0.39% COFINS: 2.78%. CEEE. 2015a. *PIS COFINS* [Online]. Porto Alegre, Brazil: Companhia Estadual de Energia Elétrica (CEEE). Available: http://www.ceee.com.br/pportal/ceee/Component/BTFormService_PisCofins.aspx [Accessed 19 August 2015.

investment, the analysis of the payback period should also consider variables such as the time value of money and risk of financing.

For all the cities, the envelope with the lowest payback period was n° 5. The payback period of this envelope was estimated to be 5.0, 17.4 and 11.3 years in Curitiba, São Paulo and Porto Alegre, respectively. Although the most cost-effective envelope n° 5 cannot deliver the same levels of thermal comfort and energy efficiency of the best performance envelopes, it can be a potential and viable alternative towards increasing thermal comfort and energy efficiency in affordable Brazilian houses.

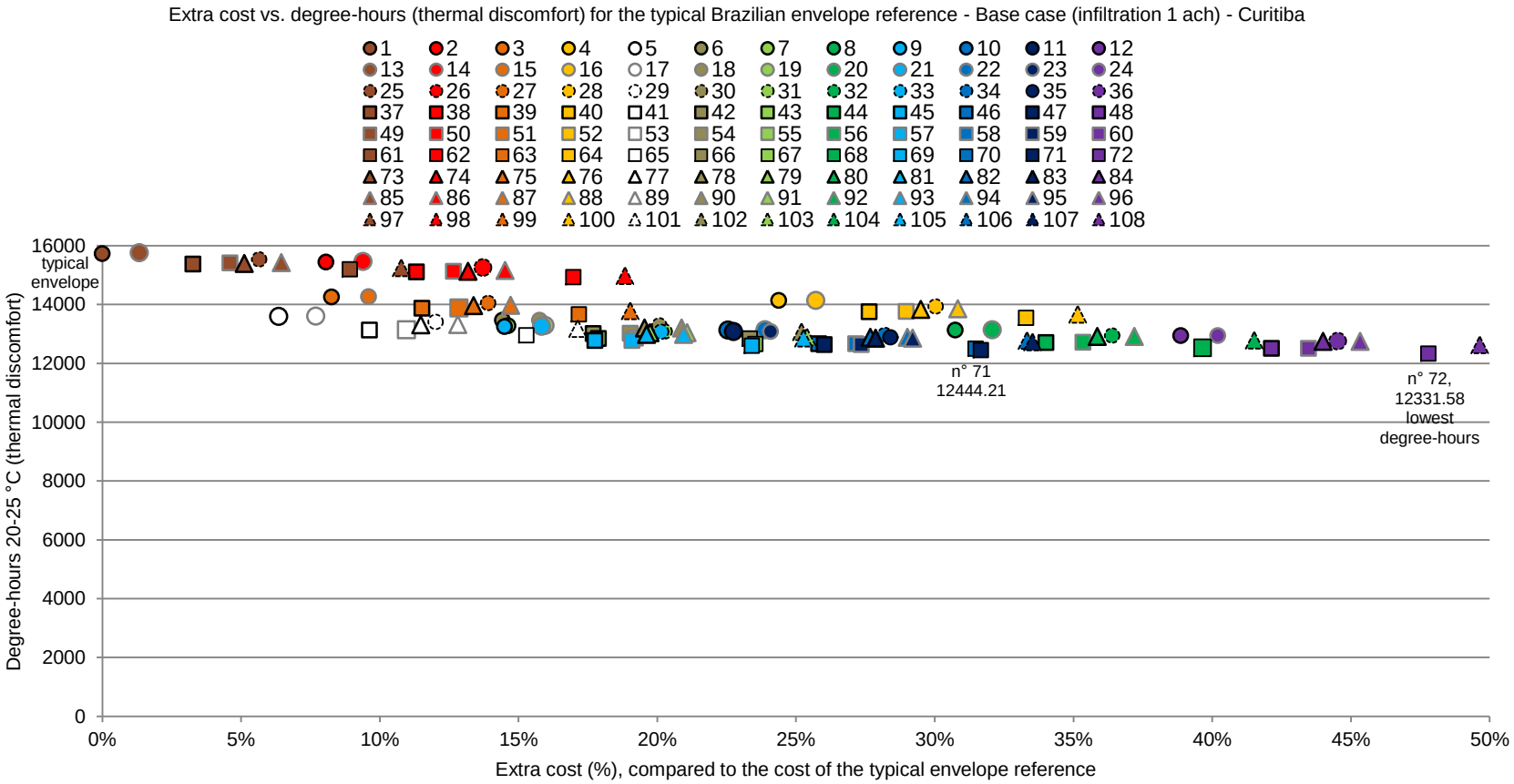


Figure 4-62: Extra cost and degree-hours of each envelope, related with the typical Brazilian envelope, Base Case, Curitiba

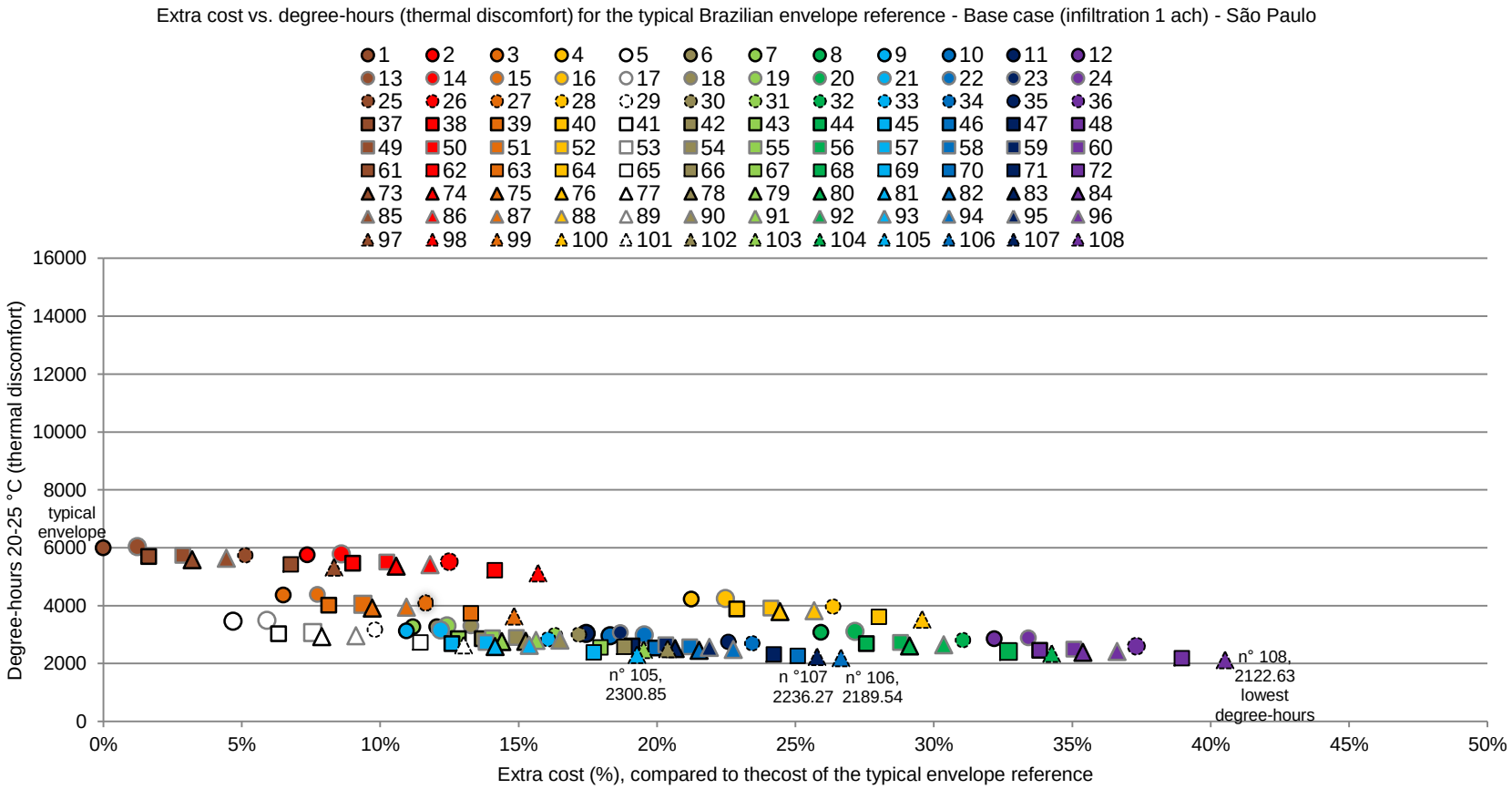


Figure 4-63: Extra cost and degree-hours of each envelope, related with the typical Brazilian envelope, Base Case, São Paulo

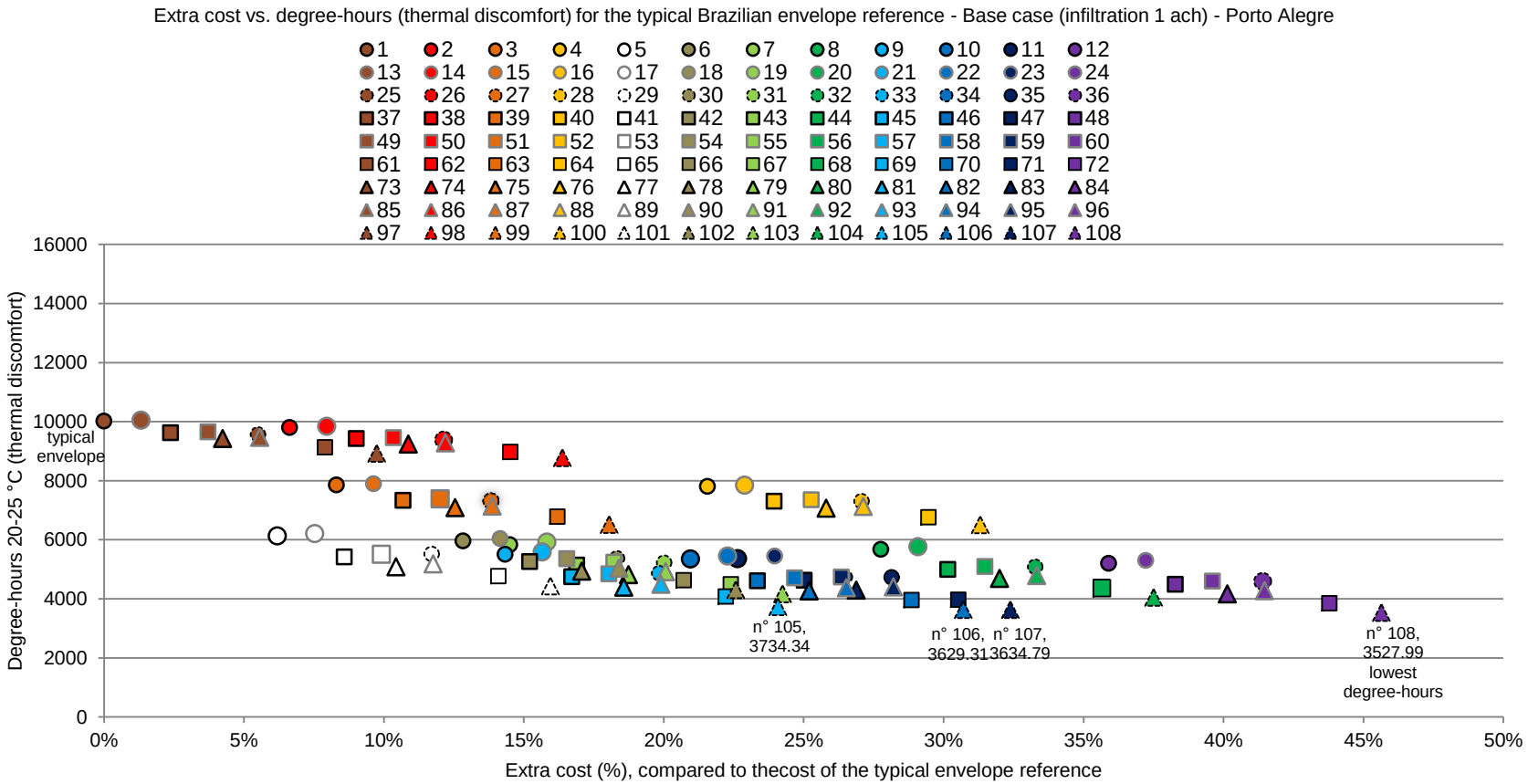


Figure 4-64: Extra cost and degree-hours of each envelope, related with the typical Brazilian envelope, Base Case, Porto Alegre

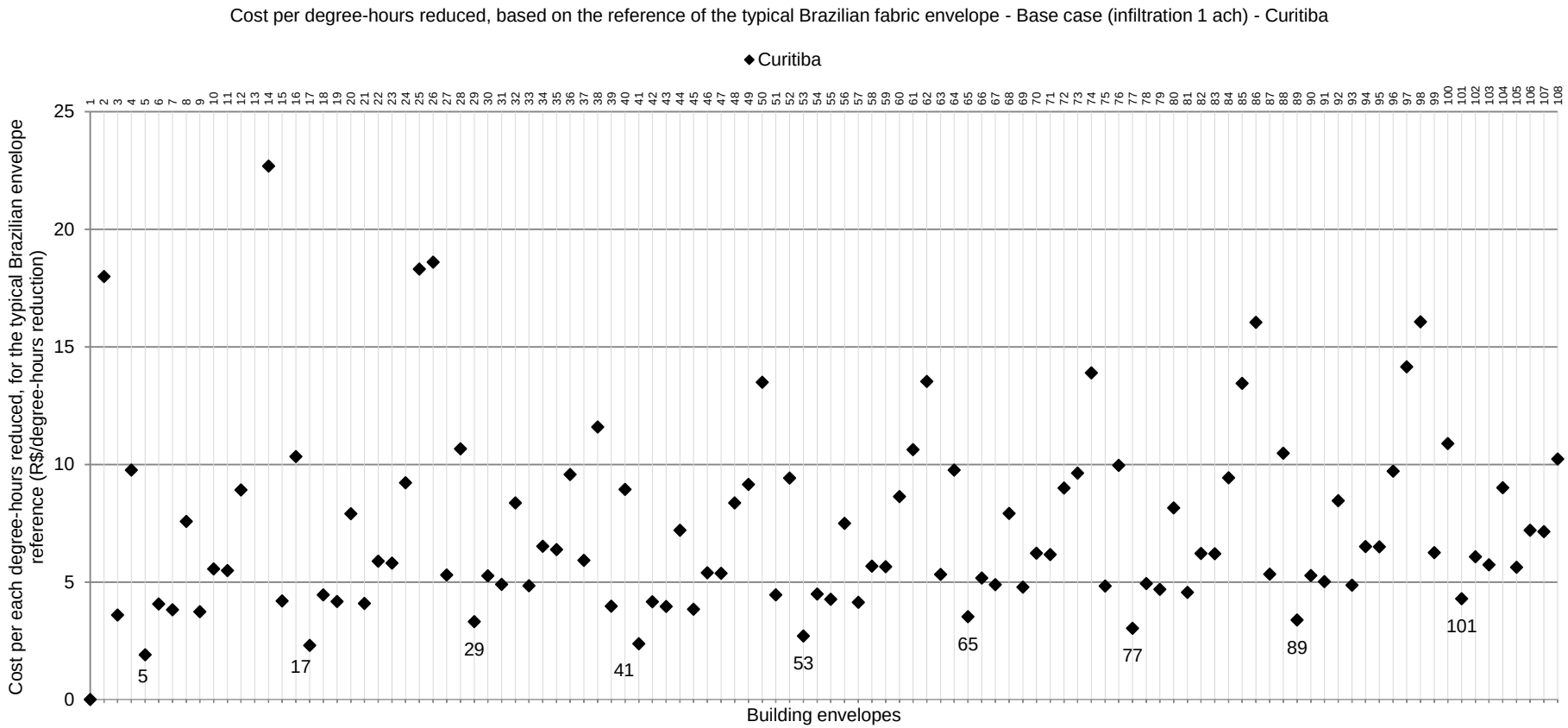


Figure 4-65: Cost per each degree-hour reduced, Base case, Curitiba

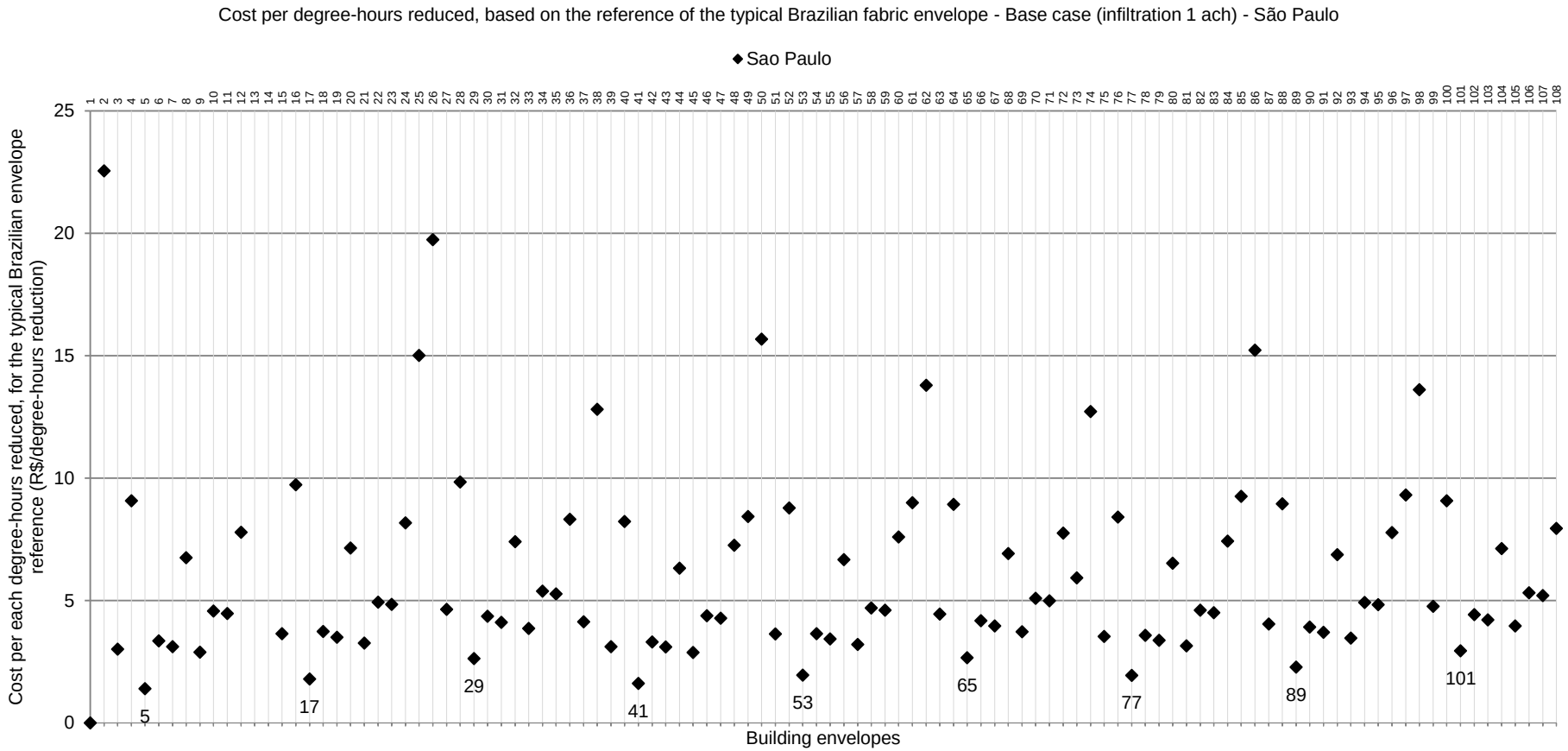


Figure 4-66: Cost per each degree-hour reduced, Base case, São Paulo

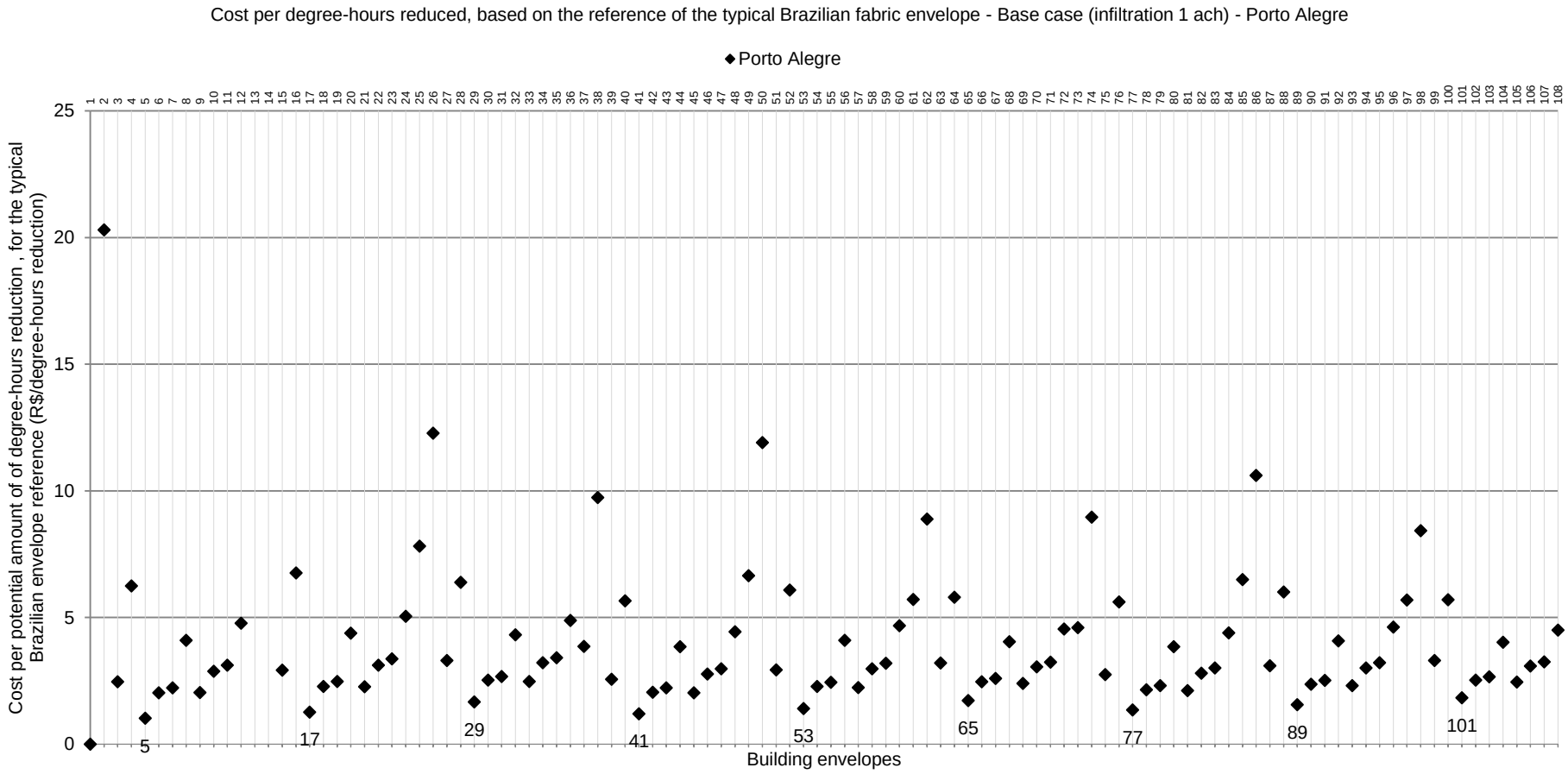


Figure 4-67: Cost per each degree-hour reduced, Base case, Porto Alegre

At the limited infiltration rate of 0.15 ach, Figure 4-68, Figure 4-69 and Figure 4-70 show the extra cost calculated for each building envelope combination related to the degree-hours of 20-25 °C (thermal discomfort) for Curitiba, São Paulo and Porto Alegre, respectively. Note that the costs of the envelopes were supposed to be the same as those found in Base Case, as the costs due to the infiltration were not considered in this chapter. However, the thermal comfort achieved in Case 1 was much higher than in Base Case. This suggests that similar levels of thermal comfort can be delivered to the occupants at a lower cost if a low infiltration rate is ensured instead of the standard infiltration rate.

In Curitiba, whilst the best performance envelope n° 72 had its degree-hours reduced by 49.21% when compared to the typical Brazilian envelope, the extra cost was increased by 48% when compared to the original housing cost. In São Paulo and Porto Alegre, whilst the best performance envelope n° 108 had the degree-hours reduced by 97.01% in São Paulo and by 95.18% in Porto Alegre when compared to the typical Brazilian envelope, the extra costs in the cities were increased by more than 40% and 45% relative to the original housing cost, respectively.

Figure 4-71, Figure 4-72 and Figure 4-73 show the cost in Brazilian reais per potential of degree-hour reduction of each envelope at a limited infiltration rate of 0.15 ach. This gives an indication of the cost-benefit of each envelope.

In particular, the envelopes close to the y axis in the Figures were those that showed to be the more cost-effective envelopes among the envelopes investigated. These cost-effective envelopes were n° 5, 17, 29, 41, 53, 65, 77, 89 and 101, that is those built out of hollow block insulated wall. These envelopes are also those represented in white in Figure 4-68, Figure 4-69 and Figure 4-70.

The estimation of the cost for heating up the house at the comfortable temperature of 20 °C was also investigated for low infiltration rates. As mentioned, the annual energy consumption would vary: from 118.85 to 24.67 kWh/m^2 in Curitiba; from 33.89 to less than 1 kWh/m^2 in São Paulo; and from 48.48 kWh/m^2 to negligible levels in Porto Alegre. The heating energy consumption for each envelope can be found in Appendix A.

If the house was made out of the typical Brazilian envelope, the annual electricity cost for heating it up would be equivalent to 12%, 2% and 4% of the minimum annual gross wage in Curitiba, São Paulo and Porto Alegre, respectively. If the house would have been built out of the best performance envelopes (n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre) the annual electricity cost would be equivalent to only 3% of

the minimum annual gross wage in Curitiba and this would be almost negligible in São Paulo and Porto Alegre.

However, although the most insulated envelopes had the best performance and also the potential lowest monthly costs in electricity, their payback period did not appear to be worthwhile. The payback period of the best performance envelope was estimated to be 32.1 years in Curitiba and beyond the lifespan of the house in São Paulo (134.9 years) and Porto Alegre (69.9 years). The lowest payback was also observed by the envelope n° 5, which had a payback estimated to be 5.9, 19.0 and 11.7 years in Curitiba, São Paulo and Porto Alegre, respectively. The estimated payback period of each envelope can be found in Appendix A.

Despite the fact that the lowest payback envelope n° 5, regarded as the most cost-effective envelope, cannot deliver the same levels of thermal comfort and energy efficiency compared to the best performance envelope, it can be a potential and viable alternative towards increased thermal comfort and energy efficiency in affordable Brazilian houses, at reasonable costs.

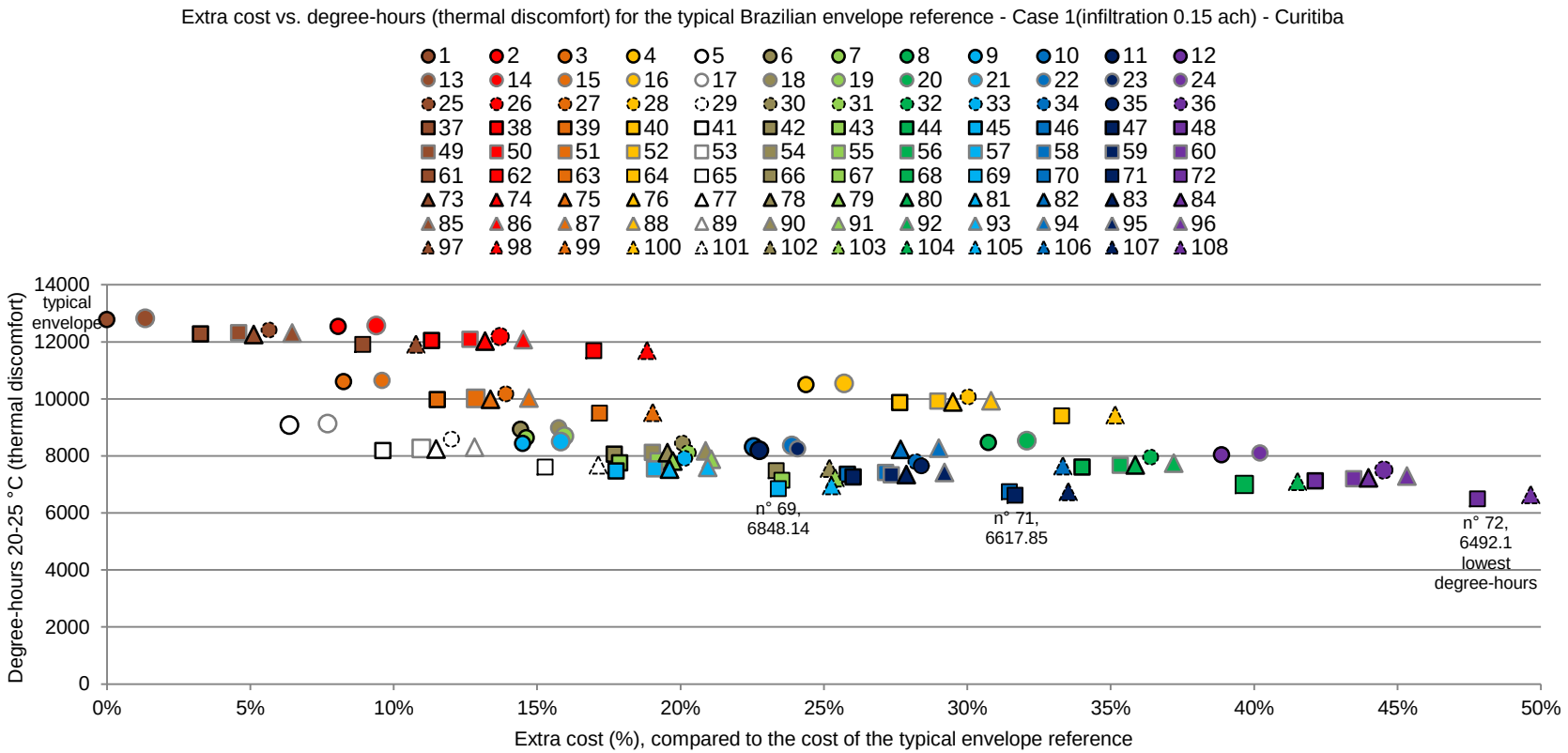


Figure 4-68: Extra cost and degree-hours of each envelope, related with the typical Brazilian envelope, Case 1, Curitiba

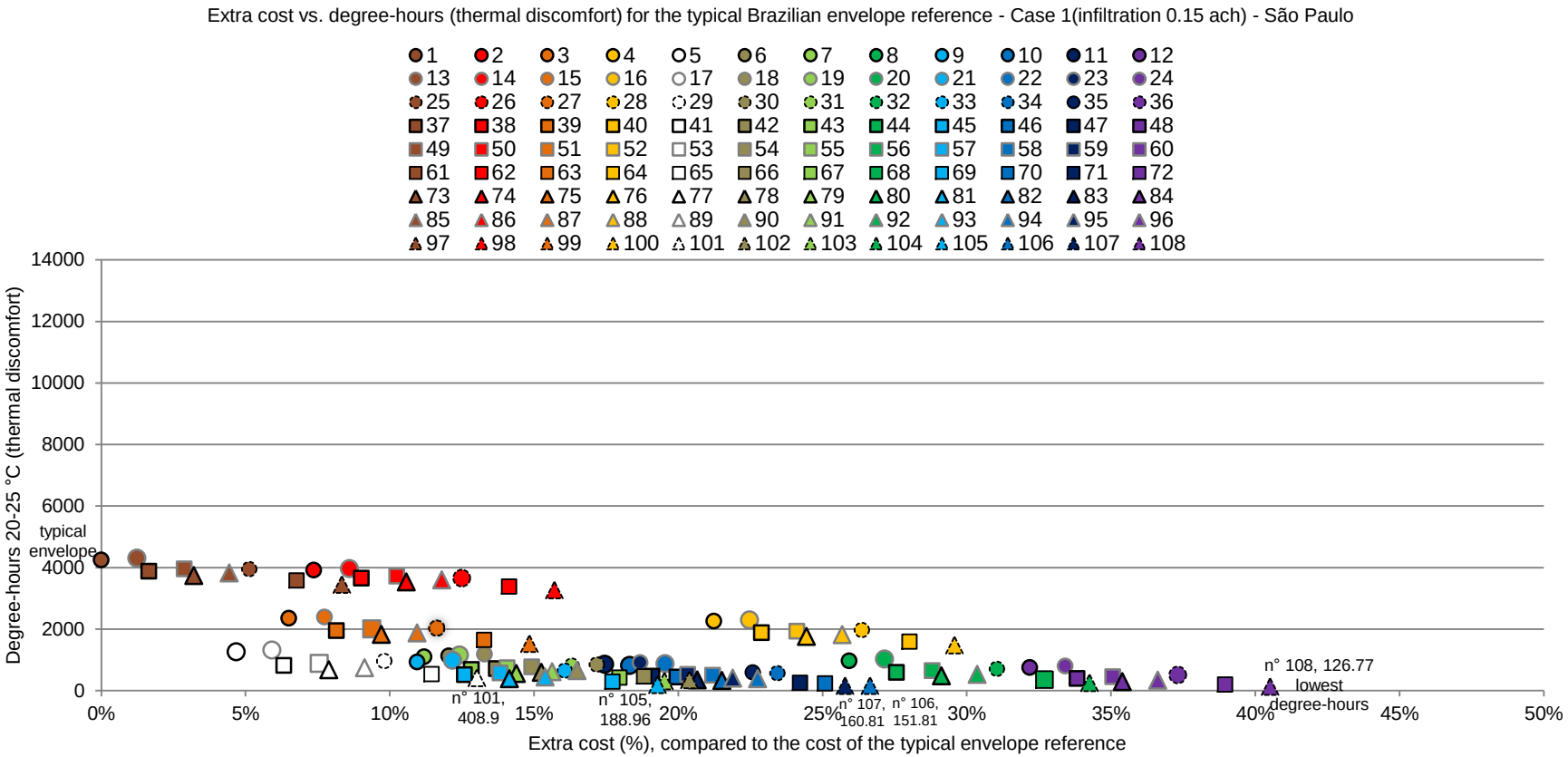


Figure 4-69: Extra cost and degree-hours of each envelope, related with the typical Brazilian envelope, Case 1, São Paulo

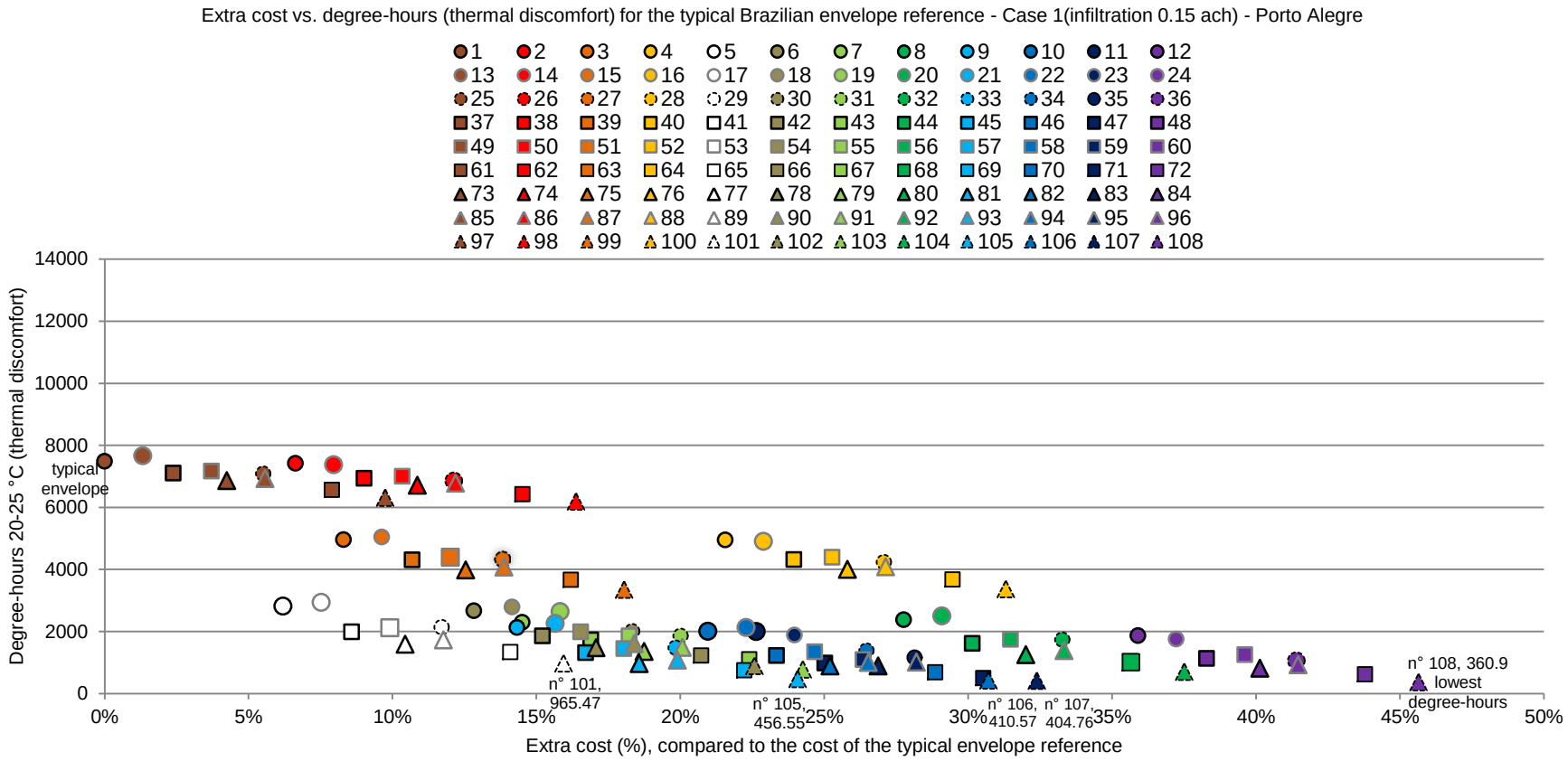


Figure 4-70: Extra cost and degree-hours of each envelope, related with the typical Brazilian envelope, Case 1, Porto Alegre

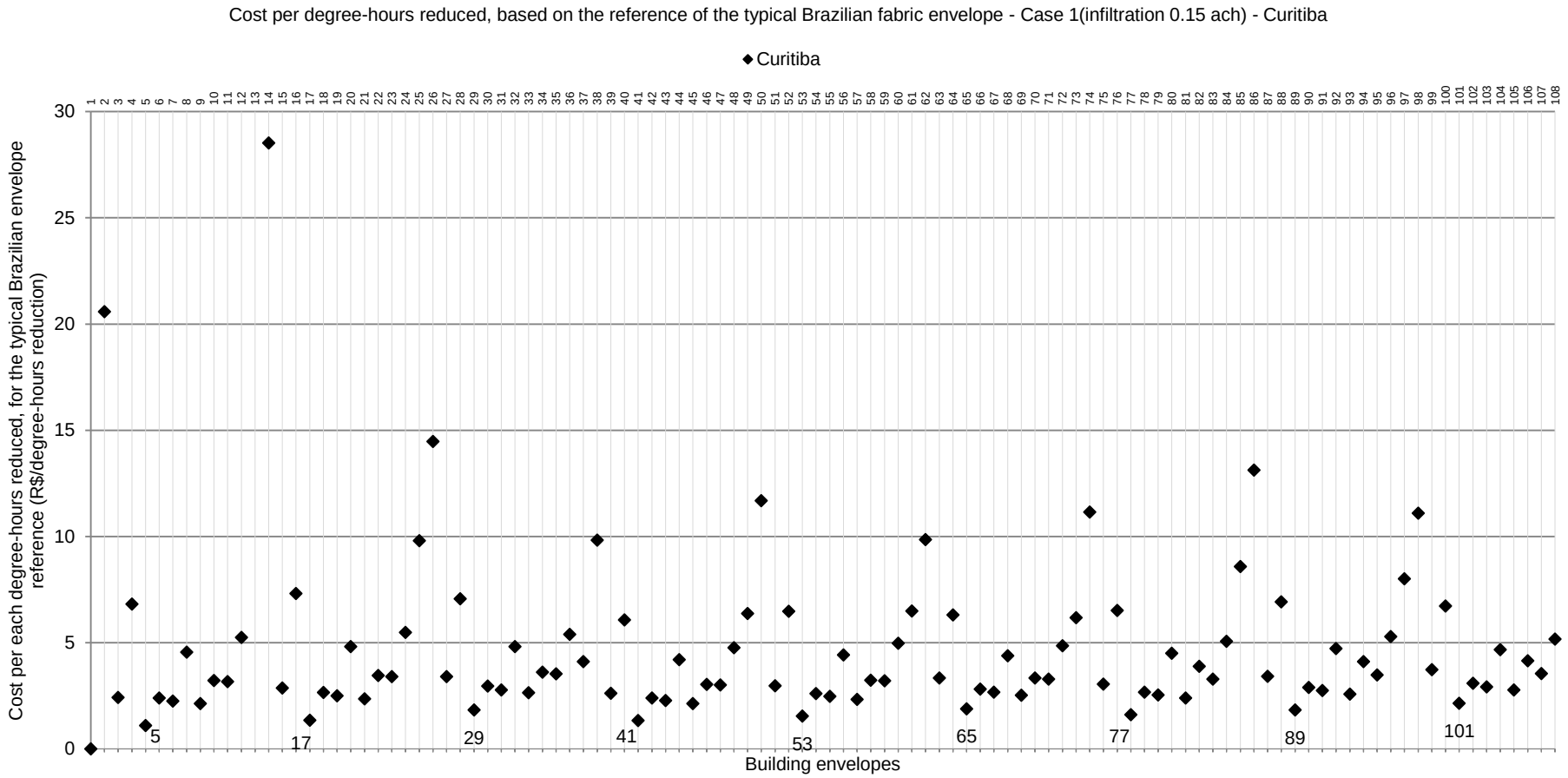


Figure 4-71: Cost per each degree-hour reduced, Case 1, Curitiba

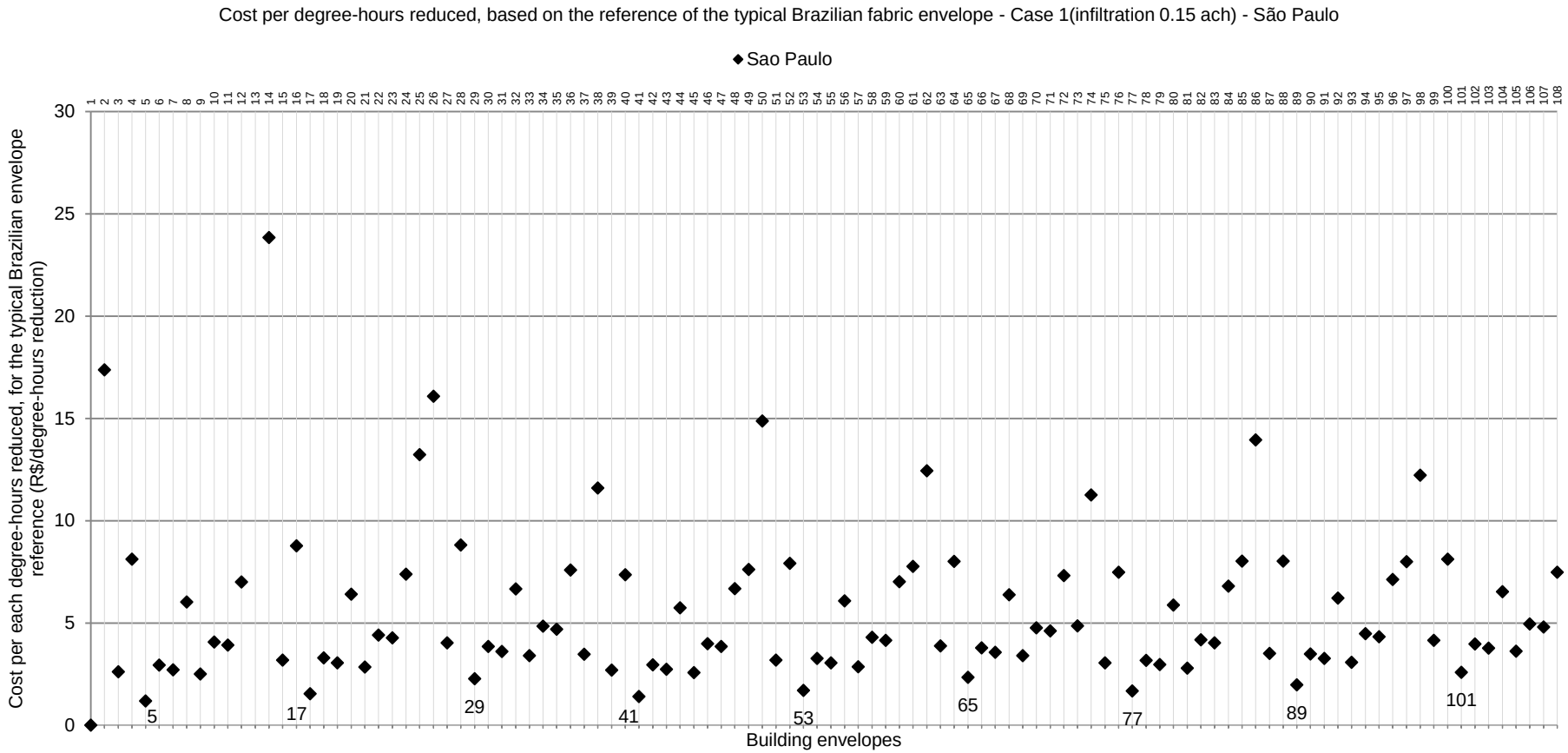


Figure 4-72: Cost per each degree-hour reduced, Case 1, São Paulo

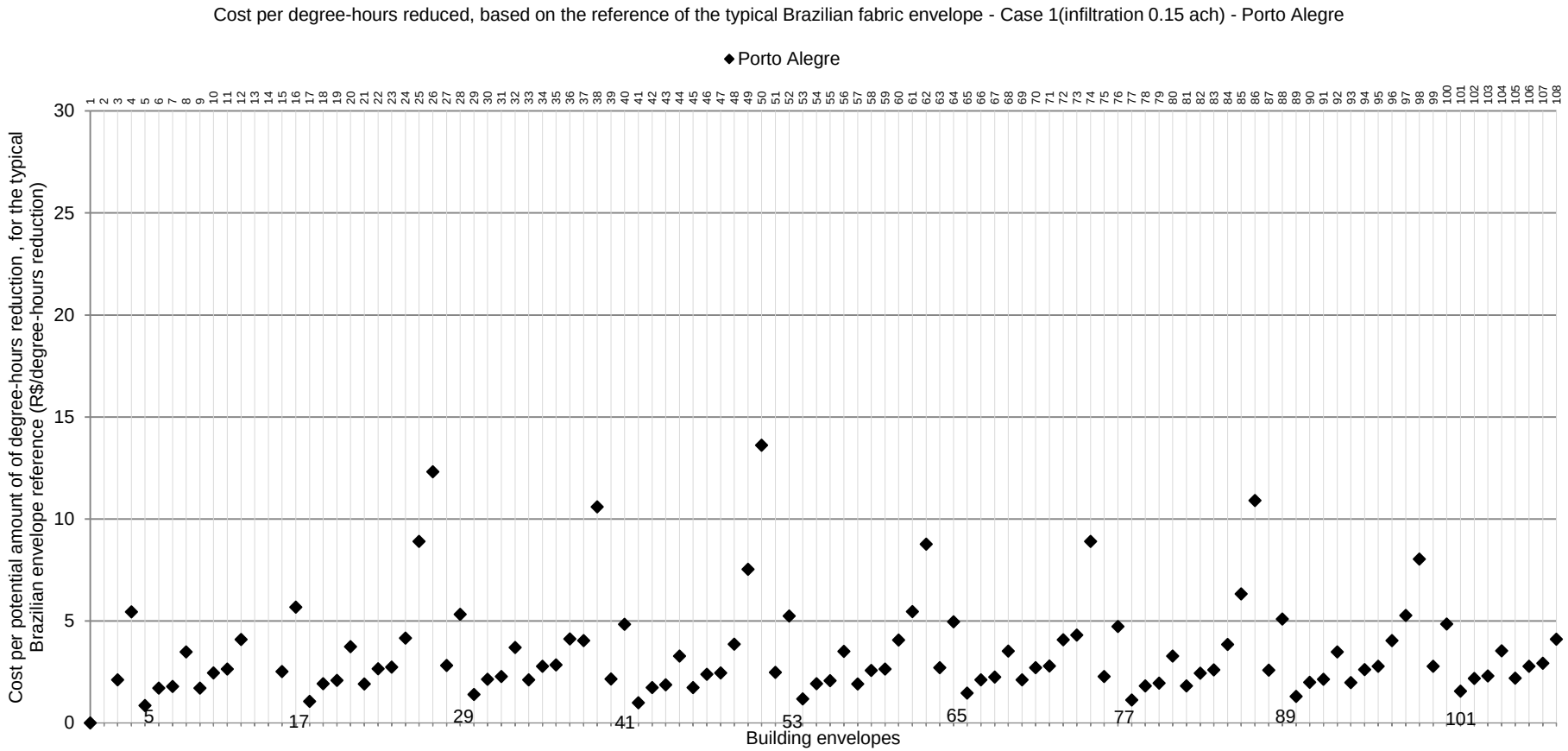


Figure 4-73: Cost per each degree-hour reduced, Case 1, Porto Alegre

4.7 Conclusions

A parametric study was conducted and a range of changeable envelope parameters were selected. The parameters consisted of traditional Brazilian building envelopes, which had their insulation level varied, resulting in a total of 12 different types of wall construction, 3 different roof constructions and 3 different glazing types. These selected envelopes were explored in three different cities in southern Brazil.

The parametric study was developed through the method of sensitivity analysis. The model was built based on a simplified affordable Brazilian housing typology. The assumptions attempted to follow the typical conditions of use in these houses and made use of basic passive design strategies such as shading and natural ventilation to deal with overheating.

The aim of this analysis was to determine the difference in the thermal performance of different building envelopes under fixed common conditions of use. Special attention was paid to thermal performance of the typical Brazilian envelope.

The parametric approach investigating the affordable housing envelope optimisation showed that insulated envelopes can increase the indoor thermal comfort in these buildings, under a given specific regime of occupancy and ventilation.

The results revealed that the typical Brazilian envelope needs to be thoroughly reviewed if an increase in its performance is desired. The typical Brazilian envelope underperformed and it had one of the poorest envelope thermal performances among the examples investigated in terms of thermal comfort. When comparing it with the most insulated envelope adopted in this research, which had U-values similar to those envelopes used in the Passivhaus standard buildings, an improvement in terms of degree-hours reduction was clearly noted.

Findings suggest that the degree-hours reduction and, consequently, the thermal comfort improvement corresponded to 21.61% in Curitiba, 64.61% in São Paulo and 64.76% in Porto Alegre by replacing the typical Brazilian envelope by an optimised one, under a typical infiltration rate of 1 ach.

Moreover, under the low infiltration rate of 0.15 ach, much higher thermal comfort would be achieved when compared to the standard infiltration rate. Thermal comfort improvement would correspond to 49.21%, 97.01% and 95.18% for Curitiba, São Paulo and Porto Alegre, respectively, if the most insulated envelope were adopted instead of the typical Brazilian envelopes. All these results were obtained through the methodology of degree-hours based for a comfort interval of 20-25 °C.

However, although the adoption of a low infiltration rate showed to be beneficial to increase thermal comfort, the nature of the Brazilian construction industry and the lack of skilled labourers would make the adoption of low level of air permeability rate in affordable housing construction difficult.

Overall, the findings suggested that the relationship between the U-value and thermal comfort seems to be inversely linear for these climates, considering those taken assumptions. This means that as the U-value decreases, the percentage of thermal comfort increases. However, this relationship presupposed the buildings with shading and ventilation use.

All the simulations were conducted considering the building as free-running, as is mostly found in affordable Brazilian houses. Although mixed-mode buildings were not part of the investigation, the evaluation of the envelopes' consumption would be relevant for further investigation given the increase of air conditioning use in Brazil.

A brief exploratory investigation showed that if the house was heated up in the winter period, since cooling demand was almost mitigated by passive means, this would represent an annual heating energy demand of up to 146.24 kWh/m^2 in Curitiba, 48.24 kWh/m^2 in São Paulo and 66.14 kWh/m^2 in Porto Alegre in cases of the typical Brazilian envelope (without considering the effect of internal walls), at standard infiltration rate. The best performing envelopes would have annual energy demands equivalent to 48.82 kWh/m^2, 7.81 kWh/m^2, 10.93 kWh/m^2, which would be 3 times lower in Curitiba and 6 times lower in São Paulo and Porto Alegre than the typical Brazilian envelope, respectively.

However, although the results of this investigation suggested that the most insulated envelopes had the highest thermal performances, it does not appear to be worthwhile from the cost perspective. The cost analyses showed that insulated envelopes would represent an additional cost of more than 45% of the housing costs in Curitiba and Porto Alegre and more than 40% of the typical housing costs in São Paulo. Their estimated payback period would be equivalent to 30.8 years in Curitiba but in São Paulo and Porto Alegre the payback period would be higher than the house lifespan of 50 years. However, detailed cost analysis remains for investigation in the next chapters.

As a next step, the present research aims to corroborate these results based on a more realistic building model. It will not only evaluate the applicability of the insulated approach from the thermal comfort point of view but also investigates its cost-effectiveness in detail.

CHAPTER 5: CASE STUDY: THE '*MINHA CASA, MINHA VIDA'* HOUSE

Minha Casa, Minha Vida (*My House, My life*) is a 2-bedroom detached Brazilian social housing typology designed to attend the minimum needs of the lowest income range population. The house is made out of standardised materials to reduce the cost involved in its construction. A case study based on a generic representative model of the MCMV House is adopted in this chapter. The case study is evaluated in detail in terms of its thermal performance for three different cities, through the use of dynamic building simulations. The outcomes show significant indoor thermal comfort and energy efficiency improvements, which could be achieved if specific changes in the building envelope were to be adopted.

''In 2009, just after the global financial crisis, the Brazilian federal government launched a program for mass housing that would be able to resolve the country's huge housing deficit and at the same time stimulate economic growth. […] In 2013, the federal government announced that more than one million units have already been built all over the country and that the target for the second phase of the program is to build a total amount of 3.4 million units by the end of 2014. Despite the program's lack of urban qualities, 'Minha Casa, Minha Vida' has provided access to housing for the low-income population and has already altered Brazil's urbanization patterns.''
Angélil and Hehl (2014, p. 31)

''It should be noted that a building lifespan of 50 years implies that annually more than 1.2 million housing should be constructed simply to replace the existing housing stock of the country.''
Brazilian standard NBR 15575 (ABNT, 2013a, p. 53, translated)

5 CASE STUDY: THE '*MINHA CASA, MINHA VIDA'* HOUSE

The *'Minha Casa, Minha Vida'* (MCMV) House is one of the two housing typologies adopted by the government housing programme to support the construction of new residential units in Brazil for the lowest income range households, as discussed in Chapter 2. Among the housing typologies, more than a million affordable residential units have been built between 2011 and 2014 (Ministério do Planejamento, 2014) and several million are planned to be built by 2022 (Carbon Trust, 2012a). Due to the significant amount of houses that are planned to be built, it is fundamental that the MCMV house typology is taken into a consideration in the present research.

Thermal comfort and energy efficiency in affordable houses in Brazil are often criticized. Most energy issues are not taken into account in the design and construction of affordable housing in Brazil (Corbella, 1984). Designers and developers often assume that there is a conflict between low cost and the possibility of providing a thermally comfortable home. It is therefore that the programme of affordable houses brings mostly schematic houses to be built throughout Brazil, without regard to orientation, building materials and their relationship with the local climate (Corbella, 1984).

In this chapter, a case study based on a generic representative model of the MCMV House typology was adopted and evaluated for three different locations: Curitiba, São Paulo and Porto Alegre. The adopted example and assumptions were based on the literature review conducted in Chapter 2. A typical example of the MCMV House settlement is illustrated in Figure 5-1.

Figure 5-1: MCMV House example of settlement (Angélil and Hehl, 2014, p. 18-19)

The main purpose of this analysis was, firstly, to explore the current thermal performance of this house and, secondly, to investigate ways of improving it, through an optimisation of the building envelope. The present analysis was undertaken through the use of dynamic building simulations. The optimisation of the building envelope

considered the results of the parametric study discussed in Chapter 4, which were developed based on the Fabric First approach principles (e.g. insulation, airtightness, ventilation and shading).

The rationale for selecting the MCMV House as a case study was because the house is adopted as a solution for a mass housing typology in Brazil. The house represents a typical affordable Brazilian house, developed under the umbrella of the government's housing policies. This case study underlines issues that are nationally important – either in theoretical or in practical terms (i.e. housing deficit, housing living conditions, housing policies, housing thermal comfort and housing energy impact). It also intends to address the prior existence of a housing problem in Brazil as the prelude of this research development.

5.1 House Design

The MCMV House is a one-storey detached house of just over 36 m^2 of internal area. It has a rectangular shape and a pitched roof, as is common in most typical Brazilian houses. The MCMV house typology can be implemented in a variety of different design configurations. In the present research, the north-south orientation was adopted, because it allows more control of the solar radiation on the building apertures. The house design is detailed in Figure 5-2.

The house attends to the very basic needs of a small family. It comprises two bedrooms, a bathroom and a living room integrated with the dining room and kitchen. The area for laundry is assumed to be outside the building, in the external space covered by the roof eaves. Table 5-1 shows MCMV House areas and volumes.

Table 5-1: MCMV House areas and volumes

	Rooms	Estimated areas (m^2) or volumes (m^3)*
Ground floor Height: variable (≥ 2.50 m)	Bedroom 1 (south-west)	8.66 m^2
	Bedroom 2 (south-east)	8.10 m^2
	Bathroom	2.27 m^2
	Living room/ Kitchen	17.46 m^2
Total of internal floor area:		36.52 m^2
Total external area (including walls):		43.83 m^2
Internal volume is estimated to be around:		108.80 m^3
Total of exposed external surface areas of the envelope (A):		165.95 m^2
Exposed external surface area of the envelope facing south		18.15 m^2
Exposed external surface of the envelope facing east		19.70 m^2
Exposed external surface the envelope facing north		18.15 m^2
Exposed external surface area of the envelope facing west		19.70 m^2
Exposed external ground floor area		43.83 m^2
Exposed external roof area		46.42 m^2
Form factor (desirable values: 2-4)		4.55
Compactness (desirable values: 0.80-2.2 m)		0.65 m

*Minimum internal floor area must not be less than 36 m^2 (Ministério das Cidades, 2014b).
Calculated according to the plans and technical drawings, based on (UN-Habitat, 2013, Angélil and Hehl, 2014, Ministério das Cidades, 2014b).
Form factor without internal walls - area: 39.19 m^2 – is calculated to be 4.23.

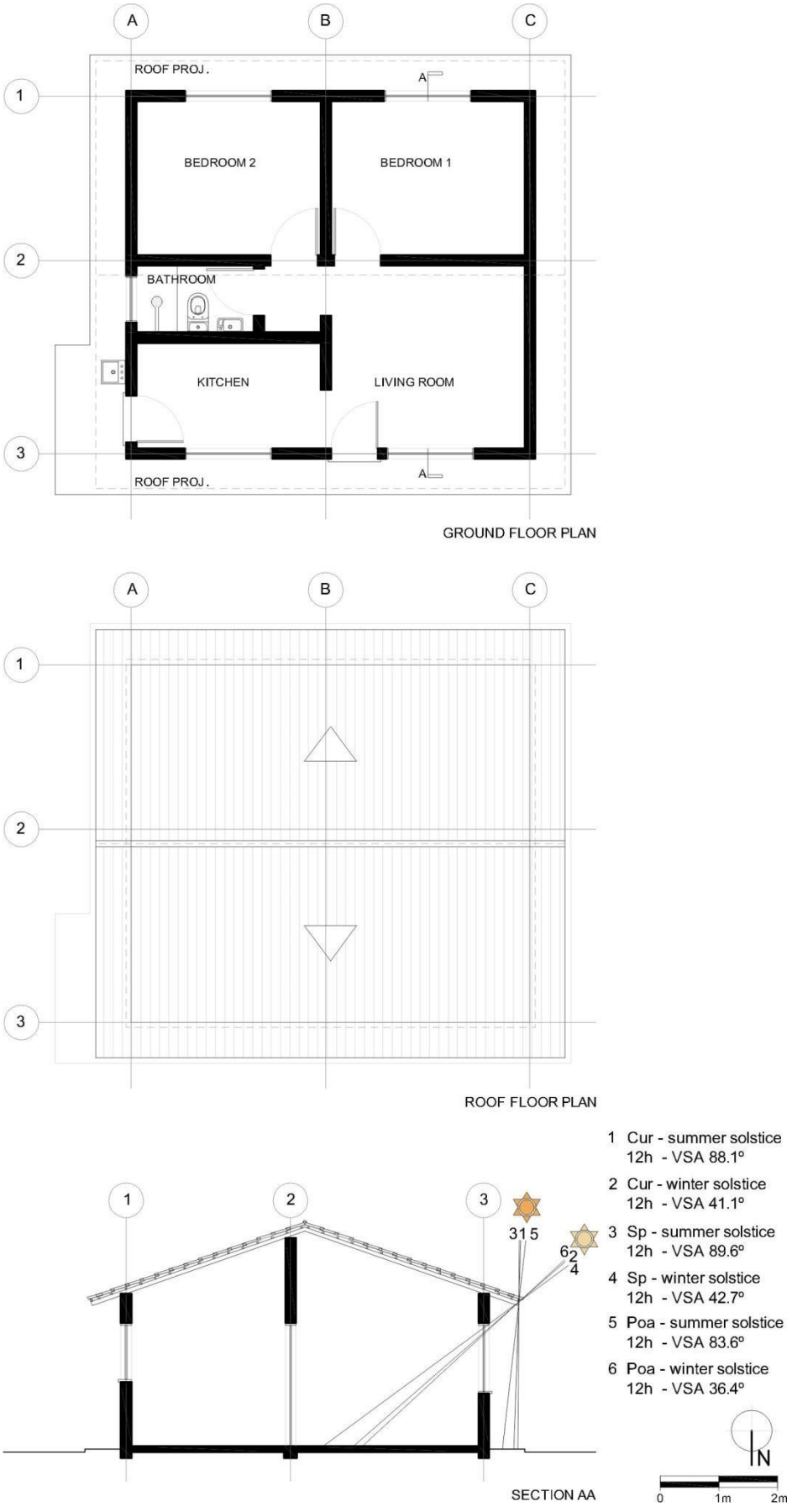


Figure 5-2: MCMV ground floor and roof plans and section

Table 5-2 shows the MCMV House fenestrations. As previously mentioned, fenestrations in Brazilian houses are mostly small to medium size and they become even smaller in affordable houses (Lara, 2010). The fenestration areas of the MCMV House were based on the requirements set by the Ministério das Cidades (2014b, p. 1), which sets out that the windows should have an area of at least 1.50 m^2 for each bedroom and 2.00 m^2 for the living room[51], with a variation of up to 5% in their area. Doors should have dimensions of 0.80 x 2.10 m. The fenestrations used in the house follow pre-fabricated standardised dimensions found on the national construction market, as mentioned in Chapter 4. Examples of typical affordable fenestrations can be found in Appendix B.

Table 5-2: MCMV House fenestrations

Type	Location		Operation	Dimension (m)	Area (m^2)	Frame pct. (%)	Ventilation area (m^2)	Vent. pct.(%)
W1	Bedroom 1	South	2 sliding panels	1.50 x 1.00 sill: 1.10	1.50	22	0.75	≤ 50
W2	Bedroom 2	South	2 sliding panels	1.50 x 1.00 sill: 1.10	1.50	22	0.75	≤ 50
W3	Bathroom	East	1 awning panel	0.80 x 0.60 sill: 1.50	0.48	27	0.48	≤ 100
W4	Living/ Kitchen	North	2 sliding panels	1.50 x 1.20 sill: 0.90	1.80	21	0.90	≤ 50
W5	Living/ Kitchen	North	2 sliding panels	1.50 x 1.20 sill: 0.90	1.80	21	0.90	≤ 50
D1	Living/ Kitchen	East	Single panel	0.80 x 2.10	1.68	16.6	NA	NA
D2	Living/ Kitchen	North	Single panel	0.80 x 2.10	1.68	16.6	NA	NA
D3	Bedrooms/ Bathroom	Int.	Single panel	0.80 x 2.10	1.68	16.6	NA	NA

Table 5-3 shows a comparison among the adopted window areas of the MCMV House of Table 5-2, the Building Codes requirements of the city of Curitiba, São Paulo and Porto Alegre (Prefeitura Municipal de Curitiba, 2013, Prefeitura Municipal de São Paulo, 1992, Prefeitura Municipal de Porto Alegre, 2001) and the MCMV House requirements (Ministério das Cidades, 2014b). As the Table shows, the MCMV House windows met all the lighting and ventilation requirements[52]. According to the local Building Codes, window lighting areas must correspond to at least 1/6 of each rooms floor area and window ventilation areas must correspond to 1/12 of the main room floor area in residential buildings[53] (Prefeitura Municipal de São Paulo, 1992, p. 52, Prefeitura Municipal de Porto Alegre, 2001, p. 74, Prefeitura Municipal de Curitiba, 2013, p. 209). This means that ventilation must correspond to a minimum of 50% of the window area. In fact, this is the most common situation in affordable Brazilian

[51] It sould be noted that the window area refers only to the living room. When the living room is combined with the kitchen, the window area is expected to be larger.

[52] Lighting corresponds to the windows size.

[53] Bathroom is not considered as occupied areas of the house because its occupancy is limited to short periods.

houses mainly because the majority of the houses have windows with a sliding operation, which allows opening to a maximum 50% of their size.

As aforementioned, the Building Codes set the ventilation area of 1/12 of the room area, which corresponds to 8.33% of the room area. Comparatively, this also meets the minimum ventilation requirement of the NBR 15575 (ABNT, 2013d, p. 28) and RTQ-R label (INMETRO, 2012, p. 26) of 7% and 8% for the corresponding climatic zones of the present research, respectively. The total of the MCMV House ventilation area roughly corresponds to 3.30 m^2 considering the occupied rooms, which is equivalent to 9.64% of the floor area.

Table 5-3: MCMV House fenestration areas requirements

Occupied room	Area (m^2)	As adopted		Requirement of:		
				MCMV	Building Codes	
		Fenestration area (m^2)	Ventilation area (m^2)	Fenestration area (m^2)	Lighting 1/6 of the room area(m^2)	Ventilation 1/12 of the room area (m^2)
Bedroom1	8.67	1.50	0.75	1.50	1.44	0.72
Bedroom2	8.10	1.50	0.75	1.50	1.35	0.67
Living/ Kitchen	17.46	3.60	1.80	2.00*	2.91	1.45
Total	34.23	6.60	3.30	5.00	5.70	2.84
Pct. of floor area (%)		19.28%	9.64%	14.60%	16.66%	8.33%

Floor area based on 34.23 m^2. Bathroom is not accounted in the calculations because it has its occupancy limited to short periods.
According to the local building codes in Brazil, ventilation and fenestration areas were roughly calculated disregarding to the windows frame.
*The MCMV requirement of 2.00 m^2 of fenestration area refers only to the living room and as the house design combines the kitchen and the living room, a larger fenestration area is expected.

5.2 House Materials

The MCMV House materials were adopted as they have been typically used over the years and also according to the minimum requirements established by Ministério das Cidades (2014b). The requirements, however, did not establish any distinction of thermal performance materials for the different regions of Brazil. The house is usually built with standardized and low quality materials, which are used across the country without regard to climatic and cultural differences.

Overall, the MCMV walls were mostly built out of a layer of load-bearing hollow block[54] of 14 cm of thickness and a layer of plaster of 2 cm of thickness each side. The walls of the kitchen and bathroom also received ceramic tiles at least up to 1.5 metres of height, as required by Ministério das Cidades (2014b).

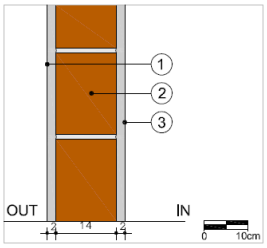
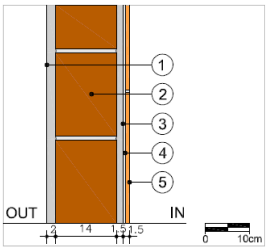
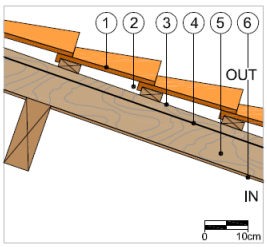
[54] Hollow blocks are mostly used due to lower costs when compared to the solid bricks.

The windows and external doors were mostly made out of aluminium[55] as this is the frame type that has high durability and low need for maintenance, at affordable costs. Also, the windows were mostly built out of 3 mm single glazing. The internal doors were built out of timber.

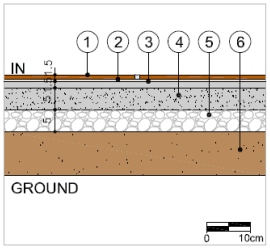
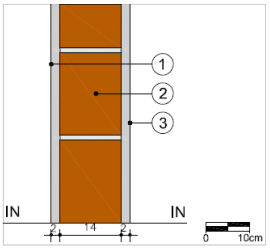
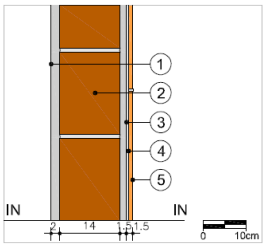
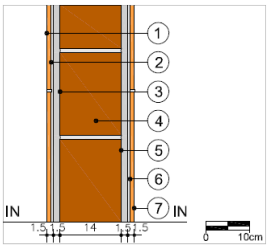
The roof was mostly made out of ceramic roof tiles, a wooden structure, and a layer of aluminium foil to reduce the downward heat emission. The ceiling was pitched and followed the roof pitch in order to increase the sensation of spaciousness inside the building.

The materials of the MCMV House are illustrated in Table 5-4. The thermal properties of the constructions elements were calculated wih the use of Dynamic Thermal Properties Calculator tool (Arup, 2010).

Table 5-4: MCMV House envelope specification

		Wall construction types (thickness and layers)	**Thermal properties**	**Section**
External walls	All walls	i. **Hollow ceramic block wall, with external and internal plaster** Total thickness:180 mm Location: Bedroom/ Living room/ Circulation and Kitchen/Bathroom above 1.5 m of height Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 140 mm Hollow ceramic block (14 x 19 x 29 cm) 3. 20 mm Lime cement plaster	**U-value** (W/m²K): 2.78 **Admittance** (W/m²K): 4.57 **Decrement factor** (0-1): 0.72 **Time Lag** (hours): 4.39	
	Specific areas of North/ East walls	ii. **Hollow ceramic block wall, with external and internal plaster and internal ceramic tile** Total thickness:190 mm Location: Kitchen/ Bathroom, up to 1.5 m of height Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 140 mm Hollow ceramic block (14 x 19 x 29 cm) 3. 15 mm Lime cement plaster 4. 5mm Adhesive mortar 5. 10mm Ceramic tile	**U-value** (W/m²K): 2.72 **Admittance** (W/m²K): 4.71 **Decrement factor** (0-1): 0.68 **Time Lag** (hours): 4.71	
Roof		iii. **Aluminium foil pitched roof** Total thickness: 133.15 mm Location: all dwelling (eaves of 50 cm) Layers from outside to inside: 1. 10 mm clay roof tiles 2. Lathes 20 x 50mm; ventilation bet cross-lathing 3. Rafters 20 x 50 mm; ventilation bet cross-rafters 4. 0.15 mm Aluminium foil 5. Rafters 70 x 50 mm; air bet cross-rafters 6. 12 mm Timber ceiling	**U-value** (W/m²K): Upward: 0.92/ Downward: 0.34 **Admittance** (W/m²K): 1.11/ 1.04 **Decrement factor** (0-1): 1.0/ 0.99 **Time Lag** (hours): 0.54/ 0.68	

[55] External fenestrations made out of steel are also accepted in non-coastal areas.

	Wall construction types (thickness and layers)	Thermal properties	Section
Ground floor	iv. **Ground floor** Total thickness: 130 mm Location: all dwelling Layers from inner to ground: 1. 10 mm Ceramic tile 2. 5 mm Adhesive mortar for sticking ceramic tiles. 3. 20 mm Cement screed (for regularization purposes) 4. 50 mm Concrete slab 5. 50 mm Stone chipping 6. Soil	**U-value** (W/m²K): Upward: 3.45/ Downward: 2.78 **Admittance** (W/m²K): 6.33/ 4.42 **Decrement factor** (0-1): 0.43/ 0.37 **Time Lag** (hours): 6.83/ 7.16	
Int. walls	v. **Hollow ceramic block wall, with plaster on both wall sides** Total thickness:180 mm Location: Bedroom/ Living room/ Circulation and Kitchen/Bathroom above 1.5 m of height Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 140 mm Hollow ceramic block (14 x 19 x 29 cm) 3. 20 mm Lime cement plaster	**U-value** (W/m²K): 2.22 **Admittance** (W/m²K): 5.24 **Decrement factor** (0-1): NA **Time Lag** (hours): NA	
	vi. **Hollow ceramic block wall, with plaster on both wall sides and ceramic tile in one wall side** Total thickness:190 mm Location: Kitchen and Bathroom, up to 1.5 m of height Layers from outside to inside: 1. 20 mm Lime cement plaster 2. 140 mm Hollow ceramic block (14 x 19 x 29 cm) 3. 15 mm Lime cement plaster 4. 5mm Adhesive mortar 5. 10mm Ceramic tile	**U-value** (W/m²K): 2.18 **Admittance** (W/m²K): 5.39 **Decrement factor** (0-1): NA **Time Lag** (hours): NA	
	vii. **Hollow ceramic block wall, with plaster and ceramic tiles in both wall sides** Total thickness:200 mm Location: Wall between Kitchen and Bathroom, up to 1.5 m of height Layers from outside to inside: 1. 10mm Ceramic tile 2. 5mm Adhesive mortar 3. 15 mm Lime cement plaster 4. 140 mm Hollow ceramic block (14 x 19 x 29 cm) 5. 15 mm Lime cement plaster 6. 5mm Adhesive mortar 7. 10mm Ceramic tile	**U-value** (W/m²K): 2.15 **Admittance** (W/m²K): 5.42 **Decrement factor** (0-1): NA **Time Lag** (hours): NA	
Window	All external windows were made out of 3mm single glazing and aluminium frame. The frame percentages are shown in Table 5-2.	Glazing g-value:0.84 Glazing U-value: 5.78 W/m²K	

5.3 Environmental Design Strategies

A very limited number of environmental design strategies can be identified in the MCMV House design. The eaves combined with the position of the medium size windows play a major role in providing shading on the north facade. However, the eaves are set as a minimum requirement of 50 cm length regardless of where the building is located and its orientation. Figure 5-3 investigates the functionality of the eaves on the north facades as a shading design strategy for the three cities under investigation in the present research. It should be stressed that the windows' dimensions and the window sill height were established as shown in Table 5-2.

In Figure 5-3, the main vertical solar shadow angles (VSA), which are required to design horizontal shading devices, were plotted against the eaves for summer solstice, winter solstice and the equinox. The VSA that reaches the north facade is quite high in summer and it reaches the north facade for a very short time as in summer the sun is mostly behind the north facade. In winter, the VSA is smaller and reaches the north facade for almost the whole of daytime. In the equinox, this angle is more constant during daytime than in the solstice and the solar radiation angle that reaches the north facade is quite uniform. Figure 5-3 was created with the angles obtained through the use of the weather data (Roriz, 2012b) and Ecotect software (Autodesk, 2010).

As shown in Figure 5-3, the north eave of the MCMV House was able to fully block the solar radiation that reached the facade in all the investigated cities in summer. In winter, the eave allowed the solar radiation to come into the house. In the equinox, the solar radiation reached to a certain degree inside the building in all the cities, bringing some heat inside the building, which may require a small additional shading device to cut-off at the equinox. In general, the eaves responded satisfactorily to a certain extent if considering the windows with the assumed dimensions and orientation.

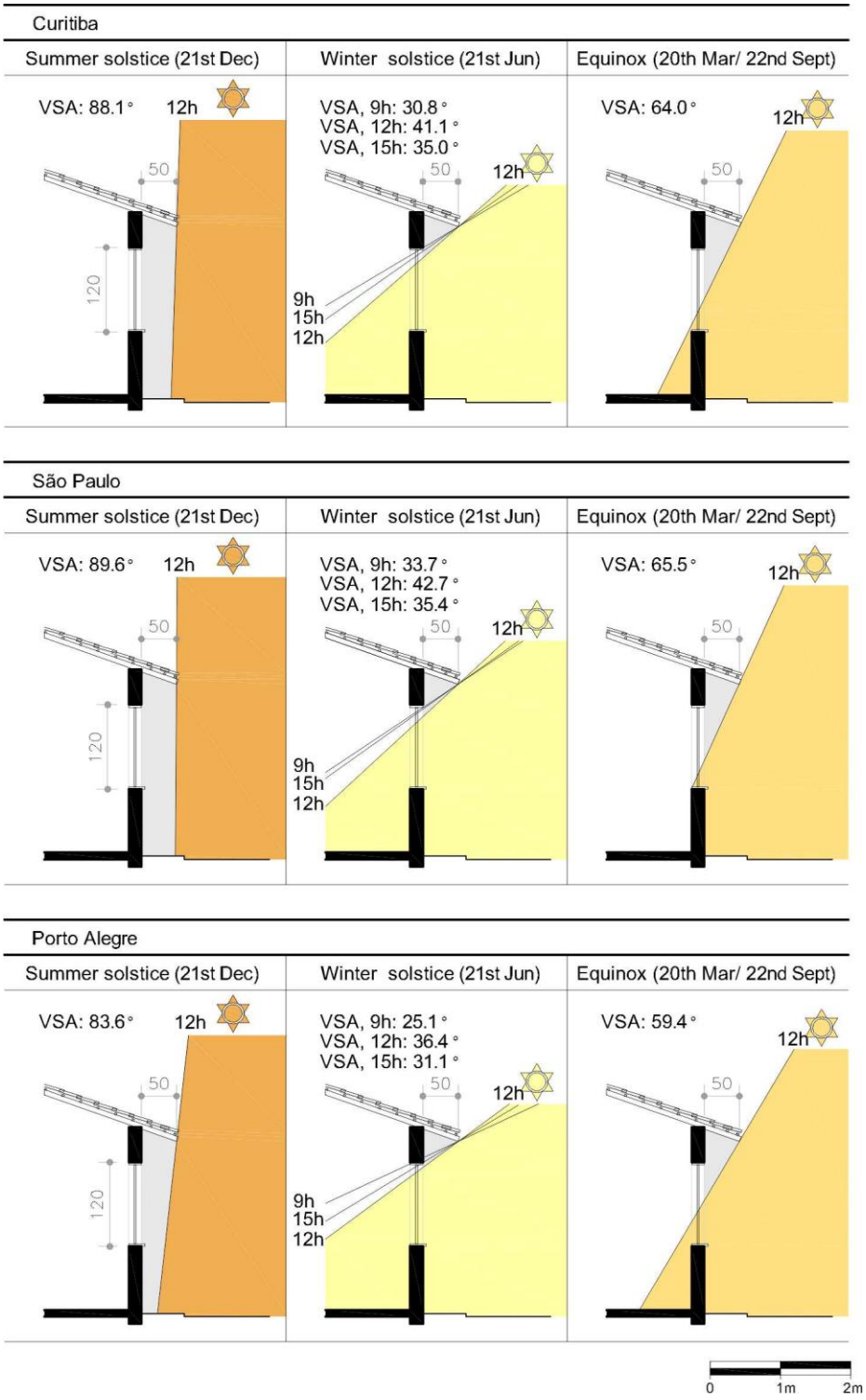


Figure 5-3: MCMV House shading on the north facade

5.4 Simulation Scope and Method

A 3D computer model of the MCMV House was built in TAS (EDSL, 2013a) based on the house design and materials described in Sections 5.1 and 5.2, respectively. The model was divided into thermal zones according to each room of the house, at both

occupant and ceiling levels. The 3D model and the thermal zones can be found in Appendix B.

In the first stage of the simulation evaluation, the model reflected the MCMV House as typically built and unoccupied. This stage was named Base Case. The model was progressively changed by assuming different conditions and design strategies with the aim of simulating the house's thermal performance as close as possible to reality and also as optimised. These constituted Cases 1 to 8. The building envelope optimisation was based on the results of Chapter 4, which adopted the Fabric First approach principles (e.g. shading, insulation, airtightness and ventilation).

The results of the simulations were assessed through the frequency of temperatures, the frequency of relative humidity levels, the degree-hours methodology and the energy demand.

5.5 Base Case Simulation Model

Base Case considered the model as typically built. The summary of Base Case model is detailed in Table 5-5 and the assumptions are detailed in Section 5.5.1.

Table 5-5: Summary of MCMV House Base Case simulation model

	Base Case
Summary	Model as typically built, unoccupied
Details	Weather data file compiled by Roriz (2012b) Building envelope as shown in Table 5-4. No shading, no internal gains, infiltration of 1 ach and no ventilation were assumed.

5.5.1 Assumptions

I. Weather data: The weather data used was compiled by Roriz (2012b), based on data collection between 2000 and 2010 for the cities of Curitiba, São Paulo and Porto Alegre.

II. Calendar: The adopted calendar was based on the environmental analysis undertaken in Chapter 3, in which summer was assumed to be between December and March and winter was assumed to be between May and September. Mid-season was considered to be the months of April, October and November.

III. Internal gains: The house was assumed unoccupied and thus, no internal gains were assumed in Base Case.

IV. Shading: No additional shading was assumed in Base Case (only the eaves).

V. Infiltration: Typical infiltration rate of the MCMV house typology is unknown. Therefore, the infiltration rate of the house was assumed at 1 ach, as the Brazilian standard NBR 15575 (ABNT, 2013d, p. 26) suggests to be adopted as an infiltration rate for the simulation analyses.

VI. Ventilation: No ventilation was assumed in Base Case. All the windows were considered fully closed at this first stage of the simulations.

VII. Comfort temperature range: As indicated in Chapter 3, a narrow and a wide thermal comfort benchmarks of 20-25 °C and 18-29 °C were considered, respectively.

VIII. Heating or Cooling: No active space conditioning was considered in Base Case.

The simulations considered internal doors as opened because it is believed that this is the pattern mostly found in houses. Internal doors are opened fairly frequently and they allow the movement of air through the house (Cotterel and Dadeby, 2012).

5.5.2 Results

Figure 5-4, Figure 5-5 and Figure 5-6 reveal the frequency of temperature in the occupied rooms of the houses in Curitiba, São Paulo and Porto Alegre, respectively. The temperatures in the occupied rooms were similar due to the compact size of the house, although the occupied rooms at ceiling level had higher temperatures than at occupant level.

In Curitiba, the occupied areas were about 30% and 56% of the time within the thermal comfort of 20-25 °C and 18-29 °C, respectively. The occupied areas were below 18 °C and 20 °C for around 44% and more than 70% of the year, respectively. The occupied areas with temperatures above 25 °C were negligible at occupant level.

In São Paulo, the occupied areas were 57% of the time within the narrow thermal comfort of 20-25 °C and 86% of the time within the wide thermal comfort interval of 18-29 °C. The occupied areas were below 18 °C and 20 °C for about 14% of the year and for no more than 40% of the year at occupant level, respectively. The occupied areas were above 25 °C for about 3% of the year at occupant level and up to 7% of the year at ceiling level.

In Porto Alegre, the occupied areas were within the thermal comfort of 20-25 °C and 18-29 °C for 45% and 81% of the year, respectively. The indoor temperatures at occupant level were below 18 °C and 20 °C for more than 18% and 39% of the year, respectively. At occupant level, the indoor temperatures were above 25 °C and 29 °C for more than 15% and less than 1% of the time, respectively. At ceiling level, the indoor temperatures were above 25 °C and 29 °C for more than 21% and about 2% of the time, respectively.

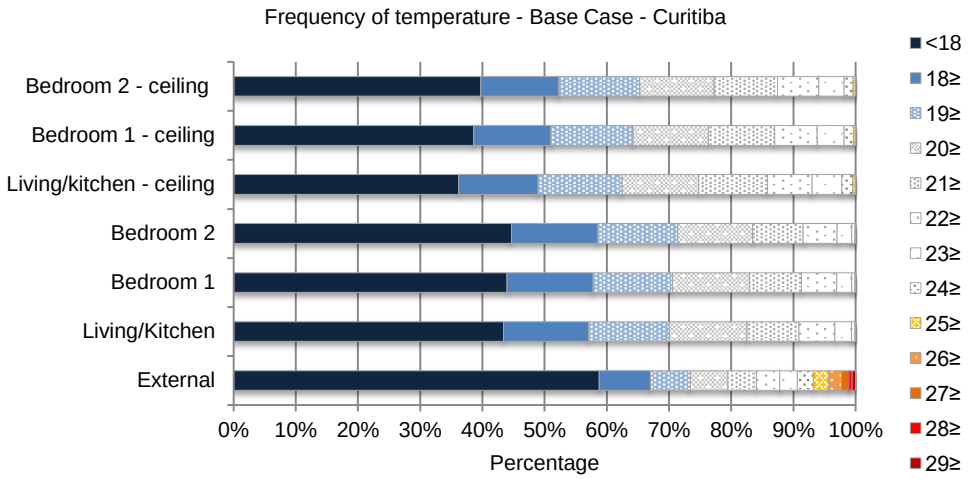


Figure 5-4: Frequency of temperature, Base Case, Curitiba

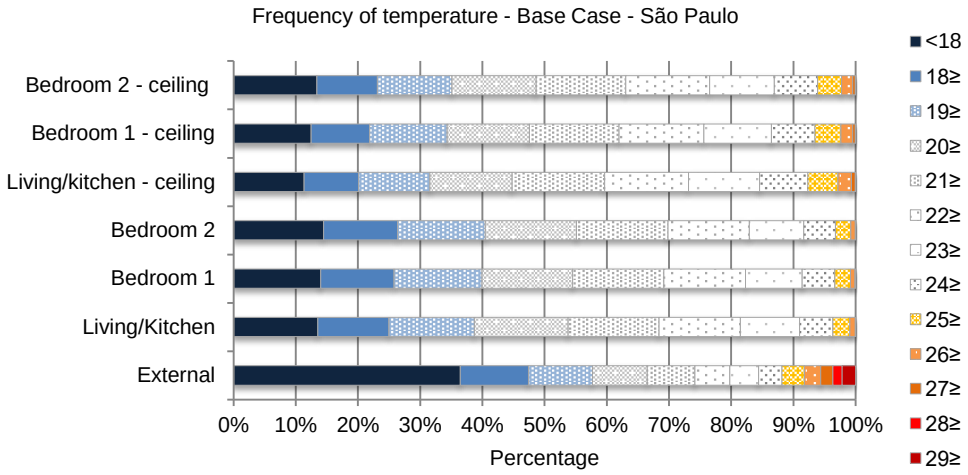


Figure 5-5: Frequency of temperature, Base Case, São Paulo

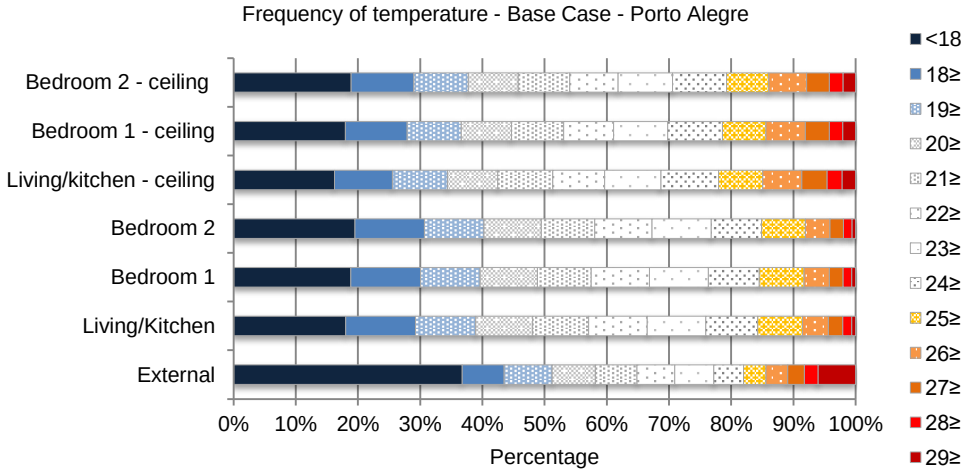


Figure 5-6: Frequency of temperature, Base Case, Porto Alegre

Figure 5-7, Figure 5-8 and Figure 5-9 show the results in terms of degree-hours for Curitiba, São Paulo and Porto Alegre, respectively.

In Curitiba, the envelope reduced by more than 37% and 55% the heating degree-hours for the base temperature of 18 °C and 20 °C at occupant level compared to external data, respectively. Even though the graph of frequency of temperature suggested a high percentage of the year below the lower comfort limit of 18 °C (Figure 5-4), it can be seen that the temperatures were not very far from the wide lower comfort limit, otherwise their impact in the degree-hours would be much higher.

In São Paulo, the envelope reduced by more than 15% and 34% the heating degree-hours for the base temperature of 18 °C and 20 °C at occupant level compared to external data, respectively. The envelope also reduced the cooling degree-hours for the base temperature of 25 °C by more than 8% at occupant level when compared to external data.

In Porto Alegre, the envelope reduced by more than 19% and 37% the heating degree-hours for the base temperature of 18 °C and 20 °C at occupant level compared to external data, respectively. The envelope also reduced by more than 39% and 3% the cooling degree-hours for the base temperature of 25 °C and 29 °C at occupant level when compared to external data, respectively.

Figure 5-10, Figure 5-11 and Figure 5-12 show the frequency of relative humidity levels in Curitiba, São Paulo and Porto Alegre, respectively. The external relative humidity levels exceeded the limit of 80% in 61%, 43% and 44% of the time in the cities, respectively. The internal relative humidity levels were above 80% for no more than 25%, 6% and 15% of the year in Curitiba, São Paulo and Porto Alegre, respectively. It should be noted that higher relative humidity levels were found more at occupant level than at ceiling level.

The next section assesses the simulation model under different use conditions and design strategies.

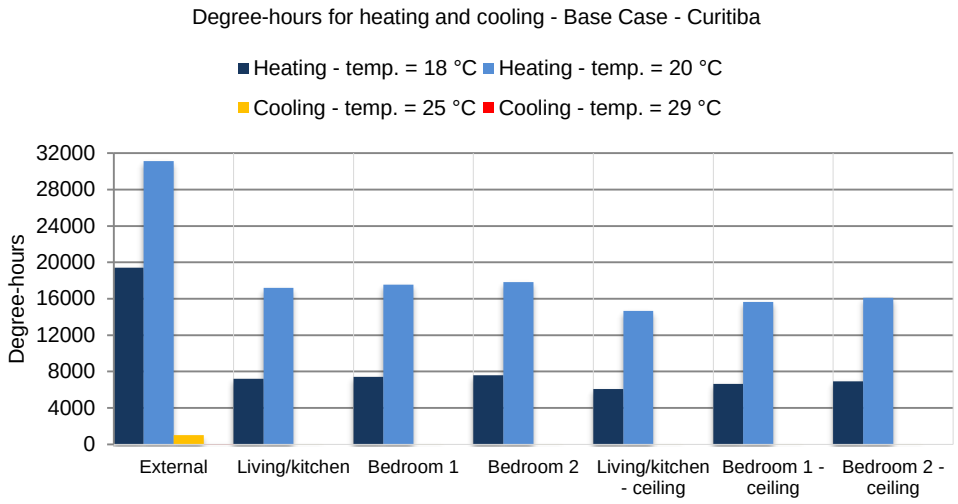


Figure 5-7: Degree-hours, Base Case, Curitiba

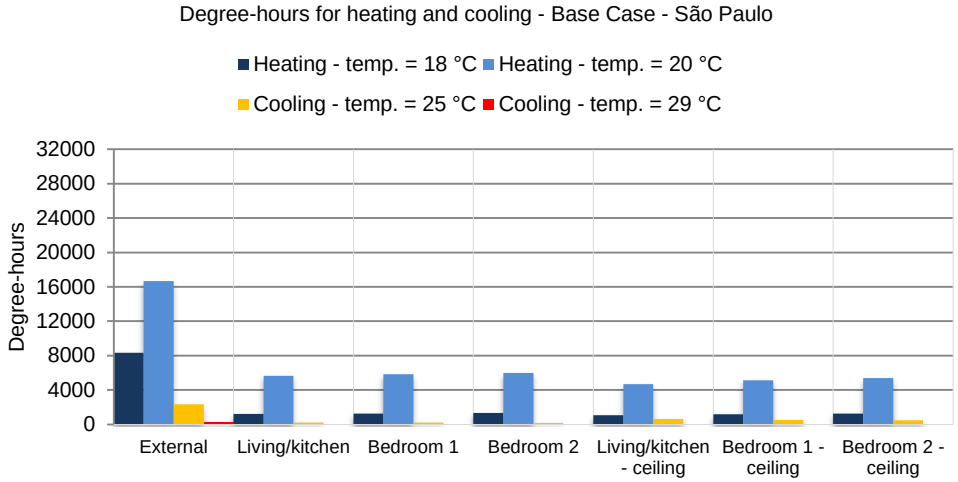


Figure 5-8: Degree-hours, Base Case, São Paulo

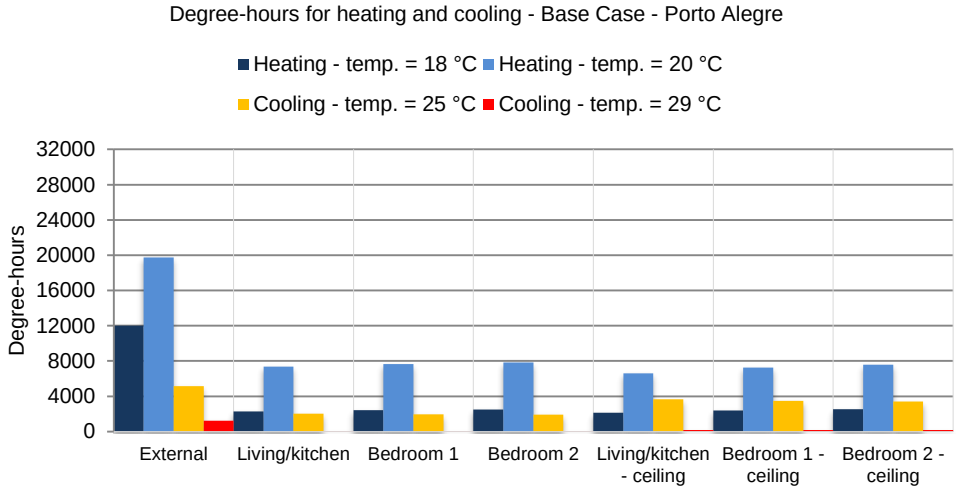


Figure 5-9: Degree-hours, Base Case, Porto Alegre

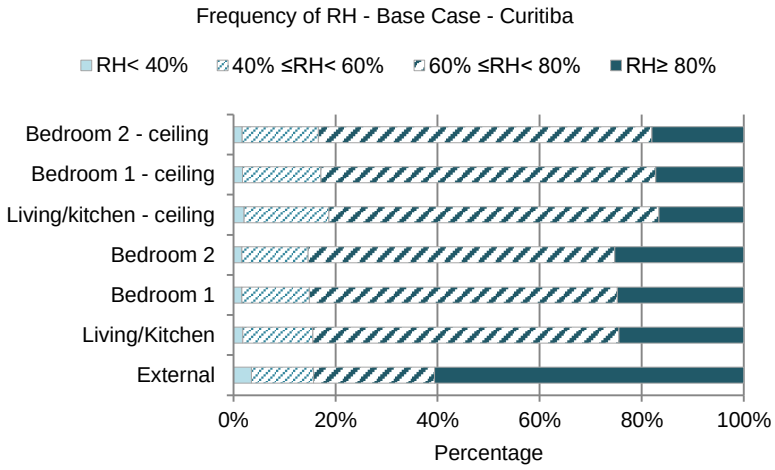


Figure 5-10: Frequency of relative humidity, Base Case, Curitiba

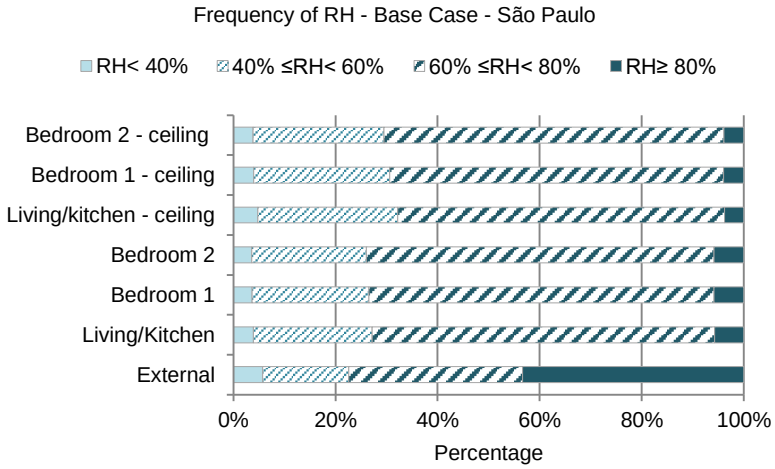


Figure 5-11: Frequency of relative humidity, Base Case, São Paulo

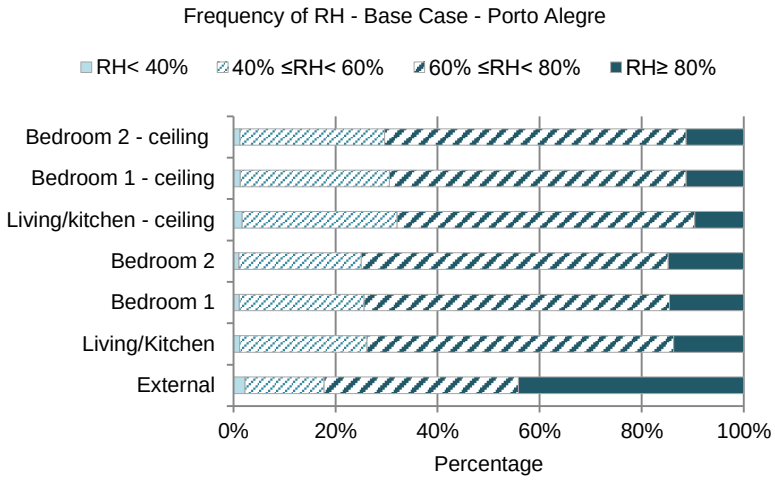


Figure 5-12: Frequency of relative humidity, Base Case, Porto Alegre

5.6 Variations of the Simulation Model

This section introduces progressive variations in the MCMV House simulation model of the previous section and for each of those variations, a simulation was undertaken.

The aim of the investigation was firstly to evaluate the performance of the MCMV House in use. Furthermore, the aim was to explore ways of increasing thermal comfort and energy efficiency in the house, through the adoption of the Fabric First approach concepts, such as increased insulation, limited infiltration, shading and selective ventilation.

The variations of the simulations are shown below and are summarized in Table 5-6. The assumptions are detailed in the next section.

i. Case 1 considered the addition of shading devices on the north windows of the simulation model (Base Case + shading). Despite the fact that the roof eaves delivered a certain amount of shading, this is uneven among the cities. Therefore, in order to have appropriate shading levels delivered and also comparable results among the cities, shading devices were individually designed for each of those locations to cut-off at the equinox.
ii. Case 2 considered internal gains due to the occupancy consistent with typical affordable house occupancy of 4 people (Case 1 + internal gains).
iii. Case 3 assumed the housing envelope as optimised (Case 2 + envelope optimisation). From this case, two scenarios were considered in the simulations, according to the findings of Chapter 4:
    a. Scenario ‘a’ consisted of the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre.
    b. Scenario ‘b’ consisted of the most cost-effective envelope n° 5 for all the cities investigated.
iv. Case 4 considered each of the optimised envelope scenarios under a regime of selective ventilation (Case 3 + ventilation).
v. Case 5 assumed each of the optimised envelope scenarios with a reduction of the infiltration rate (Case 3 + reduction of the infiltration rate).
i. Case 6 considered each of the optimised and airtight envelope scenarios under a regime of selective ventilation (Case 5 + ventilation).
vi. Case 7 assumed each of the optimised envelope scenarios under a regime of active space conditioning for heating and cooling (Case 3 + AC).
vii. Case 8 assumed each of the optimised and airtight envelope scenarios under a regime of active space conditioning for heating and cooling (Case 5 + AC).

Table 5-6: Summary of MCMV House simulation model variation

	Building naturally ventilated						Building artificially conditioned		
	Typical: shading & Internal gains		Optimised envelope: increase of insulation, reduction of infiltration and selective ventilation						
Cases investigated	**Case 1**	**Case 2** 'Typical MCMV House with internal gains'	**Case 3a** (envelope n° 72/ 108)	**Case 4a** (envelope n° 72/ 108)	**Case 5a** (envelope n° 72/ 108)	**Case 6a** (envelope n° 72/ 108)	**Case 7a** (envelope n° 72/ 108)	**Case 8a** (envelope n° 72/ 108)	Scenario 'a' used the best performance envelope n° 72 and 108
			Case 3b (envelope n° 5)	**Case 4b** (envelope n° 5)	**Case 5b** (envelope n° 5)	**Case 6b** (envelope n° 5)	**Case 7b** (envelope n° 5)	**Case 8b** (envelope n° 5)	Scenario 'b' used the most cost-effective envelope n° 5
Summary	As Base Case + **shading**	As Case 1 + **internal gains**	As Case 2 + **increase of insulation**	As Case 3 + **ventilation**	As Case 3 + **reduction of infiltration**	As Case 5 + **ventilation**	As Case 3 + **heating & cooling (AC)**	As Case 5 + **heating & cooling (AC)**	
Details	Case 1 is based on Base Case with shading devices on the north facade.	Case 2 is based on Case 1 with internal gains in order to simulated as close as possible the housing occupancy.	Case 3a/ 3b are based on Case 2 but considering the envelope optimisation. Best performance envelope and the most cost-effective envelope were evaluated.	Case 4a/ 4b are based on Case 3a/ 3b with selective ventilation strategy to reduce high temperatures inside the building.	Case 5a/ 5b are based on Case 3a/ 3b but considering the reduction of infiltration to 0.15 ach.	Case 6a/ 6b are based on Case 5a/ 5b with selective ventilation strategy to reduce high temperatures inside the building.	Case 7a/ 7b are based on Case 3a/ 3b with heating and cooling for maximizing thermal comfort. (for informative purpose)	Case 8a/ 8b are based on Case 5a/ 5b with heating and cooling for maximizing thermal comfort. (for informative purpose)	
Resumed Assumption	Shading devices designed to cut-off at the equinox on the north facade.	Internal gains compatible with an affordable house occupancy (11.6 W/m^2).	Envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre. Envelope n° 5 for all the cities.	Ventilation in summer and mid-season. Windows opening capacity according to Table 5-2.	Reduction of infiltration to 0.15 ach, as the lowest limit without using mechanical ventilation.	Ventilation in summer and mid-season. Windows opening capacity according to Table 5-2.	Thermostat to maintain the temperature within the narrow thermal comfort interval of 20-25 °C.		

The best performance envelope n° 72 (Curitiba): (DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof.
The best performance envelope n° 108 (São Paulo and Porto Alegre): (DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof.
The most effective envelope n° 5 (all cities): (SGU) Single glazing, (HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil roof.

5.6.1 Assumptions

i. Weather data: As Base Case
ii. Calendar: As Base Case
iii. Shading: Additional horizontal shading devices were placed on the north windows to cut-off at the equinox. The shading devices were designed for solar protection for VSA angles higher than 64.57°, 66.15° and 59.97° for Curitiba, São Paulo and Porto Alegre, respectively. It considered blocking radiation in summer and allowing it in winter.
iv. Internal gains: Internal gains due to the occupancy can vary widely because they depend on the lifestyle of the households. The internal gains of the MCMV House totalled on average 11.6 W/m^2, distributed among occupancy, lighting and appliances The assumptions adopted were designed for an affordable Brazilian housing occupancy, based on the findings of Chapter 2 and on assumptions of the RTQ-R label (INMETRO, 2012):
    a. Occupants: 4 people were assumed to use the house, two people in each bedroom. Different patterns of occupancy were considered for weekdays and weekends. On weekdays, all of the occupants were assumed to be out during the day and in different locations of the house during the early mornings and evenings, while at the weekends, the occupants were assumed predominantly at home. Occupants were assumed to use the spaces according to the schedules in Table 5-7. The heat gain was assumed for each person compatible with sedentary work (130 W), which corresponded to a sensible heat gain of 75 W and the latent heat gain of 55 W for kitchen and living room. For bedrooms, the heat gain was assumed seated at rest (95 W), which corresponded to a sensible heat gain of 65 W and a latent heat gain of 30 W. These values were based on ASHRAE (2009a, p. 18.4).
    b. Lighting: low energy compact fluorescent bulbs (CFL) were considered, resulting in the thermal loads of 5 W/m^2 for the bedrooms and 6 W/m^2 for the living areas when they were switched on, as suggested by the RTQ-R label assessment (INMETRO, 2012, p. 71).
    c. Equipment gains: a TV of 30 W power (INMETRO, 2014) was assumed to be used 4 hours per day. This is similar to a power of 1.5 W/m^2 set by INMETRO (2012) for 10 m^2 of living room for a 24-hour period.
    d. Household appliances: the number of household goods is smaller in affordable houses than in middle-class standard houses. Thus, internal gains from only the fridge, microwave, iron and washer were assumed for a 24-hour period. They are illustrated in Table 5-8. The appliances' power

was based on Brazilian appliances (INMETRO, 2014, PROCEL INFO, 2006), as illustrated in Chapter 2.

Table 5-7: MCMV House schedules of internal gains

0: off; 1: on

Weekdays	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
24 hours period	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Occupancy period	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Bedrooms (occupancy)	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Bedrooms (lighting)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Living/ Kitchen (occupancy, lighting)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Living/ Kitchen (TV)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Weekend	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
24 hours period	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Occupancy period	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Bedrooms (occupancy)	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Living/ Kitchen (occupancy)	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0
Living/ Kitchen (lighting)	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	0	0	0
Living/ Kitchen (TV)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0

Table 5-8: MCMV House appliances heat gains based on a given usage

Appliance	**Unity**	**Power (kW)**	**Usage**	**Daily energy consumption (kWh)**
Fridge	Per hour	0.032	year	0.790
Microwave, 30l	When on	1.250	30 min/ day	0.625
Iron	When on	1.200	2.3 hours/ week	0.40
Washer, 10 kg	1h per cycle	0.30	2 cycles/ week	0.085
Total of appliance heat gains:				1.9

v. Infiltration: The infiltration rate was assumed to be at a minimum of 0.15 ach (converted from to 3 $m^3/hr/m^2$ at 50 Pa), which is one of the lowest levels of infiltration without using any active ventilation system (Cotterel and Dadeby, 2012, p. 126).

vi. Ventilation: Selective natural ventilation was assumed for summer and mid-season as a function of the indoor temperature. All the windows started to open when the adjacent zone temperatures were above 23 °C and remained as fully opened according to their capacity at all indoor temperatures above 25 °C. The windows were closed when the outdoor temperature was higher than the indoor temperature. The opening capacity of the windows was mostly

equivalent to half of their area as they have predominantly a sliding operation, as shown in Table 5-2.

vii. Comfort temperature range: as Base Case

viii. Heating or Cooling: Active space conditioning was considered to maintain the indoor temperatures within the comfort range of 20-25 °C.

5.6.2 Results

In Cases 1 to 8, the results were also shown for the occupied areas, at both occupant and ceiling levels.

Figure 5-13, Figure 5-14 and Figure 5-15 show the results of Case 1 for Curitiba, São Paulo and Porto Alegre, respectively. The addition of extra shading did not have much effect on the building performance when compared to Base Case. The results of the implementation of shading showed a very slight reduction of high temperatures and increase of low ones, but overall the levels of thermal comfort remained the same in all the cities under investigation. This suggested that the roof eaves of the house worked as an appropriate shading device, blocking the undesired solar radiation in the most significant hot period of the year, which made the addition of an extra shading strategy less effective. This meant that despite the fact that the eaves were not designed to cut-off at the equinox, they were able to provide shading during the hottest and sunny period and therefore the north eave length requirement was sufficient to shade the windows correctly in the cities investigated.

Figure 5-16, Figure 5-17 and Figure 5-18 illustrated the results of Case 2, which consisted of the adoption of internal gains in Curitiba, São Paulo and Porto Alegre, respectively. Internal gains were responsible for the reduction of the frequency of temperatures below the lower thermal comfort limits and the slight increase of the frequency of temperatures above the upper thermal comfort limits when compared to the previous Case 1 for all the cities investigated.

In Curitiba, the internal gains had a positive impact on the indoor temperatures and the occupied areas had the thermal comfort levels increased to 43% and 70% of the year for the intervals of 20-25 °C and 18-29 °C at occupant level, respectively. This meant an increase of the narrow and the wide thermal comfort by 43% and 25% when compared to Case 1, respectively. The indoor temperatures below 18 °C and 20 °C at occupant level were reduced to up to 30% and to 56% of the year, respectively. The indoor temperatures above the upper comfort limit of 25 °C were increased to about 0.5% of the time.

In São Paulo, the occupied areas had the thermal comfort of 20-25 °C and 18-29 °C increased to more than 65% and 93% of the time, respectively. This represented an increase of the narrow and the wide thermal comfort by 14% and 8% when compared to Case 1, respectively. The indoor temperatures below 18 °C and 20 °C at occupant level were reduced to 7% and 25% of the year, respectively. The indoor temperatures above 25 °C at occupant level were increased to 8% of the year.

In Porto Alegre, the occupied areas within the thermal comfort of 20-25 °C corresponded to 45% of the year and were equal to Case 1. However, the occupied areas within the thermal comfort of 18-29 °C were increased to 87% of the time, which represented 7% more than in Case 1. The occupied areas below 18 °C and 20 °C were reduced to 11% and 31% of the year and the occupied areas above 25 °C and 29 °C were increased to more than 9% and less than 2% of the year, respectively.

Figure 5-19, Figure 5-20 and Figure 5-21 reveal the relative humidity levels in Case 1, which were found to be identical to Base Case. Figure 5-22, Figure 5-23 and Figure 5-24 show the relative humidity levels in Case 2, which were found to be increased in Curitiba and São Paulo due to the amount of moisture inside the building caused by the internal gains. At occupant level, the relative humidity levels above the limit of 80% were increased to approximately 33% of the time in Curitiba and 18% of the time in São Paulo, which meant 32% and 3 times more relative to Case 1, respectively. Surprisingly, in Porto Alegre the relative humidity levels were observed to be slightly reduced at occupant level. A possible explanation would be through the psychrometric chart, which supports that as the indoor temperatures increased considerably as occurred in Porto Alegre, the relative humidity levels could have suffered a slight reduction. The relative humidity levels above 80% were reduced to up to 13% of the time in Porto Alegre, which meant a reduction by 13% when compared to Case 1. It should be highlighted, however, that the relative humidity levels above 80% were increased in Porto Alegre at ceiling level when compared to Case 1.

Case 3 presupposes the optimisation of the building envelope based on two different scenarios, defined according to the sensitivity analysis discussed in Chapter 4. Case 3a adopted the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, whereas Case 3b adopted the most cost-effective envelope n° 5 in all the cities analysed. As shown in Chapter 4, the best performance envelope consisted of a super-insulated envelope and the most cost-effective envelope comprised a typical Brazilian envelope with a degree of insulation on the walls. The detailed description of these envelopes can be found in Appendix A.

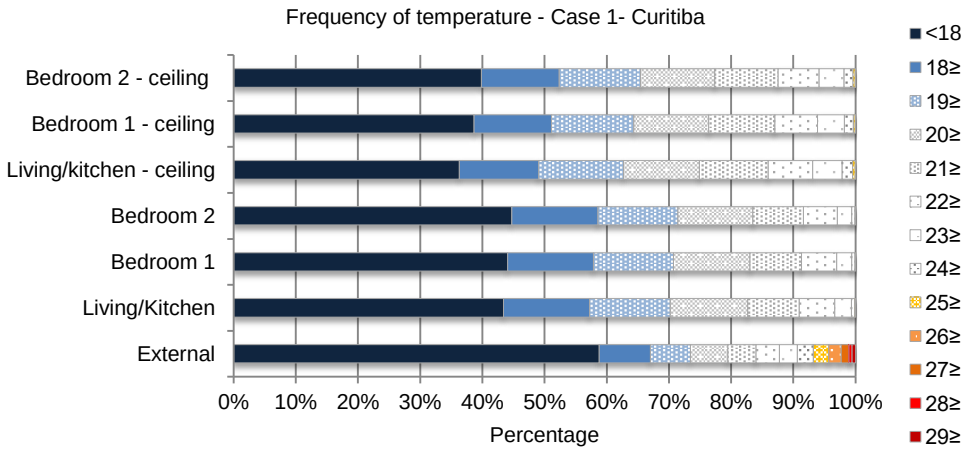


Figure 5-13: Frequency of temperature, Case 1, Curitiba

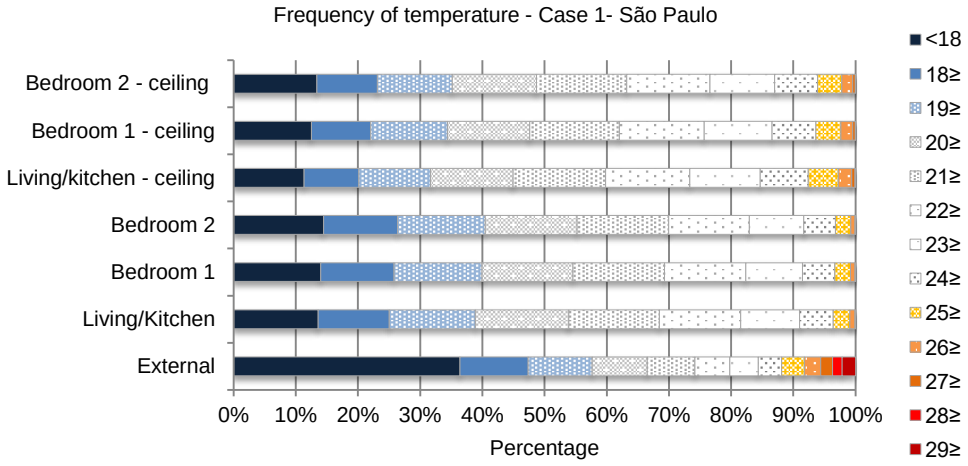


Figure 5-14: Frequency of temperature, Case 1, São Paulo

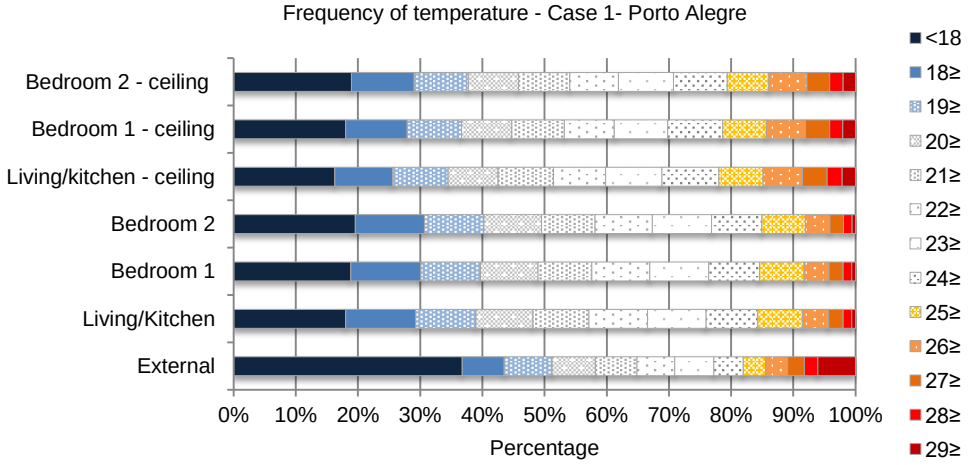


Figure 5-15: Frequency of temperature, Case 1, Porto Alegre

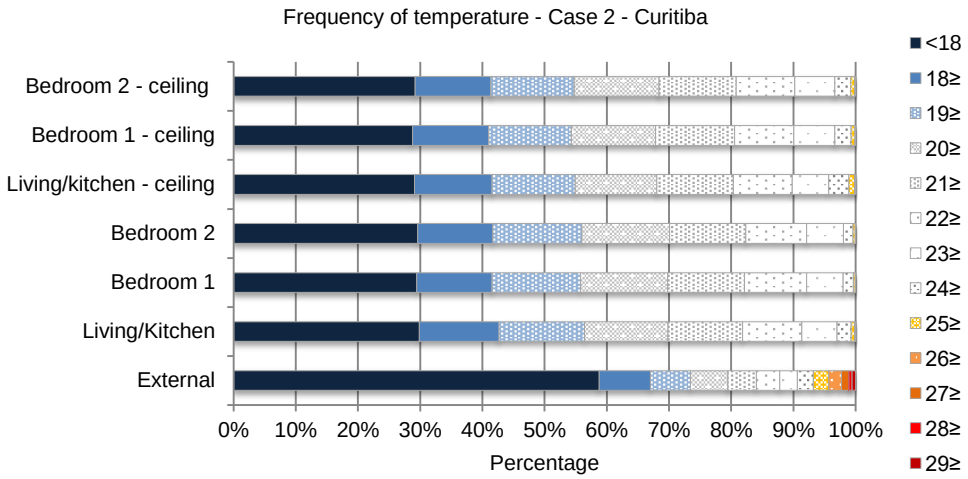


Figure 5-16: Frequency of temperature, Case 2, Curitiba

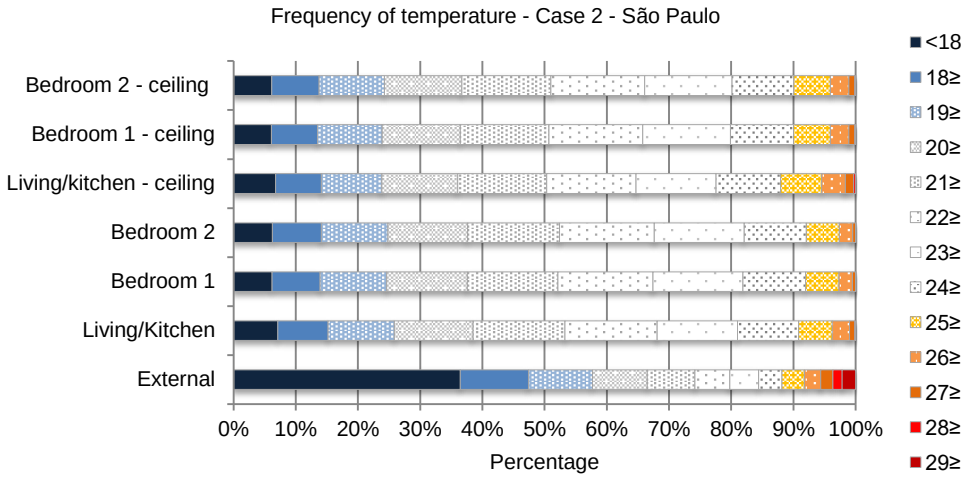


Figure 5-17: Frequency of temperature, Case 2, São Paulo

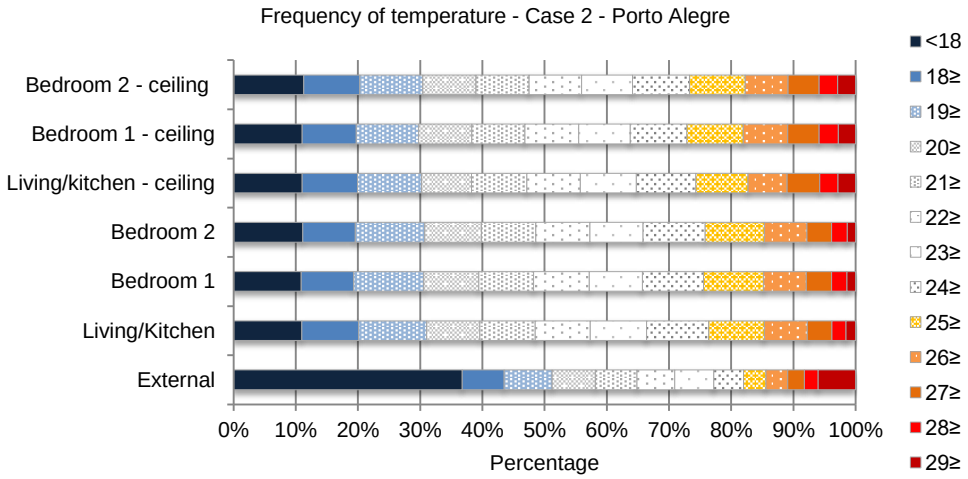


Figure 5-18: Frequency of temperature, Case 2, Porto Alegre

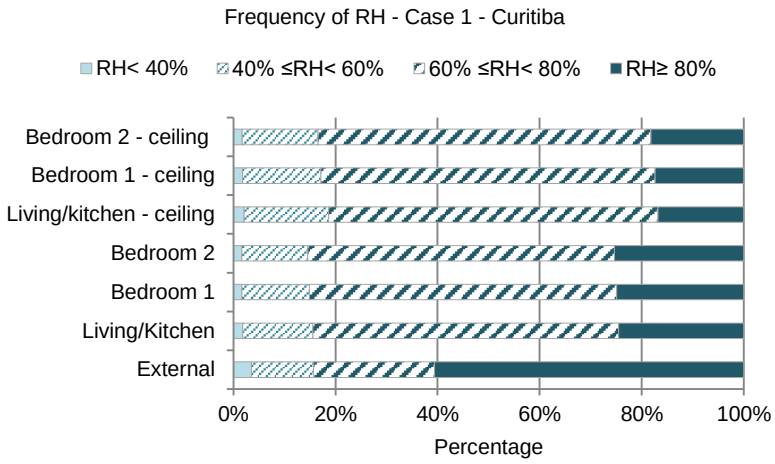


Figure 5-19: Frequency of relative humidity, Case 1, Curitiba

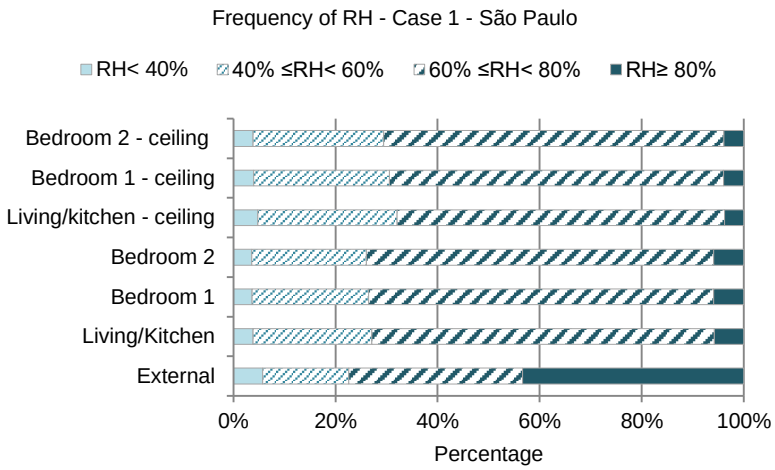


Figure 5-20: Frequency of relative humidity, Case 1, São Paulo

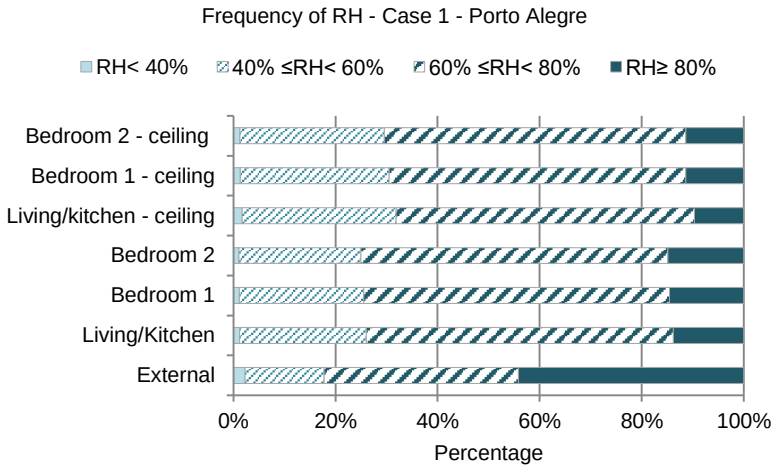


Figure 5-21: Frequency of relative humidity, Case 1, Porto Alegre

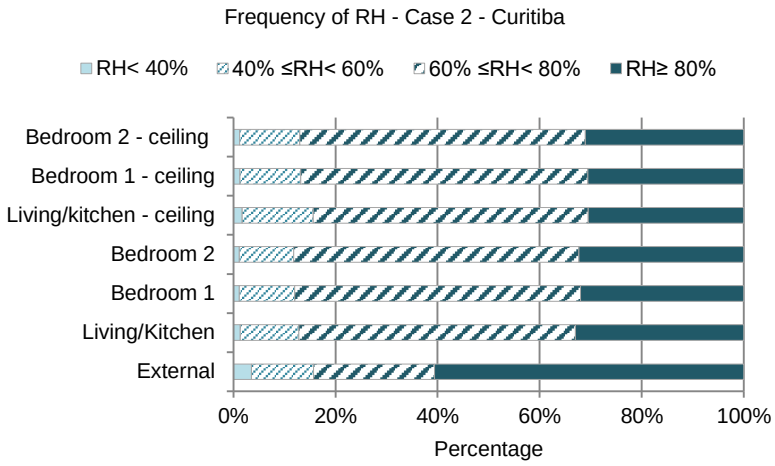


Figure 5-22: Frequency of relative humidity, Case 2, Curitiba

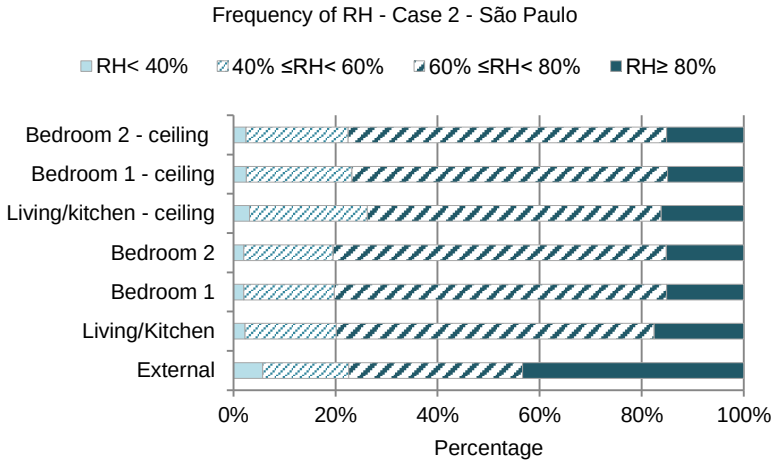


Figure 5-23: Frequency of relative humidity, Case 2, São Paulo

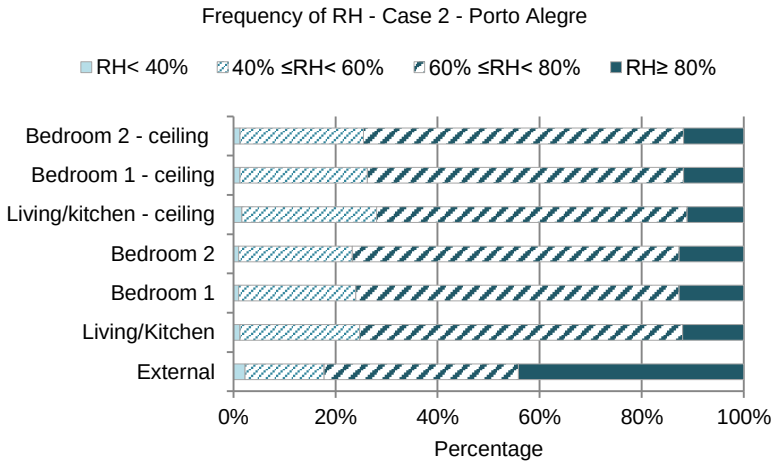


Figure 5-24: Frequency of relative humidity, Case 2, Porto Alegre

In Case 3a (Figure 5-25, Figure 5-26 and Figure 5-27) the occupied areas had a considerable increase of the thermal comfort when compared to Case 2.

In Curitiba, the occupied areas were within the thermal comfort of 20-25 °C and 18-29 °C for more than 42% and 82% of the year, respectively. When compared to Case 2, the adoption of the envelope n° 72 kept similar thermal comfort levels for the narrow thermal comfort interval but increased the thermal comfort by 17% for the wide thermal comfort interval. The temperatures below 18 °C were mostly reduced to 17% of the time and the temperatures below 20 °C appeared to be slightly increased to 58% of the time. This meant that the temperatures were close to the lower thermal comfort temperature limit, which certainly suggests an increase of the thermal comfort conditions when compared to Case 1.

In São Paulo, the envelope optimisation increased the indoor thermal comfort of 20-25 °C to more than 88% of the year in the living room and achieved up to 92% of the year in the bedroom. For the thermal comfort of 18-29 °C, the occupied areas were within the thermal comfort all year long. When compared to Case 2, the adoption of the envelope n° 108 increased the thermal comfort by more than 35% and by 7.5% for the narrow and the wide thermal comfort interval, respectively. The occupied areas were not below 18 °C at any time of the year and were below 20 °C for close to 11% of the year. The occupied areas were not above 25 °C in any circumstances of the year.

In Porto Alegre, the change in the building envelope increased the thermal comfort of 20-25 °C and 18-29 °C to 79% and 99% of the year, respectively. When compared to Case 2, the adoption of the envelope n° 108 increased the thermal comfort by more than 75% and by 14% for the narrow and the wide thermal comfort interval, respectively. The occupied areas below 18 °C and 20 °C were greatly reduced to less than 0.6% and 16% of the year, respectively. Similarly, the occupied areas above 25 °C were greatly reduced to about 5% of the time at occupant level and they corresponded to no more than 6% of the time at ceiling level. As can be observed, the main change due to the envelope optimisation was observed in the areas at the ceiling level, which were previously most prone to overheating but they turned to have more uniformity in their temperatures when compared to the previous adoption of the typical envelope.

In Case 3b (Figure 5-28, Figure 5-29 and Figure 5-30) the occupied areas showed slightly lower levels of indoor thermal comfort when compared to Case 3a, but even so the thermal comfort levels were much higher than those achieved by the typical MCMV house in use, shown in Case 2.

In Curitiba, the occupied areas within the thermal comfort of 20-25 °C and 18-29 °C corresponded to 42% and 77% of the year, respectively. In relation to Case 2, the

adoption of the most cost-effective envelope n° 5 kept similar thermal comfort levels for the narrow thermal comfort interval but increased it by 10% for the wide thermal comfort interval. The indoor temperatures below 18 °C were reduced to 23% of the year at occupant level and the indoor temperatures below 20 °C remained similar as in Case 2.

In São Paulo, the occupied areas within the thermal comfort interval of 20-25 °C were increased to 81% of the time in the living room and 84% of the time in the bedrooms. Similarly, the occupied areas within the thermal comfort interval of 18-29 °C were increased to 99% of the time in the living room and 100% of the time in the bedrooms. When compared to Case 2, the adoption of the most cost-effective envelope n° 5 increased the thermal comfort by more than 24% and 6% for the narrow and the wide thermal comfort interval, respectively. For most of the time the occupied areas were not below 18 °C and they were below 20 °C for up to 17% of the year. The occupied areas were above 25 °C for up to 2% of the year. The findings seem to suggest that in São Paulo small changes in the building envelope might be sufficient to ensure high levels of indoor thermal comfort to the households, which corroborates the idea that super-insulated envelopes are not required to provide a significant increase in the thermal comfort in this location.

In Porto Alegre, the occupied areas had the thermal comfort of 20-25 °C and 18-29 °C increased to more than 63% and 96% of the time, respectively. This meant an increase of the narrow and wide thermal comfort by 40% and 10% when compared to Case 2, respectively. The occupied areas were below the lower comfort limit of 18 °C and 20 °C for about 4% and 23% of the year, respectively. The occupied areas were above the upper comfort limit of 25 °C for about 13% of the year but they were not above 29 °C at occupant level.

Figure 5-31, Figure 5-32 and Figure 5-33 show the levels of relative humidity in Case 3. In Case 3a, for the best performance envelope n° 72 and n° 108, the relative humidity levels above 80% dropped to 29% of the time in Curitiba and to up to 14% of the time in São Paulo but they increased to up to 18% of the time in Porto Alegre. When compared to Case 2, the levels of relative humidity were decreased by 12% in Curitiba and by 22% in São Paulo but they were increased by 38% in Porto Alegre. In Case 3b, for the most cost-effective envelope n° 5, the relative humidity levels were above 80% for 29% of the time in Curitiba and for up to 13% of the time in São Paulo and Porto Alegre. As can be seen, the relative humidity levels of the most cost-effective envelope were equal or less than those of the best performance envelope. When compared to Case 2, the levels of relative humidity were decreased by 12% in Curitiba and by 28% in São Paulo but they were kept the same in Porto Alegre.

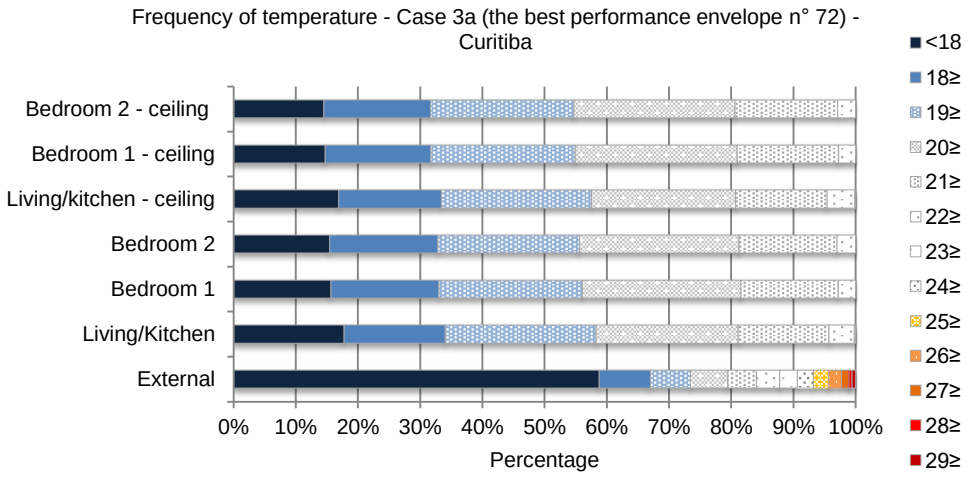


Figure 5-25: Frequency of temperature, Case 3a, Curitiba

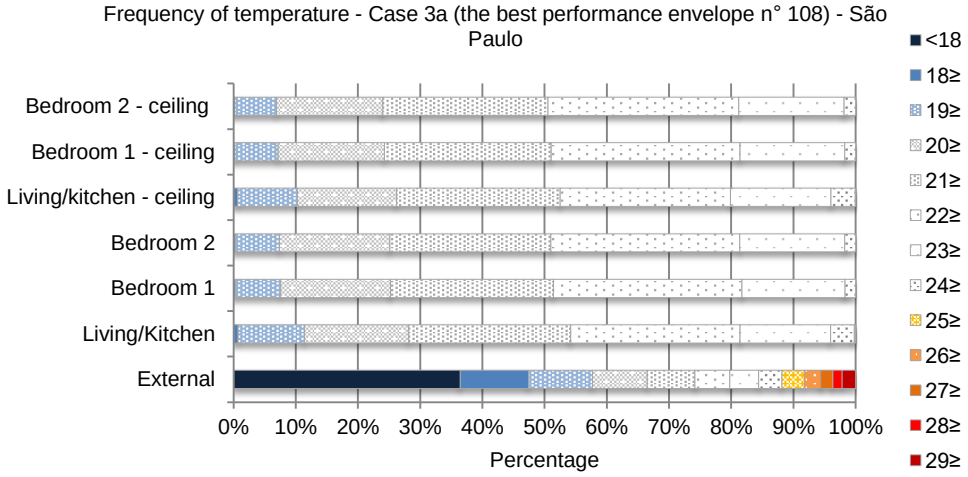


Figure 5-26: Frequency of temperature, Case 3a, São Paulo

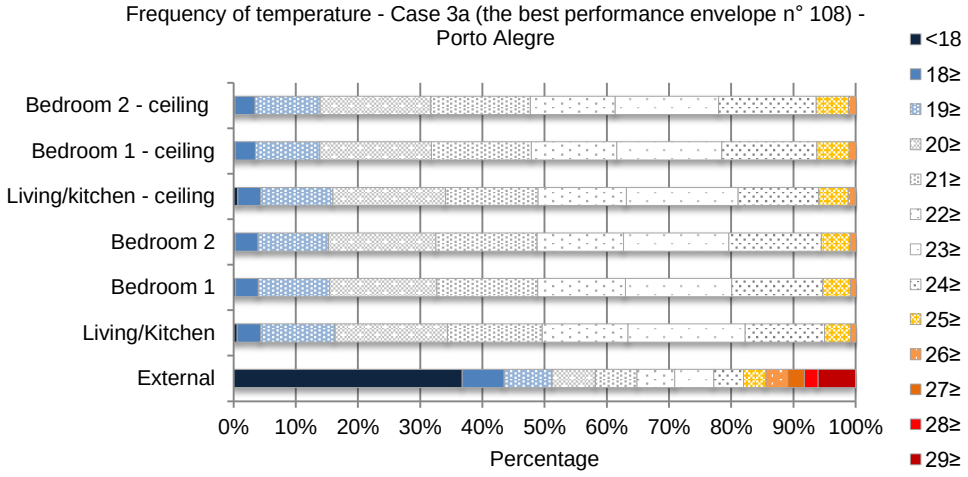


Figure 5-27: Frequency of temperature, Case 3a, Porto Alegre

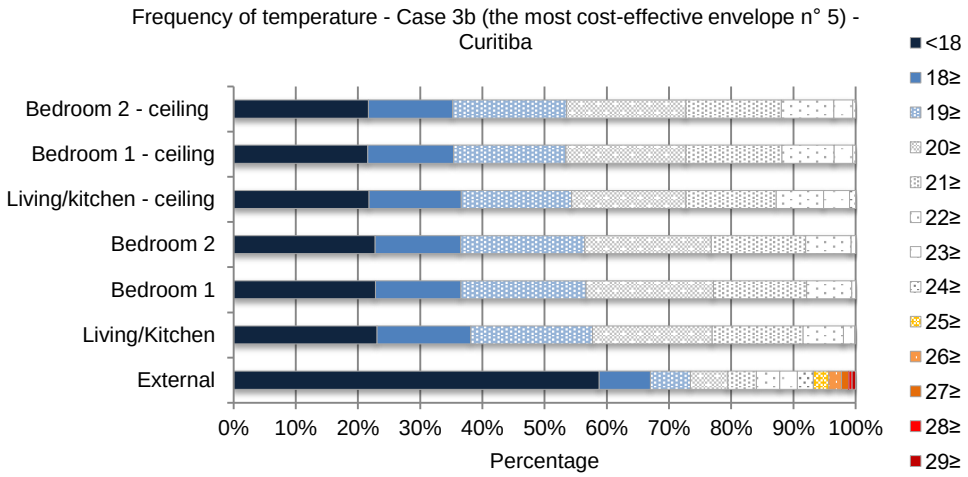


Figure 5-28: Frequency of temperature, Case 3b, Curitiba

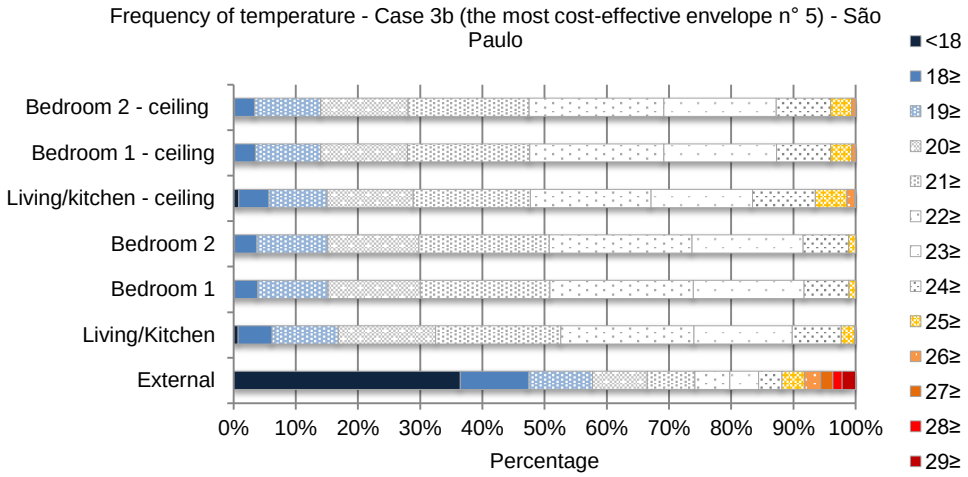


Figure 5-29: Frequency of temperature, Case 3b, São Paulo

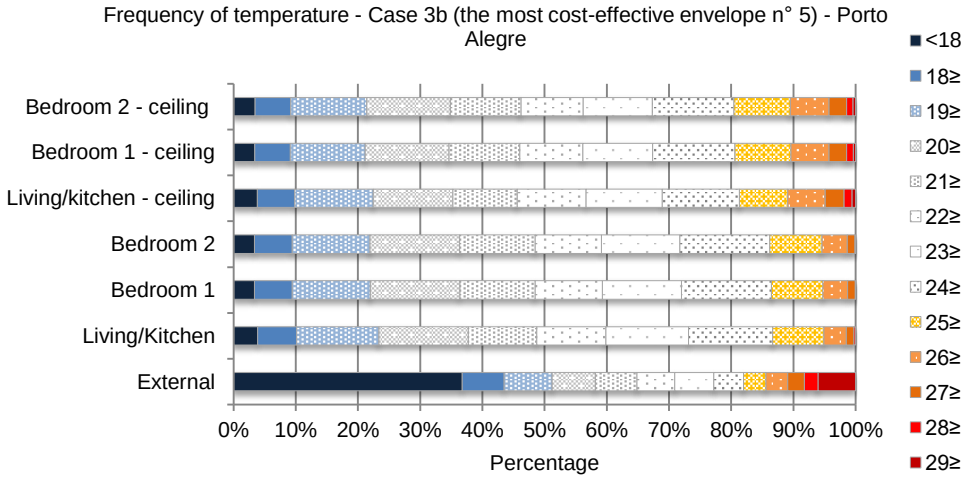


Figure 5-30: Frequency of temperature, Case 3b, Porto Alegre

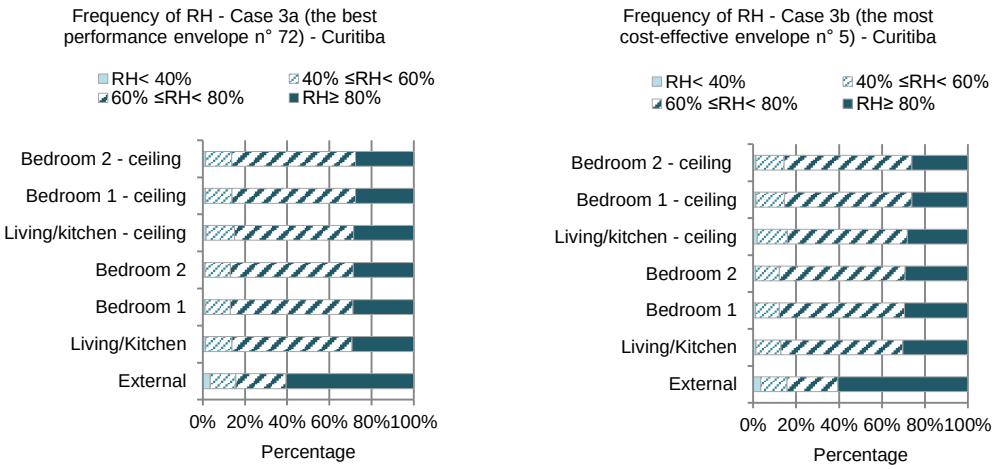


Figure 5-31: Frequency of relative humidity, Case 3a and 3b, Curitiba

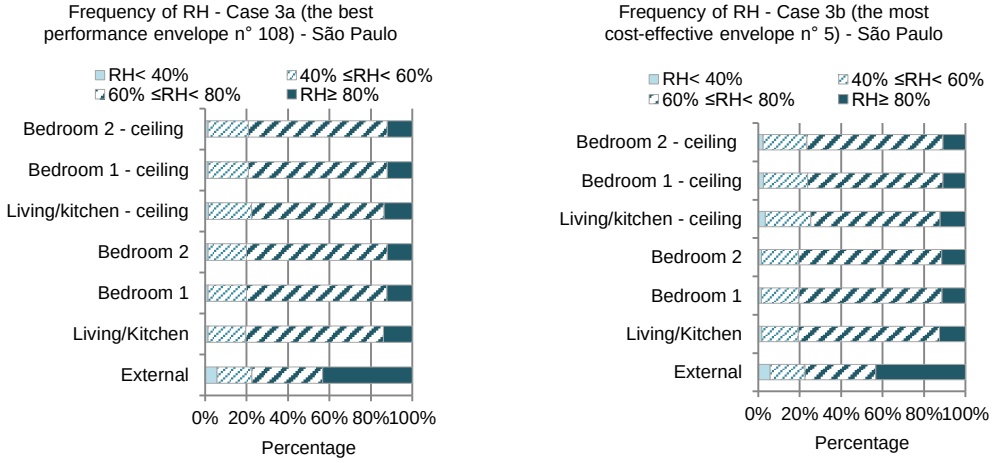


Figure 5-32: Frequency of relative humidity, Case 3a and 3b, São Paulo

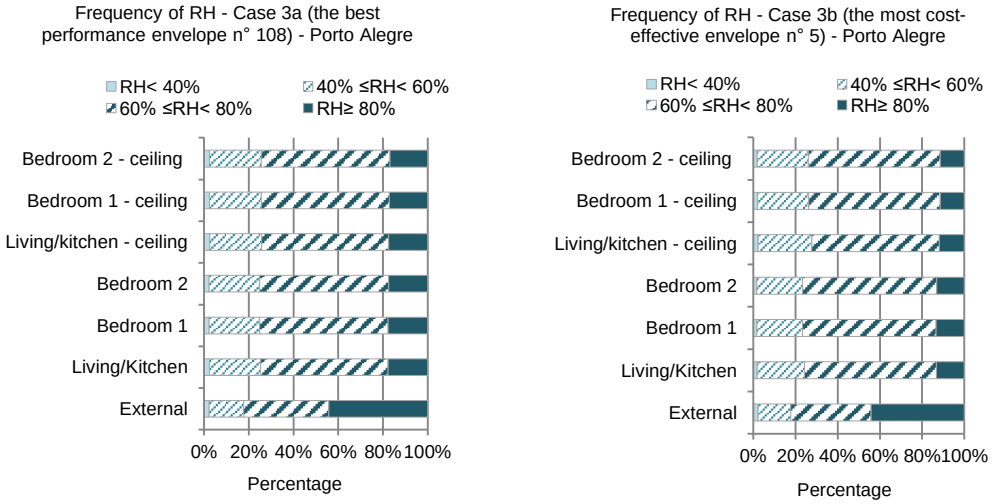


Figure 5-33:Frequency of relative humidity, Case 3a and 3b, Porto Alegre

Case 4 considered the use of selective natural ventilation as a function of the indoor temperatures, as mentioned in Section 5.6.1. The aim of adopting natural ventilation was to reduce the high temperatures inside the building, which could not be mitigated by the envelope optimisation and also to dissipate the moisture inside the building. Case 4a and 4b corresponded to the use of natural ventilation for the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre and for the most cost-effective envelope n° 5 in all the cities, respectively.

In Case 4a (Figure 5-34, Figure 5-35 and Figure 5-36), the indoor temperatures remained mostly as constant in Curitiba and in São Paulo. In Porto Alegre, however, a reduction of the indoor temperatures above the upper thermal comfort of 25 °C was observed relative to Case 3a. The occupied areas had the temperatures above 25 °C reduced by about 1% of the time and, consequently, the occupied areas within the narrow thermal comfort interval were increased for about 80% of the year.

Similarly, in Case 4b (Figure 5-37, Figure 5-38 and Figure 5-39), the indoor temperatures remained similar to those found in Case 3b mostly in Curitiba. In São Paulo, a minimal reduction of the indoor temperatures mainly in the range between 24 °C and 25 °C was observed relative to Case 3b. In Porto Alegre, the use of natural ventilation reduced the indoor temperatures above 25 °C by about 3% of the time relative to Case 3b and, consequently, the occupied areas within the narrow thermal comfort interval were increased for 66% of the year.

Figure 5-40, Figure 5-41 and Figure 5-42 show the relative humidity levels in Case 4. In Curitiba, because the windows were closed most of the time due to the mildness of the indoor temperatures, the relative humidity levels in Case 4a and 4b remained the same as in Case 3a and 3b, respectively. In São Paulo and Porto Alegre, in Case 4a, the relative humidity levels above 80% were reduced to up to 12% and 16% of the year, which meant a reduction of 2% of the time in both cities when compared to Case 3a. In Case 4b, in São Paulo, the relative humidity levels above 80% corresponded to up to 11% of the year and these levels also had a reduction of 2% of the time when compared to Case 3b. In Porto Alegre, the relative humidity levels above the limit of 80% in Case 4b corresponded to up to 13% of the time and remained constant as found in Case 3b.

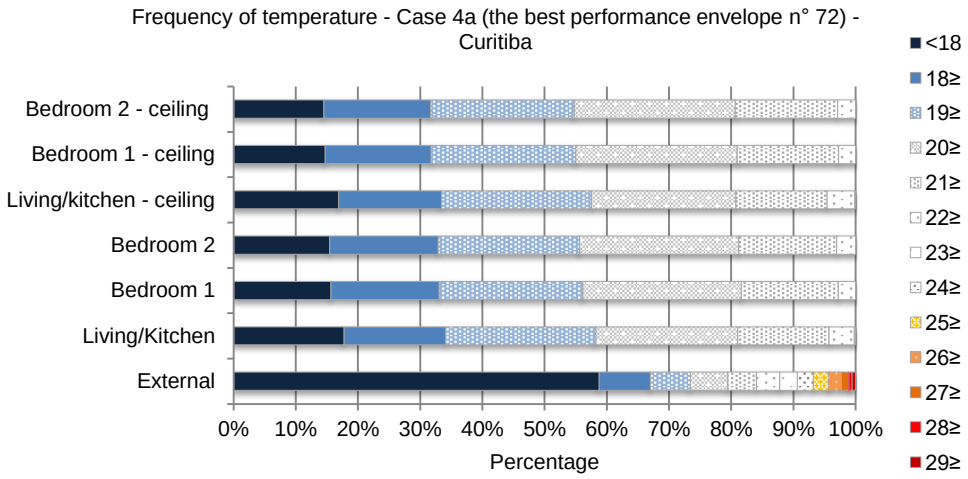


Figure 5-34: Frequency of temperature, Case 4a, Curitiba

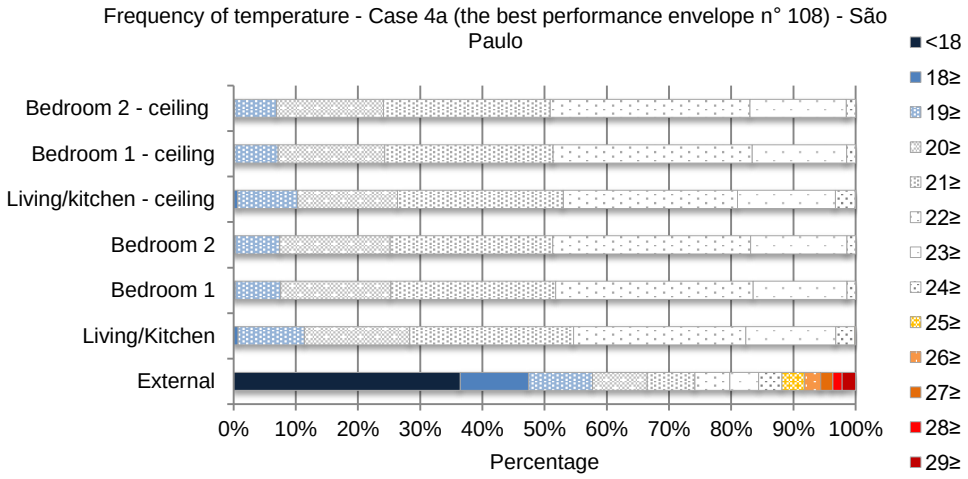


Figure 5-35: Frequency of temperature, Case 4a, São Paulo

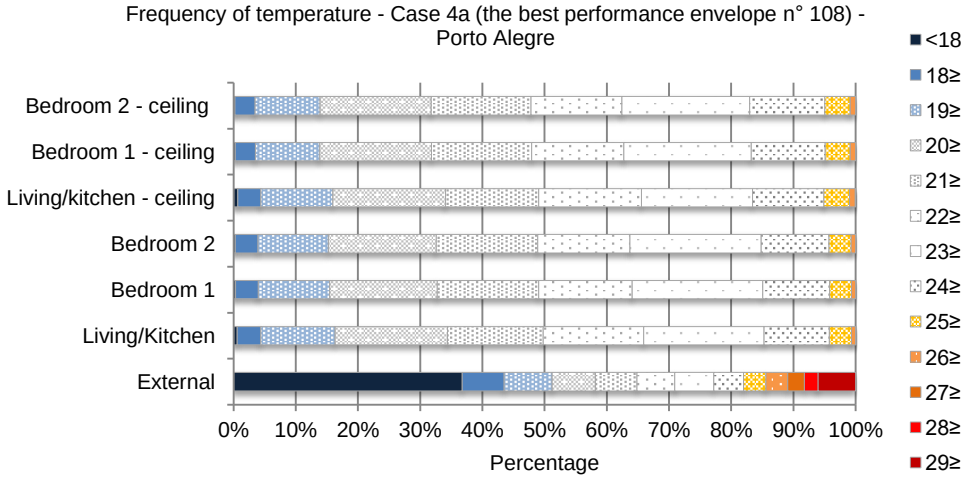


Figure 5-36: Frequency of temperature, Case 4a, Porto Alegre

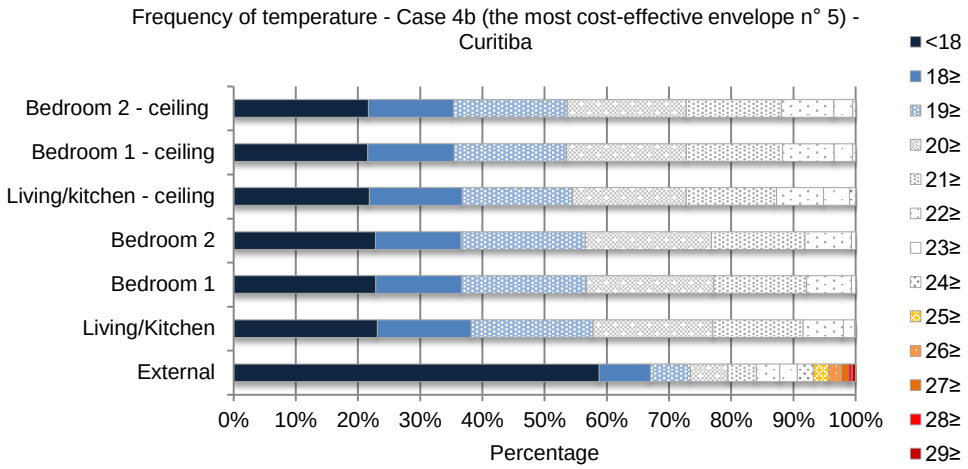


Figure 5-37: Frequency of temperature, Case 4b, Curitiba

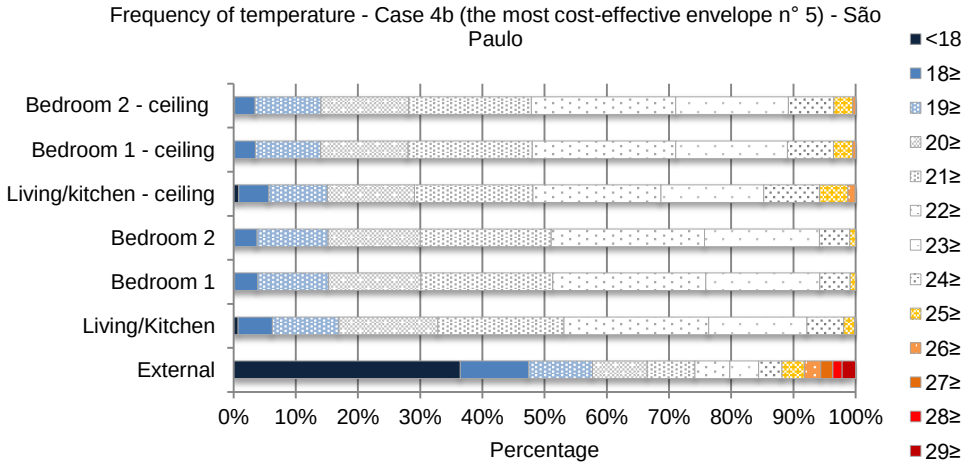


Figure 5-38: Frequency of temperature, Case 4b, São Paulo

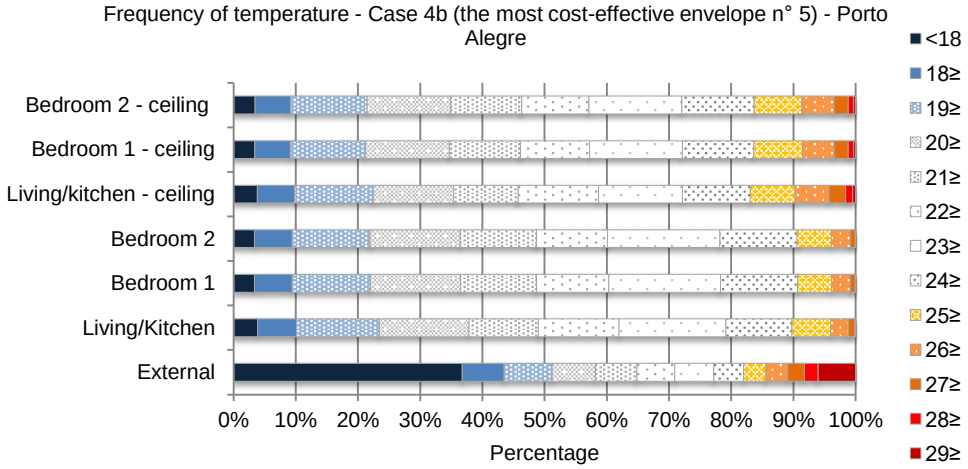


Figure 5-39: Frequency of temperature, Case 4b, Porto Alegre

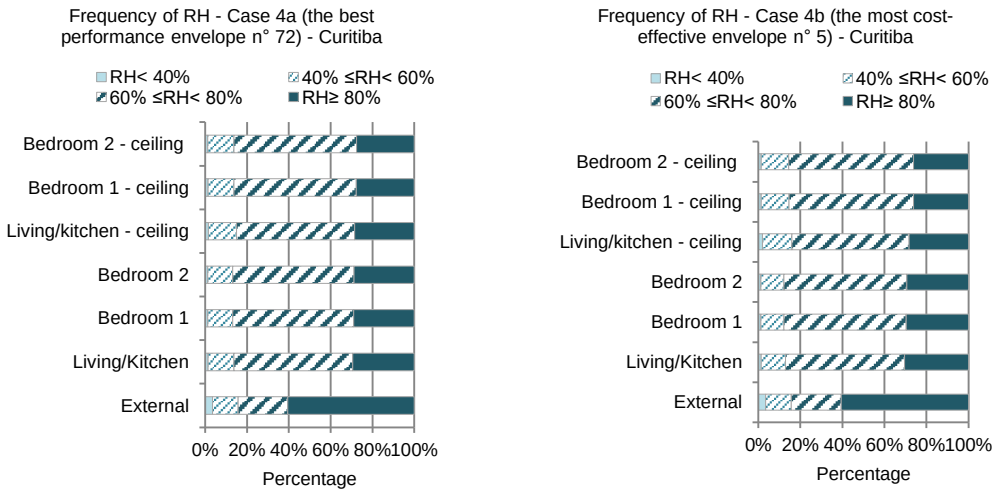


Figure 5-40: Frequency of relative humidity, Case 4a and 4b, Curitiba

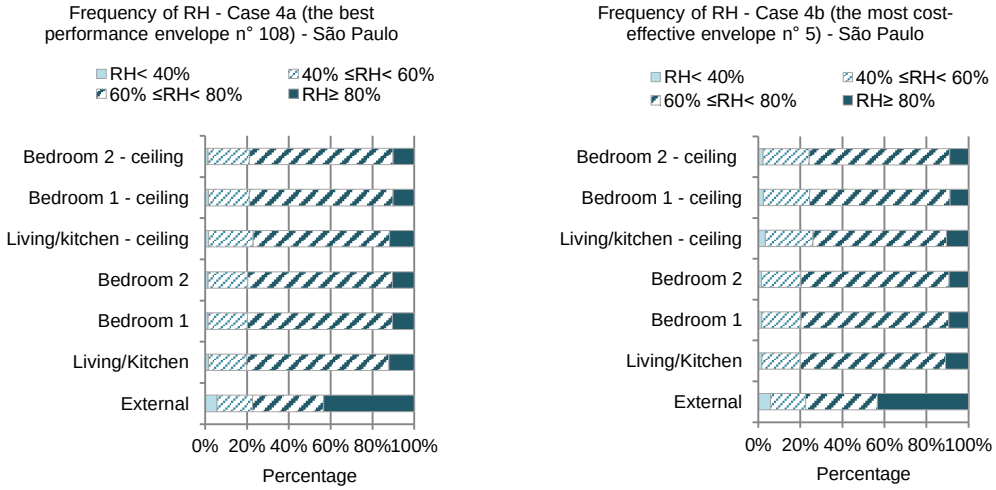


Figure 5-41: Frequency of relative humidity, Case 4a and 4b, São Paulo

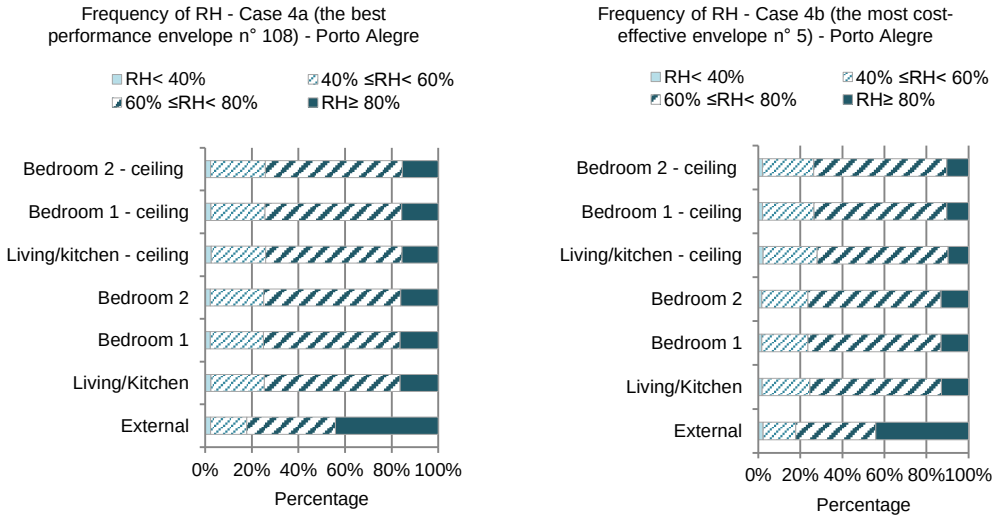


Figure 5-42: Frequency of relative humidity, Case 4a and 4b, Porto Alegre

Case 5 assumed the optimised envelopes with a reduction of the infiltration rate to 0.15 ach. Case 5a adopted the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, whereas Case 5b adopted the most cost-effective envelope n° 5 for all the cities. For both scenarios, the reduction of infiltration improved the indoor temperatures because it limited the heat exchange with the environment.

In Case 5a (Figure 5-43, Figure 5-44 and Figure 5-45) the indoor temperatures within the wide thermal comfort range were maximised considerably, at both occupant and ceiling levels.

In Curitiba, the occupied areas within the thermal comfort zone of 20-25 °C increased to more than 60% of the year and achieved more than 99% of the year for the thermal comfort interval of 18-29 °C. When compared to Case 3a, this meant an increase of the narrow and wide thermal comfort by 43% and 20%, respectively. The indoor temperatures below 18 °C and 20 °C at occupant level were mostly reduced to less than 1% and 40% of the time, respectively.

In São Paulo, the occupied areas were within the narrow thermal comfort interval of 20-25 °C throughout the year. When compared to Case 3a, this meant an increase of thermal comfort by 14% for the narrow thermal comfort interval.

In Porto Alegre, the occupied areas had the thermal comfort of 20-25 °C and 18-29 °C increased to 96.5% of the year and throughout the year, respectively. This represented an increase of the narrow and the wide thermal comfort by more than 22% and 1% when compared to Case 3a, respectively. At occupant level, the indoor temperatures below 20 °C were fully mitigated. The indoor temperatures above 25 °C were decreased to about 3.5% of the year but they were mostly in the temperature range around 25 °C.

Similarly, in Case 5b (Figure 5-46, Figure 5-47 and Figure 5-48) there was an increase of the indoor thermal comfort when compared to Case 3b.

In Curitiba, at occupant level, the reduction of the infiltration increased the indoor thermal comfort conditions to more than 54% and 91% of the time for the thermal comfort interval of 20-25 °C and 18-29 °C, respectively. When compared to Case 3b, this meant an increase of the narrow and wide thermal comfort by 28% and 18%, respectively. At occupant level, the indoor temperatures below 18 °C and 20 °C were decreased to around 9% and 46% of the time, respectively.

In São Paulo, the occupied areas had the thermal comfort increased to 94% of the time for the narrow thermal comfort of 20-25 °C and they achieved 100% of the year for the wide thermal comfort of 18-29 °C. This represented an increase of the narrow and wide

thermal comfort by 16% and 1% when compared to Case 3b. The occupied areas were below 20 °C for less than 5% of the time and they were above 25 °C for about 1% of the time.

In Porto Alegre, the occupied areas had their thermal comfort condition expanded to about 77% and 100% of the year for the thermal comfort intervals of 20-25 °C and 18-19 °C, respectively. When compared to Case 3b, this meant an increase of the narrow and wide thermal comfort by more than 22% and 4%, respectively. At occupant level, the indoor temperatures below 20 °C were reduced to about 8% of the year and the indoor temperatures above 25 °C were slightly reduced to 15% of the year.

Despite the positive contribution of the reduction of infiltration in terms of temperature, the indoor relative humidity levels increased sharply in all the cities, as shown in Figure 5-49, Figure 5-50 and Figure 5-51. A combination of high internal gains and limited air exchange between the indoors and outdoors contributed to the increase of moisture inside the building. It should be highlighted that if low infiltration was to be adopted in Brazilian dwellings, special attention should be paid to avoiding the increase of the relative humidity levels.

In Case 5a, for the best performance envelope scenario the occupied areas had relative humidity levels above 80% increased to 93%, 90% and 70% of the year, which were 3, 6 and 4 times higher than the relative humidity levels of Case 3a for Curitiba, São Paulo and Porto Alegre, respectively. In Case 5b, for the most cost-effective scenario (Case 5b), the occupied areas had relative humidity levels above 80% increased to up to 79%, 66% and 70% of the year, which were 3 times higher in Curitiba and 5 times higher in São Paulo and Porto Alegre than the relative humidity levels of Case 3b.

It should be noted that Curitiba was one of the cities that showed better benefits on limiting the infiltration rate from the temperature point of view but it was also the city that showed the highest absolute levels of relative humidity.

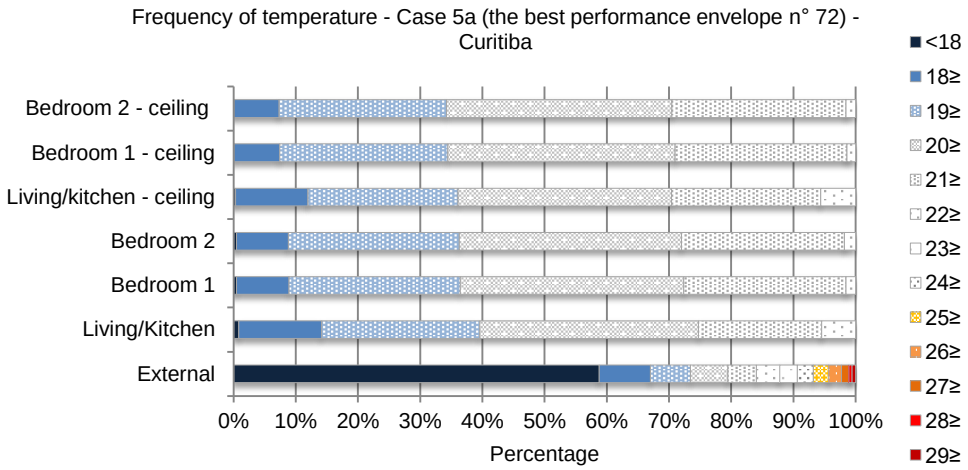


Figure 5-43: Frequency of temperature, Case 5a, Curitiba

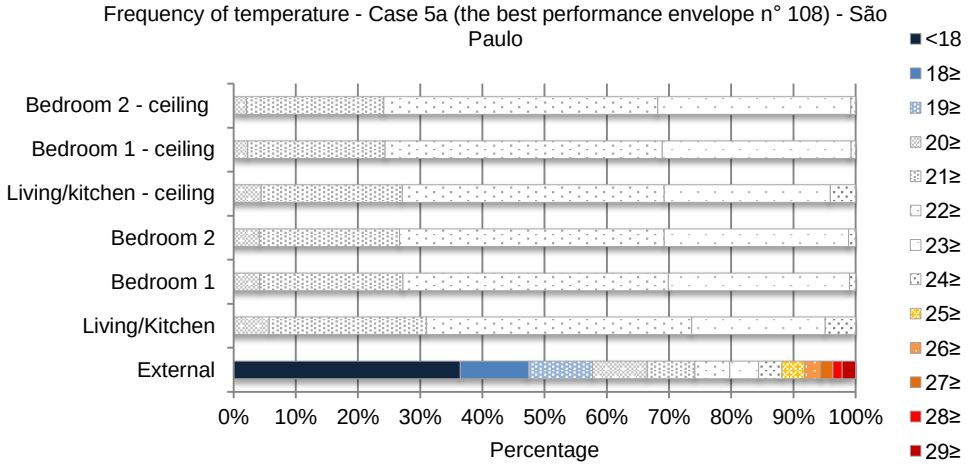


Figure 5-44: Frequency of temperature, Case 5a, São Paulo

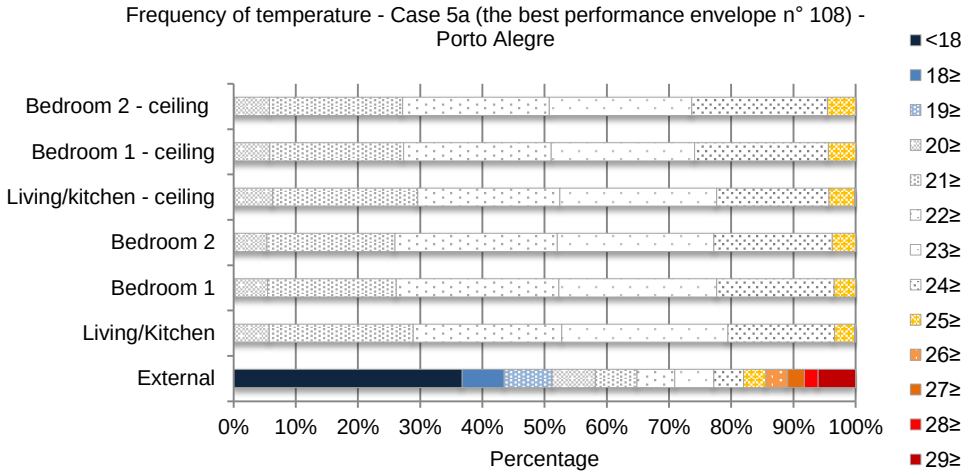


Figure 5-45: Frequency of temperature, Case 5a, Porto Alegre

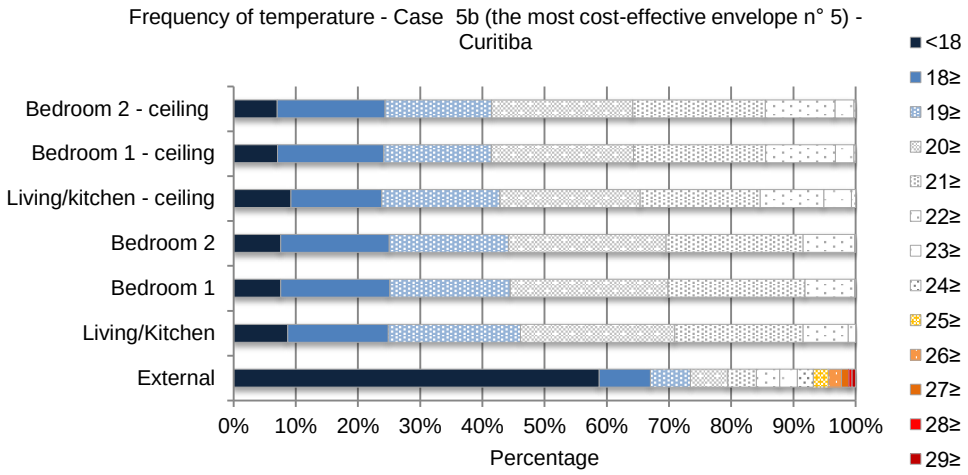


Figure 5-46: Frequency of temperature, Case 5b, Curitiba

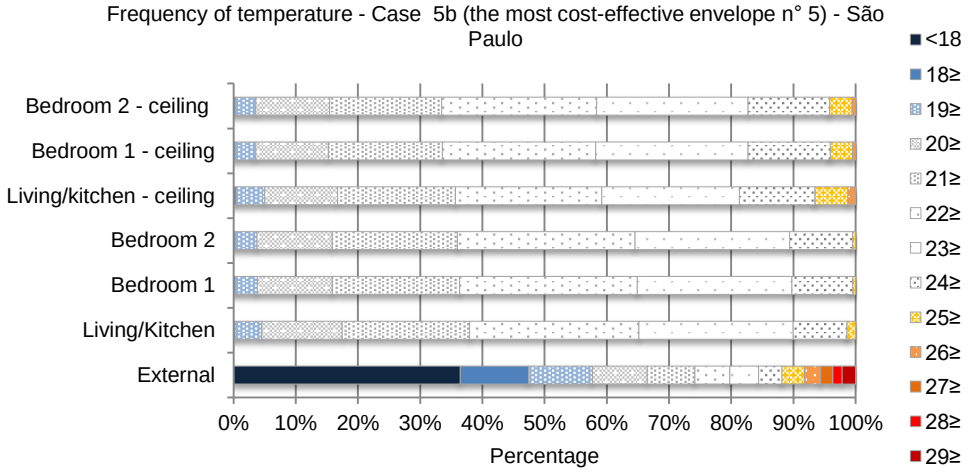


Figure 5-47: Frequency of temperature, Case 5b, São Paulo

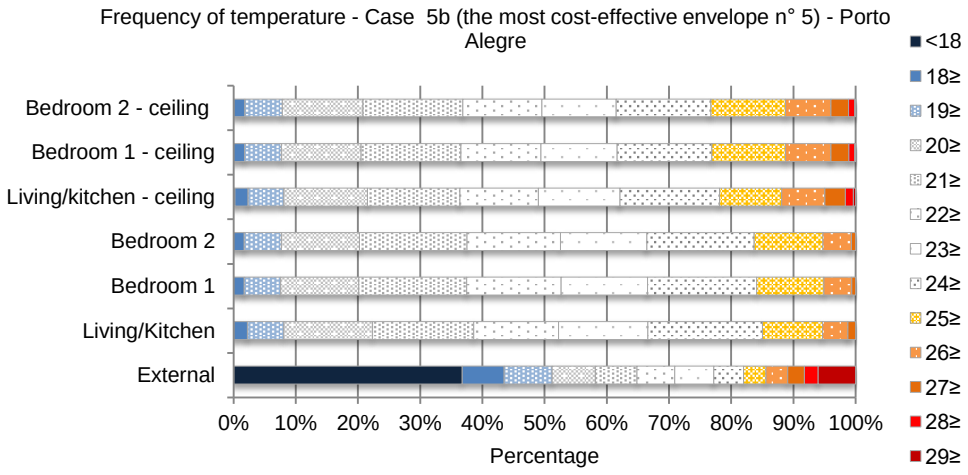
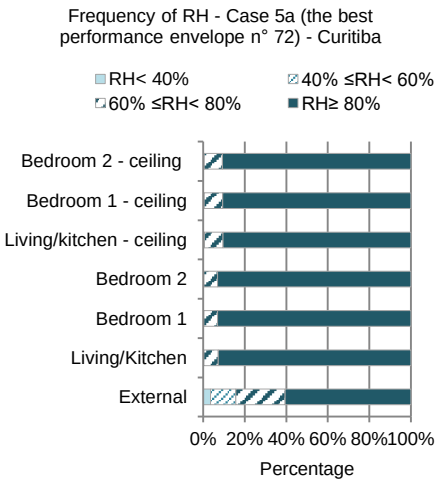


Figure 5-48: Frequency of temperature, Case 5b, Porto Alegre



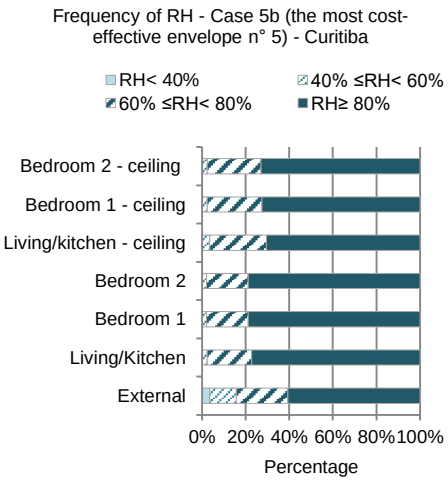
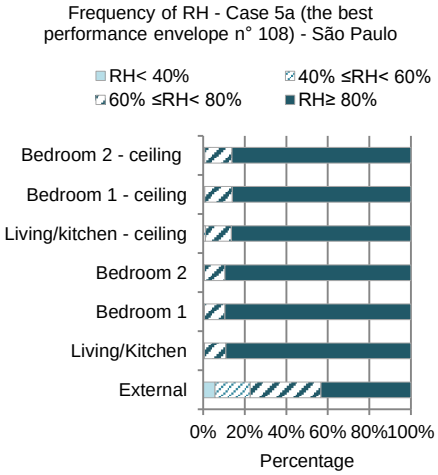


Figure 5-49: Frequency of relative humidity, Case 5a and 5b, Curitiba



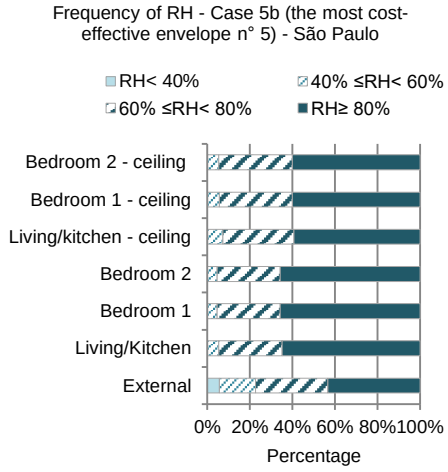
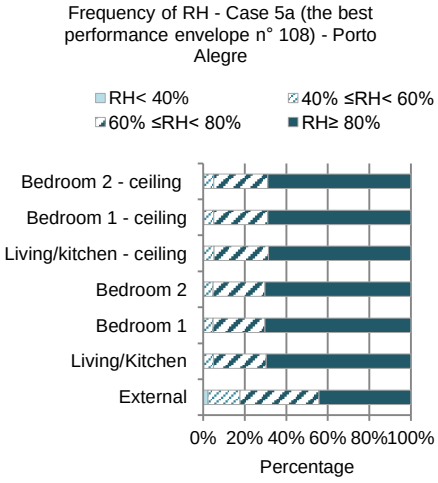


Figure 5-50: Frequency of relative humidity, Case 5a and 5b, São Paulo



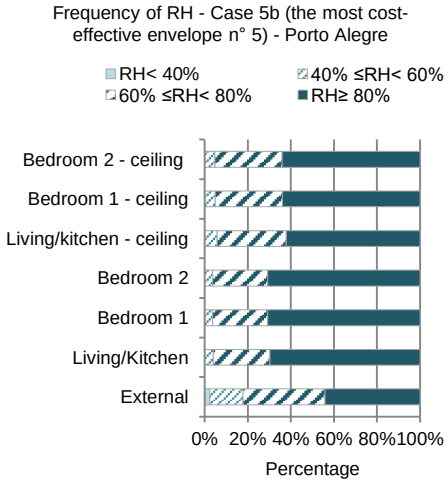


Figure 5-51: Frequency of relative humidity, Case 5a and 5b, Porto Alegre

Case 6 considered the adoption of insulated and airtight envelope scenarios under a regime of selective natural ventilation.

Case 6a adopted the best performance envelopes n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, as shown in Figure 5-52, Figure 5-53 and Figure 5-54, respectively. In Curitiba, the indoor thermal comfort condition remained constant when compared to Case 5a. In São Paulo, the use of natural ventilation slightly reduced the frequency of indoor temperatures in the range between 23 °C and 24 °C and, conversely, it increased the frequency to around 22 °C. In Porto Alegre, the use of natural ventilation reduced the indoor temperatures above 25 °C for 2% of the time at occupant level and it was 1% of the time lower than in Case 5a. The use of natural ventilation mostly reduced the frequency of indoor temperatures in the range between 24 °C and 25 °C and, conversely, it increased the frequency in the range between 22 °C and 23 °C.

Similarly, Case 6b adopted the most cost-effective envelope n° 5 in all the cites investigated and the results are shown in Figure 5-55, Figure 5-56 and Figure 5-57. In Curitiba, the indoor thermal comfort condition also remained constant when compared to Case 5b. In São Paulo, the indoor temperatures above 25 °C were reduced to no more than 1% of the time in the living areas and to negligible levels in the bedrooms at occupant level. The frequency of temperatures around 24 °C were reduced to about half when compared to Case 5b and, conversely, the frequency of temperatures in the range between 22 °C and 23 °C were increased. In Porto Alegre, the indoor temperatures above 25 °C were reduced for up to 9% of the year at occupant level, which resulted in an increase of the narrow thermal comfort zone by more than 5% of the year when compared to Case 5b.

Figure 5-58, Figure 5-59 and Figure 5-60 show the relative humidity levels in Curitiba, São Paulo and Porto Alegre, respectively. The adoption of natural ventilation in Case 6 removed a certain amount of moisture from the building. However, as the ventilation was used as a function of indoor temperatures, this benefit was only observed in São Paulo and Porto Alegre. Curitiba did not use natural ventilation in the same way as the other cities due to its low temperatures and, therefore, the levels of relative humidity, remained the same as in Case 5. In São Paulo and Porto Alegre, the occupied areas had the relative humidity levels above 80% reduced to 80% and 50% of the time for the best performance envelope n° 108 (Case 6a) and to 51% and 48% of the time for the most cost-effective performance n° 5 (Case 6b), respectively. This meant that the relative humidity levels above 80% were reduced by 11% and 28% in Case 6a and by 23% and 31% in Case 6b in São Paulo and Porto Alegre when compared to Case 5a and 5b, respectively.

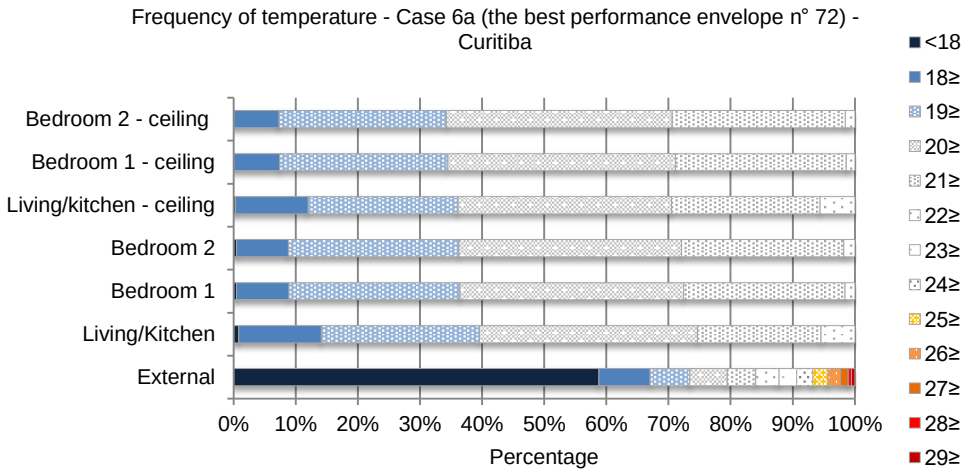


Figure 5-52: Frequency of temperature, Case 6a, Curitiba

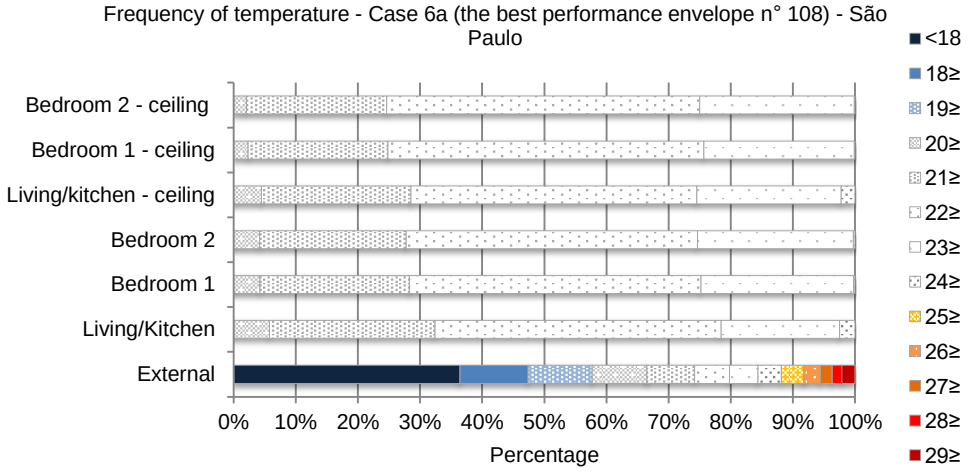


Figure 5-53: Frequency of temperature, Case 6a, São Paulo

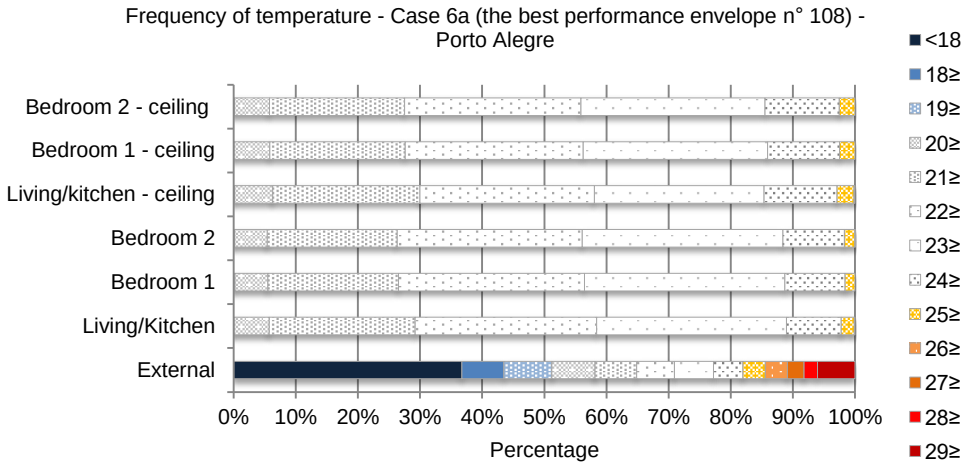


Figure 5-54: Frequency of temperature, Case 6a, Porto Alegre

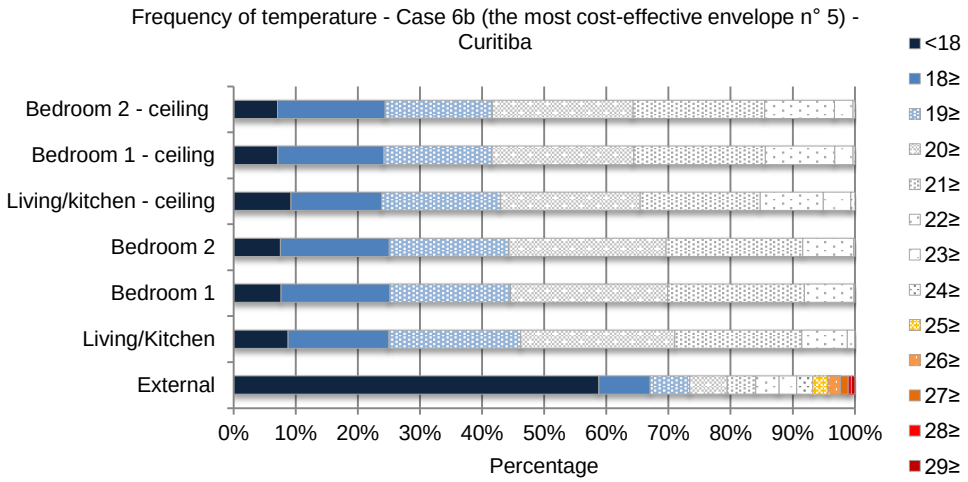


Figure 5-55: Frequency of temperature, Case 6b, Curitiba

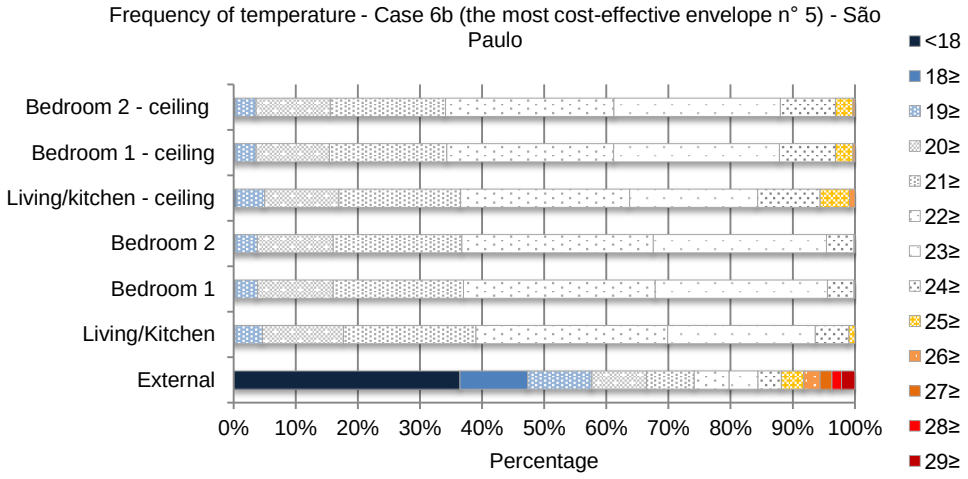


Figure 5-56: Frequency of temperature, Case 6b, São Paulo

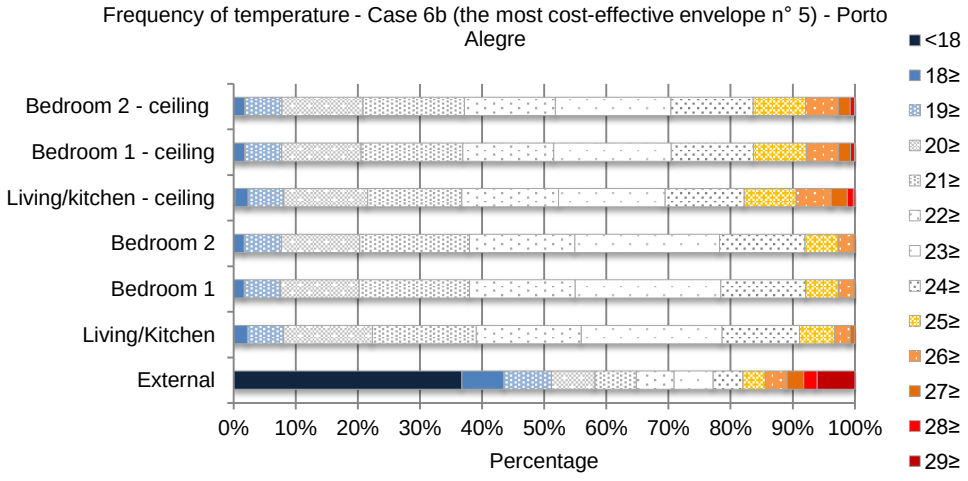


Figure 5-57: Frequency of temperature, Case 6b, Porto Alegre

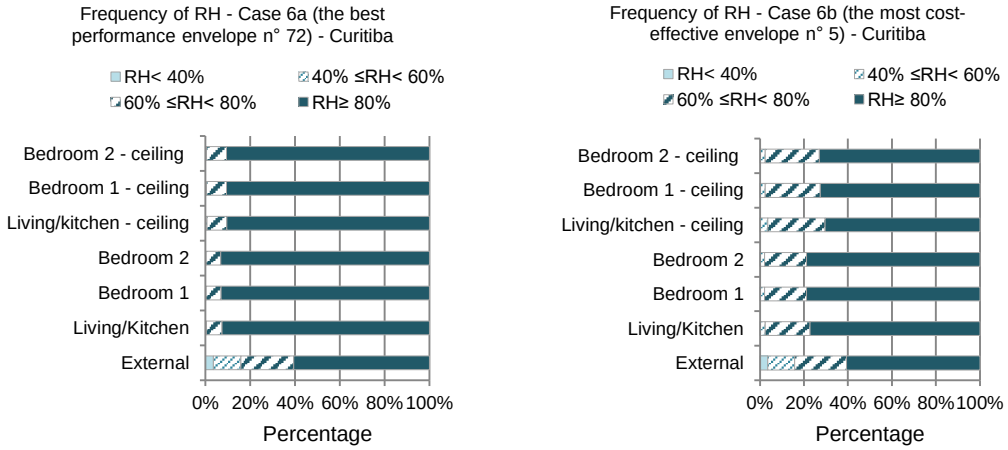


Figure 5-58: Frequency of relative humidity, Case 6a and 6b, Curitiba

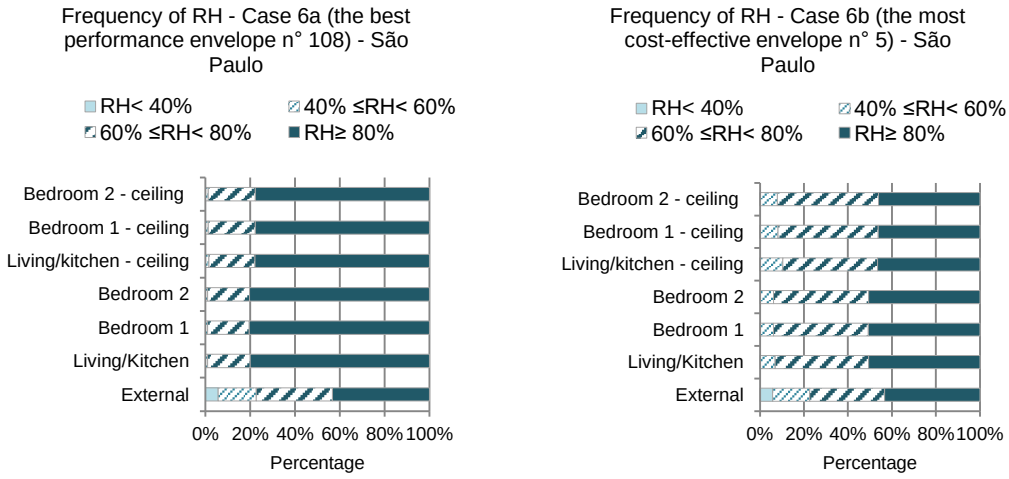


Figure 5-59: Frequency of relative humidity, Case 6a and 6b, São Paulo

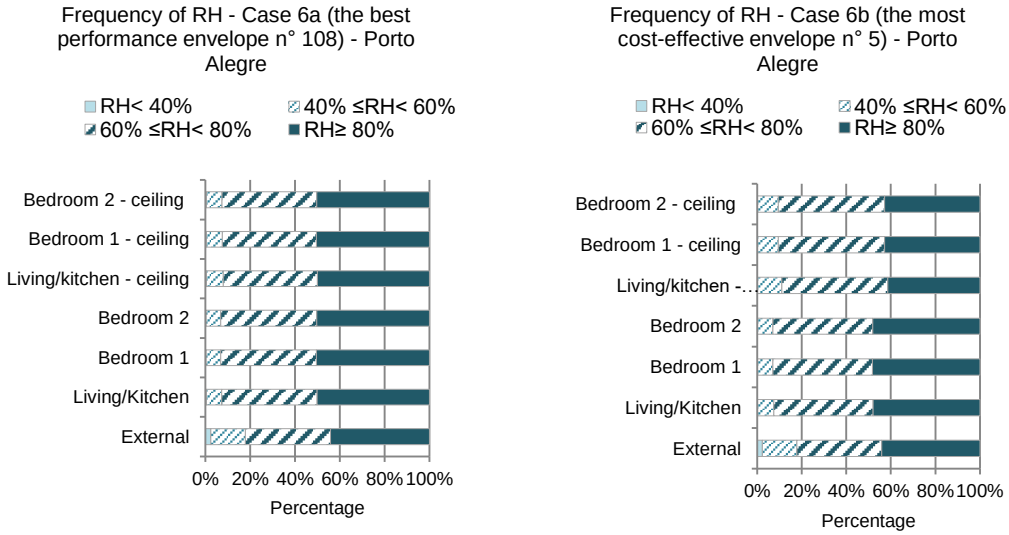


Figure 5-60: Frequency of relative humidity, Case 6a and 6b, Porto Alegre

Table 5-9 shows the thermal comfort percentages achieved for each case investigated.

Table 5-9: Thermal comfort percentage in a year, all cases – Curitiba, São Paulo and Porto Alegre

Thermal comfort – 20-25 °C							
Curitiba	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	30.0%	30.0%	43.0%	42.0%	42.0%	60.0%	60.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				42.0%	42.0%	54.0%	54.0%
São Paulo	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	57.0%	57.0%	65.0%	88.0%	88.0%	100.0%	100.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				81.0%	81.2%	94.0%	94.4%
Porto Alegre	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	45.0%	45.0%	45.0%	79.0%	80.0%	96.5%	97.7%
				Case 3b	Case 4b	Case 5b	Case 6b
				63.0%	66.0%	77.0%	83.0%
Thermal comfort – 18-29 °C							
Curitiba	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	56.0%	56.0%	70.0%	82.0%	82.0%	99.0%	99.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				77.0%	77.0%	91.0%	91.0%
São Paulo	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	86.0%	86.0%	93.0%	100.0%	100.0%	100.0%	100.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				99.0%	99.0%	100.0%	100.0%
Porto Alegre	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	81.0%	81.0%	87.0%	99.0%	99.0%	100.0%	100.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				96.0%	96.0%	100.0%	100.0%

Base Case: as built + unoccupied; Case 1: Base Case + shading; Case 2: Case 1 + internal gains; Case 3: Case 2 + increase of insulation; Case 4: Case 3 + ventilation; Case 5: Case 3 + reduction of infiltration; Case 6: Case 5 + ventilation.

Figure 5-61, Figure 5-62 and Figure 5-63 compare the heating degree-hours for the base temperature of 18 °C, whereas Figure 5-64, Figure 5-65 and Figure 5-66 compare the heating degree-hours for the base temperature of 20 °C in Curitiba, São Paulo and Porto Alegre, respectively. As the Figures show, the different envelope optimisation scenarios (‘a’ and ‘b’) were comparatively analysed side by side. The aim of the degree-hour analysis was to show the effect of each of those strategies investigated on the temperature’s magnitude. The heating demand was mostly reduced by the internal gains in Case 2, the optimisation of the envelope in Case 3 and the reduction of infiltration in Case 5.

In Curitiba, the adoption of an insulated and airtight envelope was extremely beneficial from the temperature point of view, as it significantly reduced the magnitude of the temperatures below the lower thermal comfort limit. For the base temperature of 18 °C, the heating degree-hours of the typical MCMV House envelope in Case 2 (in use) corresponded to 4000 degree-hours. The use of an insulated envelope at a standard infiltration rate in Case 3 reduced the degree-hours to up to 900 in scenario 3a (envelope n° 72) and to up to 1900 in scenario 3b (envelope n° 5), which corresponded to a reduction in degree-hours by more than 77% and 52% relative to Case 2,

respectively. Considering the insulated and airtight envelope in Case 5, the degree-hours were reduced to negligible levels in scenario 5a (envelope n° 72) and to about 300 degree-hours in scenario 5b (envelope n° 5), which meant a reduction of degree-hours by 100% and by more than 92% relative to Case 2.

In São Paulo and Porto Alegre, the degree-hours were also reduced considerably for the base temperature of 18 °C. The heating degree-hours of the typical MCMV House envelope in Case 2 corresponded to approximately 500 degree-hours and 1400 degree-hours, respectively. In São Paulo, any of the changes adopted were able to mitigate the heating demand. In Porto Alegre, with the adoption of an insulated envelope at a standard infiltration rate in Case 3, the degree-hours were reduced to negligible levels in scenario 3a (envelope n° 108) and to about 200 degree-hours in scenario 3b (envelope n° 5). For the insulated and airtight envelope in Case 5a and 5b, the degree-hours were also reduced to negligible levels.

Similarly, in Curitiba, for the base temperature of 20 °C, the typical MCMV House envelope in Case 2 corresponded to 12000 degree-hours. The use of an insulated envelope at a standard infiltration rate in Case 3 reduced to 7000 degree-hours in scenario 3a (envelope n° 72) and to more than 8000 degree-hours in scenario 3b (envelope n° 5), which meant a reduction of degree-hours by more than 42% and 33% when compared to Case 2, respectively. With the insulated and airtight envelope in Case 5, the degree-hours were reduced to more than 2000 and to almost 5000 degree-hours for scenarios 5a and 5b, respectively. This meant that the degree-hours were reduced by more than 83% and 58% when compared to Case 2, respectively.

In São Paulo, the typical MCMV House in Case 2 had the heating degree-hours reduced from 3000 degree-hours to up to 500 degree-hours in Case 3a (envelope n° 108) and to up to 1200 degree-hours in Case 3b (envelope n° 5), which meant a reduction of the degree-hours by 83% and 60%, respectively. Considering the insulated and airtight envelope, the degree-hours were reduced to negligible levels in Case 5a (envelope n° 108) and to up to 150 degree-hours in Case 5b (envelope n° 5) and this corresponded to a reduction of the degree-hours by 100% and 95% when compared to Case 2, respectively.

In Porto Alegre, the heating degree-hours for the base temperature of 20 °C was reduced from 5000 degree-hours in Case 2 to 1000 degree-hours in Case 3a (envelope n° 108) and to 2200 degree-hours in Case 3b (envelope n° 5). This represented a reduction of degree-hours by more than 80% and 66% relative to Case 2, respectively. Considering the insulated and airtight envelope, the degree-hours were reduced to up to negligible levels in Case 5a (envelope n° 72) and to up to 500 degree-hours in Case 5b (envelope n° 5) and this represented a reduction of the degree-hours by 100% and 90% when compared to Case 2, respectively.

Figure 5-67, Figure 5-68 and Figure 5-69 reveal the cooling degree-hours for the base temperature of 25 °C in Curitiba, São Paulo and Porto Alegre, respectively. Figure 5-70 illustrates the cooling degree-hours for the base temperature of 29 °C only in Porto Alegre, as this was negligible in the other cities. The different envelope optimisation scenarios (‘a’ and ‘b’) were also comparatively analysed side by side.

In Curitiba, for the base temperature of 25 °C, the cooling degree-hours of the typical MCMV House envelope in Case 2 corresponded to up to 40 degree-hours and they were fully mitigated in any of the cases of the envelope optimisation.

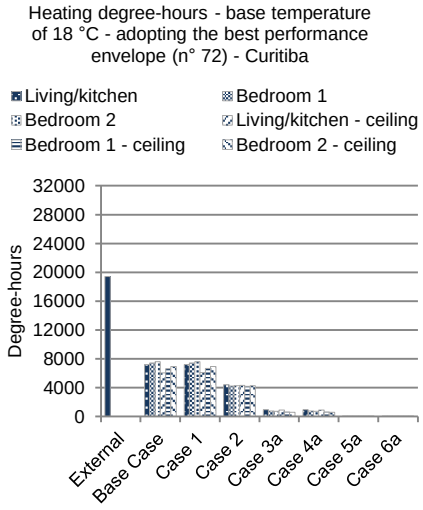
In São Paulo, the cooling degree-hours of the typical MCMV House envelope in Case 2 corresponded to up to 800 degree-hours. The degree-hours were reduced to negligible levels in Case 3a (envelope n° 108) and to less than 100 degree-hours in Case 3b (envelope n° 5). Considering the insulated and airtight envelope, the degree-hours were reduced to negligible levels in both scenarios of Case 5.

Porto Alegre had by far the most cooling degree-hours when compared to the other cities. For the base temperature of 25 °C, the cooling degree-hours of the typical MCMV House envelope in Case 2 at occupant level corresponded to 3500 degree-hours. The degree-hours were reduced to 250 degree-hours in Case 3a (envelope n° 108) and to 1100 degree-hours in Case 3b (envelope n° 5). This meant a reduction of the cooling degree-hours by 93% and 69% relative to Case 2, respectively. For the insulated and airtight envelope in Case 5, the degree-hours were reduced to about 100 degree-hours for scenario 5a and remained constant at 1100 degree-hours for scenario 5b, which corresponded to a reduction of the degree-hours by 97% and 69% when compared to Case 2, respectively.

For the base temperature of 29 °C, at both occupant and ceiling levels, the cooling degree-hours in Porto Alegre were reduced from 10 degree-hours to negligible levels for all the cases and scenarios investigated.

It should be noted that the temperatures at occupant and ceiling level were very distinct between each other for the cooling degree-hours, differently from the heating degree-hours in which the temperatures were more uniform between the house’s levels. The temperatures at ceiling level were much higher than at occupant level and, consequently, the cooling degree-hours were as well.

In particular, the living room/kitchen area had both higher cooling and heating degree-hours than the bedrooms. The main cause for that may be linked to the large size of this area that is more difficult to keep warm in winter and also to the high internal gains and solar orientation that contribute to higher temperatures in summer.



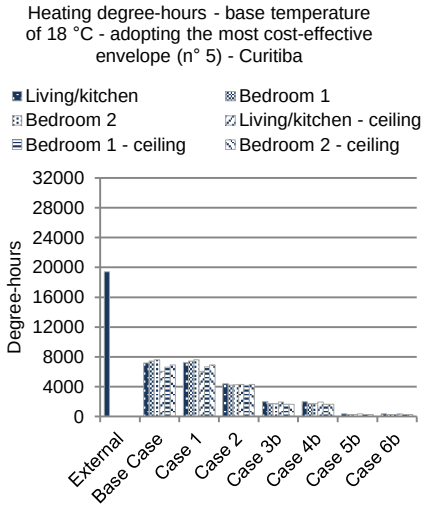
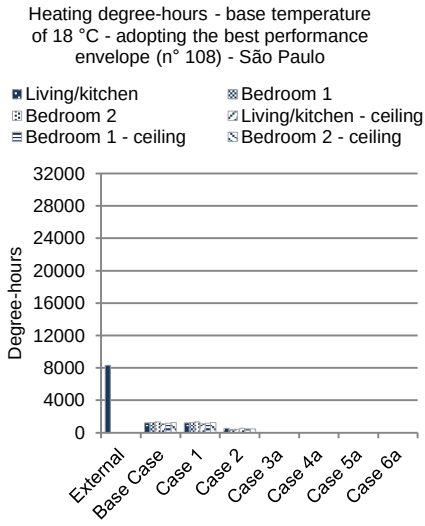


Figure 5-61: Comparison of heating degree-hours, base temperature of 18 °C, all cases, Curitiba



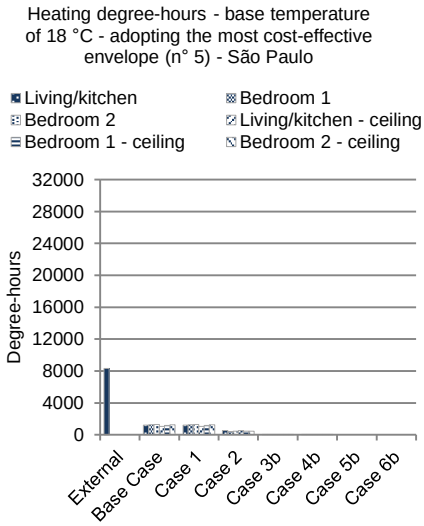
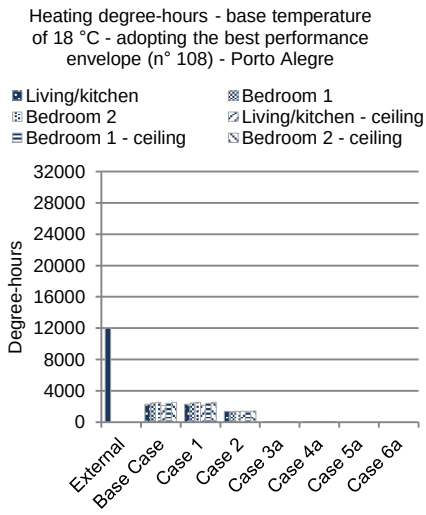


Figure 5-62: Comparison of heating degree-hours, base temperature of 18 °C, all cases, São Paulo



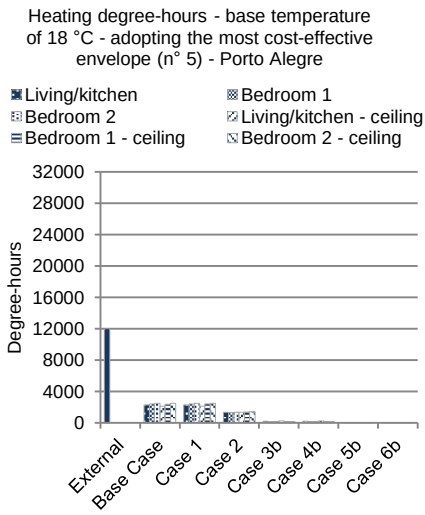
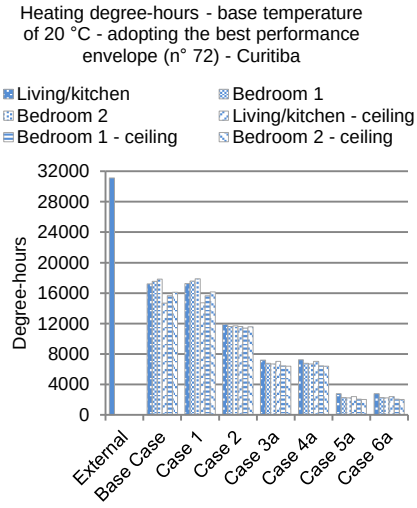


Figure 5-63: Comparison of heating degree-hours, base temperature of 18 °C, all cases,Porto Alegre



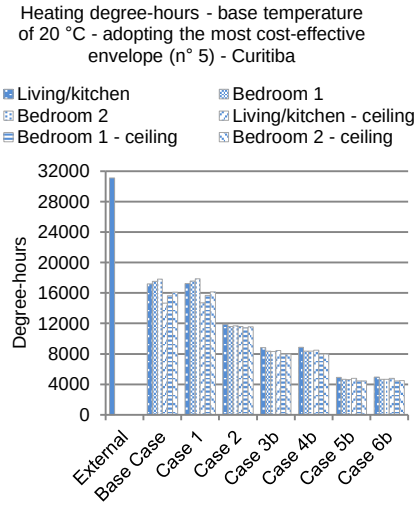
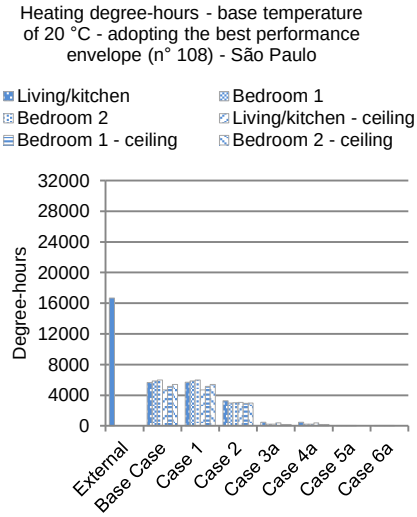


Figure 5-64: Comparison of heating degree-hours, base temperature of 20 °C, all cases, Curitiba



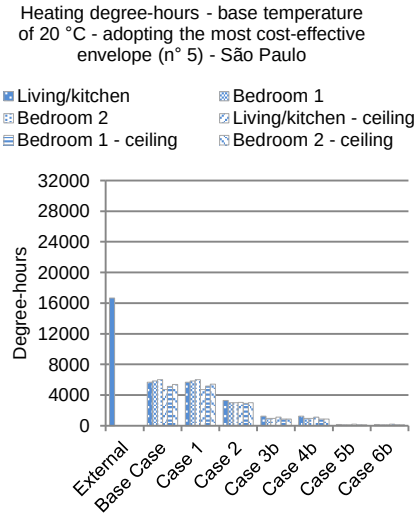
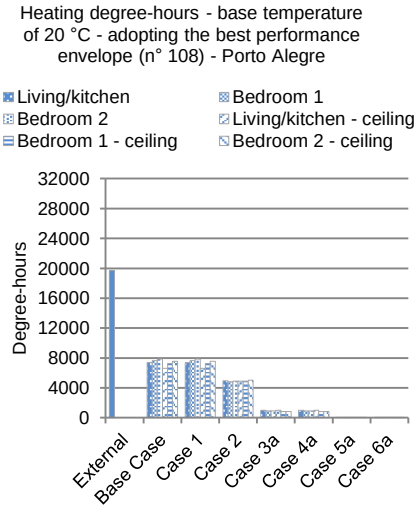


Figure 5-65: Comparison of heating degree-hours, base temperature of 20 °C, all cases, São Paulo



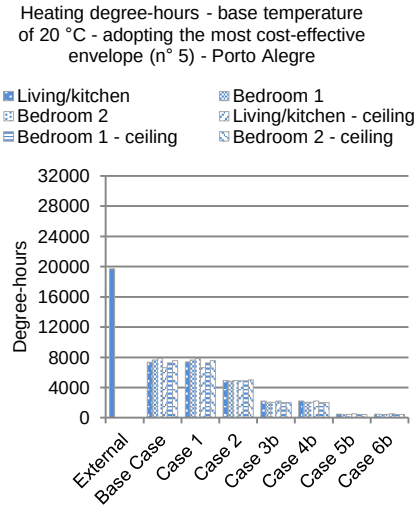


Figure 5-66:Comparison of heating degree-hours, base temperature of 20 °C, all cases,Porto Alegre

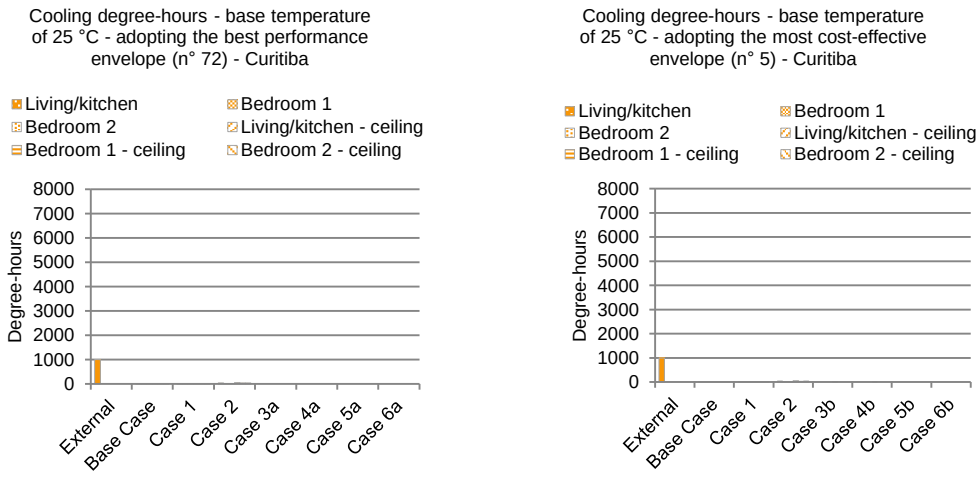


Figure 5-67: Comparison of cooling degree-hours, base temperature of 25 °C, all cases, Curitiba

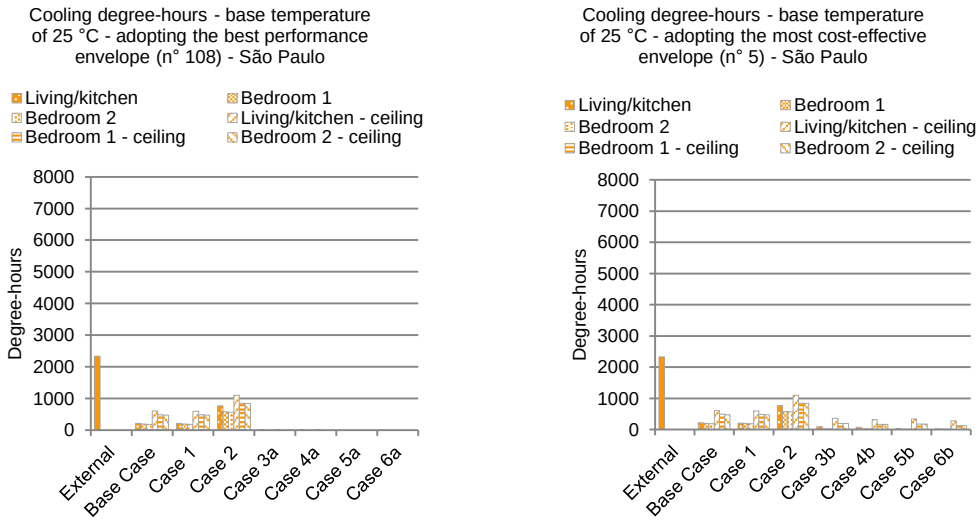


Figure 5-68: Comparison of cooling degree-hours, base temperature of 25 °C, all cases, São Paulo

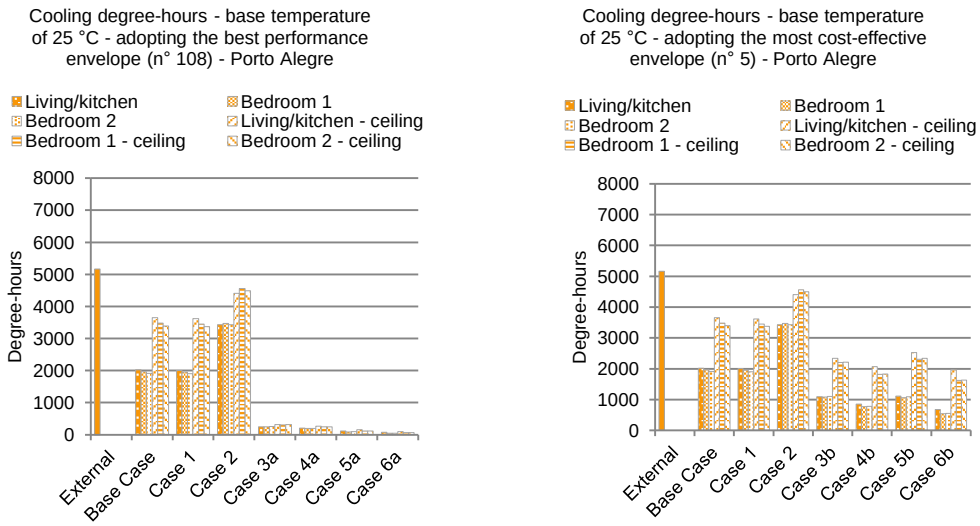


Figure 5-69: Comparison of cooling degree-hours, base temperature of 25 °C, all cases, Porto Alegre

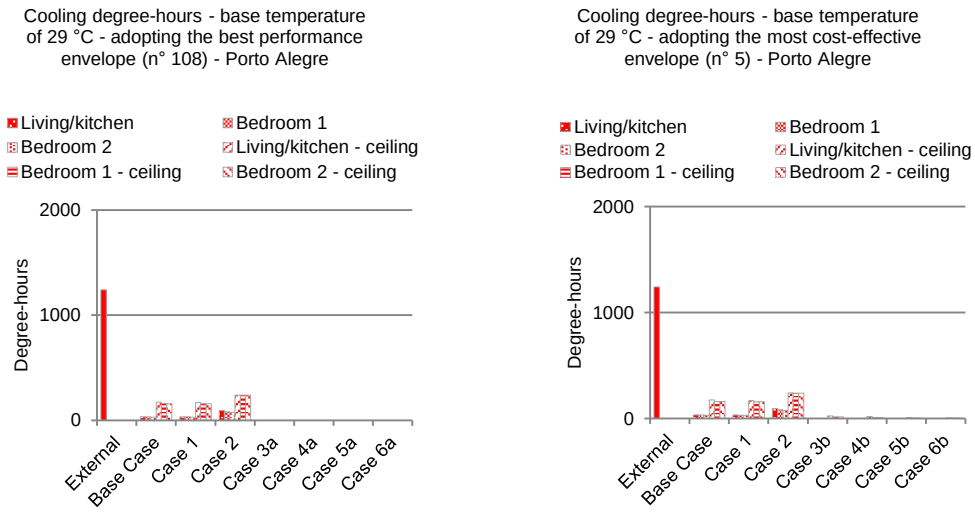


Figure 5-70: Comparison of cooling degree-hours, base temperature of 29 °C, Porto Alegre

Figure 5-71, Figure 5-72 and Figure 5-73 show the peak temperatures for all cases, in Curitiba, São Paulo and Porto Alegre, respectively.

The living room/ kitchen was the room that had the highest peak temperatures due to it solar orientation and the amount of internal gains when compared to the bedrooms. The ceiling level also had the highest peak temperatures when compared to the occupant level and this was more evident in Porto Alegre, where the level's peak temperature difference almost reached a difference of 2 K.

In Curitiba, the occupied areas of the house in Case 2 (in use) had the maximum temperature of 27.17 °C in the living room/ kitchen. In the scenario of Case 3a (the best performance envelope n° 72) and Case 3b (the most cost-effective envelope n° 5) the indoor peak temperature was reduced by 3.5 K and 2.5 K when compared to Case 2, respectively. In the scenario of Case 5a and Case 5b, with a limited infiltration rate of 0.15 ach, the adoption of the best performance and the most cost-effective envelopes both had the indoor peak temperatures 0.7 K lower than in Case 3a and Case 3b, respectively.

In São Paulo, the occupied areas of the house in Case 2 had the peak temperature of 28.59 °C also in the living room/ kitchen. In the scenario of Case 3a (the best performance envelope n° 108) and Case 3b (the most cost-effective envelope n° 5) the indoor peak temperature was reduced by about 3.3 K and 2.1 K when compared to Case 2, respectively. In the scenario of Case 5a and Case 5b, in which the infiltration was reduced, the adoption of the best performance and the most cost-effective

envelopes had the indoor peak temperatures reduced by 3.7 K and 2.7 K relative to Case 2, which corresponded to less than 1 K lower than in Case 3, respectively.

In Porto Alegre, the occupied areas of the house in Case 2 had the peak temperature of 31.14 °C in the living room/ kitchen. In the scenario of Case 3a (the best performance envelope n° 108) and Case 3b (the most cost-effective envelope n° 5) the indoor peak temperature was reduced by about 4.1 K and 2.5 K when compared to Case 2, respectively. In the scenario of Case 5a and Case 5b, in which the infiltration was limited, the adoption of the best performance and the most cost-effective envelopes both had the indoor peak temperatures 0.7 K lower than Case 3a and Case 3b, respectively.

Case 7 and 8 considered the MCMV House as fully space conditioned in order to keep the ideal indoor thermal comfort levels (20-25 °C). The results suggested the estimated energy demand for space conditioning and were expressed in kWh/m^2. Specifically, Case 7 assumed the optimised envelope at a standard infiltration rate of 1 ach. Case 8 adopted the optimised envelope at a limited infiltration rate of 0.15 ach. It should be highlighted that Case 7 and 8 were analysed for both scenario 'a' and 'b', which comprised the adoption of the best performance envelope (n° 72 or n° 108) and the most cost-effective envelope (n° 5).

Case 7 and 8 are shown comparatively in Figure 5-74, Figure 5-75 and Figure 5-76 against the energy demand of the typical MCMV house in use for Curitiba, São Paulo and Porto Alegre, respectively. The breakdown of energy demand in each of those cases can be found in Appendix B.

In Curitiba, the typical MCMV House in use had an annual energy demand estimated to be 40.61 kWh/m^2. In scenario 'a', with the adoption of the best performance envelope n° 72 in Case 7a, the energy demand was reduced to 15.66 kWh/m^2. Then, with the limited infiltration rate in Case 8a, the energy demand was reduced to 5.09 kWh/m^2. In scenario 'b', with the adoption of the most cost-effective envelope n° 5 in Case 7b, the energy demand was reduced to 21.74 kWh/m^2. Then, with the limited infiltration rate in Case 8b, the energy demand was reduced to 10.31 kWh/m^2. Comparatively, this meant that the best performance envelope n° 72 and the most cost-effective envelope n° 5 with the standard infiltration rate (Case 7a and 7b) reduced the annual energy demand by 61.4% and 46.4% when compared to the typical MCMV House, respectively. The greatest reduction of the annual energy demand was achieved by the best performance envelope n° 72 and the most cost-effective envelope n° 5 with limited infiltration rate (Case 8a and 8b), which had a reduction by 87.5% and 74.6% in comparison to the typical MCMV House.

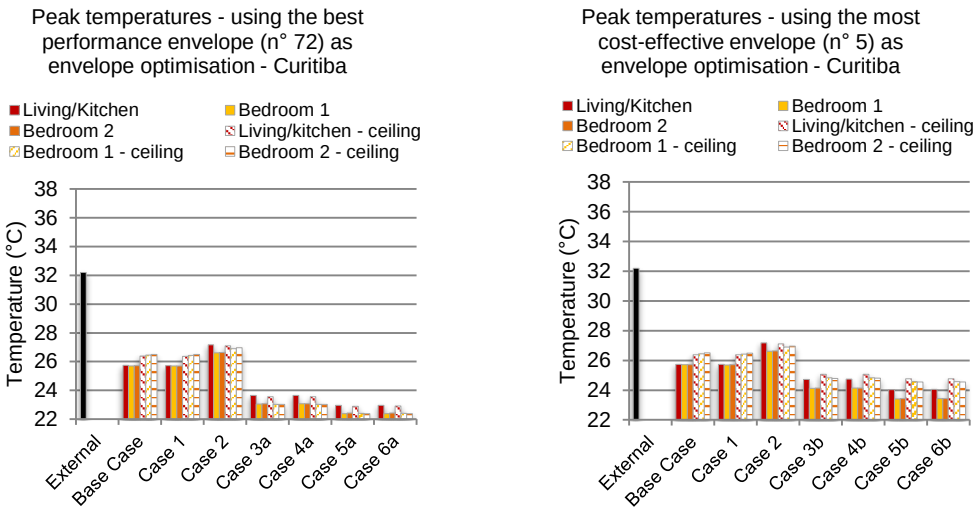


Figure 5-71: Comparison of peak temperatures, all cases, Curitiba

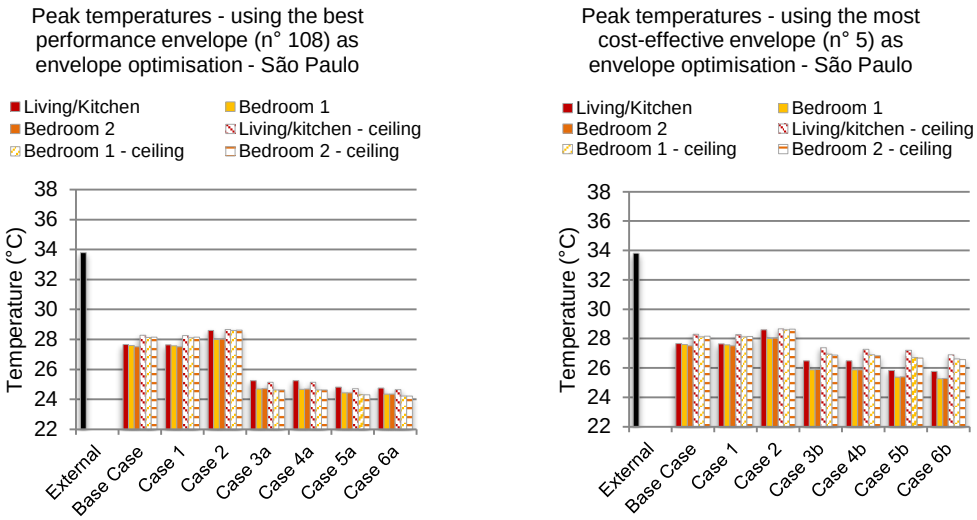


Figure 5-72: Comparison of peak temperatures, all cases, São Paulo

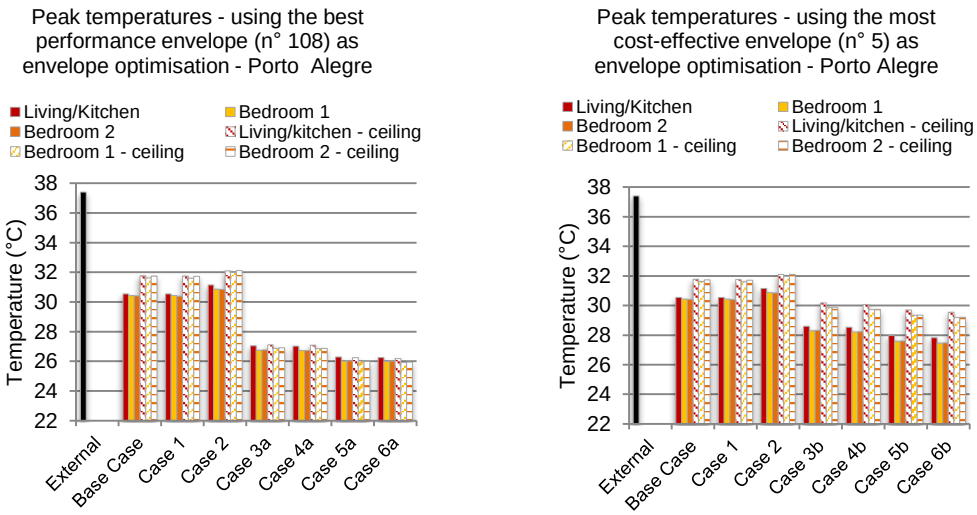


Figure 5-73: Comparison of peak temperatures, all cases, Porto Alegre

In São Paulo, the annual energy demand of the typical MCMV House in use was very low when compared to the other cities, equivalent to 14.31 kWh/m^2. In scenario 'a', with the adoption of the best performance envelope n° 108 in Case 7a, the energy demand was reduced to 1.24 kWh/m^2. Then, with limited infiltration rate in Case 8a, the energy demand was reduced to negligible levels. In scenario 'b', with the adoption of the most cost-effective envelope n° 5 in Case 7b, the energy demand was reduced to 3.83 kWh/m^2. Then, with limited infiltration rate in Case 8b, the energy demand was reduced to 0.82 kWh/m^2. When compared to the typical MCMV House, the annual energy demand of the best performance envelope n° 108 and the most cost-effective envelope n° 5 with standard infiltration rate (Case 7a and 7b) was reduced by 91.3% and 73.2%, respectively. Considering the same envelopes with limited infiltration rate (Case 8a and 8b), the annual energy demand was reduced by 100% and 94.3% relative to the typical MCMV House energy demand, respectively. These results appear to suggest that in São Paulo very small building envelope optimisation could ensure very low annual energy demand closer to negligible levels, which supports that super-insulated and airtight envelopes are not suitable in a cost-effective way in this city.

In Porto Alegre, the annual energy demand of the MCMV House in use corresponded to 30.88 kWh/m^2. The envelope optimisation in scenario 'a', which comprised the best performance envelope n° 108 at standard infiltration rate (Case 7a), greatly reduced the annual energy demand to 3.80 kWh/m^2. Then, with limited infiltration (Case 8a), the energy demand would be reduced to almost negligible levels. The optimisation in scenario 'b' was also meaningful, the most cost-effective envelope n° 5 at standard infiltration rate (Case 7b) reduced the energy demand to 11.03 kWh/m^2. Then, with the limited infiltration rate (Case 8b), the annual energy demand was reduced to 5.32 kWh/m^2. This represented a reduction by 87.7% and 64.3% for adopting the best performance envelope n° 108 and the most cost-effective envelope n° 5 with standard infiltration rate (Case 7a and 7b) when compared to the typical MCMV House energy demand in use, respectively. An energy demand reduction by 98.6% and 82.8% would be achieved by adopting the optimised envelopes n° 108 and n° 5 with a limited infiltration rate (Case 8a and 8b) when compared to the typical MCMV House in use, respectively.

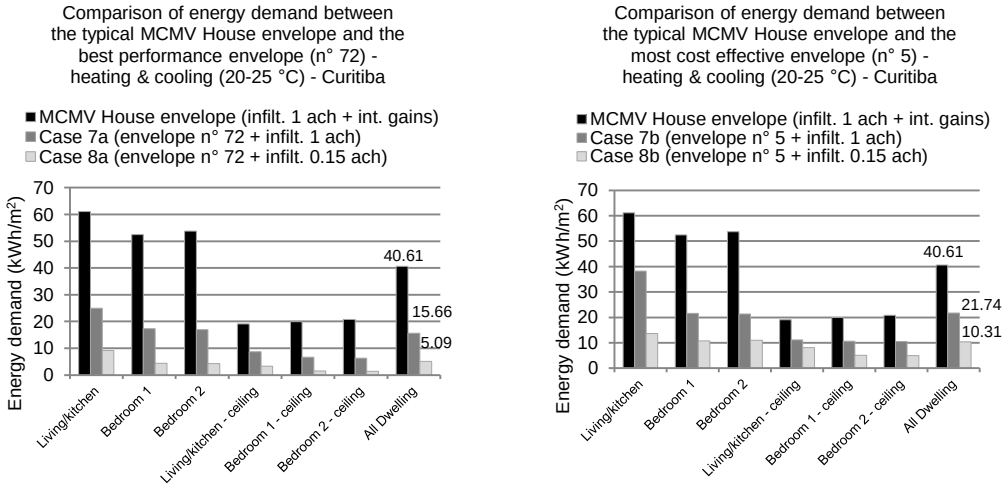


Figure 5-74: Comparison of annual energy demand, Case 7a, 7b, 8a and 8b, Curitiba

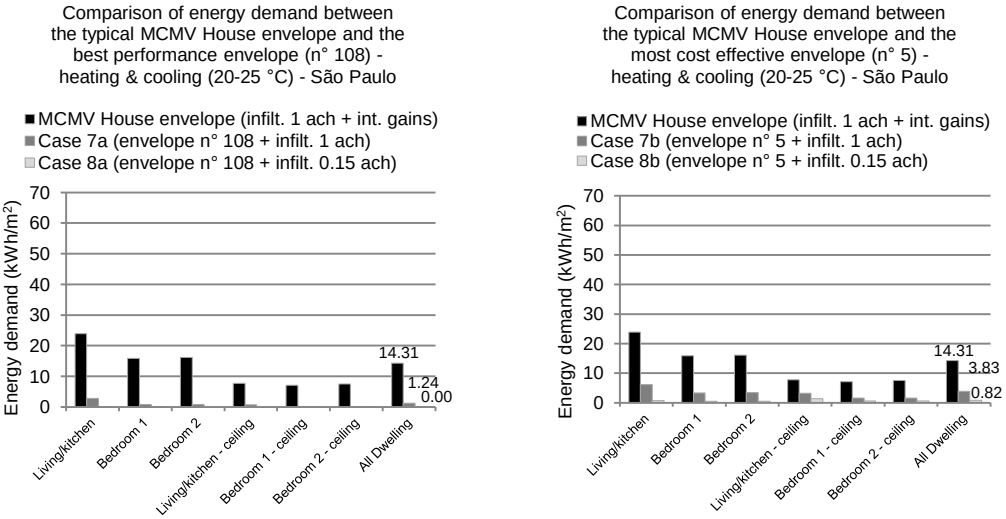


Figure 5-75: Comparison of annual energy demand, Case 7a, 7b, 8a and 8b, São Paulo

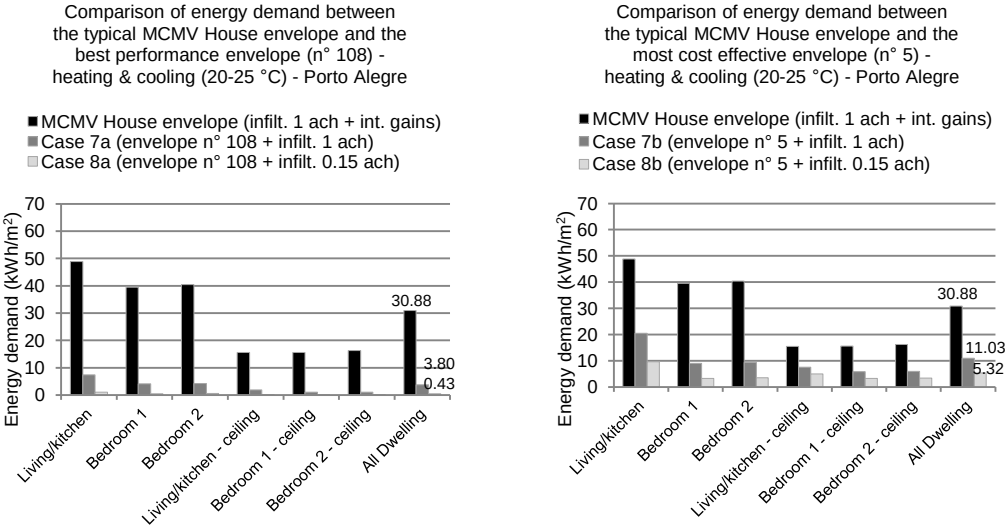


Figure 5-76: Comparison of annual energy demand, Case 7a, 7b, 8a and 8b, Porto Alegre

As both the best performance envelope and the most cost-effective envelope showed an improvement in the thermal comfort conditions and a reduction of their potential annual energy demands, a running cost evaluation was conducted in order to make an informed decision about the cost-effectiveness of the envelopes investigated.

Table 5-10 shows the running cost evaluation for all the envelopes investigated. The running costs of the house were calculated for a 1-year period and also for a 50-year period considering both scenarios with and without the inflation impact. A 50-year period was taken into account because this is considered as being the lifespan of a house (ABNT, 2013a, p. 53). The annual inflation index was considered at 6%, which was found to be an average value in Brazil in the last few years (Banco Central do Brasil, 2014a), as shown in Chapter 2.

The results suggested that the typical MCMV House envelope had running costs much higher than any optimised envelope investigated in the present research, based on a 50-year period with the impact of inflation on the energy tariffs. The best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre (Case 7a) had running costs 2.6, 11.5 and 8.1 times smaller than the typical MCMV House envelope for delivering the same levels of thermal comfort, respectively. The most cost-effective envelope n° 5 (Case 7b) had running costs slightly higher than the best performance envelopes but they were 1.9, 3.7 and 2.8 times smaller than the typical MCMV House envelope in Curitiba, São Paulo and Porto Alegre, respectively.

The running costs were reduced even more for a limited infiltration rate. In this context, the best performance envelope (Case 8a) had running costs 8 times smaller than the typical MCMV House envelope in Curitiba and the energy costs were negligible and very low in São Paulo and Porto Alegre, respectively. For the most cost-effective envelope (Case 8b), the running costs were 3.9, 17.5 and 5.8 times smaller when compared to the typical MCMV House envelope in the cities, respectively.

The next section investigates in detail the costs for constructing an optimised envelope which is compared against the typical MCMV House envelope and then the payback period is established in order to show the cost-effectiveness of the MCMV optimisation solutions for the cities investigated.

Table 5-10: Estimated running costs of the MCMV House according to the envelope type and infiltration rate - Curitiba, São Paulo and Porto Alegre

		Energy demand & costs	Curitiba	São Paulo	Porto Alegre
		Cost of kWh/m², in Brazilian reais (R$)	0.74592	0.50305	0.63570
		Cost of kWh/m², in US dollars (US$)	0.24536	0.16547	0.20911
Case 7a envelope n° 72 or 108 infiltration 1 ach	R$	Energy demand (kWh/m²)	15.66	1.24	3.80
		Cost per m² per annum (R$/m²a)	11.68	0.92	2.83
		Estimated cost for 1-year (R$)	426.59	33.78	103.52
		Estimated cost for 50-year (R$)	21,329.70	1,688.94	5,175.79
		Estimated cost for 50-year (R$), with inflation of 6% per year	123,855.57	9,807.21	30,054.35
	US$	Energy demand (kWh/m²)	15.66	1.24	3.80
		Cost per m² per annum (US$/m²a)	3.84	0.30	0.93
		Estimated cost for 1-year (US$)	140.33	11.11	34.05
		Estimated cost for 50-year (US$)	7,016.35	555.57	1,702.56
		Estimated cost for 50-year (US$), with inflation of 6% per year	40,741.96	3,226.06	9,886.30
Case 7b envelope n° 5, infiltration 1 ach	R$	Energy demand (kWh/m²)	21.74	3.83	11.03
		Cost per m² per annum (R$/m²a)	16.22	2.86	8.23
		Estimated cost for 1-year (R$)	592.22	104.33	300.47
		Estimated cost for 50-year (R$)	29,610.97	5,216.65	15,023.41
		Estimated cost for 50-year (R$), with inflation of 6% per year	171,942.53	30,291.62	87,236.71
	US$	Energy demand (kWh/m²)	21.74	3.83	11.03
		Cost per m² per annum (US$/m²a)	5.33	0.94	2.71
		Estimated cost for 1-year (US$)	194.81	34.32	98.84
		Estimated cost for 50-year (US$)	9,740.45	1,716.00	4,941.91
		Estimated cost for 50-year (US$), with inflation of 6% per year	56,560.04	9,964.35	28,696.29
Case 8a envelope n° 72 or 108, infiltration 0.15 ach	R$	Energy demand (kWh/m²)	5.09	0.00	0.43
		Cost per m² per annum (R$/m²a)	3.80	0.00	0.32
		Estimated cost for 1-year (R$)	138.66	0.00	11.71
		Estimated cost for 50-year (R$)	6,932.83	0.00	585.68
		Estimated cost for 50-year (R$), with inflation of 6% per year	40,257.01	0.00	3,400.89
	US$	Energy demand (kWh/m²)	5.09	0.00	0.43
		Cost per m² per annum (US$/m²a)	1.25	0.00	0.11
		Estimated cost for 1-year (US$)	45.61	0.00	3.85
		Estimated cost for 50-year (US$)	2,280.54	0.00	192.66
		Estimated cost for 50-year (US$), with inflation of 6% per year	13,242.44	0.00	1,118.71
Case 8b envelope n° 5, infiltration 0.15 ach	R$	Energy demand (kWh/m²)	10.31	0.82	5.32
		Cost per m² per annum (R$/m²a)	7.69	0.61	3.97
		Estimated cost for 1-year (R$)	280.85	22.34	144.92
		Estimated cost for 50-year (R$)	14,042.73	1,116.88	7,246.11
		Estimated cost for 50-year (R$), with inflation of 6% per year	81,542.20	6,485.41	42,076.09
	US$	Energy demand (kWh/m²)	10.31	0.82	5.32
		Cost per m² per annum (US$/m²a)	2.53	0.20	1.31
		Estimated cost for 1-year (US$)	92.39	7.35	47.67
		Estimated cost for 50-year (US$)	4,619.32	367.40	2,383.59
		Estimated cost for 50-year (US$), with inflation of 6% per year	26,823.09	2,133.36	13,840.82
MCMV House envelope as built, infiltration 1 ach, internal gains	R$	Energy demand (kWh/m²)	40.61	14.31	30.88
		Cost per m² per annum (R$/m²a)	30.29	10.67	23.03
		Estimated cost for 1-year (R$)	1,106.26	389.82	841.20
		Estimated cost for 50-year (R$)	55,312.85	19,490.93	42,060.10
		Estimated cost for 50-year (R$), with inflation of 6% per year	321,186.11	113,178.36	244,231.15
	US$	Energy demand (kWh/m²)	40.61	14.31	30.88
		Cost per m² per annum (US$/m²a)	9.96	3.51	7.58
		Estimated cost for 1-year (US$)	363.90	128.23	276.71
		Estimated cost for 50-year (US$)	18,195.02	6,411.49	13,835.56
		Estimated cost for 50-year (US$), with inflation of 6% per year	105,653.33	37,229.72	80,339.19

Exchange rate: R$ 3.04 ~ US$ 1.00[56].
Prices estimated for 2015.

[56] BANCO CENTRAL DO BRASIL. 2015. Dólar americano [Online]. Available: http://www4.bcb.gov.br/pec/taxas/batch/taxas.asp?id=txdolar [Accessed 08 May 2015.

5.7 Cost Analysis

The cost analysis consisted of comparing the costs of the main envelope elements for constructing a typical and an optimised MCMV House, for both the best and the most cost-effective scenarios. The main aim of the analysis was to evaluate the viability of the optimised envelopes by looking at the increase in their costs and the payback period in comparison to the typical envelope. It has been assumed that the costs for the other common building elements (i.e. floor and internal walls) would be the same between the typical and the optimised MCMV House envelope.

The main costs for constructing each envelope were estimated using the TCPO's web database (PINI, 2015b). As mentioned in Chapter 4, TCPO, developed by PINI publishing, is a Brazilian database that examines more than 5 thousand typical Brazilian construction composition prices and estimates reasonable quantities of labour and materials required[57] (PINI, 2015a, PINI, 2015b).

It should be noted that when there was no information available on the database regarding a specific envelope component due to its innovativeness in the construction market, the prices were consulted against main suppliers across the cities explored.

Table 5-11 summarizes the estimated costs of the envelopes investigated. Table 5-12, Table 5-13 and Table 5-14 show the detailed costs of the typical MCMV House envelope. Table 5-15, Table 5-16 and Table 5-17 reveal the detailed costs of the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, respectively. Table 5-18, Table 5-19 and Table 5-20 reveal the detailed costs of the most cost-effective envelope n° 5 in Curitiba, São Paulo and Porto Alegre, respectively. The envelope costs are shown in Brazilian reais currency and the envelope costs converted to US dollars currency can be found in Appendix B. The tables show the prices as at May 2015. Labour costs included a tax allowance of 127.95% for Curitiba and Porto Alegre and 129.34% for São Paulo due to the compulsory worker pension fees (PINI, 2015b).

Table 5-11: Summary of the main envelope costs – Curitiba, São Paulo and Porto Alegre

Envelope	Currency	Curitiba	São Paulo	Porto Alegre
Typical MCMV Envelope	R$	11,110.47	11,025.56	10,476.89
	US$	3,654.76	3,626.83	3,446.35
The best performance envelope	R$	41,624.22	41,859.55	39,858.22
	US$	13,692.17	13,769.59	13,111.25
The most cost-effective envelope	R$	16,001.36	15,095.25	16,536.67
	US$	5,263.61	4,965.55	5,439.69

[57] It also includes the SINAPI database, which is the database for affordable houses in Brazil. CAIXA & IBGE 2015. Relatórios de Insumo e Composição após Julho/2014 - Não Desonerado. *SINAPI - Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil.* 13 May 2015 ed.: Caixa Econômica Federal (CAIXA) & Instituto Brasileiro de Geografia e Estatística (IBGE).

Table 5-12: Estimated costs of the typical MCMV House envelope, in Brazilian Reais - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Hollow ceramic block wall 14 cm (14x19x29cm)	66.51[58]	0.47 0.75	Servant 4.73 Brick layer 6.67	Block 43.20 Mortar[59] 6.77	1.22	7.23	49.97	m^2	81.14	480.57	614.90	3,323.50	4,418.97	11,110.47
Roof	Aluminium foil	43.95	0.22 0.22	R. Servant 5.12 Roofer 6.67	295.90/ roll of 50m^2 [60]	0.44	2.59	295.90	m^2	19.34	114.00	145.86	295.90	555.76	
Window frame	Aluminium frame - Awning (1un 80x60cm)	0.48	1.00 1.50	Servant 4.73 Brick layer 6.67	Window 488.75 Others 1.67	2.50	14.74	490.42	m^2	1.20	7.07	9.05	235.40	251.52	
	Aluminium frame - Sliding (2un150x100cm) (2un150x120cm)	6.60	1.00 1.50	Servant 4.73 Brick layer 6.67	Window 526.42 Others 1.67	2.50	14.74	528.09	m^2	16.50	97.25	124.43	3,485.39	3,707.08	
Window glazing	Single glazing	7.08	-	Installation 15.81	40.89	-	15.81	40.89	m^2	-	111.93	-	289.50	401.44	
Door	Aluminium (2un 80x210cm)	3.36	2.00 2.00	Servant 4.73 Brick layer 6.67	Door 474.49 Others 2.02	4.00	22.80	476.51	m^2	13.44	76.61	98.02	1,601.07	1,775.70	

[58] South facade: 14.68 m^2, north facade: 14.08 m^2, west facade: 19.12 m^2, east facade: 18.64 m^2.

[59] It assumes 10mm thick joints.

[60] Aluminum foil is sold in rolls of 10, 25 or 50 m^2. For the quote, Durafoil Extra product - Gibwood brand was assumed, which consists of an aluminum foil of width of 130 cm in a roll of 50 m^2. For the installation, 10-15% of extra material is suggested due to the overlap of the product on the roof structure. More information can be found at http://www.duralfoil.com.br/produto_res_durExtra.aspx) [Accessed on 20th May 2015]. The prices quote were obtained through Leroy Merlin, which is a home retailer serving 33 countries. The company has 33 stores in Brazil, including stores in Porto Alegre, Curitiba and São Paulo. More information can be found at http://www.leroymerlin.com.br/isolamento-de-teto [Accessed on 20th May 2015].

Table 5-13: Estimated costs of the typical MCMV House envelope, in Brazilian Reais - São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 129.34% (R$)	Material (R$)		
Wall	Hollow ceramic block wall 14 cm (14x19x29cm)	66.51	0.47	Servant 5.64	Block 37.53	1.22	7.80	44.13	m^2	81.14	518.50	670.63	2,935.09	4,124.21	11,025.56
			0.75	Brick layer 6.86	Mortar 6.60										
Roof	Aluminium foil	43.95	0.22	R. Servant 5.64	293.88/ roll of 50m^2	0.44	2.75	293.88	m^2	19.34	120.86	156.32	293.88	571.07	
			0.22	Roofer 6.86											
Window frame	Aluminium frame - Awning (1un 80x60cm)	0.48	1.00	Servant 5.64	Window 488.75	2.50	15.93	490.32	m^2	1.20	7.65	9.89	235.35	252.89	
			1.50	Brick layer 6.86	Others 1.57										
	Aluminium frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.00	Servant 5.64	Window 526.42	2.50	15.93	527.99	m^2	16.50	105.14	135.99	3,484.73	3,725.86	
			1.50	Brick layer 6.86	Others 1.57										
Window glazing	Single glazing	7.08	-	Installation 15.00	41.33	-	15.00	41.33	m^2	-	106.20	-	292.62	398.82	
Door	Aluminium (2un 80x210cm)	3.36	2.00	Servant 5.64	Door 521.62	4.00	25.00	523.83	m^2	13.44	84.00	108.65	1,760.07	1,952.71	
			2.00	Brick layer 6.86	Others 2.21										

Table 5-14: Estimated costs of the typical MCMV House envelope, in Brazilian Reais - Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Hollow ceramic block wall 14 cm (14x19x29cm)	66.51	0.47 0.75	Servant 4.00 Brick layer 5.40	Block 46.44 Mortar 6.91	1.22	5.93	53.35	m^2	81.14	394.40	504.64	3,548.31	4,447.35	10,476.89
Roof	Aluminium foil	43.95	0.22 0.22	R. Servant 4.42 Roofer 5.40	300.90/ roll of 50m^2	0.44	2.16	300.90	m^2	19.34	94.95	121.49	300.90	517.34	
Window frame	Aluminium frame - Awning (1un 80x60cm)	0.48	1.00 1.50	Servant 4.00 Brick layer 5.40	Window 496.98 Others 1.72	2.5	12.10	498.70	m^2	1.20	5.81	7.43	239.38	252.62	
	Aluminium frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.00 1.50	Servant 4.00 Brick layer 5.40	Window 535.28 Others 1.72	2.5	12.10	537.00	m^2	16.50	79.96	102.18	3,544.20	3,726.24	
Window glazing	Single glazing	7.08	-	Installation 12.80	37.86	-	12.80	37.86	m^2	-	90.62	-	268.05	358.67	
Door	Aluminium (2un 80x210cm)	3.36	2.00 2.00	Servant 4.00 Brick layer 5.40	Door 304.54 Others 2.21	4.00	18.80	306.75	m^2	13.44	63.17	80.82	1,030.68	1,174.67	

Table 5-15: Estimated costs of the best performance MCMV House envelope (n° 72), in Brazilian Reais - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	144.49 [61]	1.81	Servant 4.73	Brick 49.78	4.23	24.70	83.19	m^2	611.19	3,569.29	4,566.91	12,020.12	20,156.33	41,624.22
			2.42	Brick layer 6.67	Mortar 33.41										
	EPS 30 cm	72.25	0.30	Servant 4.73	Insulat.[62] 105.36	0.60	3.42	116.11	m^2	43.35	247.10	316.16	8,388.95	8,952.20	
			0.30	Brick layer 6.67	Other 10.75										
Roof	Mineral wool panels bet. Roof structure	43.95	0.66	R. Servant 5.12	75.18 [63]	1.32	7.78	75.18	m^2	58.01	341.99	437.58	3,304.16	4,083.73	
			0.66	Roofer 6.67											
Window frame	PVC frame - Awning (1un 80x60cm)	0.48	1.00	Servant 4.73	Window 616.84	2.00	11.40	638.76	m^2	0.96	5.47	7.00	306.60	319.08	
			1.00	Brick layer 6.67	Others 21.92										
	PVC frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.50	Servant 4.73	Window 542.33	3.00	17.10	544.60	m^2	19.80	112.86	144.40	3,594.36	3,851.62	
			1.50	Brick layer 6.67	Others 2.27										
Window glazing	Double uncoated glazing	7.08	-	Installation 15.81	140.00	-	15.81	140.00	m^2	-	111.93	-	991.20	1,103.13	
Door	PVC (2 un 80x210cm)	2.00	3.00	Servant 4.73	Door 1,489.09	6.00	34.20	1,501.10	un	12.00	68.40	87.52	3,002.20	3,158.12	
			3.00	Brick layer 6.67	Other 12.01										

[61] Best performance envelope – per layer: internal layer: 66.63 m^2; external layer: 77.86 m^2.

[62] EPS panels of 10 cm (included taxes) cost approximately 35.84 Brazilian Reais/m^2 in Curitiba and Porto Alegre and 31.82 Brazilian Reais/m^2 in São Paulo. EPS panels of 30 cm (included taxes) cost approximately 105.36 Brazilian Reais/m^2 in Curitiba and Porto Alegre and 95.39 Brazilian Reais/m^2 in São Paulo. TUBELO, R. (renata.tubelo@nottingham.ac.uk), 26th-28th August 2015 Knauf Isopor Prices. Email to Knauf Isopor (comercial@knauf-isopor.com.br).

[63] Mineral wool panels of 75 mm cost 25.06 Brazilian Reais/m^2 in Curitiba and Porto Alegre and 26.88 Brazilian Reais/m^2 in São Paulo. The cost was calculated based on the use of 3 layers of the insulation product in order to achieve roughly the insulation thickness required. TUBELO, R. (renata.tubelo@nottingham.ac.uk), 19th May 2015 Saint-Gobain Isover Prices. Email to Saint-Gobain Isover Technical Insulation (roberto.aneas@saint-gobain.com). The material quantity represented did not consider in detail the material cuts due to the fittings.

Table 5-16: Estimated costs of the best performance MCMV House envelope (n° 108), in Brazilian Reais – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 129.34% (R$)	Material (R$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	144.49	1.81	Servant 5.64	Brick 46.34	4.23	26.81	79.33	m^2	611.19	3,873.72	5,010.27	11,462.39	20,346.38	41,859.55
			2.42	Brick layer 6.86	Mortar 32.99										
	EPS 30 cm	72.25	0.30	Servant 5.64	Insulat. 95.39	0.60	3.75	102.50	m^2	43.35	270.94	350.43	7,405.63	8,026.99	
			0.30	Brick layer 6.86	Other 7.11										
Roof	Mineral wool panels bet. Roof structure	43.95	0.66	R. Servant 5.64	80.64	1.32	8.25	80.64	m^2	58.01	362.59	468.97	3,544.13	4,375.69	
			0.66	Roofer 6.86											
Window frame	PVC frame - Awning (1un 80x60cm)	0.48	1.00	Servant 5.64	Window 559.27	2.00	12.50	585.33	m^2	0.96	6.00	7.76	280.96	294.72	
			1.00	Brick layer 6.86	Others 26.06										
	PVC frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.50	Servant 5.64	Window 491.71	3.00	18.75	493.83	m^2	19.80	123.75	160.06	3,259.28	3,543.09	
			1.50	Brick layer 6.86	Others 2.12										
Window glazing	Double coated glazing	7.08	-	Installation 15.00	320.00[64]	-	15.00	320.00	m^2	-	106.20	-	2,265.60	2,371.80	
Door	PVC (2 un 80x210cm)	2.00	3.00	Servant 5.64	Door 1350.10	6.00	37.50	1,364.44	un	12.00	75.00	97.01	2,728.88	2,900.89	
			3.00	Brick layer 6.86	Other 14.34										

[64] TUBELO, R. (renata.tubelo@nottingham.ac.uk), 22nd May 2015. Glazing specification. Email to Saint-Gobain Cebrace Technical Consultancy (danila.ferrari@cebrace.com.br).

Table 5-17: Estimated costs of the best performance MCMV House envelope (n° 108), in Brazilian Reais - Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	144.49	1.81	Servant 4.00	Brick 44.63	4.23	20.31	81.37	m^2	611.19	2,934.30	3,754.44	11,757.15	18,445.89	39,858.22
			2.42	Brick layer 5.40	Mortar 36.74										
	EPS 30 cm	72.25	0.30	Servant 4.00	Insulat. 105.36	0.60	2.82	116.08	m^2	43.35	203.75	260.69	8,386.78	8,851.22	
			0.30	Brick layer 5.40	Other 10.72										
Roof	Mineral wool panels bet. Roof structure	43.95	0.66	R. Servant 4.42	75.18	1.32	6.48	75.18	m^2	58.01	284.85	364.46	3,304.16	3,953.47	
			0.66	Roofer 5.40											
Window frame	PVC frame - Awning (1un 80x60cm)	0.48	1.00	Servant 4.00	Window 526.37	2.00	9.40	544.57	m^2	0.96	4.51	5.77	261.39	271.68	
			1.00	Brick layer 5.40	Others 18.20										
	PVC frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.50	Servant 4.00	Window 462.79	3.00	14.10	465.13	m^2	19.80	93.06	119.07	3,069.86	3,281.99	
			1.50	Brick layer 5.40	Others 2.34										
Window glazing	Double coated glazing	7.08	-	Installation 12.80	320.00	-	12.80	320.00	m^2	-	90.62	-	2,265.60	2,356.22	
Door	PVC (2 un 80x210cm)	2.00	3.00	Servant 4.00	Door 1270.69	6.00	28.20	1,284.59	un	12.00	56.4	72.16	2,569.18	2,697.74	
			3.00	Brick layer 5.40	Other 13.90										

Table 5-18: Estimated costs of the most cost-effective MCMV House envelope (n° 5), in Brazilian reais – Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm)	66.63	0.51	Servant 4.73	Brick 44.80	1.30	7.68	53.08	m^2	86.62	511.83	654.88	3,536.72	4,703.43	16.001,36
			0.79	Brick layer 6.67	Mortar 8.28										
	EPS 10 cm	69.95	0.30	Servant 4.73	Insulat. 35.84	0.60	3.42	46.59	m^2	41.97	239.23	306.09	3,258.97	3,804.29	
			0.30	Brick layer 6.67	Other 10.75										
Roof	Aluminium foil	43.95	0.22	R. Servant 5.12	295.90 /roll of 50m^2	0.44	2.59	295.90	m^2	19.34	114.00	145.86	295.90	555.76	
			0.22	Roofer 6.67											
Window frame	Timber frame - Awning (1un 80x60cm)	0.48	2.00	Servant 4.73	Window 260.42	14.30	83.52	263.11	m^2	6.86	40.09	51.29	126.29	217.68	
			2.00	Brick layer 6.67											
			5.15	W. servant 5.12	Other 2.69										
			5.15	W.worker 6.67											
	Timber frame - Sliding + shutter (2un150x100cm) (2un150x120cm)	6.60	2.00	Servant 4.73	Window 382.62	14.30	83.52	487.16	m^2	94.38	551.22	705.29	3,215.26	4,471.77	
			2.00	Brick layer 6.67											
			5.15	W. servant 5.12	Other 104.54										
			5.15	W.worker 6.67											
Window glazing	Single glazing	7.08	-	Installation 15.81	Glass 40.89	-	15.81	40.89	m^2	-	111.93	-	289.50	401.44	
Door	Timber (2un 80x210cm)	2.00	1.40	Servant 4.73	Door 461.37	10.30	60.17	786.34	un	20.6	120.35	153.98	1,572.68	1,847.01	
			1.40	Brick layer 6.67											
			3.75	W. servant 5.12	Other 324.97										
			3.75	W.worker 6.67											

Table 5-19: Estimated costs of the most cost-effective MCMV House envelope (n° 5), in Brazilian reais – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 129.34% (R$)	Material (R$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29 cm)	66.63	0.51	Servant 5.64	Brick 38.92	1.30	8.30	46.99	m^2	86.62	552.75	714.93	3,130.94	4,398.62	15,095.25
			0.79	Brick layer 6.86	Mortar 8.07										
	EPS 10 cm	69.95	0.30	Servant 5.64	Insulat. 31.82	0.60	3.75	38.93	m^2	41.97	262.31	339.27	2,723.15	3,324.74	
			0.30	Brick layer 6.86	Other 7.11										
Roof	Aluminium foil	43.95	0.22	R. Servant 5.64	293.88 /roll of 50m^2	0.44	2.75	293.88	m^2	19.34	120.86	156.32	293.88	571.07	
			0.22	Roofer 6.86											
Window frame	Timber frame - Awning (1un 80x60cm)	0.48	2.00	Servant 5.64	Window 308.43	14.30	89.38	310.88	m^2	6.86	42.90	55.49	149.22	247.61	
			2.00	Brick layer 6.86											
			5.15	W. servant 5.64	Other 2.45										
			5.15	W.worker 6.86											
	Timber frame - Sliding + shutter (2un150x100cm) (2un150x120cm)	6.60	2.00	Servant 5.64	Window 306.80	14.30	89.38	427.60	m^2	94.38	589.88	762.94	2,822.16	4,174.98	
			2.00	Brick layer 6.86											
			5.15	W. servant 5.64	Other 120.80										
			5.15	W.worker 6.86											
Window glazing	Single glazing	7.08	-	Installation 15.00	Glass 41.33	-	15.00	41.33	m^2	-	106.20	-	292.62	398.82	
Door	Timber (2un 80x210cm)	2.00	1.40	Servant 5.64	Door 499.34	10.30	64.38	842.07	un	20.6	128.75	166.53	1,684.14	1,979.42	
			1.40	Brick layer 6.86											
			3.75	W. servant 5.64	Other 342.73										
			3.75	W.worker 6.86											

Table 5-20: Estimated costs of the most cost-effective MCMV House envelope (n° 5), in Brazilian reais – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm	66.63	0.51	Servant 4.00	Brick 48.16	1.30	6.31	56.61	m^2	86.62	420.17	537.61	3,771.92	4,729.70	16,536.67
			0.79	Brick layer 5.40	Mortar 8.45										
	EPS 10 cm	69.95	0.30	Servant 4.00	Insulat. 35.84	0.60	2.82	46.56	m^2	41.97	197.26	252.39	3,256.87	3,706.52	
			0.30	Brick layer 5.40	Other 10.72										
Roof	Aluminium foil	43.95	0.22	R. Servant 4.42	300.90 /roll of 50m^2	0.44	2.16	300.90	m^2	19.34	94.95	121.49	300.90	517.34	
			0.22	Roofer 5.40											
Window frame	Timber frame - Awning (1un 80x60cm)	0.48	2.00	Servant 4.00	Window 260.42	14.30	69.37	263.29	m^2	6.86	33.30	42.61	126.38	202.28	
			2.00	Brick layer 5.40											
			5.15	W. servant 4.42	Other 2.87										
			5.15	W.worker 5.40											
	Timber frame - Sliding + shutter (2un150x100cm) (2un150x120cm)	6.60	2.00	Servant 4.00	Window 475.42	14.30	69.37	603.65	m^2	94.38	457.86	585.83	3,984.09	5,027.79	
			2.00	Brick layer 5.40											
			5.15	W. servant 4.42	Other 128.23										
			5.15	W.worker 5.40											
Window glazing	Single glazing	7.08	-	Installation 12.80	Glass 37.86	-	12.80	37.86	m^2	-	90.62	-	268.05	358.67	
Door	Timber (2un 80x210cm)	2.00	1.40	Servant 4.00	Door 530.31	10.30	49.99	883.24	un	20.6	99.97	127.91	1,766.48	1,994.36	
			1.40	Brick layer 5.40											
			3.75	W. servant 4.42	Other 352.93										
			3.75	W.worker 5.40											

It should be noted that the products that compose the optimised envelopes of the present research, especially those used for the best performance envelope such as glazing type and insulation product are innovative in the Brazilian construction sector. Despite the fact that these products are produced and sold in the Brazilian market, their trade-in is much more explored by the industry sector than the civil construction sector.

An example is the high performance insulation product. The available thicknesses of this product in the market do not fit properly in the typical room between roof structures in dwellings. In other words, it seems that these products are not fully adapted to the housing market yet. It is believed, however, that if Brazil wants to move toward to optimising the housing envelope through the use of highly efficient materials, the market should be encouraged to adapt to this context.

Another example is the use of double coated glazing, which added a substantial cost to the optimised envelope. The reason for that lies in the fact that double coated glazing still has very limited use in Brazilian construction, despite its mentioned benefits in southern Brazilian climates. In addition, there are very limited suppliers of this product in the national market and the majority of them originated from the European market.

Similarly, PVC windows still have a limited use in the Brazilian market. In 2001, PVC windows corresponded to 1% of the national market of windows and this is immensely smaller than in England, where the use of PVC windows corresponded to over 70% of the market (Tachinardi, 2001). The use of PVC windows in Brazil is still associated with a niche of consumers with higher purchasing power and the use of PVC windows still need to be promoted for lower economic classes (Tachinardi, 2001).

It is believed that the costs of PVC window frames of high performance windows might be even higher than those available on the TCPO's database (PINI, 2015b). The explanation is that the prices of the PVC windows increase with the robustness of the windows (Tachinardi, 2001). PVC windows with two chambers for double glazing would require the use of frames that are much more robust and are of a higher quality than those used for standard single glazing windows.

For illustrative purposes only, a quotation for PVC windows in the MCMV House were estimated in Porto Alegre. Two PVC windows supplier companies were consulted. Both companies adopted a robust structure and airtight frames. The companies were identified as A and B and the prices are shown in Table 5-21.

Table 5-21: Comparative of the MCMV house PVC windows prices in Porto Alegre

Window type	Supplier A	Supplier B	TCPO's data base	Average (A+B)/ TCPO's data base
Awning window, 80x60 cm, 1 units	R$ 681.16	R$ 673.15	R$ 261.39	2.6
Sliding window, 150x100 cm, 2 units	R$ 2,435.80	R$ 2,966.26	R$ 1,395.39	1.7-2.1
Sliding window, 150x100 cm, 2 units (estimated)	R$ 2,922.96	R$ 3,559.51	R$ 1,674.47	1.7-2.1
Door, 80x210, 2 units	R$ 5,927.62	R$ 4,532.53	R$ 2,569.18	2.0

The prices refer only to the material of the window and they exclude glazing.

As shown in Table 5-21, the prices of the PVC windows were estimated to be about 2 times higher than those prices found in TCPO's database (PINI, 2015b). This result certainly shows that high performance products can considerably impact on the costs in Brazilian construction. However, the prices could drop as these high performance products become more popular. The use of high performance products needs to get higher attention on the market given the availability of similar cheaper and low performance products. Also, tax incentives might be critical to support the use of these high performance materials and the government can play an important role promoting the use of these efficient materials in the housing sector to increase a dwelling's energy efficiency.

With regard to the cost analysis, the best performance envelope had a cost 3.7 times more in Curitiba and 3.8 times more in São Paulo and Porto Alegre than the typical MCMV House envelope. A cross-analysis between the costs of the best performance envelope and their running costs for a standard infiltration of 1 ach showed that the payback period would be equivalent to 23, 32 and 21 years in Curitiba, São Paulo and Porto Alegre, respectively.

In parallel, the most cost-effective envelope had a cost 1.4 times more in Curitiba and São Paulo and 1.6 times more in Porto Alegre than the typical MCMV House envelope. A cross-analysis between the costs of the most cost-effective envelope and their running costs at standard infiltration of 1 ach showed that the payback period would correspond to 8, 11 and 9 years in Curitiba, São Paulo and Porto Alegre, respectively. The estimated payback period according to the envelope type is shown in Figure 5-77.

Comparing the best performance envelope and the most cost-effective envelope, it should be noted that the costs of the most cost-effective envelope were 62%, 64% and 59% lower than the best performance envelope. These results seem to indicate that the most cost-effective envelope could be a reasonable alternative to improve the indoor thermal comfort and energy efficiency in affordable building without considerably increasing the upfront housing costs.

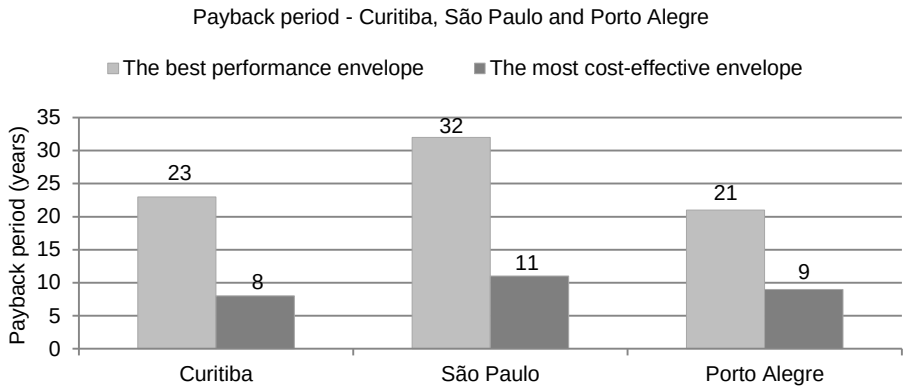


Figure 5-77: Estimated payback period of the MCMV House according to the envelope type - Curitiba, São Paulo and Porto Alegre

The overall construction costs of a typical MCMV House and its optimised variant were estimated using the Brazilian standard NBR 12721 (ABNT, 2006). The standard classifies the buildings according to their standard levels and typologies. According to the NBR 12721 (ABNT, 2006), the MCMV House is classified as a low standard house (R1-B). As mentioned in Chapter 2, a low standard house consists of a compact 1-floor single-family house of a built area of up to 58.64 m^2 with two bedrooms, living room, bathroom, kitchen and area for laundry.

The classification of buildings into different standard levels by the Brazilian standard NBR 12721 (ABNT, 2006) is used as a guide to calculate the CUB/ m^2 (Basic Unity Cost per m^2, in English). CUB is a regional construction cost indicator and it is calculated monthly by the Sinduscon (Syndicate of the Industry of the Civil Construction, in English) of each Brazilian state (SINDUSCON-MG, 2007).

The CUB calculation considers the costs of construction materials, labour, administrative and equipment expenses, quality of materials and average type of finishing for each building standard level (SINDUSCON-MG, 2007). With that in mind, Table 5-22 shows the CUB for low standard houses in the three cities investigated.

Table 5-22: CUB of low standard single-family house – R1-B, based on May 2015 (SINDUSCON-PR, 2015, SINDUSCON-SP, 2015, SINDUSCON-RS, 2015, p. 2).

	CUB/PR - Curitiba	CUB/SP - São Paulo	CUB/RS - Porto Alegre
R$/$m^2$	1,233.64	1,190.85	1,180.08
US$/$m^2$	405.80	391.73	388.18
Exchange rate: R$ 3.04 ~ US$ 1.00			

Table 5-23 shows the share of contribution of each construction activity among the cities investigated. For instance, São Paulo has the lowest share of contribution of material but also the highest prices in terms of labour when compared to the other cities. This might be due to the proximity of the city to the national industry centre that is mostly located in São Paulo state, and also due to the more specialized workforce, which tends to be concentrated in the biggest cities.

Table 5-23: share of contribution of each construction activity on the overall CUB of low standard single-family house – R1-B, based on May 2015 (SINDUSCON-PR, 2015, SINDUSCON-SP, 2015, SINDUSCON-RS, 2015, p. 2)

Activity	CUB/PR - Curitiba	CUB/SP - São Paulo	CUB/RS - Porto Alegre
Labour	52.69%	53.59%	45.14%
Material	38.15%	40.35%	44.18%
Administrative Expenses	8.96%	6.06%	9.93%
Equipment Expenses	0.20%	Not known	0.75%

Table 5-24 estimates the overall MCMV House construction costs. The estimated costs for constructing the MCMV House would correspond to 54.0, 52.1 and 51.7 thousand Brazilian reais (approximately 17.7, 17.1 and 17.0 thousand US dollars) in Curitiba, São Paulo and Porto Alegre, respectively.

Table 5-24: Estimation of the MCMV House cost through the CUB methodology

Currency	Curitiba	São Paulo	Porto Alegre
R$	54,070.44	52,194.95	51,722.91
US$	17,786.33	17,169.39	17,013.68
Based on a built area of 43.83 m^2			

These specified costs seem to be realistic. However, the MCMV House costs for these locations were estimated by the Brazilian government to vary from 60 to 76 thousand Brazilian reais for the metropolitan areas of southeast Brazilian region (e.g. São Paulo) and to be about 64 thousand Brazilian reais for the metropolitan areas of the south region (e.g. Curitiba and Porto Alegre)(Angélil and Hehl, 2014, p. 39). It should be considered that this difference in terms of the prices might be due to the use of the methodology of the CUB, which does not take into account the expense particularities of each house construction, such as foundations and architectural and other designs costs (hydraulic, electric and structural).

Crossing the data of the estimated main envelope costs, shown in Table 5-12 to Table 5-20, with the overall costs of the typical MCMV House, shown in Table 5-24, it could be inferred that the best performance envelope would add 56%, 59% and 57% more to the overall typical MCMV House costs in Curitiba, São Paulo and Porto Alegre, respectively. However, the most cost-effective envelope would add only 9%, 8% and 12% more to the overall typical MCMV House costs in Curitiba, São Paulo and Porto Alegre, respectively.

However, the costs for constructing an optimised envelope could be higher than those estimated costs if expenses with design and construction management are also considered, especially if an airtight envelope would be desired. Designing and delivering airtight envelopes increases the complexity of the process, impacting on costs.

The architectural design costs were estimated through CAU's (Council of Architecture and Urban Design, in English) methodology. CAU is the organization that governs the

technical responsibility of architects in Brazil. According to CAU's methodology, the estimated cost of the architectural design should consider the predicted cost of construction calculated using CUB, the built area of the building and the building typology (CEAU, 2014a). The calculation of the architectural design costs of the MCMV House are shown in detail in Appendix B. Table 5-25 summarizes the architectural design costs of the typical MCMV House and also the costs of the MCMV House with optimised envelopes.

The architectural design costs of the optimised MCMV House envelope (for both the best performance and the most cost-effective) were estimated to be 1.5 times more than the design cost of the typical house. The main difference in these values relies on the fact that the design of optimised envelopes requires more research, specialised people working on the design, consultancy to experts, a high level of detailing, and high communication between the architects and suppliers to deliver the expected performance. All these characteristics attribute to the design of the building a special character, which increases its degree of complexity and, consequently, the costs of the architectural design.

Table 5-25: Estimated cost of the architectural design

	Currency	Curitiba	São Paulo	Porto Alegre
Traditional envelope	R$	3,963.36	3,825.89	3,791.29
	US$	1,303.74	1,258.52	1,247.13
Optimised envelope	R$	5,947.75	5,741.44	5,689.52
	US$	1,956.50	1,888.63	1,871.55

In the case of designing for limiting infiltration, all the critical parts of the building should be identified in the early stages of design in order to avoid an undesired leaky envelope and each transition point of the building elements will need to be detailed separately (Cotterel and Dadeby, 2012). There is a special need for commitment of the complementary designs (hydraulic, electric and structural) with the architectural design in order to avoid unplanned holes through the envelope.

The costs of construction management would also be increased due to the optimisation of the envelope. This is because the construction management fees represent a percentage of the overall value of the construction, which is estimated to be 17% of the overall construction cost, according to CAU's methodology (CEAU, 2014b, p. 15).

In the case of constructing airtight dwellings, careful workmanship and tight supervision are the key elements. The labour costs would also be increased even beyond the typical costs due to the recruitment of more specialised workers, who have experience and more training. The time for execution of specific tasks would also be increased due to the complexity of the work. The workers should be aware of the potential implications of their work and the purpose of the tasks developed (Cotterel and Dadeby, 2012). It is important to encourage the team to have a responsible attitude towards airtightness

and to think in airtightness terms by suggesting improved techniques and solutions (Cotterel and Dadeby, 2012).

Nevertheless, Brazilian construction workers are very unlikely to be familiar with the airtightness concepts and it would be expected to impact the construction costs initially. Moreover, the workforce in Brazil has low educational levels. Workers in civil construction usually have 2 years less education than the average workers in other sectors (Neri, 2010, p. 14). The average time spent in education is 6.3 years although 22% of workers undertake less than 3 years of studying (Neri, 2010, p. 14, 20). These factors seem to suggest that it would be a significant issue to increase the quality of the construction industry worker and the awareness and commitment of the workforce in order to achieve more energy efficient homes.

However, it should be noted that all these cited costs with design and construction are expected to be reduced over the years, as soon as the professionals and workers acquire experience and expertise in designing and constructing these optimised housing envelopes. In other words, as soon as these tasks become part of the common practices, these additional costs tend to be reduced at typical costs by the acquirement of the knowledge required by the professionals and workers involved.

To sum up, Equation 5-1 summaries the overall costs for designing and constructing a typical MCMV House for all the cities investigated. Equation 5-2, Equation 5-3 and Equation 5-4 reveal the estimated costs of the best performance envelope, whereas Equation 5-5, Equation 5-6 and Equation 5-7 show the estimated costs of the most cost-effective envelope for the cities of Curitiba, São Paulo and Porto Alegre, respectively. The costs of materials, labour, design and construction management were considered in the Equations.

Equation 5-1: Estimated cost of the typical MCMV House envelope - Curitiba, São Paulo and Porto Alegre

$$C_{typical,\ Cur,\ Sp,\ Poa} = p \times 1.17 + 0.733\ d_{typical}$$

Equation 5-2: Estimated cost of the MCMV House best performance envelope - Curitiba

$$C_{best\ perf.\ Cur} = (p \times 1.56)\ \times 1.17 + 0.11\ d_{best\ perf.\ Cur}$$

Equation 5-3: Estimated cost of the MCMV House best performance envelope - São Paulo

$$C_{best\ perf.\ Sp} = (p \times 1.59)\ \times 1.17 + 0.11\ d_{best\ perf.\ Sp}$$

Equation 5-4: Estimated cost of the MCMV House best performance envelope - Porto Alegre

$$C_{best\ perf.\ Poa} = (p \times 1.57)\ \times 1.17 + 0.11\ d_{best\ perf.\ Poa}$$

Equation 5-5: Estimated cost of the MCMV House most cost-effective envelope - Curitiba

$$C_{cost-effect.\ Cur} = (p \times 1.09)\ \times 1.17 + 0.11\ d_{cost-effect.\ Cur}$$

Equation 5-6: Estimated cost of the MCMV House most cost-effective envelope - São Paulo

$$C_{cost-effect.\ Sp} = (p \times 1.08)\ \times 1.17 + 0.11\ d_{cost-effect.\ Sp}$$

Equation 5-7: Estimated cost of the MCMV House most cost-effective envelope - Porto Alegre

$$C_{cost-effect.\ Poa} = (p \times 1.12)\ \times 1.17 + 0.11\ d_{cost-effect.\ Poa}$$

Where,
C = cost of the MCMV House construction, in Brazilian reais.
p = standard price of the house construction, calculated through the multiplication of the CUB by the built area of the house (*p* = CUB x Area), in Brazilian reais.
d = cost of the architectural design. For the typical MCMV House, this is obtained through the multiplication of the CUB by the built area of the house, as shown in Table 5-25.

5.8 Conclusions

The MCMV House has been adopted as a housing solution for the lowest income Brazilian households. The house was evaluated in this chapter as it is likely to be widely spread over the coming years, given the government's ambitious target of 24 million residential units, which are planned to be built in Brazil by 2022. Therefore, an investigation to optimise the building envelope and, consequently, to improve the indoor thermal comfort conditions was conducted, underpinned by the findings in Chapter 4.

The MCMV house is a 1-storey 2-bedroom detached house and it consisted of a limited useful floor area over 36 m^2. The housing design allows different orientation, which can negatively impact on the indoor environmental condition. In the present research, a house with north-south orientation was adopted, which allows higher solar control. Table 5-26 summarizes the main house characteristics.

Table 5-26: MCMV House summary

	Characteristics:
House type	Affordable house for the lowest income range households
Total internal area	36.52 m^2
Total external area	43.83 m^2
Orientation	North-south orientated
Typology	1-storey 2-bedroom detached house
Features	rectangular plan and pitched roof
Materials	Standardised and culturally accepted materials: ceramic block and ceramic roof tiles

Despite the fact that there is a great need for the application of environmental design strategies in affordable houses, the design conception of the MCMV house did not include any design strategy to increase the indoor thermal comfort conditions. However, the eaves, which were set to have at least a length projection of 50 cm, demonstrated to be effective in adding shade to the north windows in summer and part of mid-season in the locations investigated. However, this might not be effective for other orientations in which the building could be placed.

The MCMV house was found to be built with affordable materials with low quality and low innovation. The material used for the walls is mostly hollow blocks, which reduces the overall masonry costs. Most of the materials used for the fenestrations are standardised and the fenestration dimensions are small to reduce the costs involved in the construction. As a consequence of the limited size of the fenestrations, the risk of overheating was found to be reduced in these locations.

The typical MCMV House in use was estimated to have internal gains equivalent to 11.6 W/m^2. The reason why the internal gains in affordable Brazilian houses are high is related to the small area of the houses and a high occupancy. The internal gains of the MCMV House were found to be 5.5 times higher than the Passivhaus standard

internal gains of 2.10 W/m^2, while the house size is equivalent to 3 times smaller than the typical size of a Passivhaus standard house.

The analysis of the typical MCMV House performance when occupied suggested that the envelope underperformed in terms of thermal comfort when compared with the scenarios of optimised envelopes. The super-insulated envelope scenario increased the narrow thermal comfort by 35% in São Paulo and 75% in Porto Alegre. The most cost-effective envelope scenario increased the narrow thermal comfort by 25% in São Paulo and 40% in Porto Alegre. In Curitiba, in both scenarios the increase of thermal comfort was only observed for the wide thermal comfort.

With the adoption of low air infiltration, the improvements in terms of the indoor temperatures relative to the typical MCMV House were even more significant. The super-insulated envelope scenario increased the narrow thermal comfort by 39.5% and 54% and 114% in Curitiba, São Paulo and Porto Alegre, respectively. The most cost-effective envelope scenario increased the narrow thermal comfort by 25.5% and 45% and 71% in these cities, respectively.

Despite its benefit on keeping the temperatures mostly within the thermal comfort zone, airtightness also increased the levels of relative humidity. The relative humidity levels above 80% were more than 2.5, 4 and 5 times higher than the typical MCMV House envelope in Curitiba, São Paulo and Porto Alegre, respectively. These results suggested that airtightness should be handled with care in the locations and if adopted in Brazilian dwellings, dehumidification strategies may need to be accounted for in the building design.

Limited infiltration rates are unlikely to be delivered effectively due to the poor workmanship and the shortage of a skilled workforce in the Brazilian construction sector in a short term. Moreover, the findings suggested that limited infiltration rates as those levels adopted in the present research are unlikely to be the standard required in the locations investigated, given the nature of Brazilian construction. However, the results also indicated that the use of the most cost-effective envelope at standard infiltration rate when considering wide thermal comfort criterion showed that for more than 77% of the time thermal comfort would be achieved in Curitiba and near 100% of the time thermal comfort would be achieved in São Paulo and Porto Alegre, respectively. As the Brazilian houses are mostly naturally ventilated and given that the thermal comfort is a subjective matter, based on personal feelings and adaptation to the environment, this may suggest that a person can easily feel comfortable most of the time in these cities with small specific improvements in the building envelope.

Moreover, the results also indicated that super-insulated envelopes are not cost-effective. Their costs would add more than 56%, 59% and 57% to the typical MCMV

House costs and their payback period would correspond to 23, 32 and 21 years in Curitiba, São Paulo and Porto Alegre, respectively. In contrast, the most cost effective envelopes would add only 9%, 8% and 12% to the typical MCMV House costs and the payback period would correspond to 8, 11 and 9 year in Curitiba, São Paulo and Porto Alegre, respectively.

Overall, the results do not corroborate that the adoption of all criteria of the Fabric First approach are suitable for the Brazilian context. On the contrary, small improvements in the traditional envelope elements, as those pointed out in the most cost-effective envelope, can increase the indoor thermal comfort levels without significantly compromising the upfront constructions costs.

The next chapter will analyse a real affordable house built in the city of Porto Alegre, in which design strategies were put in place to deliver more indoor thermal comfort. The analysis will make use of data collected on site and dynamic building simulations.

CHAPTER 6: CASE STUDY: THE 'ALVORADA' HOUSE

The Alvorada House is a one-storey case study house, built in Porto Alegre and conceived including passive design strategies to deliver thermal comfort. The house was designed with a traditional typology which comprises the use of rectangular plan, porches and pitched roof. The house is a good representation of the use of regional and commonly used materials. The Alvorada House case study is shown in detail in this chapter. The case study is evaluated through the use of dynamic building simulation and changes in the house's envelope are adopted as a means of increasing its thermal performance. Empirical data collection is used to calibrate the model.

''The development process of the Casa Alvorada prototype began with the analysis of award-winning ideas in the International Competition Project of Design Ideas, with the support of […] Passive and Low Energy Association (PLEA), titled "Design Ideas Competition Sustainable Housing for Poor" - International Competition of Ideas Project […] and it aimed to discuss new parameters for housing policies, according to sustainable principles. From the ideas of the award-winning proposals in the competition, a team composed of students and lecturers of NORIE (Hub for Innovation of Building, in English) started to develop a housing project of low-cost and low environmental impact for the city of Alvorada, in order to meet a demand established through an agreement with its city council. This process, subsequently, became part of a larger work package: the development of a research project […], aiming for the development of a detailed design for a housing prototype for demonstration and experimental purposes […]. The Alvorada House would be one of these housing typologies […].''
Sattler (2007, p. 240, adapted, translated)

''The Alvorada House is a model of housing for low-income householders, part of a forward looking process of developing more sustainable benchmarks for the production of housing and for the built environment.''
Sattler (2007, p. 242, adapted, translated)

6 CASE STUDY: THE 'ALVORADA' HOUSE

The Alvorada House was built on the Federal University of Rio Grande do Sul (UFRGS)' Vale Campus, in Porto Alegre (Figure 6-1). The house was designed, constructed and monitored by NORIE, which is a sector of the civil engineering postgraduate programme dealing with construction at UFRGS. The house construction involved a strong body of postgraduate students of the University and resulted in the involvement of more than 30 students in areas of architecture, civil engineering and agronomy.

The Alvorada House was funded by CAIXA[65] (Federal Savings Bank, in English) and FINEP[66] (Funding Authority for Studies and Projects, in English) (Sattler, 2007). The Alvorada House construction was based on a self-build scheme and took place mainly between 2001 and 2003. The house cost[67] was estimated to be 17.4 thousand Brazilian reais (approximately 7.9 thousand US dollars) and its cost per square metre represented 345 Brazilian reais (approximately 157 US dollars) for the 2006 reference period (Kuhn, 2006, p. 138-139).

The Alvorada House was designed to be a showcase of potential solutions for increasing thermal comfort in affordable houses. Moreover, the house was designed to be a place for investigation and experimentation of passive design solutions applied to the context of compact affordable houses.

The thermal performance of the Alvorada House was assessed previously by Morello (2005) in an uninhabited condition. The findings of this analysis suggested that the Alvorada House had indoor temperatures below the lower thermal comfort limit of 18 °C for 26.3% of the year (Morello, 2005, p. 160). The occupation of the house would ensure high levels of indoor thermal comfort through the internal gains but also could negatively impact on the increase of temperatures above the upper comfort limit of 29 °C (Morello, 2005, p.157). The temperatures above 29 °C for the uninhabited condition were estimated to be 0.9% of the year (Morello, 2005, p. 160). Considering a thermal comfort interval of 20-25 °C, the results indicated that the house was 42% of the year

[65] CAIXA is one of the government-owned banks in Brazil and a major player in the housing finance system. It is responsible for the distribution of public subsidies related to housing. UN-HABITAT 2013. Scaling-Up Affordable Housing Supply in Brazil: The 'My House My Life' Programme. United Nations Humans Settlements Programme (UN-Habitat).

[66] FINEP is a Brazilian public company which promotes studies and projects in areas of science, technology and innovation.

[67] The Alvorada House costs did not included expenses with design, construction management and labour costs mainly because the house was based on self-build.

below the lower comfort limit, 38% within the thermal comfort interval and 20% of the year above the comfort limit (Morello, 2005, p. 156).

Moreover, the study (Morello, 2005, p. 167-168) pointed out the need for further investigation of the Alvorada House by adopting dynamic building simulations in order to experimentally assess the suitability of the house in other regions, which share cultural and climatic similarities.

Figure 6-1: Alvorada House site plan. Based on Google (2014)

Despite the fact that the Alvorada House has been designed for residential use, over the last few years the house has never been inhabited. Hence, there is no study that has evaluated the Alvorada House's predicted thermal performance in use so far.

In this chapter, the Alvorada thermal performance was assessed in detail through the use of dynamic building simulations. Empirical data of a 1-year data monitoring was used for calibrating the simulation model in order to obtain a good representation of the real house.

The present chapter is structured into four key points. First, all the information about the Alvorada House is discussed. Then, the Alvorada House performance is evaluated based on data collection, following which the optimisation of the Alvorada House is investigated for two different scenarios, using the results of Chapter 4 as reference. Finally, a cost analysis is carried out with the aim of assessing the viability of the envelope optimisation in the context of the affordable Brazilian housing.

The aim of this analysis was to investigate the thermal performance of the affordable Alvorada house as close as possible to its real functioning. Also, the purpose of this analysis was to investigate the envelope optimisation of the affordable house for increasing indoor thermal comfort and energy efficiency and its potential cost.

The rationale for selecting the Alvorada House case study relies on the fact that the house represents a unique case, which was designed, constructed and monitored within an academic environment. More importantly, it fitted into the house characteristics investigated in the present research such as typology and construction techniques and it is located in one of the cities of interest. Another criterion for selecting the Alvorada House was the fact that access to the property was made easy by prior personal contact with some of the research team.

6.1 House Design

The Alvorada House has a traditional look due to its typology and selection of materials (Figure 6-2). It is a one-storey detached house with a built area of 49.43 m². However, the internal house area is much smaller and corresponds to only 38.67 m². The remaining amount corresponds to sheltered external areas of the house. The house is north-south orientated and has a rectangular shape on the plan, which is a common plan typology found in Brazil, as identified in Chapter 2 and 3.

Figure 6-2: Alvorada House view from the north (left) and west (right) facades (Sattler, 2007)

The house design meets the needs of a small family. The house internally consists of two bedrooms, a living room integrated with dining room and kitchen, and a bathroom, and externally it includes two porches (Figure 6-3). One porch, on the north facade, is used as house access and the other one, on the west facade, is used as a laundry space. As mentioned in Chapter 3, porches are traditional architectural elements in Brazil, which act as an element of transition between internal and external spaces and are used to enlarge the shading area, protecting the facade from sun and rain (Lara, 2010).

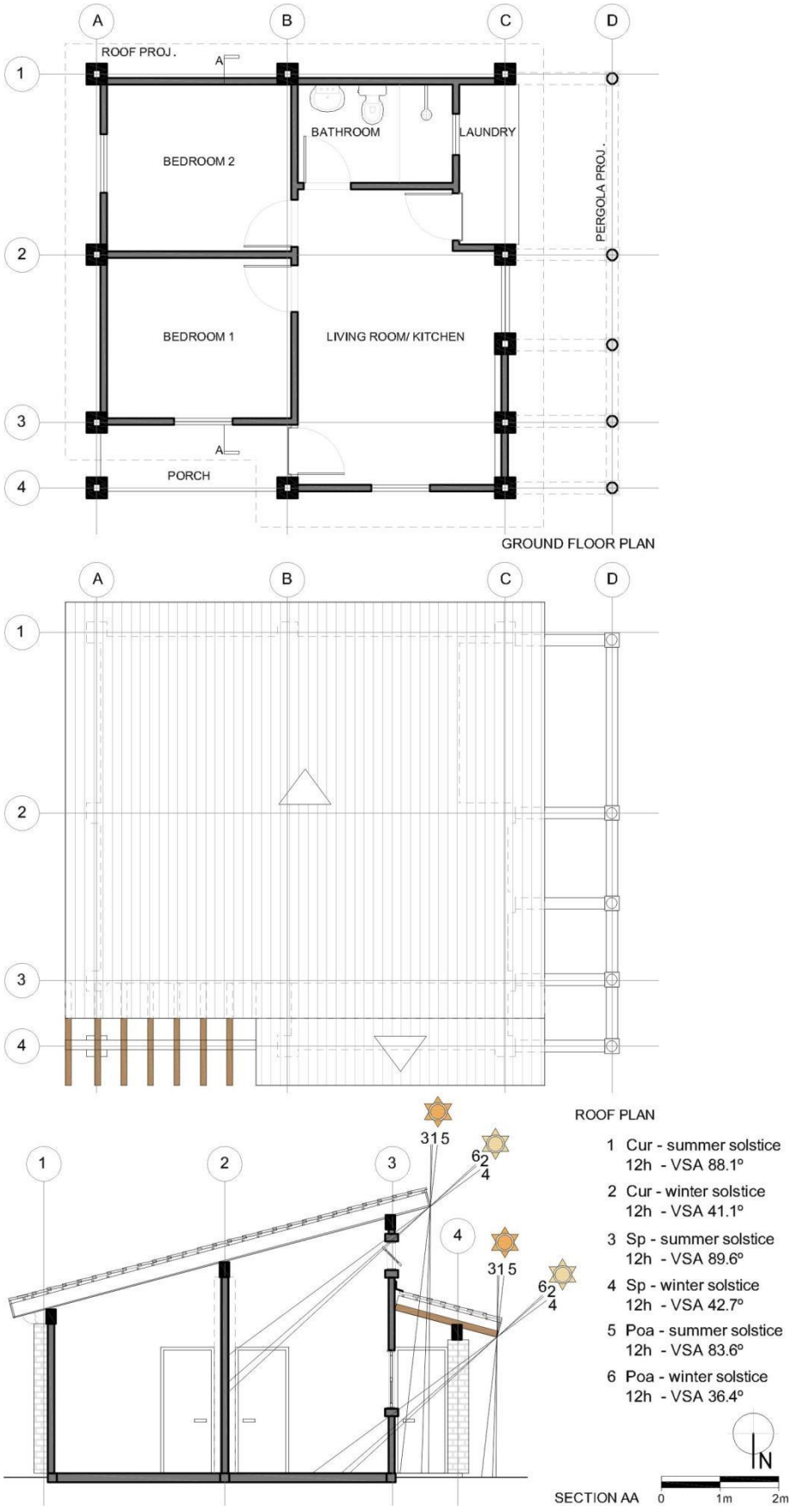


Figure 6-3: Alvorada House ground floor plan, roof plan and section

Table 6-1 shows the Alvorada House areas and volumes. As shown in the Table, the Alvorada House form factor exceeds the recommended values of a compact house and its form factor is equivalent to a less compact detached house as most of the affordable detached houses in Brazil are.

Table 6-1: Alvorada House areas and volumes

	Rooms	Estimated areas (m^2) or volumes (m^3)*
Ground floor Height: variable (≥ 2.50 m)	Bedroom 1 (north)	8.59 m^2
	Bedroom 2 (east)	8.89 m^2
	Bathroom	4.42 m^2
	Living room/ Kitchen	16.77 m^2
Total of internal floor area:		38.67 m^2
Sheltered areas (porches):		6.43 (north: 3.70 m^2/ west: 2.73 m^2)
Total external area (including walls):		43.00 m^2
Total area (including porches):		49.43 m^2
Internal volume:		130.70 m^3
Total of exposed external surface areas of the envelope (A):		221.35 m^2
Exposed external surface area of the envelope facing south		22.52 m^2
Exposed external surface of the envelope facing east		24.33 m^2
Exposed external surface the envelope facing north		31.89 m^2
Exposed external surface area of the envelope facing west		24.33 m^2
Exposed external ground floor area		49.43 m^2
Exposed external roof area		68.75 m^2
Form factor (desirable values: 2-4)		5.72
Compactness (desirable values: 0.80-2.2)		0.59 m

*Calculated based on the plans and technical drawings.
Form factor without internal walls - area: 39.87 m^2 – is calculated to be 5.55.

Table 6-2 shows the Alvorada House fenestrations. Most of the windows (58.5%) were placed on the north facade. The Alvorada House windows were made out of timber and most of them were designed with awning operation. The windows were subdivided into small squares (see Figure 6-2), which increased the window frame percentage to around 50% of their dimension. This is believed to be a common strategy used for increasing a house's security. The area destined for ventilation in the Alvorada House was found to be limited when compared to the windows' size. This was due to the size of the frame and the operation type of each window, which help determine the house's ventilation area.

Table 6-2: Alvorada House fenestrations (Morello, 2005, p. 65, Sattler, 2007, p. 424-427, 430, 434, 442)

Type w:window d: door	Location		Operation	Dimension (m)[68] w:width h:height	Area (m^2)	Frame pct. (%)	Glazing area (m^2)	Glazing pct. (%)	Ventilation area (m^2)	Ventilation pct. (%)
W1	Bathroom	West	1 awning panel	w:0.81 h:0.40 sill:1.71	0.32	59.5	0.13	40.5	0.23	70.5
W2	Bedroom 2	East	2 sliding panels + folding shutters	w:1.19 h:1.19 sill: 0.92	1.42	49.0	0.72	51.0	0.50	35.3
W3	Bedroom 1	North	2 bottom fixed panels, 2 top awning panels	w:1.19 h:1.18 sill: 0.92	1.41	54.0	0.65	46.0	0.80	56.3
W4	Bedroom 1	North	2 awning panels	w:1.53 h:0.48 sill: 3.37	0.74	56.5	0.32	43.5	0.55	74.5
W5	Living/ Kitchen	North	2 bottom fixed panels, 2 top awning panels	w:1.19 h:1.18 sill: 0.92	1.41	54.0	0.65	46.0	0.80	56.3
W6	Living/ Kitchen	North	2 awning panels	w:1.53 h:0.48 sill: 3.37	0.74	59.5	0.30	40.5	0.55	74.5
W7	Living/ Kitchen	West	2 bottom fixed panels, 2 top awning panels	w:1.14 h:0.93 sill: 1.18	1.06	53.0	0.50	47.0	0.51	47.5
D1	Living/ Kitchen	West	Single panel	w:0.81 h:2.07	1.67	26.5	NA	NA	NA	NA
D2	Living/ Kitchen	East	Single panel	w:0.86 h:2.07	1.78	26.5	NA	NA	NA	NA
D3	Bedroom/ Bathroom	Int.	Single panel	w:0.81 h:2.07	1.67	26.5	NA	NA	NA	NA

6.2 House Materials

The main concern of the Alvorada House's design team was to deliver an affordable house without the stigma of a low quality building. Thus, the Alvorada house was built with a selection of materials of low environmental impact, high cultural acceptability and high quality standard, at an affordable cost (Sattler, 2007). It should be stressed that the main difference between the materials used in the Alvorada House and those of the MCMV House (shown in the previous Chapter 5) was the superior quality standard of the Alvorada House materials.

The Alvorada House was constructed using uninsulated materials, as the typical houses are built in Brazil. The house was structured using a combination of brick and concrete columns. The walls were built out of a non-load-bearing masonry, which allowed a small wall thickness because they did not have structural purposes.

The walls were overall built out of a layer of solid bricks of 11 cm of thickness. On the north and east facade, no external layer of plastering was applied on the walls. On the

[68] Rough openings of windows, in metre: W1: 0.84 x 0.44, W2:1.23 x 1.23, W3: 1.23 x 1.22, W4:1.55 x 0.50, W5: 1.22 x 1.22, W6:1.55 x 0.52, W7: 1.16 x 0.95, D1: 0.89 x 2.12, D2: 0.94 x 2.12, D3: 0.88 x 2.12

walls facing the south and the west, an external layer of cement mortar was applied to decrease the overall thermal transmittance of these facades (applied also internally on the south wall). On the west facade, which is the facade most exposed to sun, some parts of the wall were made with a double layer of solid bricks in order to increase its thermal resistance. Also, on the west facade the plastered walls were painted in white to increase solar radiation reflection.

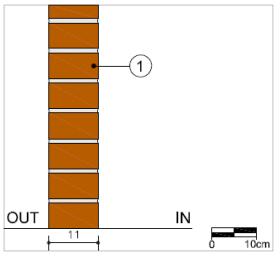
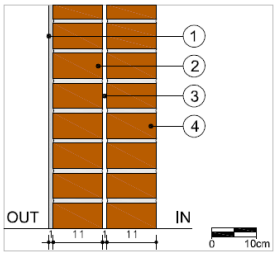
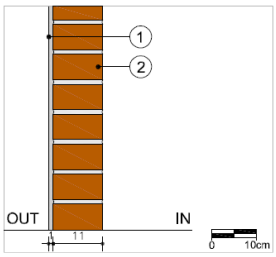
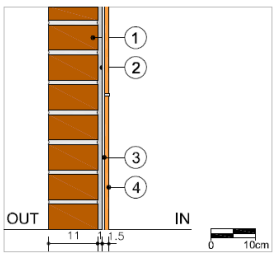
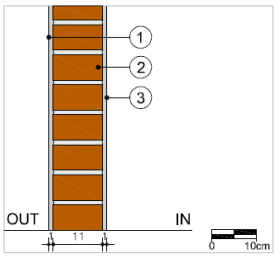
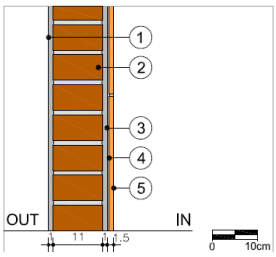
The windows were made out of 32 mm timber frame and 3 mm single glazing[69]. The internal and external doors were also built out of timber frame and panels of 32 mm (Sattler, 2007, p. 410).

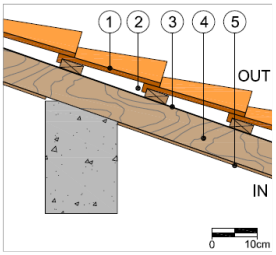
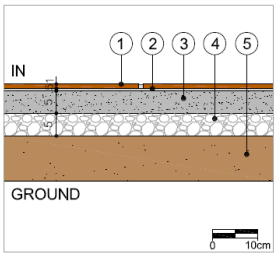
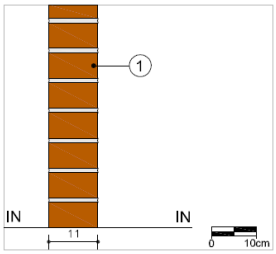
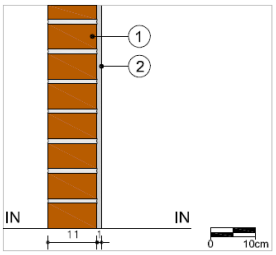
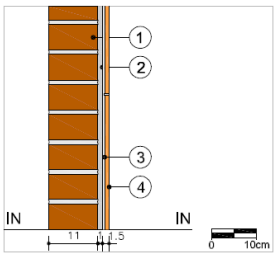
The roof was constituted by a total of 5 layers: non-enamelled roman ceramic tiles, air cavity, aluminium foil (to reduce the downward heat emission), air cavity and a ceiling of cedar lumber (Morello, 2005, Kuhn and Sattler, 2006). The house was designed with an inclined roof facing predominantly south to reduce the incidence of radiation that comes mostly from the north (Kuhn and Sattler, 2006). The roof also presented a strategy of being ventilated by the use of fenestrations on the ceiling in order to extract the heat during the summer. This roof ventilation strategy is detailed in Section 6.3. Similarly, the ceiling was also adopted as pitched following the roof's pitch. A pitched ceiling was adopted to increase the air volume inside the building (Sattler, 2007) and it also contributed to increasing the internal sensation of spaciousness in the house.

The materials of the Alvorada House are illustrated in Table 6-3. The thermal properties of the constructions elements were calculated wih the use of Dynamic Thermal Properties Calculator tool (Arup, 2010). It should be noted that the Alvorada house was built in the early 2000s, long before the standard NBR 15575 came into force (ABNT, 2013a) and thus, this is the reason why some of the envelope elements have U-values slightly lower than the standard requires, as shown in Chapter 2.

[69] Density of the timber used was 900 Kg/m^3. p. 412 .SATTLER, M. 2007. *Habitações de baixo custo mais sustentáveis: a Casa Alvorada e o Centro Experimental de Tecnologias Habitacionais Sustentáveis,* Porto Alegre, Brazil, Associação Nacional de Tecnologia do Ambiente Construído (ANTAC).

Table 6-3: Alvorada House envelope specification. Based on Morello (2005) and Grigoletti (2007)

		Wall construction types (thickness and layers)	**Thermal prop.**	**Section**
External walls	North/ East/ West walls	i. **Solid ceramic brick wall, without plaster** Total thickness:110 mm Location: Bedrooms and Living room/ Kitchen Layers from outside to inside: 1. 110 mm Solid ceramic brick (11 x 5 x 22 cm)	**U-value** (W/m²K): 3.57 **Admittance** (W/m²K): 4.61 **Decrement factor** (0-1): 0.83 **Time Lag** (hours): 3.02	
	West walls	ii. **2-layer solid ceramic brick wall, with external plaster** Total thickness:~240 mm Location: Living room/ Kitchen Layers from outside to inside: 1. 10 mm Lime cement plaster 2. 110 mm Solid ceramic brick (11 x 5 x 22 cm) 3. ~10 mm air cavity (for building up) 4. 110 mm Solid ceramic brick (11 x 5 x 22 cm)	**U-value** (W/m²K): 1.82 **Admittance** (W/m²K): 5.12 **Decrement factor** (0-1): 0.38 **Time Lag** (hours): 8.24	
		iii. **Solid ceramic brick wall, with external plaster** Total thicness:120 mm Location: Living room/ Kitchen Layers from outside to inside: 1. 10 mm Lime cement plaster 2. 110 mm Solid ceramic brick (11 x 5 x 22 cm)	**U-value** (W/m²K): 3.46 **Admittance** (W/m²K): 4.65 **Decrement factor** (0-1): 0.80 **Time Lag** (hours): 3.46	
		iv. **Solid ceramic brick wall, with internal plaster and ceramic tile** Total thickness:135 mm Location: Bathroom Layers from outside to inside: 1. 110 mm Solid ceramic brick (11 x 5 x 22 cm) 2. 10 mm Lime cement plaster 3. 5mm Adhesive mortar 4. 10mm Ceramic tile	**U-value** (W/m²K): 3.32 **Admittance** (W/m²K): 4.82 **Decrement factor** (0-1): 0.74 **Time Lag** (hours): 3.84	
	South walls	v. **Solid ceramic brick wall, with external and internal plaster** Total thickness:130 mm Location: Bedroom Layers from outside to inside: 1. 10 mm Lime cement plaster 2. 110 mm Solid ceramic brick (11 x 5 x 22 cm) 3. 10 mm Lime cement plaster	**U-value** (W/m²K): 3.36 **Admittance** (W/m²K): 4.75 **Decrement factor** (0-1): 0.76 **Time Lag** (hours): 3.70	
		vi. **Solid ceramic brick wall, with external and internal plaster and internal ceramic tile** Total thickness:145 mm Location: Bathroom Layers from outside to inside: 1. 10 mm Lime cement plaster 2. 110 mm Solid ceramic brick (11 x 5 x 22 cm) 3. 10 mm Lime cement plaster 4. 5mm Adhesive mortar 5. 10mm Ceramic tile	**U-value** (W/m²K): 3.23 **Admittance** (W/m²K): 4.86 **Decrement factor** (0-1): 0.71 **Time Lag** (hours): 4.16	

	Wall construction types (thickness and layers)	Thermal properties	Section
Roof	vii. **Aluminium foil pitched roof** (eaves ~ 60 cm) Total thickness: 106.15 mm Location: all dwelling Layers from outside to inside: 1. 10 mm Roman clay roof tiles 2. Lathes 20 x 50mm; ventilation bet cross-lathing 3. 0.15 mm Aluminium foil 4. Rafters 70 x 50 mm; ventilation bet cross-rafters 5. 12 mm Cedar lumber ceiling	**U-value** (W/m²K): Upward: 0.98/ Downward:0.51 **Admittance** (W/m²K): 1.11/ 1.04 **Decrement factor** (0-1): 1.0/ 0.99 **Time Lag** (hours): 0.54/ 0.68	
Ground floor	**viii. Ground floor** Total thickness: 610 mm Location: all dwelling Layers from inner to ground: 1. 10 mm Ceramic tile 2. 5 mm Adhesive mortar for sticking ceramic tiles 3. 50 mm Concrete slab 4. 50 mm Stone chipping 5. Soil	**U-value** (W/m²K): Upward: 3.67/ Downward: 2.92 **Admittance** (W/m²K): 6.54/ 4.52 **Decrement factor** (0-1): 0.47/ 0.41 **Time Lag** (hours): 6.28/ 6.62	
Internal walls	Internal walls were built out of solid ceramic brick ix. **Solid ceramic brick wall, without plaster** Total thickness:110 mm Location: Between Bedrooms and Living room/ Kitchen Layers from outside to inside: 1. 110 mm Solid ceramic brick (11 x 5 x 22 cm)	**U-value** (W/m²K): 2.70 **Admittance** (W/m²K): 4.96 **Decrement factor** (0-1): NA **Time Lag** (hours): NA	
	x. **Solid ceramic brick wall, without plaster on one wall side and plaster on the other wall side** Total thickness:120 mm Location: Between Bedrooms Layers from outside to inside: 1. 110 mm Solid ceramic brick (11 x 5 x 22 cm) 2. 10 mm Lime cement plaster	**U-value** (W/m²K): 2.64 **Admittance** (W/m²K): 5.12 **Decrement factor** (0-1): NA **Time Lag** (hours): NA	
	xi. **Solid ceramic brick wall, without plaster on one side and with plaster and internal ceramic tile on the other side** Total thickness:135 mm Location: Bathroom Layers from outside to inside: 1. 110 mm Solid ceramic brick (11 x 5 x 22 cm) 2. 10 mm Lime cement plaster 3. 5mm Adhesive mortar 4. 10mm Ceramic tile	**U-value** (W/m²K): 2.56 **Admittance** (W/m²K): 5.38 **Decrement factor** (0-1): NA **Time Lag** (hours): NA	
Window	All windows were made out of 32 mm timber frame and 3mm of single glazing. The frame percentages varied according to each window type (see Table 6-2)	Glazing g-value:0.84 Glazing U-value: 5.78 W/m²K	

6.3 Environmental Design Strategies

The Alvorada House was built with a set of environmental design strategies aiming to deliver thermal comfort to the occupants. These strategies were conceived based on the use of simple, sustainable and affordable technologies. Figure 6-4 shows in detail the environmental design strategies applied to the house.

The majority of the design strategies were related to the position of the fenestrations and their effect on the ventilation strategy. Most of the windows were placed on the north facade, which is the orientation that allows better solar control than others. This was also a strategy used as passive solar heating in winter to allow warming up the house through the glazing surfaces. No fenestrations were placed on the south facade mainly to avoid heat losses in winter period, because the prevailing cold winds come from this direction in winter. The remaining windows were placed on the east facade (Bedroom 2) and on the west facade (Living room/ Kitchen).

On all orientations, the fenestrations were designed to receive shading. On the east facade, the fenestration was covered up by a folding shutter[70], which allowed control of the amount of solar radiation that comes into the building though this element. On the west facade, the fenestration was covered up by an external structure. However, this structure, designed to support a water tank and a solar collector, in itself was not able to deliver the intended shading. Morello (2005) pointed out that this structure might not be effective as a shading device. The design presupposed that deciduous vegetation would have been applied on this structure to effectively protect the facade from solar radiation. However, this strategy was not implemented and verified.

The same shading issue was also noted on the pergola on the north facade, at the house entrance. The pergola was designed to hold deciduous vegetation to help deliver the desired thermal comfort both in summer and winter. Once again, the strategy was not entirely implemented. However, the pergola in itself was able to deliver some degree of shading.

With regard to the shading delivered by the roof eaves, the roof eaves were designed with a projection of approximately 60 cm over the wall and they work by blocking the solar radiation in summer and allowing it to come into the building in winter. Figure 6-5 shows the overhangs' shading effect according to the main seasons, in Porto Alegre. The drawings were elaborated through the use of TAS Software (EDSL, 2013a).

[70] The fin of the shutter had a thickness of 0.8 mm. Ibid.

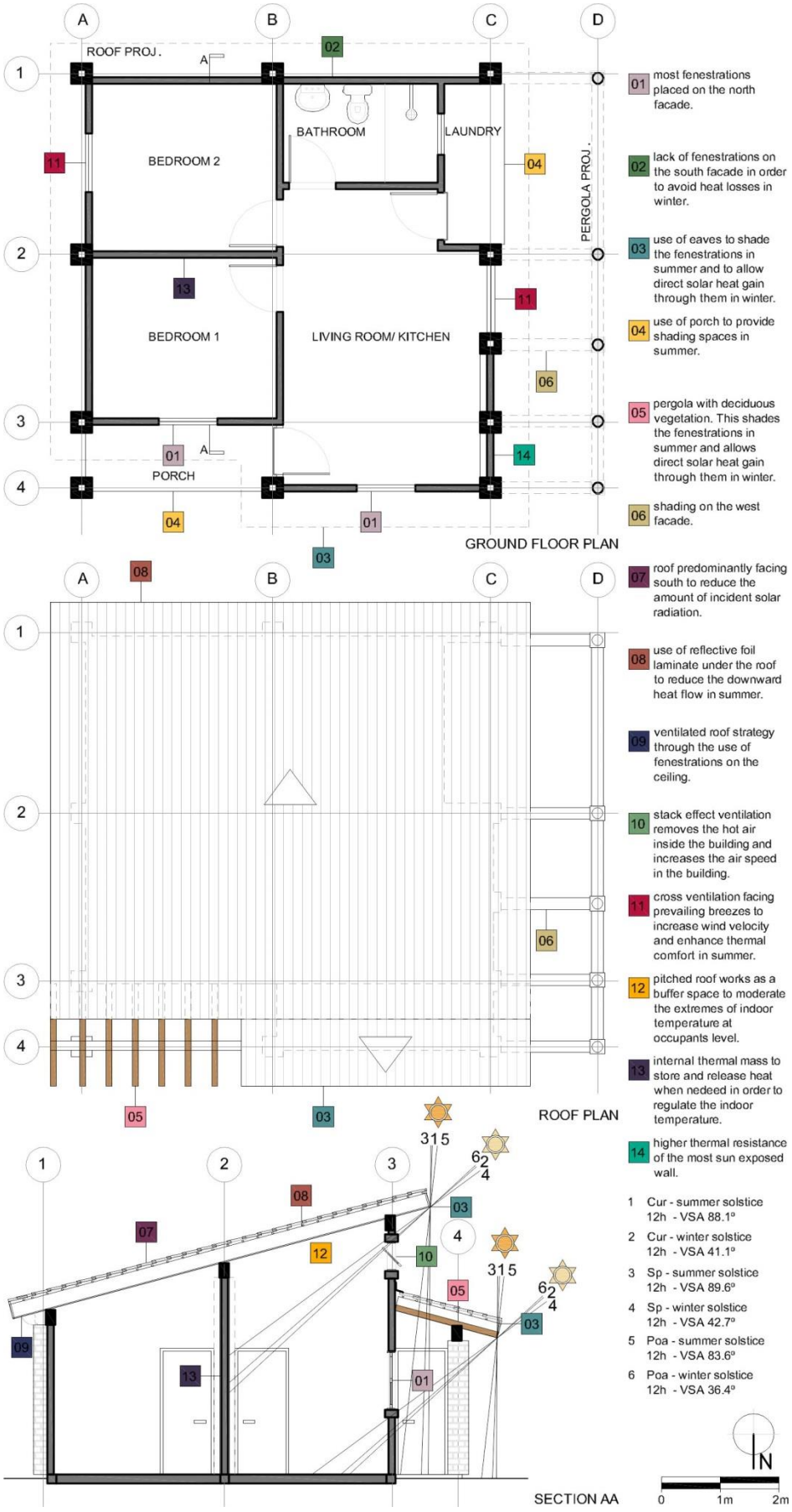


Figure 6-4: Alvorada House design strategies

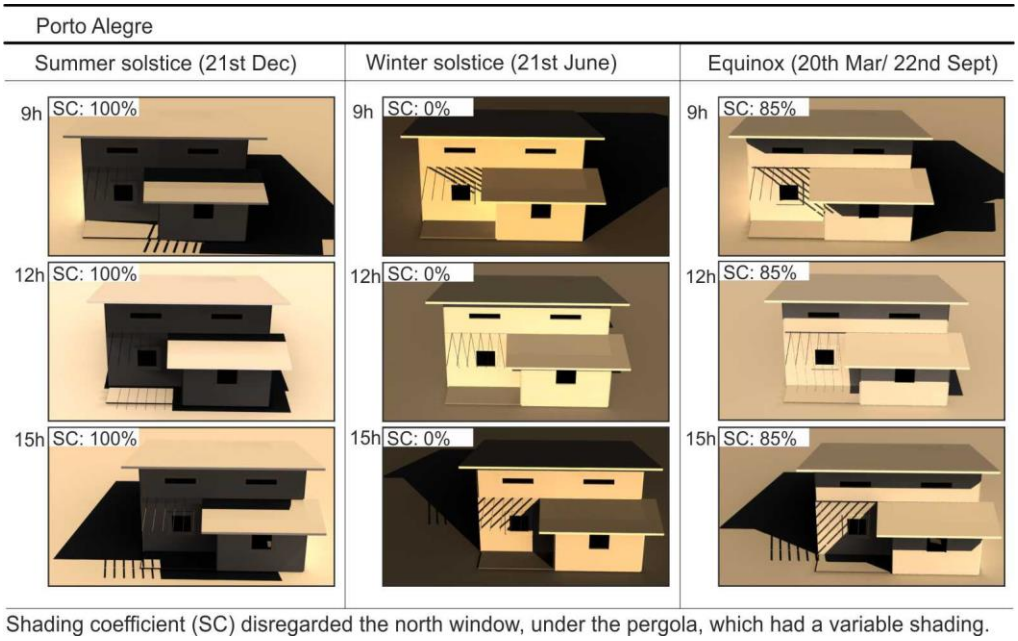


Figure 6-5: Eaves' shading effect in Porto Alegre

The Alvorada House's roof had 87% of its area positioned on the south direction (Kuhn, 2006, p. 104). This was designed to reduce the solar gain in summer, which is mostly obtained from the flat surfaces of the house rather than the vertical ones. In addition, the roof was conceived with an aluminium layer to reduce the downward heat flow.

The roof was also designed to have its own ventilation system through the use of fenestrations in the ceiling area. Figure 6-6 shows the roof ventilation system. The system comprised a permanent fenestration in the north part of the major pitched roof`s ceiling and another movable fenestration in the south part of this roof`s ceiling, which should be opened only during the hot period to force the air to be renewed and thus, to remove the heat in the roof areas. It is believed that this strategy, however, might not be effective mainly because the prevailing summer winds come from the southeast and east direction.

The Alvorada House was designed to be naturally ventilated and the fenestrations of the north facade were placed at different heights, which allows for the warm air to be removed from the house by stack effect. In addition, when the internal doors are opened, the windows of the east-west facade allow cross-ventilation since this is the prevailing direction of the cool winds in summer.

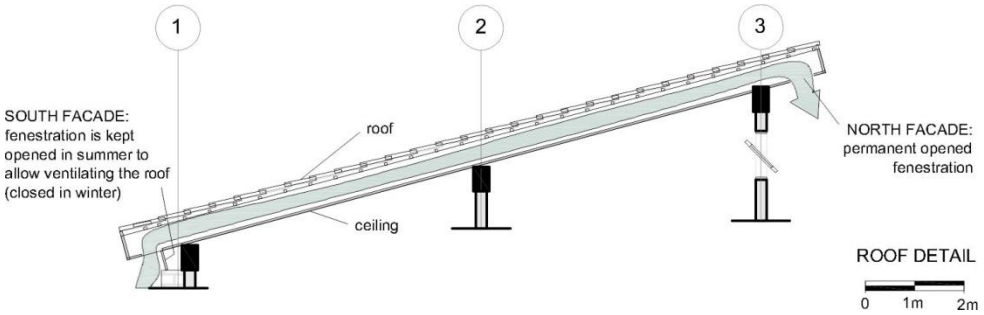


Figure 6-6: Roof ventilation system

6.4 Data Collection

The present research used empirical data collection, obtained through a desk-based approach, kindly provided by Prof Miguel Sattler, from the Federal University of Rio Grande do Sul.

The data collection consisted of both external and internal measurements of the environmental conditions of the Alvorada House. The details of the equipment used to collect the data are shown in Table 6-4.

Table 6-4: Measured data and equipment details (Morello, 2005, p. 68-76, 91-98)

	Data measured	Equipment	Equipment resolution/ Equipment range	Equipment accuracy
External data	Air temperature	Temperature Sensor	± 0.1 °C	± 0.5 °C
	Dew point temperature			
	Global solar radiation	NA	NA	NA
	Wind direction	Anemometer	22.5 °	± 7 °
	Wind speed	Anemometer	From 0.45 m/s to 39 m/s	± 5%
	Air relative humidity	Relative humidity sensor	1%	± 3%
Internal data	Globe Temperature	BABUC/A Globe Thermometer	From -10 °C to 100 °C	± 0.15 °C for temperature around 0 °C
	Dry bulb temperature (Indoor temp.)	BABUC/A Psychrometer	From -25 °C to 150 °C	± 0.1 °C for temperature around 0 °C; and ± 0.13 °C for temperature around 20 °C
	Wet bulb temperature	BABUC/A Wet bulb Thermometer	From 0 °C to 60 °C	± 0.15 °C for temperature around 0 °C
	Dew point temperature	BABUC/A Psychrometer	From -20 °C to 60 °C	± 0.1 °C for temperature around 0 °C; and ± 0.13 °C for temperature around 20 °C
	Radiant temperature asymmetry	BABUC/A Radiometer	From -40 °C to 70 °C; From -150 W/m^2 to 1500 W/m^2	3%; ± 1 W/m^2
	Air relative humidity	BABUC/A Psychrometer	From 0 % to 100%	2% for relative humidity between 15 % and 40%; 1% for relative humidity between 40% and 70%; and 0.5% for relative humidity between 70% and 98%;

The external data was obtained from the meteorological station of the IPH (Institute of Hydraulic Research, in English) located in the University's Vale Campus, within 500 metres of the Alvorada House (Morello, 2005). The external data consisted of measurements of air temperature, dew point temperature, wind speed, wind direction, air relative humidity, global solar radiation (horizontal plan) and rainfall, collected between 2003 and 2004 (Morello, 2005).

The internal data was collected by Morello (2005) for a 1-year period, between 2003 and 2004. The data collection was recorded for each 1-hour interval. The equipment used for data collection was BABUC/A[71] from the LSI[72] (Laboratory of Industrial Instrumentation, in English). The measured data was collected with the equipment placed in the middle of the living room/ kitchen area, at a height of 1.10 m from the floor, at occupant body level.

As mentioned previously, during all the monitored period the house was unoccupied. All the external windows were kept closed but the internal doors were kept opened to allow air circulation among all the rooms (Morello, 2005, p. 80, Sattler, 2007). The south fenestration of the roof's ceiling was opened during the warmer period (from 11th November to 11th May) to allow ventilating the roof and was closed for the remaining period (Morello, 2005, p. 80, Sattler, 2007, p. 324).

6.5 Simulation Scope and Method

A 3D TAS model of the Alvorada House was built based on the house design and materials described in Sections 6.1 and 6.2, respectively. The simulation model was calibrated as mentioned in Section 6.6 to ensure it was representative of the house. The Alvorada House simulation model was divided into several thermal zones according to each of the house's rooms and each room had the thermal zones split between occupant and ceiling levels. The 3D model and the thermal zones can be found in Appendix C.

At the first stage of the simulation assessment, the simulation model was kept as simple as possible to help reduce uncertainties (Base Case). Changes were introduced step by step in order to understand the impact of each change in the building thermal performance (Case 1 to Case 8).

[71] LSI-LASTEM 2008. BABUC A/M: a portable instrument for acquisition, display, storage and processing of envirionmental data. User`s Manual. *In:* LSI-LASTEM (ed.). Milan, Italy LSI-Lastem.

[72] LSI-LASTEM. 2013. *LSI-Lastem Webpage* [Online]. Milan, Italy: LSI-Lastem. Available: http://www.lsi-lastem.it/ [Accessed 8 December 2014.

It must be remembered that the aim of the simulations was to try to get as close as possible to the real condition of the house operation in order to predict its performance. Also, the purpose was to evaluate the performance resultant of the adoption of an optimised envelope (insulated and airtight), based on the results of the sensitivity analysis showed in Chapter 4.

The findings of the simulation were analysed in terms of frequency of temperatures, frequency of relative humidity levels, degree-hours methodology and overall energy demand.

6.6 Simulation Validation

The measured external data from the IPH weather station was used to produce a new climatic data set. All the collected data replaced each of the variables of the original weather data file of Porto Alegre.

The design details and the properties of the materials of the Alvorada House used to calibrate the simulation model were adopted according to the available information of the house, mainly found in Morello (2005), Grigoletti (2007) and Sattler (2007), which were summarised in Sections 6.1 and 6.2.

All the simulations performed considered the roof without its ventilation system as the system could not be properly simulated in TAS software. As mentioned, the roof ventilation system presupposed that the ceiling's openings (see Figure 6-6) would be opened for ventilating the roof during the summer period.

The precise air infiltration rate of the Alvorada House was not available. An accurate value could only be obtained by performing a blower door test[73], which is not commonly conducted in Brazil. Thus, the infiltration rate was estimated based on the measured data. The infiltration equivalent to 1 ach shows a closer agreement with the collected data among other different infiltration rates tested and thus, this value was assumed in the simulations. The infiltration of 1 ach is also recommended to be used in the dynamic building simulations, according to the Brazilian standard NBR 15575 (ABNT, 2013d, p.26).

[73] Blower door test determines the overall house leakage and it consists of using a fan sealed into an opening which creates a positive or negative pressure differential between the building and the external environment. The level of pressure applied in the entire building ranges from 10 Pa to 70 Pa and the volume of air transferred due to this pressure differential is measured and a logarithmic regression is used to establish the volume of air transferred at pressure difference of 50 Pa. p. 22. IBO - AUSTRIAN INSTITUTE FOR HEALTHY AND ECOLOGICAL BUILDING 2009. *Details for Passive Houses.,* Vienna, Austria, Springer Vienna Architecture.

Table 6-5 shows the data set resulting from the calibration of the simulation model. The mean bias error, which statistically measures how consistent the simulated data is in comparison to the measured data, was estimated to be 0.7% (zero means that the data is unbiased). The root mean square error, which statistically measures the magnitude of the varying quantity, was calculated to be 5.6%. As the Table shows, these values were much lower than the maximum limits acceptable for the hourly calibration data, established by ASHRAE Guideline (2002, p. 18, 41).

Table 6-5: Calibration of the simulation model - validation between measured and simulated data

Number of calibrated points	8424 hourly data
Measured mean indoor temperature	20.86 °C
Simulated mean indoor temperature	20.76 °C
Measured – Simulated mean indoor temperature	0.11 K
Standard deviation of measured indoor temperature	4.30
Standard deviation of simulated indoor temperature	3.85
Correlation coefficient	0.93
Mean Bias Error (< 10%)	0.7%
Root Mean Square Error (< 30%)	5.6%

Figure 6-7 shows the correlation between measured and simulated indoor temperature. As is illustrated by the Figure, a good agreement was verified between the measured and the simulated data, which showed a strong correlation of 0.93.

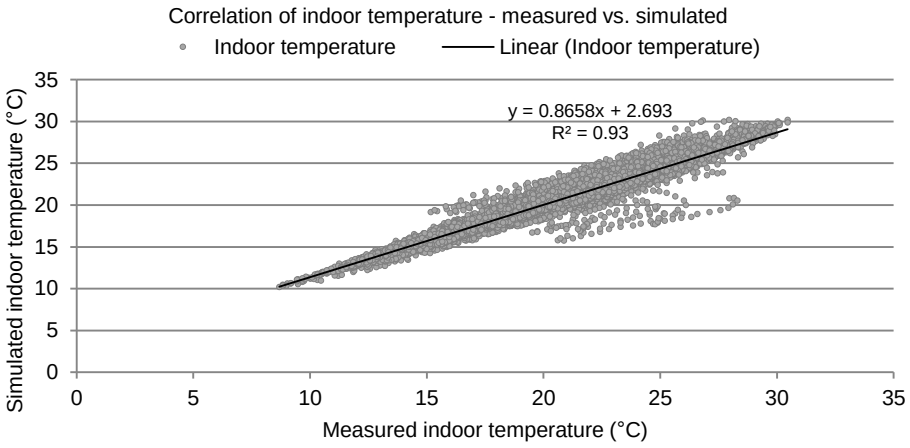


Figure 6-7: Calibration of the simulation model - correlation between measured and simulated data

Figure 6-8, Figure 6-9 and Figure 6-10 shows the comparison between measured and simulated indoor temperature for 1-whole-year, for a summer period and for a winter period, respectively. As the Figures reveal, a close agreement between measured and simulated data was verified mainly in the winter period, which might be associated to the lack of roof ventilation in the simulation. It should be noted that a small amount of missing data in the Figures corresponded to problems of recording the measured data.

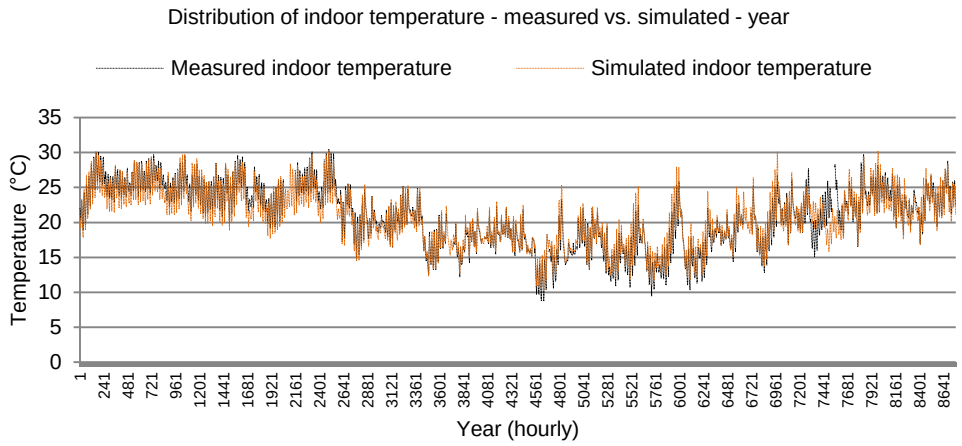


Figure 6-8: Calibration of the simulation model - comparison between measured and simulated indoor temperatures for a year period

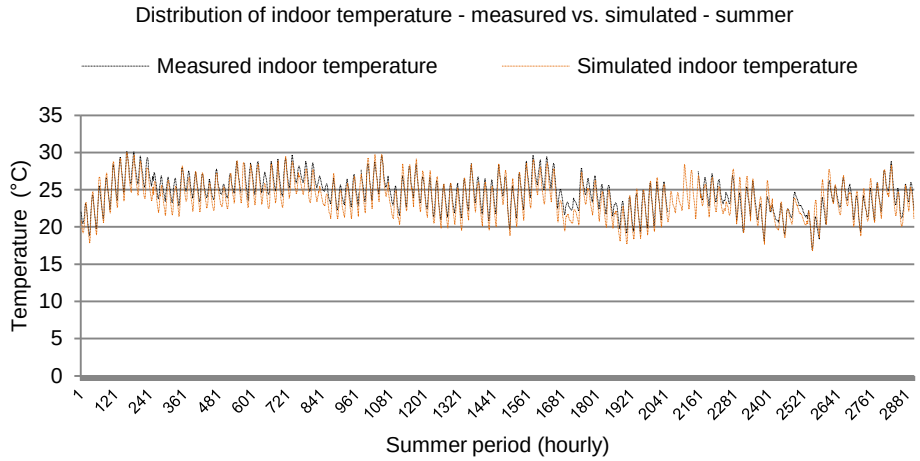


Figure 6-9: Calibration of the simulation model - comparison between measured and simulated indoor temperatures for a summer period

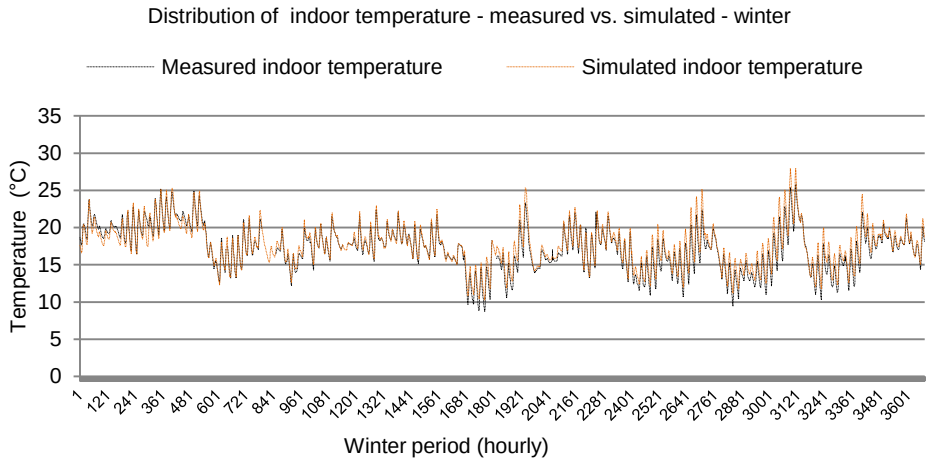


Figure 6-10: Calibration of the simulation model - comparison between measured and simulated indoor temperatures for a winter period

The thermal performance of the Alvorada House using the IPH measured weather file was estimated to be as shown in Figure 6-11 and Figure 6-12. The living room area at occupant level was below the temperature of 18 °C for 27.9% of the year and above 29 °C for 0.9% of the year. These values were similar to some of the conclusions of the previous work conducted in the Alvorada House, which obtained percentages of 26.3% and 0.9% of the year, respectively (Morello, 2005, p. 156-160). In terms of degree-hours, the simulated data also proved to be quite similar to the measured data, albeit slightly warmer in terms of the magnitude of lower temperatures.

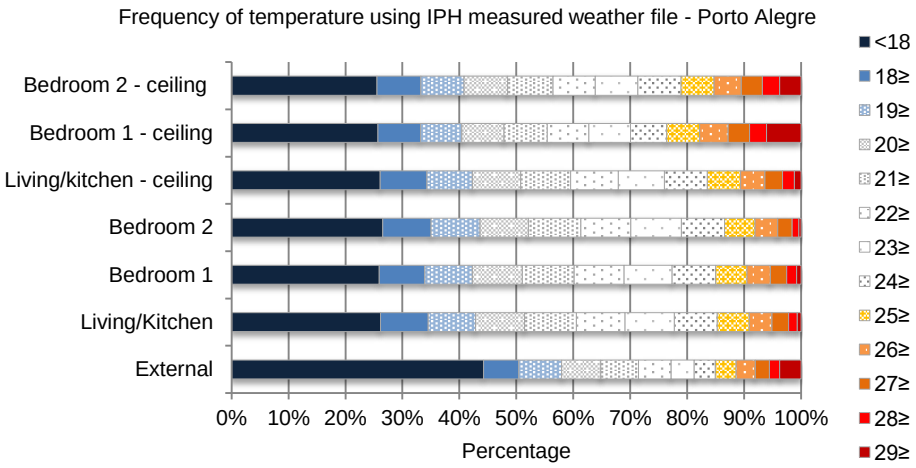


Figure 6-11: Calibration of the simulation model - simulated frequency of temperatures for the monitored year (2003-2004)

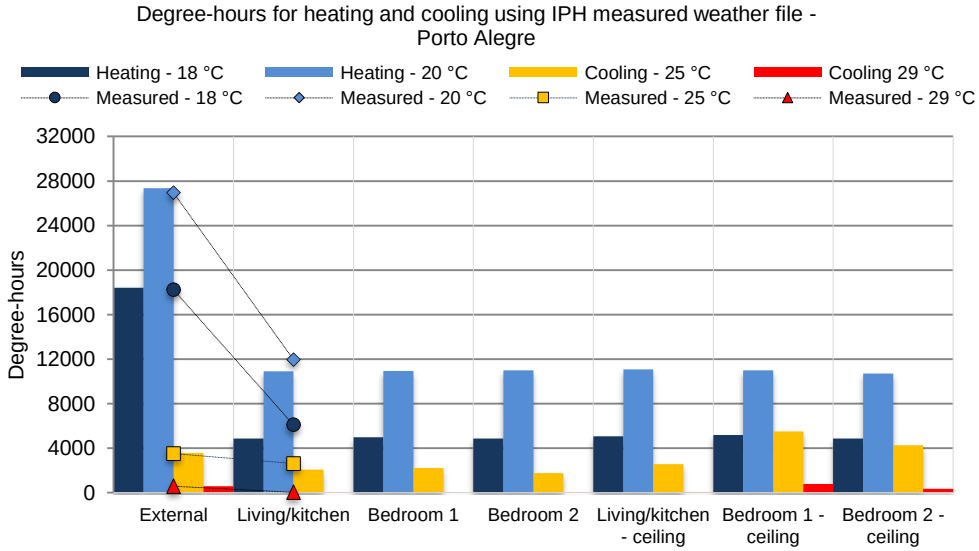


Figure 6-12: Calibration of the simulation model - comparison between simulated and measured degree-hours for the monitored year (2003-2004)

The Alvorada House was never occupied and, hence its thermal performance under real circumstance of use could never be properly assessed. This present research aims to address this gap and the next sections describe simulated house performance as close as possible to a real operation.

Because the Alvorada House was also analysed for different locations from that where the house was originally built (Curitiba and São Paulo), the dynamic building simulation considered the standard weather data file instead of the IPH measured weather data file in order to allow comparison among the cities investigated.

The standard weather data file was found to appropriately represent the monitored period and it represents an average of the climate conditions of each city. As expected, the standard weather data file differed somewhat from the measured weather data file, as Figure 6-13 shows. The average monthly temperature of the measured weather data file was lower than the average monthly temperature of the standard weather data file. This might be due to the site of the Alvorada House, which is surrounded by vegetation and it is more likely to have lower temperatures than those obtained in the standard weather data file of Porto Alegre itself (Morello, 2005, p. 91).

It should be noted that as the standard weather data file showed temperatures slightly higher than the IPH measured weather data file, it is expected the simulation results will reflect this.

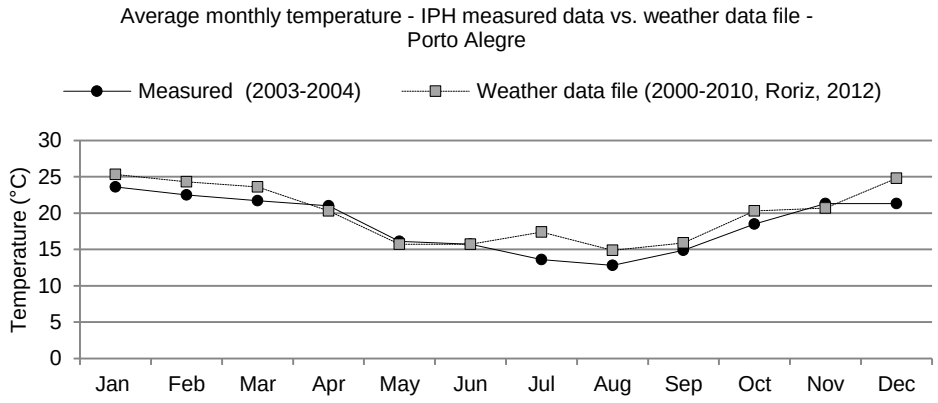


Figure 6-13: Comparison between measured data and weather data file

6.7 Base Case Simulation Model

Base Case considered the Alvorada House model as built and unoccupied. The summary of the Base Case model is detailed in Table 6-6.

Table 6-6: Summary of Alvorada House Base Case simulation model

	Base Case
Summary	As built, unoccupied.
Details	Weather file compiled by Roriz (2012b). Building envelope as shown in Table 6-3 No additional shading, no internal gains due to the occupancy, infiltration estimated to be 1 ach and no ventilation were assumed.

6.7.1 Assumptions

i. Weather data: The weather data used, compiled by Roriz (2012b), was based on data collection between 2000 and 2010 for the cities of Curitiba, São Paulo and Porto Alegre.
ii. Calendar: The adopted calendar was based on the environmental analysis undertaken in Chapter 4, in which summer was considered to be between December and March and winter was considered to be between May and September. Mid-season was assumed to be the months of April, October and November.
iii. Internal gains: The house was assumed unoccupied and thus, no internal gains were considered.
iv. Shading: No additional shading was assumed in Base Case.
v. Infiltration: The infiltration was estimated to be 1 ach at atmospheric pressure based on the agreement with the calibration model and according to the standard NBR 15575 (ABNT, 2013d, p. 26).
vi. Ventilation: No natural ventilation was assumed in Base Case. All the windows were considered fully closed at this first stage of the simulations.
vii. Comfort temperature range: As indicated in Chapter 4, a narrow thermal comfort benchmark of 20-25 °C and a wide thermal comfort benchmark of 18-29 °C were considered.
viii. Heating or Cooling: No active space conditioning was considered in Base Case.

6.7.2 Results

As mentioned, despite the fact that the Alvorada House has been built only in Porto Alegre, this work also assumed that the house could be built in the other cities under investigation (Curitiba and São Paulo), given the suitability of the house typology and construction techniques for these cities. The aim for this assumption is to show

comparatively the differences in thermal performance due to the potential optimisation of the house envelope in these three different cities.

Figure 6-14, Figure 6-15 and Figure 6-16 shows the frequency of temperatures of Base Case for Curitiba, São Paulo and Porto Alegre, respectively. The temperatures inside the rooms were quite similar due to the compact size of the house. The results are showed both in the occupied areas, at occupant and ceiling levels. The main difference between ceiling and occupant levels is the higher frequency of higher temperatures close to the roof areas.

In Curitiba, the occupied areas were about 30% of the time within the narrow thermal comfort of 20-25 °C and up to 55% of the time within the wide thermal comfort of 18-29 °C. The occupied areas were up to 46% of the time below 18 °C and up to 70% of the time below 20 °C. However, for less than 1% of the time the indoor temperatures were above 25 °C at occupant level.

In São Paulo, the occupied areas were up to 53% of the time within the narrow thermal comfort of 20-25 °C and about 83% of the time within the wide thermal comfort of 18-29 °C. The occupied areas were about 17% of the time below 18 °C and up to 42% of the time below 20 °C. The indoor temperatures at occupant level were above 25 °C for about 6% of the time.

In Porto Alegre, the occupied areas were within the thermal comfort of 20-25 °C and 18-29 °C for 42% and 76% of the year, respectively. The occupied areas were up to 22% of the time below 18 °C and up to 41% of the time below 20 °C. The indoor temperatures at occupant level were above 25 °C and 29 °C for up to 18% and 2% of the time, respectively. At ceiling level, the indoor temperatures were considerably higher than at occupant level and were above 29 °C for 6% of the time.

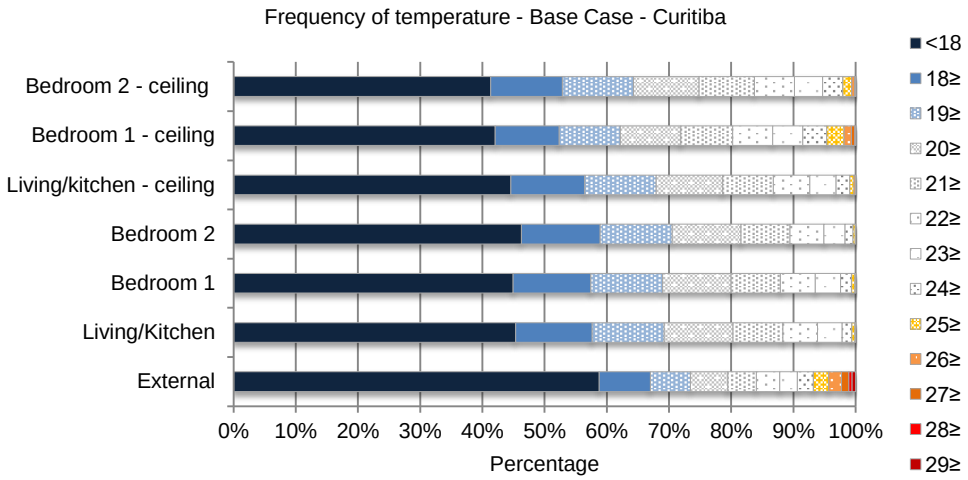


Figure 6-14: Frequency of temperature, Base Case, Curitiba

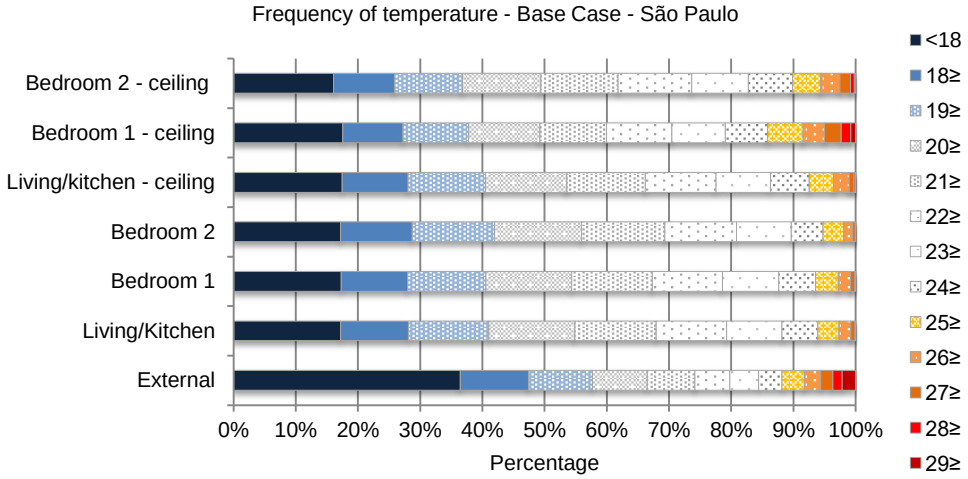


Figure 6-15: Frequency of temperature, Base Case, São Paulo

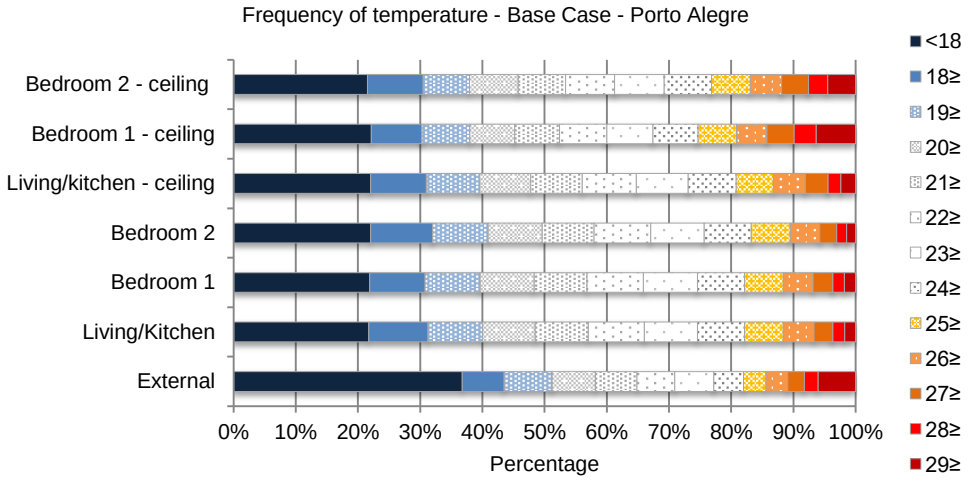


Figure 6-16: Frequency of temperature, Base Case, Porto Alegre

Figure 6-17, Figure 6-18, and Figure 6-19 show the degree-hours for Curitiba, São Paulo and Porto Alegre, respectively.

In Curitiba, the existing envelope would reduce the heating demand to about 56% and 40% for the base temperature of 18 °C and 20 °C relative to the external temperatures, respectively. In São Paulo, the envelope would be able to reduce the heating demand at occupant level to about 76% and 58% for the base temperature of 18 °C and 20 °C relative to the external temperatures, respectively. For both Curitiba and São Paulo, the magnitude of cooling degree-hours at occupant level was not as significant as it was in Porto Alegre.

In Porto Alegre, the existing envelope greatly reduced the demand for heating for more than 72% for the base temperature of 18 °C and for more than 55% for the base temperature of 20 °C when compared to the external heating demand. Similarly, the envelope reduced the cooling demand at occupant level for more than 44% relative to the external levels. Despite the fact that reduced cooling demand was observed inside the house at occupant level, at ceiling level the cooling demand was found to be much more significant, similar to the external levels.

Figure 6-20, Figure 6-21 and Figure 6-22 show the frequency of relative humidity levels in Curitiba, São Paulo and Porto Alegre, respectively. The external relative humidity exceeded the limit of 80% for 61%, 43% and 44% of the time in the cities, respectively. Internally, the higher levels of relative humidity were found mostly at occupant level rather than at ceiling level. The relative humidity levels in the occupied areas were above 80% for 28%, 8% and 15% of the time in Curitiba, São Paulo and Porto Alegre, respectively.

As the house was assumed as fully closed up and unoccupied in Base Case, this could have impacted on its performance, overestimating cooling needs and underestimating heating and relative humidity. The next section undertakes progressive changes in the simulation model in order to simulate the Alvorada House as close as possible to its real use.

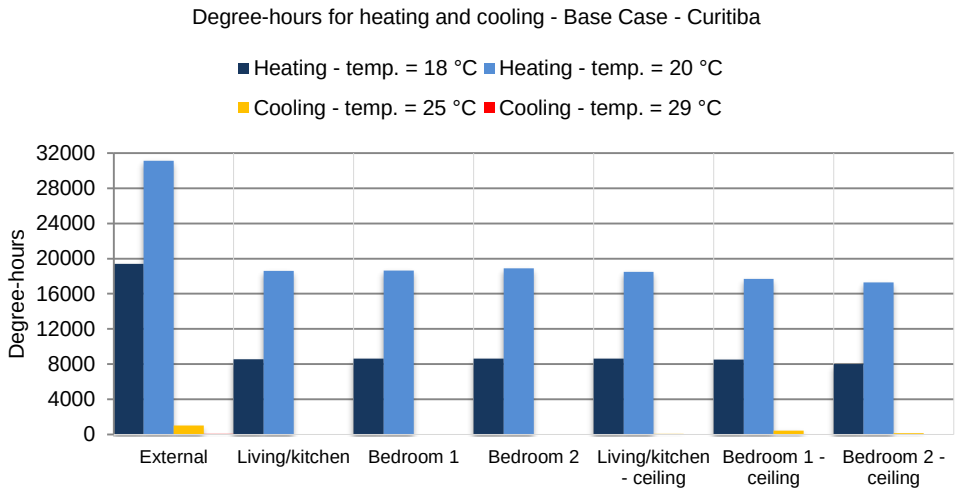


Figure 6-17: Degree-hours, Base Case, Curitiba

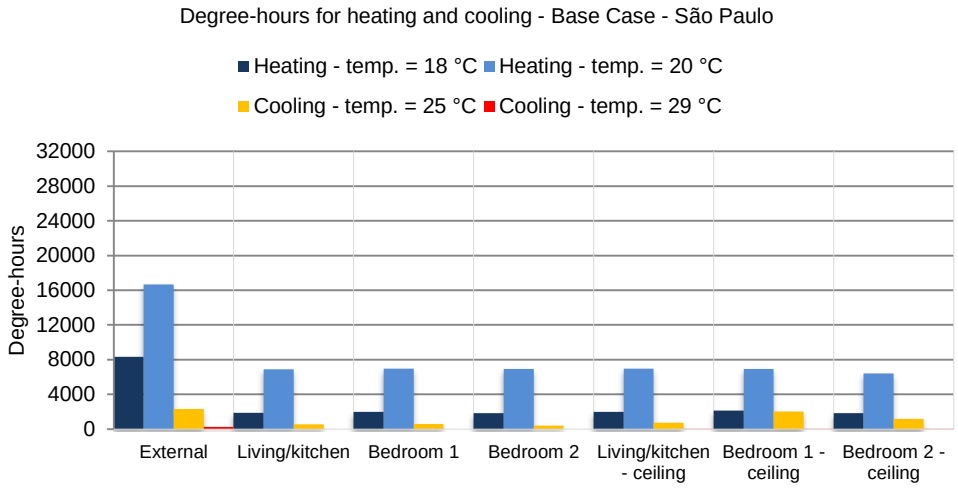


Figure 6-18: Degree-hours, Base Case, São Paulo

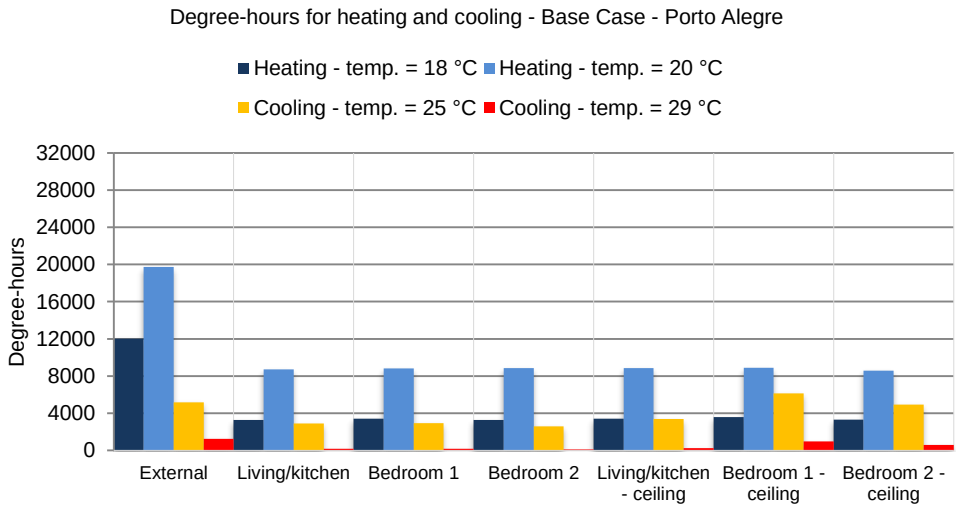


Figure 6-19: Degree-hours, Base Case, Porto Alegre

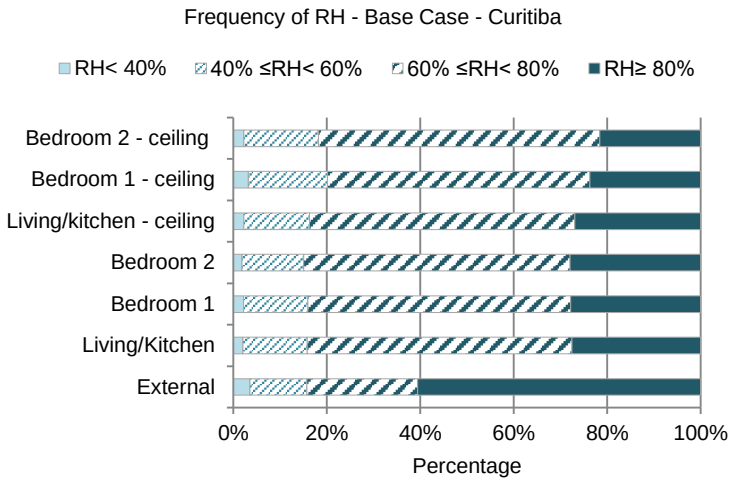


Figure 6-20: Frequency of relative humidity, Base Case, Curitiba

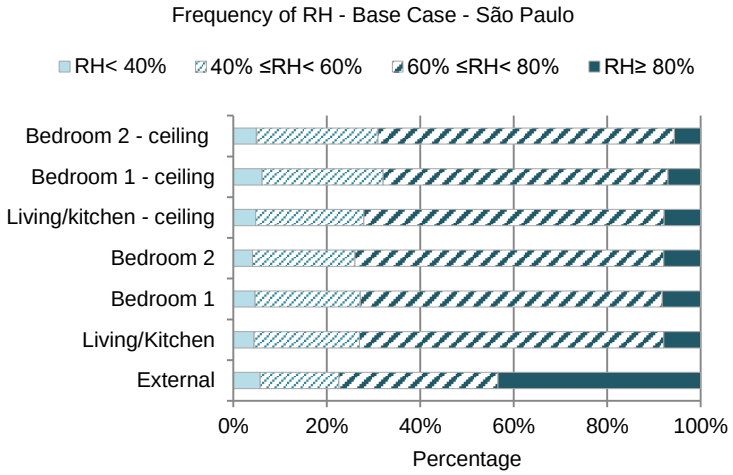


Figure 6-21: Frequency of relative humidity, Base Case, São Paulo

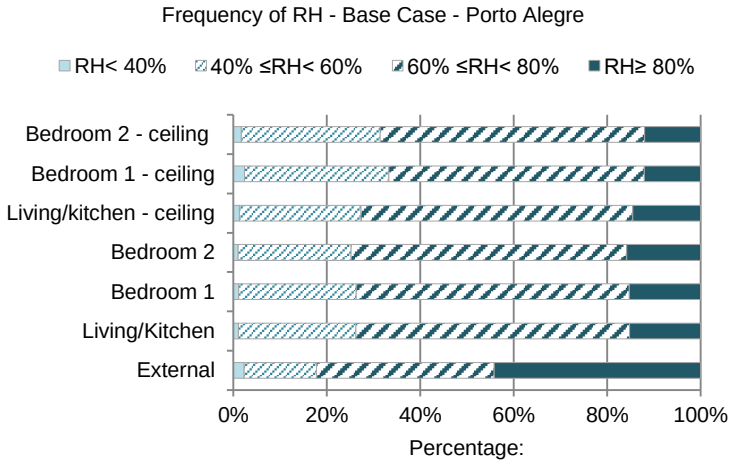


Figure 6-22: Frequency of relative humidity, Base Case, Porto Alegre

6.8 Variation of the Simulation Model

The initial purpose of these simulations was to understand the performance of the house as close as possible to its real functioning. Moreover, the aim was also to investigate ways of optimising the envelope, through the use of specific concepts of the Fabric First approach, such as increased insulation, limited infiltration and selective ventilation.

The simulation model was built up in stages and for each of those stages a simulation was conducted. The stages of the simulations are shown below and in Table 6-7. The assumptions are detailed in the next section.

ii. Case 1 consisted of the addition of shading devices to the Base Case model (Base Case + shading). Despite the fact that the Alvorada House was designed with appropriate shading on the north facade as shown in Figure 6-5, the window of the north bedroom, under the pergola, at occupant level, is exposed as the use of deciduous vegetation was not properly implemented. Also, in order to have comparable results among the cities investigated and because for the cities of São Paulo and Curitiba the shading devices are required in different dimensions, the shading devices were individually designed for each of the cities investigated.

iii. Case 2 added typical internal gains to the simulations, compatible with an affordable house occupancy of 4 people (Case 1 + internal gains).

iv. Case 3 assumed the building envelope as optimised (Case 2 + envelope optimisation). From this point, two scenarios were evaluated, based on the findings of Chapter 4:
    a. Scenario ‘a’ comprised the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre.
    b. Scenario ‘b’ included the most cost-effective envelope n° 5 for all the cities investigated.

v. Case 4 assumed each of the optimised envelope scenarios under a regime of selective ventilation (Case 3 + ventilation).

vi. Case 5 assumed each of the optimised envelope scenarios with a reduction of the infiltration rate (Case 3 + reduction of the infiltration rate).

vii. Case 6 considered each of the optimised and airtight envelope scenarios under a regime of selective ventilation (Case 5 + ventilation).

viii. Case 7 assumed each of the optimised envelope scenarios under a regime of active space conditioning for heating and cooling (Case 3 + AC).

ix. Case 8 assumed each of the optimised and airtight envelope scenarios under a regime of active space conditioning for heating and cooling (Case 5 + AC).

Table 6-7: Summary of Alvorada House simulation model variation

	Building naturally ventilated						Building artificially conditioned		
	As built: shading & Internal gains		Optimised envelope: increase of insulation, reduction of infiltration and selective ventilation						
Cases investigated	**Case 1**	**Case 2** 'Alvorada House as built with internal gains'	**Case 3a** (envelope n° 72/ 108)	**Case 4a** (envelope n° 72/ 108)	**Case 5a** (envelope n° 72/ 108)	**Case 6a** (envelope n° 72/ 108)	**Case 7a** (envelope n° 72/ 108)	**Case 8a** (envelope n° 72/ 108)	Scenario 'a' used the best performance envelope n° 72 and 108
			Case 3b (envelope n° 5)	**Case 4b** (envelope n° 5)	**Case 5b** (envelope n° 5)	**Case 6b** (envelope n° 5)	**Case 7b** (envelope n° 5)	**Case 8b** (envelope n° 5)	Scenario 'b' used the most cost-effective envelope n° 5
Summary	As Base Case + **shading**	As Case 1 + **internal gains**	As Case 2 + **increase of insulation**	As Case 3 + **ventilation**	As Case 3 + **reduction of infiltration**	As Case 5 + **ventilation**	As Case 3 + **heating & cooling (AC)**	As Case 5 + **heating & cooling (AC)**	
Details	Case 1 is based on Base Case with shading devices on the north facade.	Case 2 is based on Case 1 with internal gains in order to simulated as close as possible the housing occupancy.	Case 3a/ 3b are based on Case 2 but considering the envelope optimisation. Best performance envelope and the most cost-effective envelope were evaluated.	Case 4a/ 4b are based on Case 3a/ 3b with selective ventilation strategy to reduce high temperatures inside the building.	Case 5a/ 5b are based on Case 3a/ 3b but considering the reduction of infiltration to 0.15 ach.	Case 6a/ 6b are based on Case 5a/ 5b with selective ventilation strategy to reduce high temperatures inside the building.	Case 7a/ 7b are based on Case 3a/ 3b with heating and cooling for maximizing thermal comfort. (for informative purpose)	Case 8a/ 8b are based on Case 5a/ 5b with heating and cooling for maximizing thermal comfort. (for informative purpose)	
Resumed Assumption	Shading devices designed to cut-off at the equinox on the north facade.	Internal gains compatible with an affordable house occupancy (10.9 W/m^2).	Envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre. Envelope n° 5 for all the cities.	Ventilation in summer and mid-season. Windows opening capacity according to Table 6-2.	Reduction of infiltration to 0.15 ach, as the lowest limit without using mechanical ventilation	Ventilation in summer and mid-season. Windows opening capacity according to Table 6-2.	Thermostat to maintain the temperature within the narrow thermal comfort interval of 20-25 °C.		

The best performance envelope n° 72 (Curitiba): (DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof.
The best performance envelope n° 108 (São Paulo and Porto Alegre): (DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof.
The most effective envelope n° 5 (all cities): (SGU) Single glazing, (HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil roof.

6.8.1 Assumptions

i. Weather data: As Base Case

ii. Calendar: As Base Case

iii. Shading: Additional horizontal shading devices were placed on the north windows to cut-off at the equinox. The resultant VSA angles correspond to 64.57°, 66.15° and 59.97° for Curitiba, São Paulo and Porto Alegre, respectively. It considered blocking radiation in summer and allowing it in winter. The model with additional shading can be found in Appendix C.

iv. Internal gains: Typical internal gains for family routine and lifetime habits have been assumed based on affordable Brazilian housing occupancy. The internal gains of the Alvorada house totalled on average 10.9 W/m^2, distributed among occupancy, lighting and appliances. The assumptions used in the simulations were based on the RTQ-R label (INMETRO, 2012) and are described below:

   a. Occupants: 4 people were assumed to use the house, a couple using one bedroom and two people in the other bedroom. Different patterns of occupancy were considered for weekdays and weekends. In weekdays, all of the occupants were assumed to be out during the day and in different locations during the early mornings and evenings, while in the weekends, the occupants were assumed to be predominantly at home. Occupants were assumed to use the spaces according to the schedules in Table 6-8. The heat gain assumed for each person was compatible with sedentary work (130 W), which corresponded to a sensible heat gain of 75 W and the latent heat gain of 55 W for kitchen and living. For bedrooms, the heat gain was assumed seated at rest (95 W), which corresponded to a sensible heat gain of 65 W and the latent heat gain of 30 W. These values were based on ASHRAE (2009a, p. 18.4).

   b. Lighting: Low energy compact fluorescent bulbs (CFL) were considered, resulting in the thermal loads of 5W/m^2 for the bedrooms and 6W/m^2 for the living room/ kitchen when they were switched on, as suggested by RTQ-R label assessment (INMETRO, 2012, p. 71).

   c. Equipment gains: a TV of 30 W power (INMETRO, 2014) was assumed to be used 4 hours per day. This is similar to a power of 1.5 W/m^2 set by INMETRO (2012) for 10 m^2 of living for a 24-hour period.

   d. Household appliances: The number of household goods tends to be more limited in affordable houses than in middle-class standard houses. Thus, internal gains from only the fridge, microwave, iron and washer were calculated in a 24-hour period. They are illustrated in Table 5-8. The

appliances' power were based on Brazilian appliances reference (INMETRO, 2014, PROCEL INFO, 2006), illustrated in Chapter 2.

Table 6-8: Alvorada House schedules of internal gains

0: off; 1: on																								
Weekdays	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
24 hours period	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Occupancy period	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Bedrooms (occupancy)	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Bedrooms (lighting)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Living/ Kitchen (occupancy, lighting)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Living/ Kitchen (TV)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Weekend	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
24 hours period	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Occupancy period	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Bedrooms (occupancy)	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Bedrooms (lighting)	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Living/ Kitchen (occupancy)	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0
Living/ Kitchen (lighting)	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	0	0	0
Living/ Kitchen (TV)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0

Table 6-9: Alvorada House appliances heat gains based on a given usage

Appliance	Unity	Power (kW)	Usage	Daily energy consumption (kWh)
Fridge	Per hour	0.032	year	0.790
Microwave, 30l	When on	1.250	30 min/ day	0.625
Iron	When on	1.200	2.3 hours/week	0.40
Washer, 10 kg	1h per cycle	0.30	2 cycles/ week	0.085
Total of appliance heat gains:				1.9

v. Infiltration: The infiltration rate was assumed to be at a minimum of 0.15 ach (converted from to 3 $m^3/hr/m^2$ at 50 Pa), which is one of the lowest levels of infiltration without using any active ventilation system combined.

vi. Ventilation: Selective natural ventilation was considered for summer and mid-season as a function of the indoor temperature. All the windows started to open when their adjacent zone temperatures were above 23 °C and remained as fully opened according to their capacity at all temperatures above the upper comfort limit of 25 °C. The windows were closed when the outdoor temperature was higher than the indoor temperature. The windows' opening capacity was defined according to Table 6-2.

vii. Comfort temperature range: As Base Case

viii. Heating and Cooling: Active space conditioning was considered to keep the temperature inside the comfort range of 20-25 °C.

6.8.2 Results

In Cases 1 to 8, as in Base Case, the results were shown for the rooms of prolonged occupancy, at both occupant and ceiling levels.

Figure 6-23, Figure 6-24 and Figure 6-25 show the results of Case 1 for Curitiba, São Paulo and Porto Alegre, respectively. The addition of shading in Case 1 did not impact on the building performance when compared to Base Case. The results showed a very slight reduction of high temperatures, which can be considered practically as negligible. This was due to the roof eaves of the house, which were designed to work as an effective shading device for both summer and mid-seasons, as illustrated in Figure 6-5. The results seem to suggest that the existing eaves work properly for delivering the amount of shading needed on the north facade of the building.

As expected, the addition of internal gains due to the occupancy in Case 2 (Figure 6-26, Figure 6-27 and Figure 6-28) showed a considerable reduction of the heating demand for all the cities investigated. Despite the fact that the temperatures increased inside the building, they did not impact on cooling demand in the same manner that they impacted on the heating demand.

In Curitiba, the indoor temperatures within the thermal comfort zone 20-25 °C and 18-29 °C at occupant level were increased to more than 40% and around 65% of the year, respectively. This meant an increase of the narrow and the wide thermal comfort by approximately 33% and 18% when compared to Case 1, respectively. The indoor temperatures below 18 °C and 20 °C at occupant level were reduced to up to 35.3% and 59.2% of the year, respectively. The indoor temperatures above the upper comfort limits of 25 °C were increased slightly but they did not exceed 2% of the time at occupant level.

In São Paulo, the internal gains increased the thermal comfort of 20-25 °C and 18-29 °C to more than 58% and 89% of the year in the occupied areas, respectively. When compared to Case 1, the thermal comfort increased by 10% and 7% for the narrow and wide thermal comfort range, respectively. The occupied areas below 18 °C and 20 °C were reduced to up to 11.3% and 30.8% of the year, respectively. Also, at occupant level, the indoor temperatures above the upper limit of 25 °C were slightly increased to up to 11.2% but this increase was negligible above the upper limit of 29 °C.

In Porto Alegre, the occupied areas within the narrow thermal comfort of 20-25 °C corresponded to 42% of the year and they were identical as in Case 1. However, the occupied areas within the wide thermal comfort 18-29 °C were increased to more than 81% of the year, which represented 6% more than in Case 1. The occupied areas below 18 °C and 20 °C were reduced to up to 15.5% and 33% of the year, respectively. The occupied areas above 25 °C and 29 °C were increased to about 25% and 3% of the year, respectively.

Figure 6-29, Figure 6-30 and Figure 6-31 reveal the relative humidity levels in Case 1, which were found to be equivalent to those found in Base Case. The relative humidity levels in Case 2 (Figure 6-32, Figure 6-33 and Figure 6-34) were increased considerably when compared to Case 1. The occupied areas had the relative humidity levels above 80% increased to approximately 44%, 19% and 21% of the time in Curitiba, São Paulo and Porto Alegre, respectively. This meant an increase of the relative humidity levels above 80% by 57%, 137.5% and 40% when compared to Case 1, respectively.

To sum up, the increase of the thermal comfort in Porto Alegre due to the internal gains seemed to be limited when compared to the other cities because in this city the cooling demand also rose. The next cases focus on reducing both indoor cooling and heating demand of the Alvorada House by adopting Fabric First approach key elements, such as the increase of envelope insulation, the use of selective ventilation and the reduction of infiltration rate.

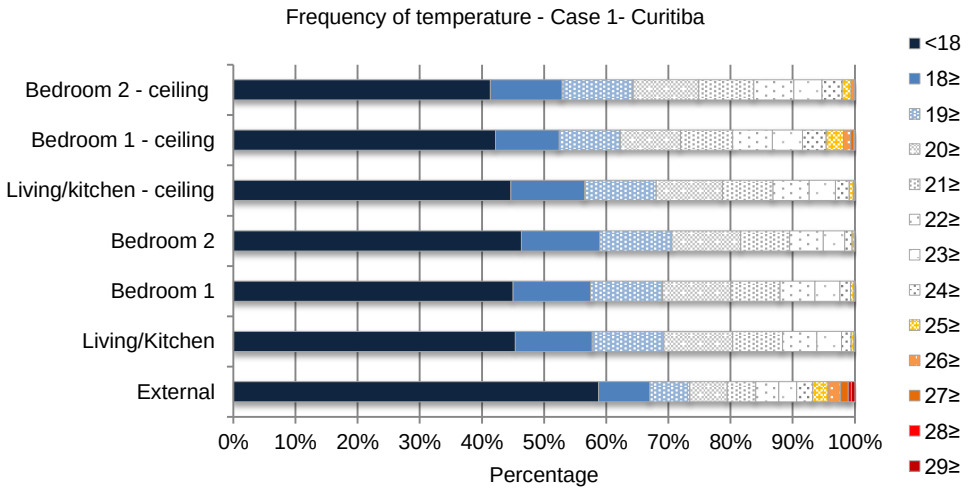


Figure 6-23: Frequency of temperature, Case 1, Curitiba

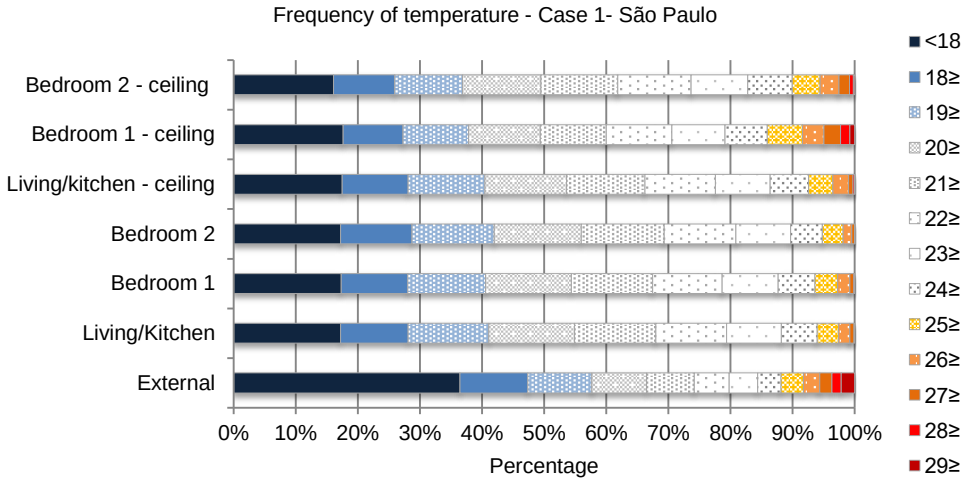


Figure 6-24: Frequency of temperature, Case 1, São Paulo

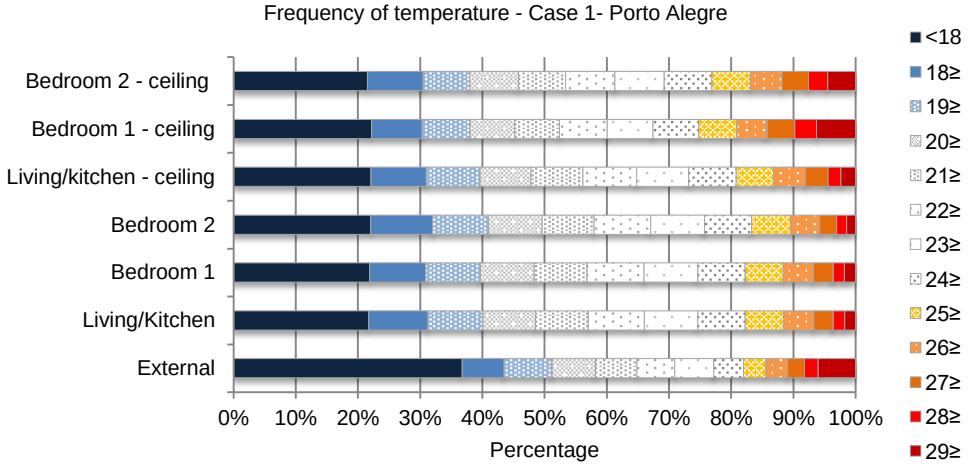


Figure 6-25: Frequency of temperature, Case 1, Porto Alegre

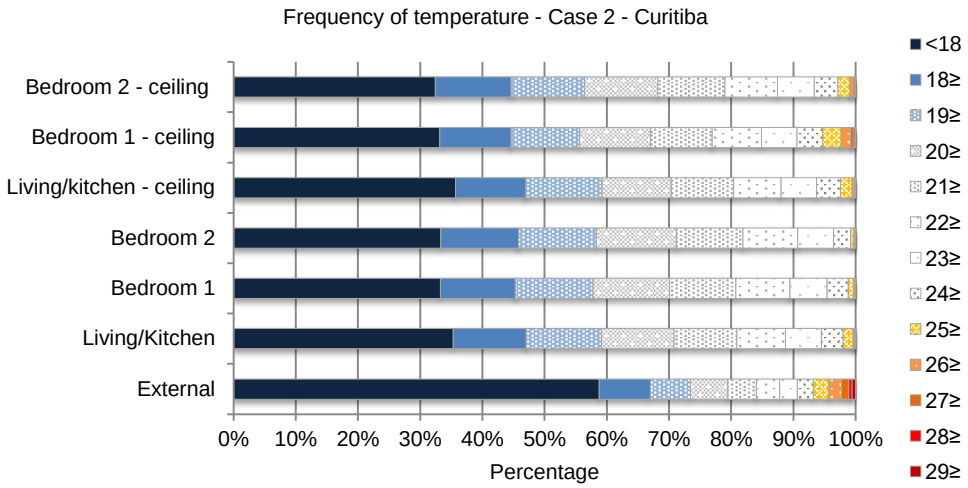


Figure 6-26: Frequency of temperature, Case 2, Curitiba

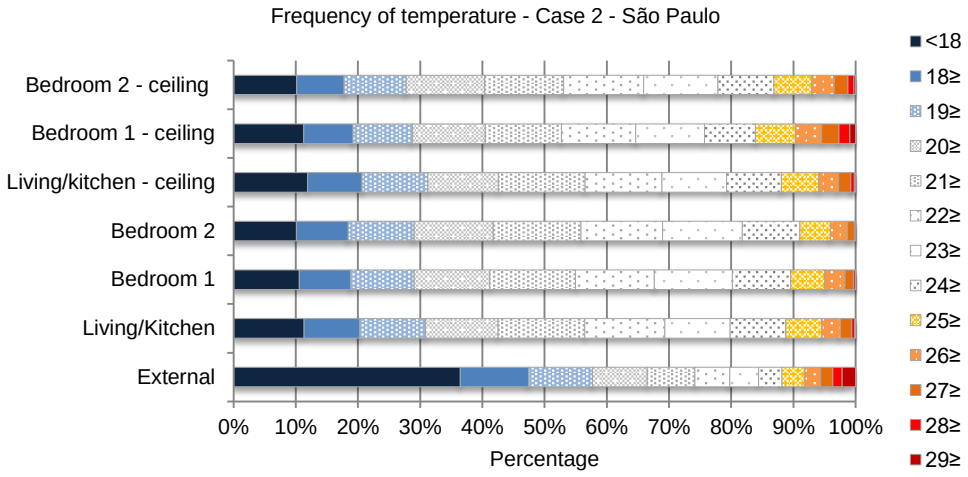


Figure 6-27: Frequency of temperature, Case 2, São Paulo

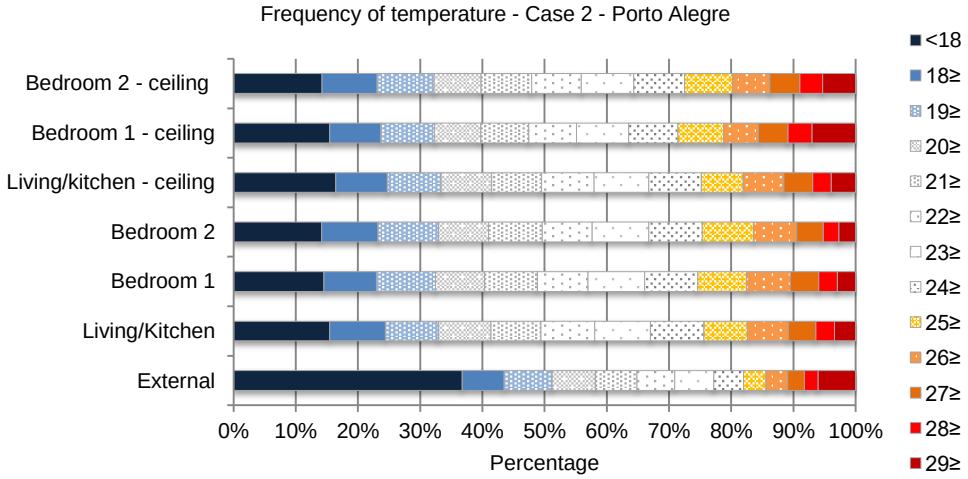


Figure 6-28: Frequency of temperature, Case 2, Porto Alegre

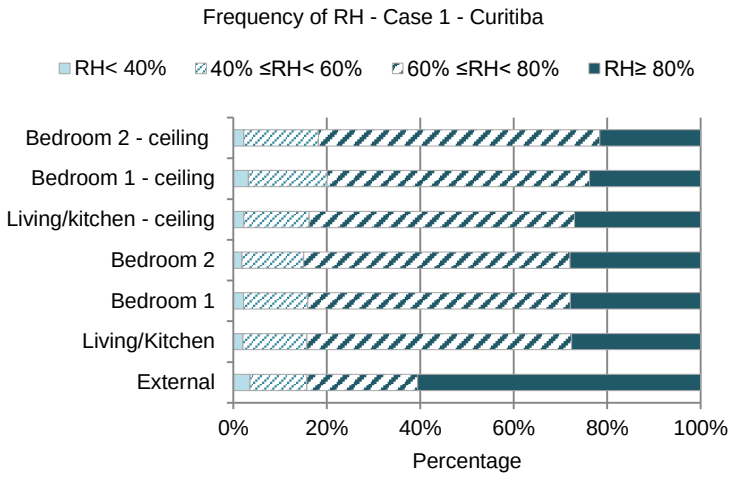


Figure 6-29: Frequency of relative humidity, Case 1, Curitiba

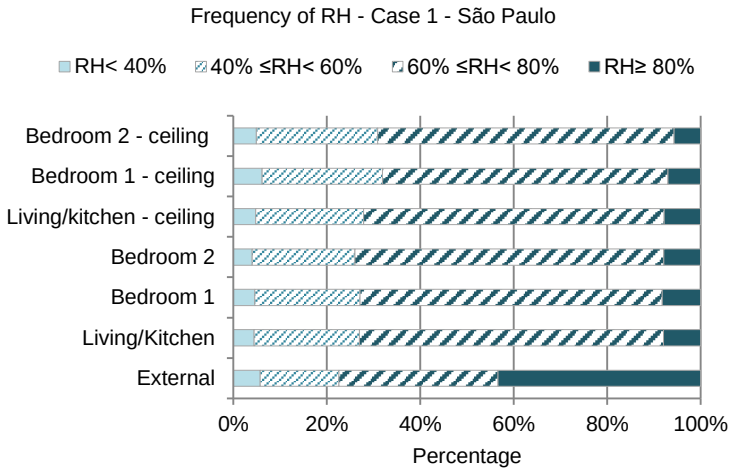


Figure 6-30: Frequency of relative humidity, Case 1, São Paulo

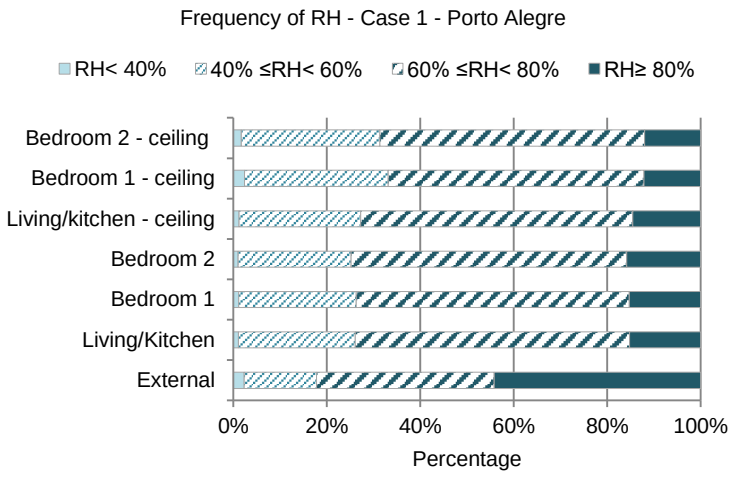


Figure 6-31: Frequency of relative humidity, Case 1, Porto Alegre

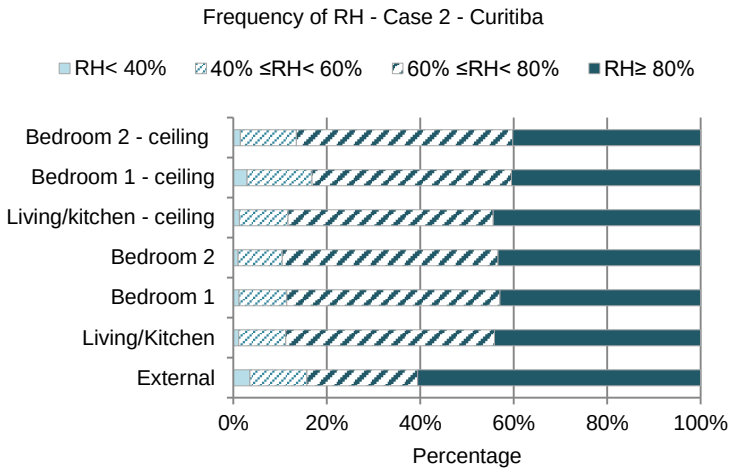


Figure 6-32: Frequency of relative humidity, Case 2, Curitiba

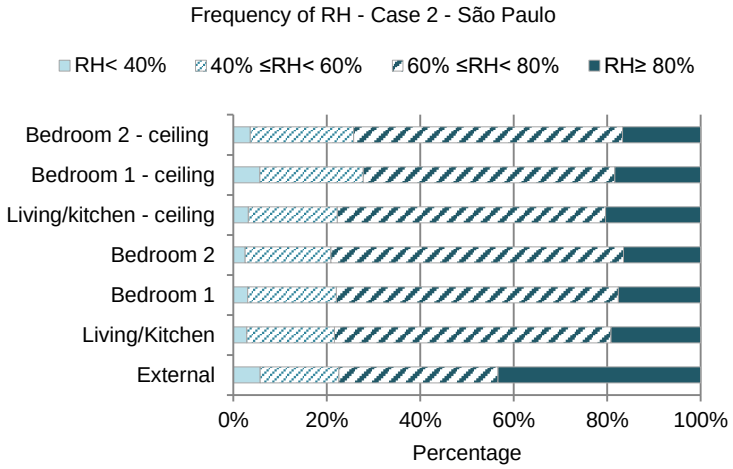


Figure 6-33: Frequency of relative humidity, Case 2, São Paulo

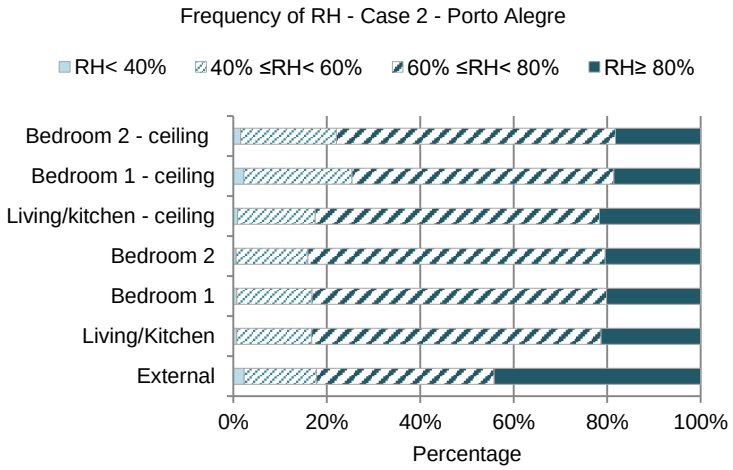


Figure 6-34: Frequency of relative humidity, Case 2, Porto Alegre

Case 3 considered the optimisation of the building envelope for two different scenarios, based on the findings of the sensitivity analysis shown in Chapter 4. Case 3a adopted the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, which consisted of a fully insulated envelope similar to the Passivhaus standard level. Case 3b adopted the most cost-effective envelope n° 5 for all the cities investigated, which consisted of the typical Brazilian building envelope with an insulation layer of 10 cm on the external walls. The detailed description of these envelopes can be found in Appendix A.

In Case 3a (Figure 6-35, Figure 6-36 and Figure 6-37) the occupied areas suffered a dramatic increase of the thermal comfort when compared to Case 2.

In Curitiba, the thermal comfort in occupied areas corresponded to more than 34.6% and 77.5% of the year for the comfort range of 20-25 °C and 18-29 °C, respectively. When compared to Case 2, the adoption of the envelope n° 72 reduced the thermal comfort by 13.5% for the narrow thermal comfort interval but increased it by 19% for the wide thermal comfort interval. Despite the fact that the temperature frequency below 20 °C were increased to 65.4% of the year, the temperature frequency below 18 °C were diminished to up to 22.5% of the year.

In São Paulo, the occupied areas were within the thermal comfort of 20-25 °C and 18-29 °C for more than 84% of the year and for all year long, respectively. This result corroborated the analyses shown in Chapter 3 and 4, in which the thermal comfort in São Paulo can be achieved easier with appropriate changes in the envelope and by passive means. When compared to Case 2, the adoption of the envelope n° 108 increased thermal comfort by 45% and 12% for the narrow and wide thermal comfort interval, respectively. The occupied areas weren't below 18 °C in any circumstance and were below 20 °C for no more than 16% of the year. The occupied areas also weren't above 25 °C at any time of the year.

In Porto Alegre, the occupied areas were within the thermal comfort of 20-25 °C and 18-29 °C for more than 72.5% and for 98% of the time, respectively. When compared to Case 2, the adoption of the envelope n° 108 increased thermal comfort by 73% and 21% for the narrow and wide thermal comfort interval, respectively. The occupied areas below 18 °C and 20 °C were reduced to 2% and 21% of the year, respectively. The indoor temperatures above 25 °C were reduced to up to 6% of the time.

Comparatively, as expected, Case 3a showed better results in terms of the frequency of temperatures within thermal comfort when compared to Case 3b (Figure 6-44, Figure 6-45 and Figure 6-46) due to its more insulated envelope.

In Case 3b, in Curitiba, the thermal comfort in occupied areas corresponded to more than 37.6% and 73.5% of the year for the thermal comfort range of 20-25 °C and 18-29 °C, respectively. When compared to Case 2, the adoption of the most cost-effective envelope n° 5 reduced the thermal comfort by 6% for the narrow thermal comfort interval but increased it by 13% for wide thermal comfort interval, respectively. The indoor temperatures below 18 °C were diminished to up to 26.5% of the year and the indoor temperatures below 20 °C were slightly increased to 62.4% of the year in the occupied areas, respectively.

In São Paulo, the narrow and the wide thermal comfort were increased to more than 77.9% and to 99% in the occupied areas, respectively. When compared to Case 2, the adoption of the most cost-effective envelope n° 5 increased thermal comfort by 34% and 11% for the narrow and wide interval, respectively. Taking into account the wide thermal comfort interval of 18-29 °C, the results between Case 3a and Case 3b showed to be quite similar, which might suggest that small improvements on the building envelope in São Paulo could be sufficient to ensure better levels of indoor thermal comfort. The occupied areas were below 18 °C and 20 °C for no more than 1% and around 20% of the time, respectively. The indoor temperatures at occupant level were above 25 °C for less than 2% of the time.

In Porto Alegre, the occupied areas were within the thermal comfort interval of 20-25 °C and 18-29 °C for about 61% and 95% of the time, respectively. When compared to Case 2, the adoption of the most cost-effective envelope n° 5 increased thermal comfort by 45% and 17% for the narrow and wide thermal comfort interval, respectively. The occupied areas were below 18 °C and 20 °C for no more than 5% and 26% of the time, respectively. They were above 25 °C up to 13.5% of the time but they were not above 29 °C at any time of the year.

The relative humidity levels above 80% dropped in Curitiba and São Paulo but increased slightly in Porto Alegre in Case 3 (Figure 6-41, Figure 6-42 and Figure 6-43). In particular, the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre had slightly higher levels of relative humidity than the most cost-effective envelope n° 5. For the best performance envelope, the relative humidity levels were above 80% for approximately 39%, 14% and 26% of the time in Curitiba, São Paulo and Porto Alegre, respectively. The levels of relative humidity were decreased by 11% and 26% in Curitiba and São Paulo, respectively, and were increased by 24% in Porto Alegre relative to Case 2. For the most cost-effective envelope, the relative humidity levels were above 80% for 39%, 12% and 22% of the time in Curitiba, São Paulo and Porto Alegre, respectively. This meant that the levels of relative humidity were decreased by 11% and 37% in Curitiba and São Paulo, respectively, and were increased by 5% in Porto Alegre relative to Case 2.

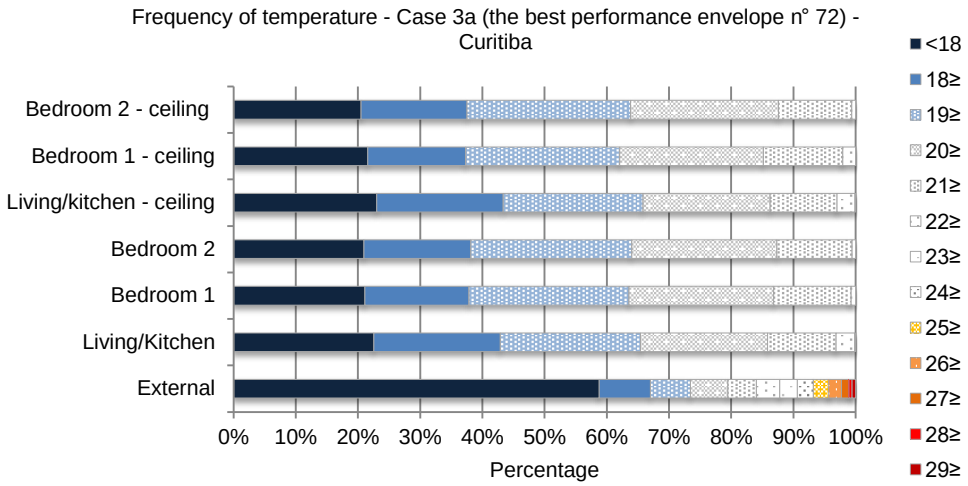


Figure 6-35: Frequency of temperature, Case 3a, Curitiba

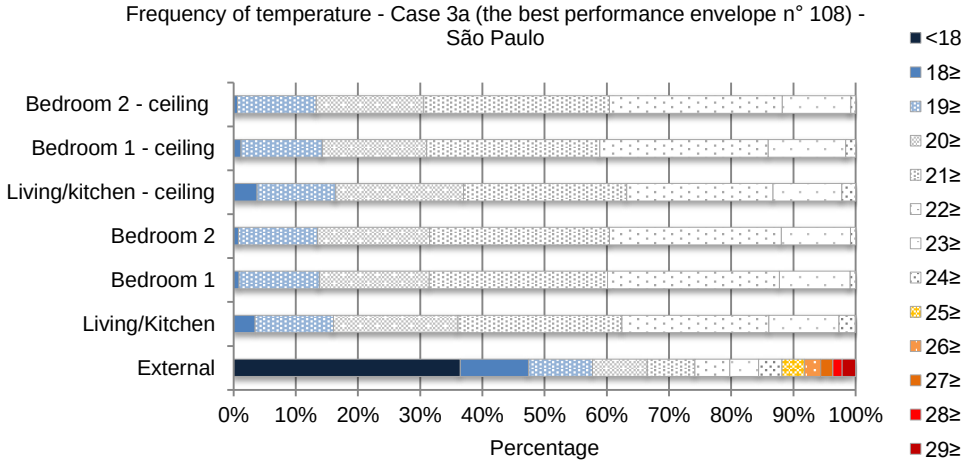


Figure 6-36: Frequency of temperature, Case 3a, São Paulo

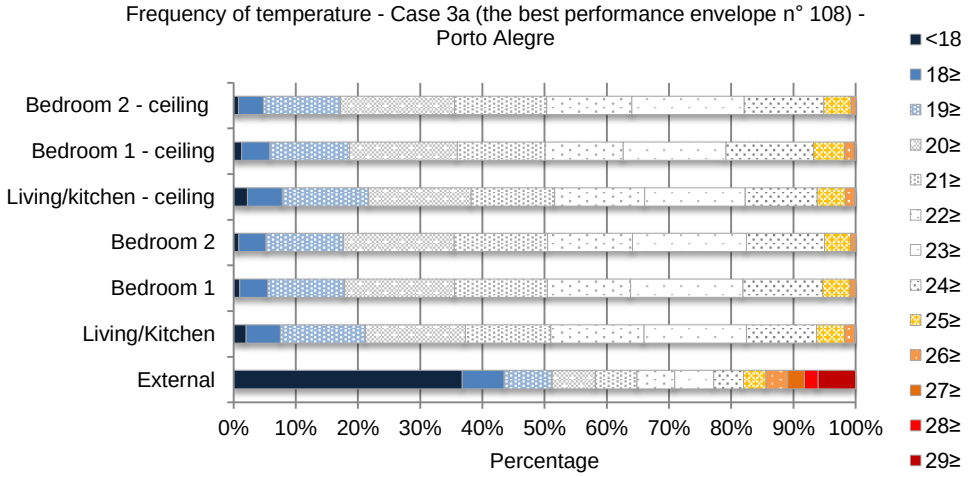


Figure 6-37: Frequency of temperature, Case 3a, Porto Alegre

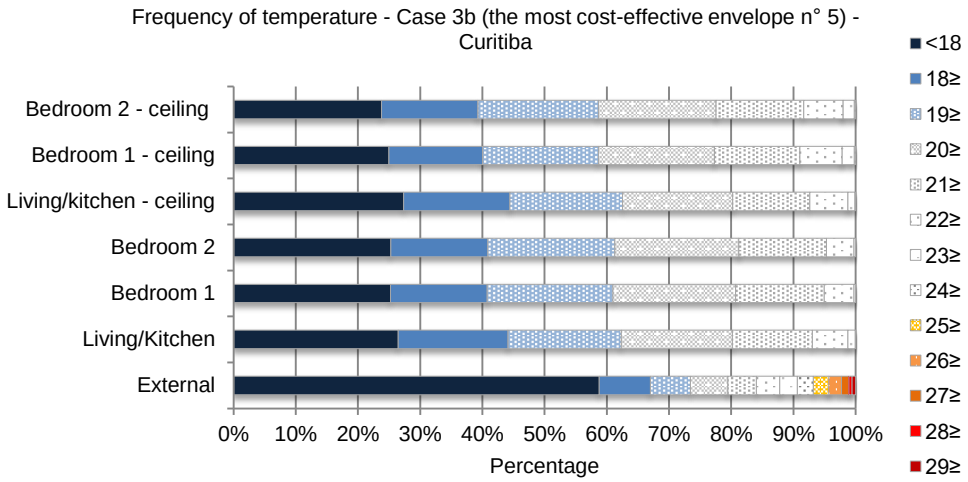


Figure 6-38: Frequency of temperature, Case 3b, Curitiba

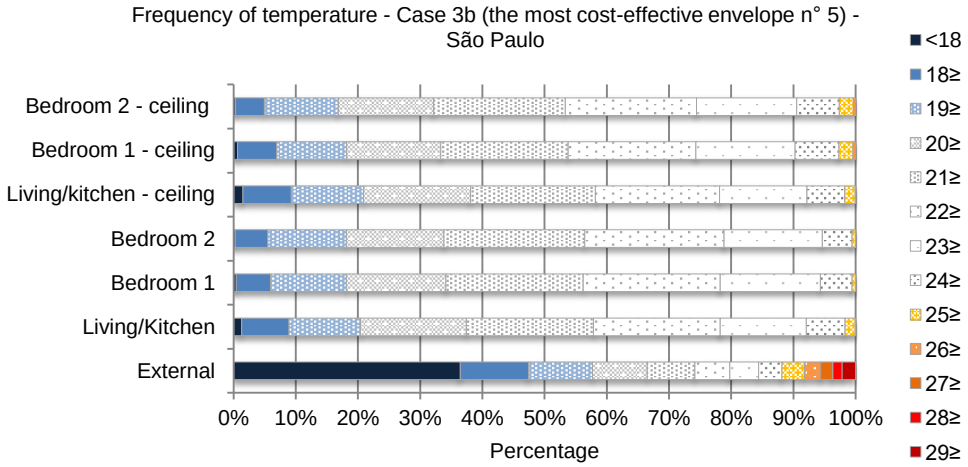


Figure 6-39: Frequency of temperature, Case 3b, São Paulo

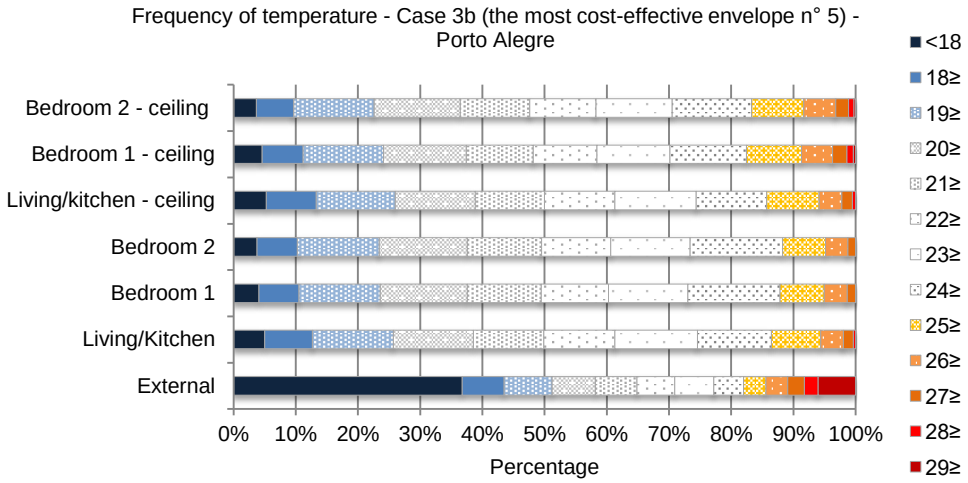


Figure 6-40: Frequency of temperature, Case 3b, Porto Alegre

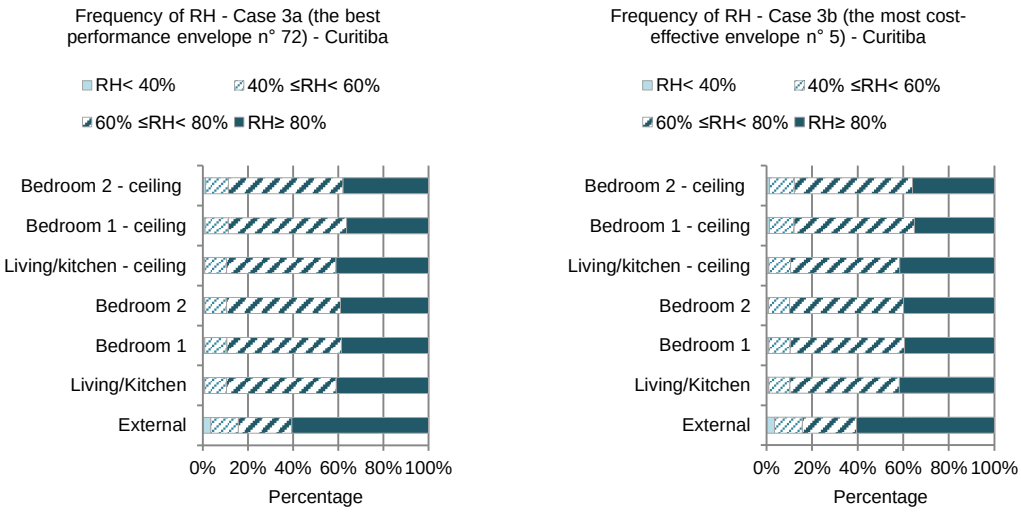


Figure 6-41: Frequency of relative humidity, Case 3a and 3b, Curitiba

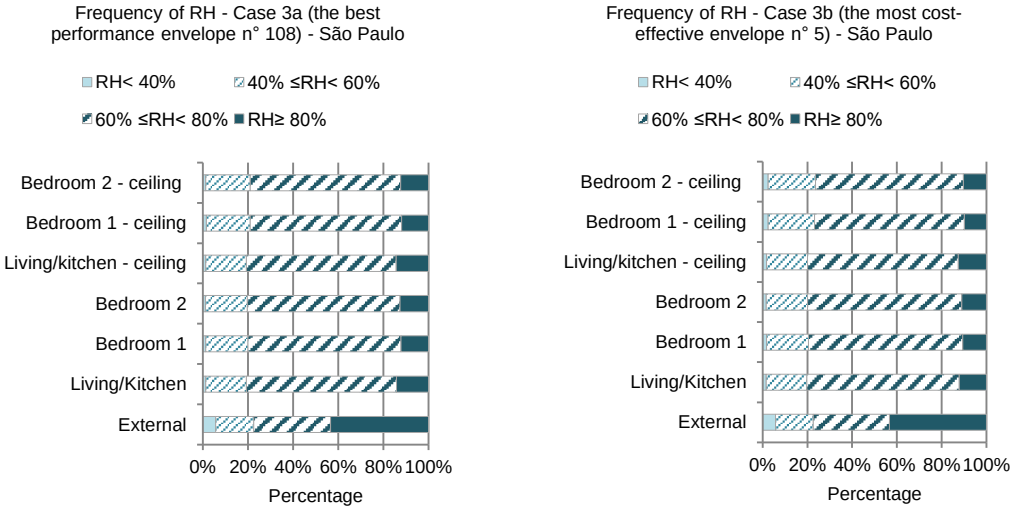


Figure 6-42: Frequency of relative humidity, Case 3a and 3b, São Paulo

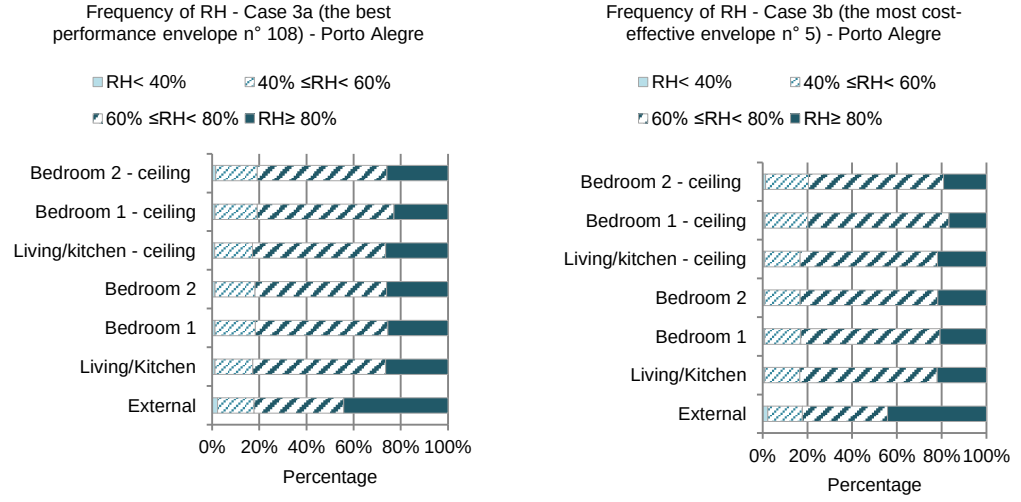


Figure 6-43: Frequency of relative humidity, Case 3a and 3b, Porto Alegre

Case 4 used selective natural ventilation to reduce the high temperatures inside the building that the envelope was not able to mitigate in itself and also to help dissipate the relative humidity inside the building. The selective ventilation assumptions were shown in Section 6.8.1. Case 4a consisted of natural ventilation for the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, whereas Case 4b consisted of natural ventilation for the most cost-effective envelope n° 5, adopted all over the cities.

In Case 4a (Figure 6-44, Figure 6-45 and Figure 6-46) the changes in the indoor temperatures were negligible due to the adoption of natural ventilation in Curitiba and São Paulo when compared to Case 3a. As expected, the reason for that was because most of the indoor temperatures above the upper thermal comfort limit were already mitigated by the optimisation of the envelope in Curitiba and São Paulo. In Porto Alegre, a very slight change in the indoor temperatures above the upper limit of thermal comfort was observed when compared to Case 3a. In this location, the occupied areas had their temperatures above 25 °C reduced by approximately 1% of the time when compared to Case 3a. The thermal comfort of 20-25 °C was increased to over 73% of the time in the occupied areas.

Similarly, in Case 4b (Figure 6-47, Figure 6-48 and Figure 6-49) the benefit of adopting natural ventilation was mostly observed in Porto Alegre. For the other cities the thermal comfort levels remained more or less the same. The occupied areas in Porto Alegre had their temperatures above 25 °C reduced to less than 9% of the year, which meant a reduction by more than 3% of the year when compared to Case 3b. The thermal comfort of 20-25 °C was increased to 64% of the time.

Figure 6-50, Figure 6-51 and Figure 6-52 show the relative humidity levels in Case 4. The Figures reveal that ventilation can successfully remove the moisture inside the building. However, because in Curitiba the windows were mostly closed as a function of the temperatures, the levels of humidity were kept almost unchanged relative to Case 3. However, in São Paulo and Porto Alegre, the relative humidity levels in occupied areas above 80% were reduced to 13% and 24% of the time for the best performance envelope n° 108 (Case 4a) and to 11% and 20% for the most cost-effective performance n° 5 (Case 4b). This meant that the ventilation in both Case 4a and 4b reduced the relative humidity above 80% by 1% of the time in São Paulo and by 2% of the time in Porto Alegre when compared to Case 3a and 3b.

As long as ventilation is used, the relative humidity tends to drop inside the building when the external conditions are favourable. It should be highlighted, however, that ventilation can be counterproductive in terms of temperatures if the occupants are not aware how to manage it correctly, i.e. to open or close the windows according to the outdoor conditions.

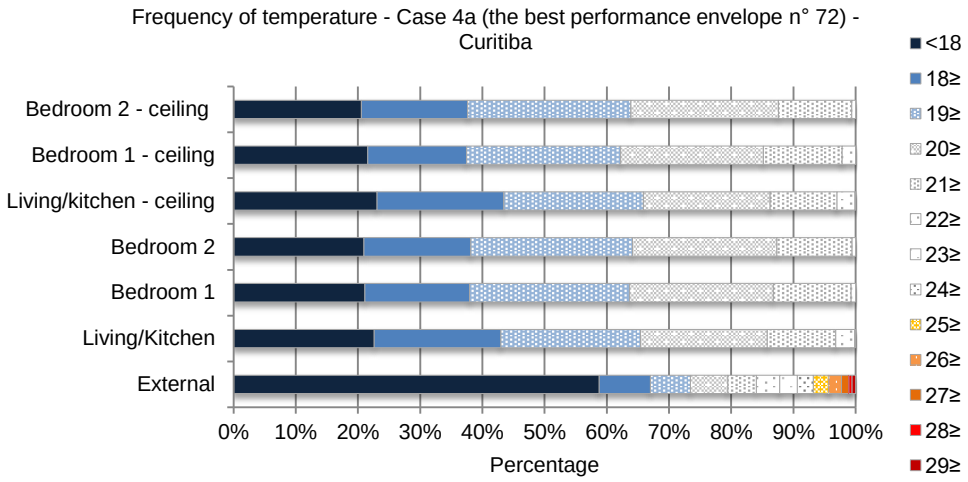


Figure 6-44: Frequency of temperature, Case 4a, Curitiba

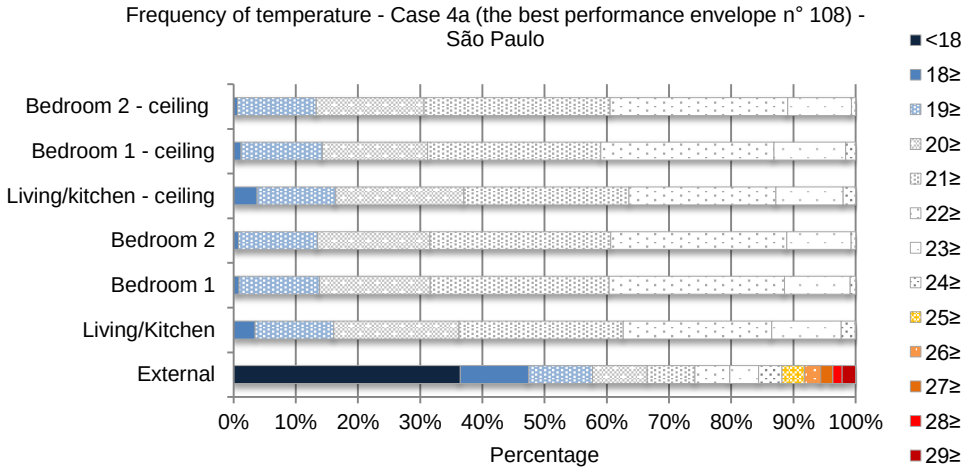


Figure 6-45: Frequency of temperature, Case 4a, São Paulo

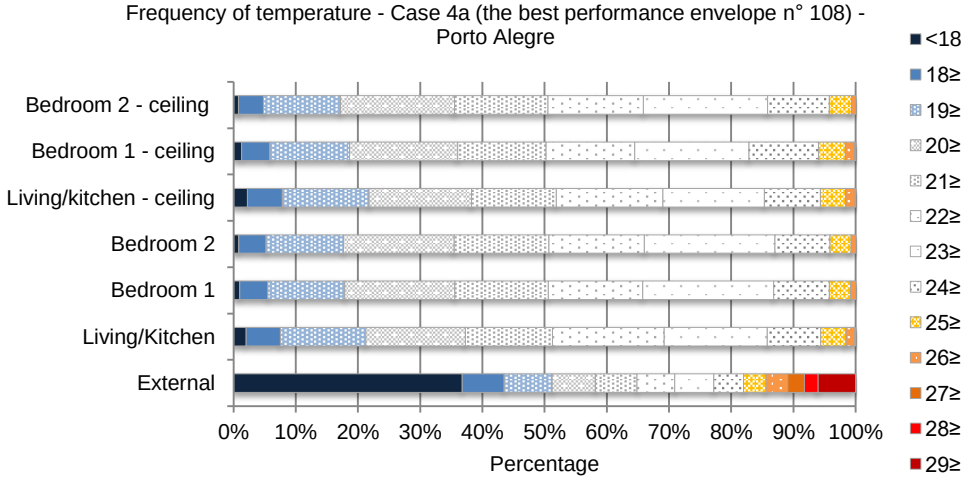


Figure 6-46: Frequency of temperature, Case 4a, Porto Alegre

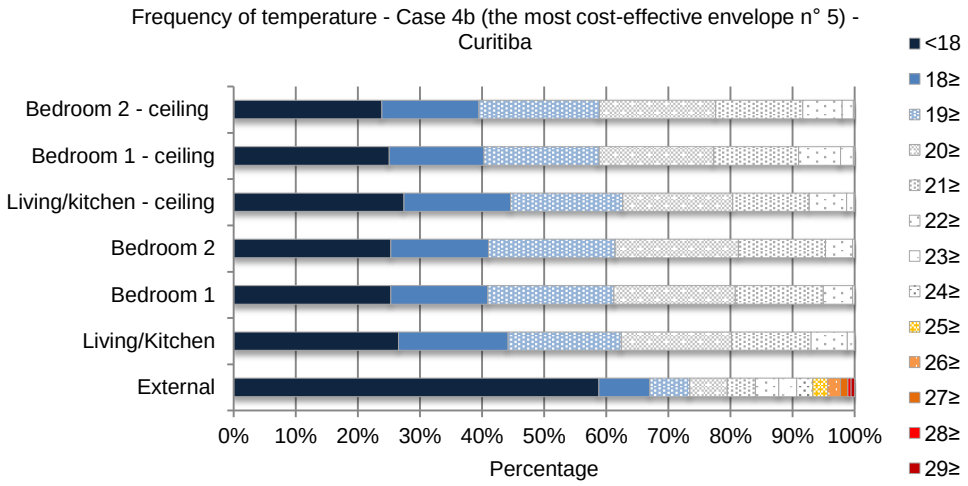


Figure 6-47: Frequency of temperature, Case 4b, Curitiba

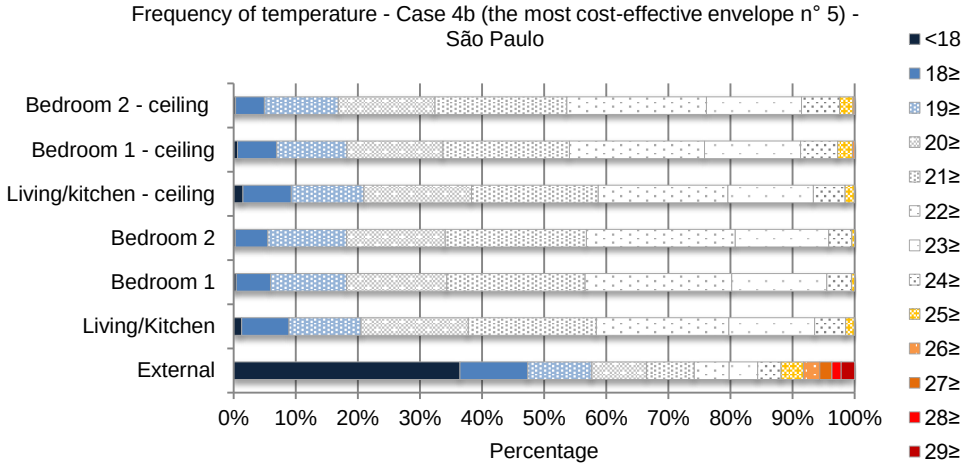


Figure 6-48: Frequency of temperature, Case 4b, São Paulo

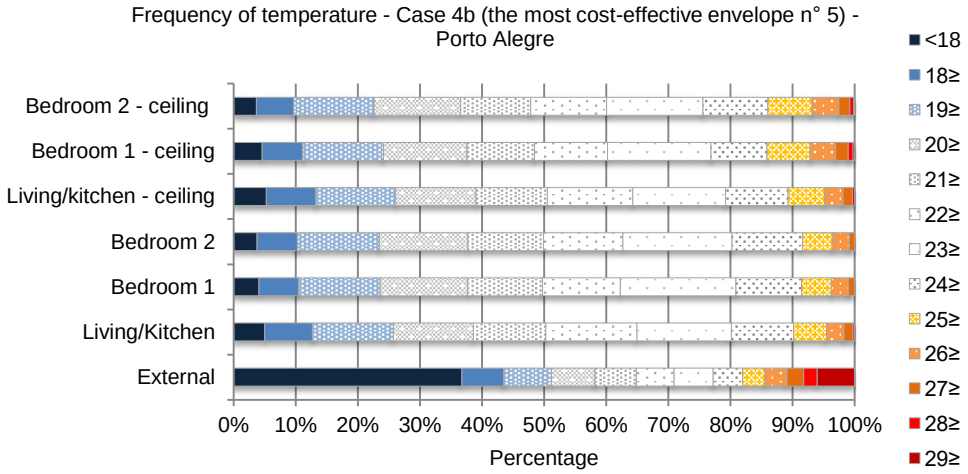


Figure 6-49: Frequency of temperature, Case 4b, Porto Alegre

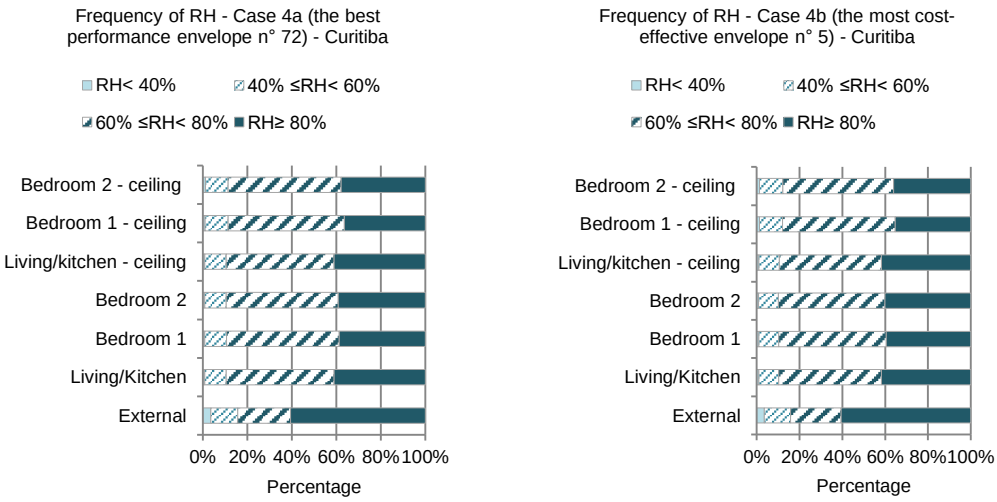


Figure 6-50: Frequency of relative humidity, Case 4a and 4b, Curitiba

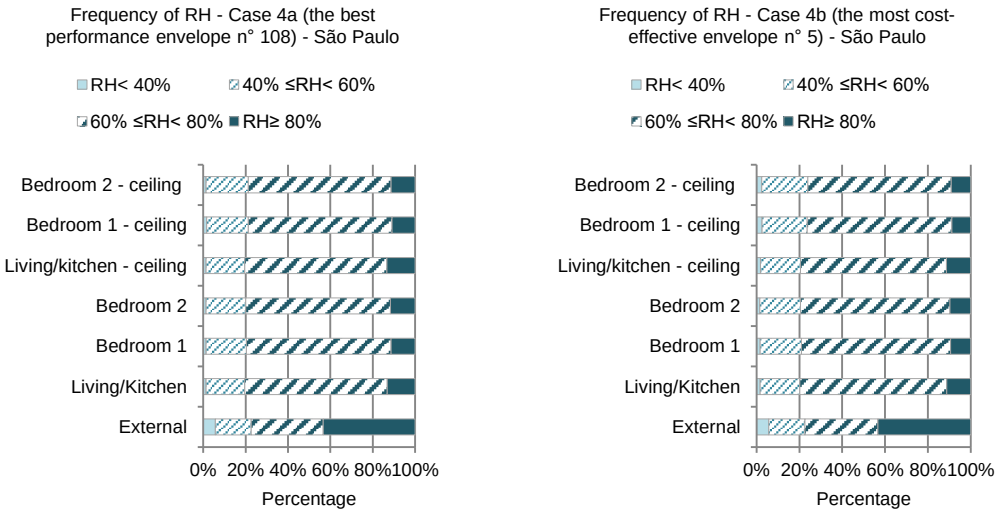


Figure 6-51: Frequency of relative humidity, Case 4a and 4b, São Paulo

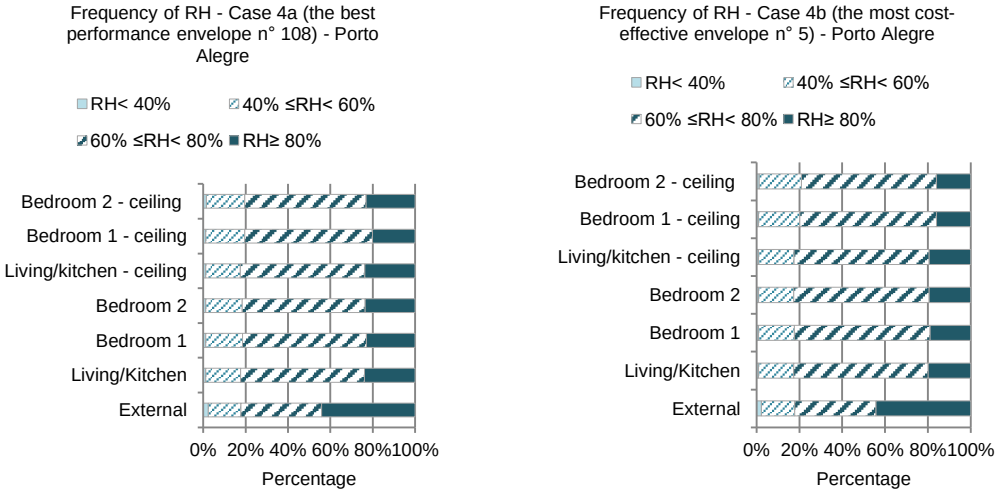


Figure 6-52: Frequency of relative humidity, Case 4a and 4b, Porto Alegre

Case 5 considered the optimised envelopes with a reduced infiltration rate of 0.15 ach (previously 1 ach). Case 5a used the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, whereas Case 5b adopted the most cost-effective envelope n° 5 for all the cities investigated. The reduction of infiltration increased the indoor thermal comfort when compared to Case 3 mainly because the heat exchange to the environment was limited, which reduced both maximum and minimum temperatures inside the building.

In Case 5a (Figure 6-53, Figure 6-54 and Figure 6-55), the cities investigated showed great increase of the indoor thermal comfort, at both occupant and ceiling levels mainly due to the reduction of the frequency of lower temperatures.

In Curitiba, the thermal comfort of occupied areas increased to more than 49.6% and to over 98.7% of the year for a temperature range of 20-25 °C and 18-29 °C, respectively. When compared to Case 3a, this meant an increase of thermal comfort by 43% and by more than 27% for the narrow and wide thermal comfort interval, respectively. At occupant level, the indoor temperatures below 18 °C and 20 °C were greatly decreased to no more than 1.3% and 50% of the time, respectively.

In São Paulo, the occupied areas were within the narrow thermal comfort interval of 20-25 °C throughout the year. When compared to Case 3a, the increase of the indoor thermal comfort was mainly due to the mitigation of indoor temperatures below 20 °C.

In Porto Alegre, the reduction of infiltration increased the indoor thermal comfort to 96.8% and 100% of the time for a temperature range of 20-25 °C and 18-29 °C, respectively. This meant an increase of the narrow and the wide thermal comfort by more than 33% and 2% when compared to Case 3a. At occupant level, the indoor temperatures below 20 °C were reduced to up to 1.2% of the time and the indoor temperatures above 25 °C were decreased to less than 2% of the time.

Similarly, in Case 5b (Figure 6-56, Figure 6-57 and Figure 6-58) there was an increase of the indoor thermal comfort when compared to Case 3b. Specifically in Porto Alegre, where the cooling demand existed, the reduction of infiltration also reduced the indoor temperatures above 25 °C at occupant level, although they were slightly increased at celling level.

In Curitiba, the occupied areas were within the narrow and wide thermal comfort interval for more than 48% and 86.2% of the time, respectively. Compared to Case 3b, this meant an increase of the indoor thermal comfort condition by more than 27% and 17% for the narrow and wide comfort interval, respectively. The occupied areas were below 18 °C and 20 °C for less than 13.8% and 52% of the time, respectively.

In São Paulo, the occupied areas had the thermal comfort increased to 93.1% for the narrow thermal comfort criterion and they achieved 100% of the year for the wide thermal comfort interval. This represented an increase of the narrow and wide thermal comfort interval by 19% and 1% when compared to Case 3b, respectively. The occupied areas were below 20 °C for no more than 6.3% of the time and they were above 25 °C for less than 1% of the time.

In Porto Alegre, the occupied areas had their thermal comfort condition enlarged to 78.6% and 100% of the year for the thermal comfort intervals of 20-25 °C and 18-19 °C, respectively. When compared to Case 3b, this represented an increase of the narrow and wide thermal comfort by 29% and 5%, respectively. The indoor temperatures below 20 °C were reduced to less than 10% of the year at occupant level. The indoor temperatures above 25 °C were slightly reduced to up to 12% of the year at occupant level, but these temperatures were increased from 17.5% to 19% of the time at ceiling level relative to Case 3b.

Despite the fact that a huge benefit in the indoor temperatures was observed reducing the infiltration, the indoor relative humidity levels increased significantly in all the cities, as shown in Figure 6-59, Figure 6-60 and Figure 6-61. This occurred mainly due to the typical high internal gains in affordable houses combined with the lack of air exchange at sufficient levels to reduce the moisture inside the building. This might suggest that if a low infiltration rate was to be adopted for the Brazilian housing context, especial attention should be paid to reducing the potentially high levels of relative humidity.

For the best performance envelope scenario (Case 5a), the relative humidity levels above 80% were increased to 78%, 89% and 68% of the year in the occupied areas, which were 2, 6 and 3 times bigger than the relative humidity levels of Case 3a for Curitiba, São Paulo and Porto Alegre, respectively. For the most cost-effective scenario (Case 5b), the relative humidity levels above 80% were increased to 93%, 62% and 67% of the year, which were 2, 5 and 3 times bigger than the relative humidity levels of Case 3b for Curitiba, São Paulo and Porto Alegre, respectively.

It should be noted that when the temperatures are within the thermal comfort interval, the discomfort sensation due to the high levels of relative humidity on the occupants tends to be considerably smaller than when the temperatures are above or below the thermal comfort zone.

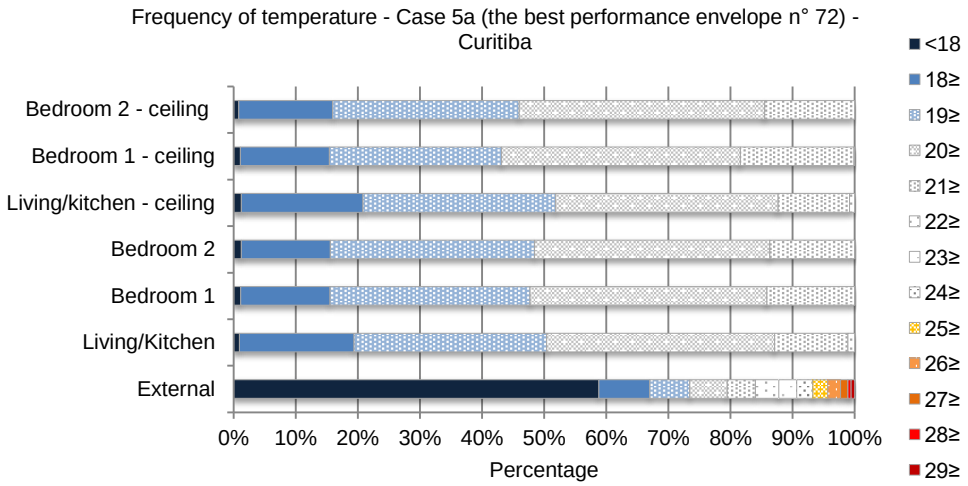


Figure 6-53: Frequency of temperature, Case 5a, Curitiba

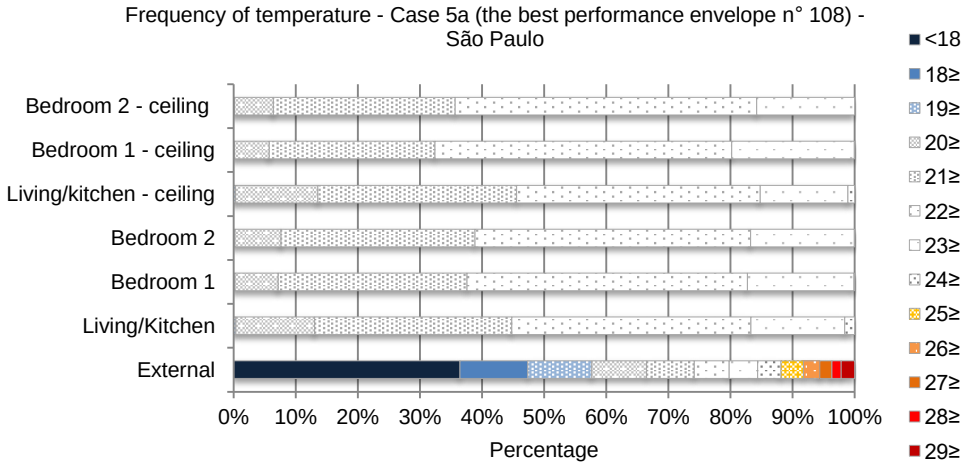


Figure 6-54: Frequency of temperature, Case 5a, São Paulo

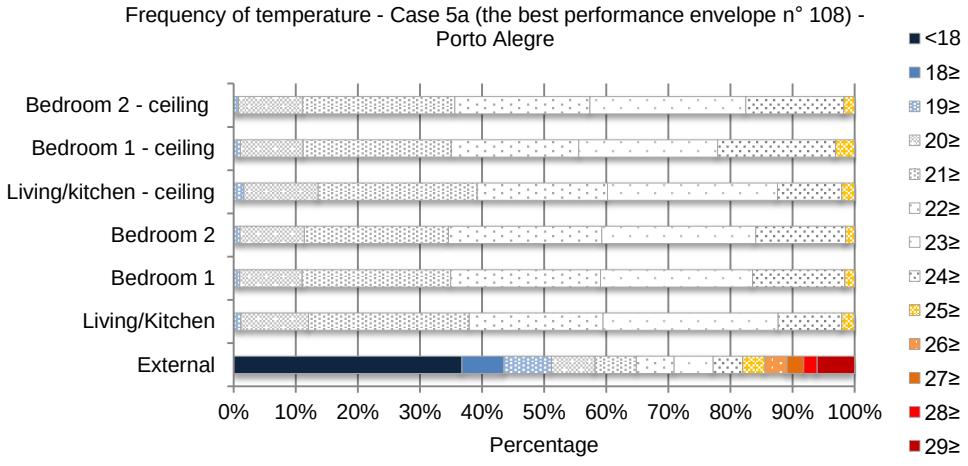


Figure 6-55: Frequency of temperature, Case 5a, Porto Alegre

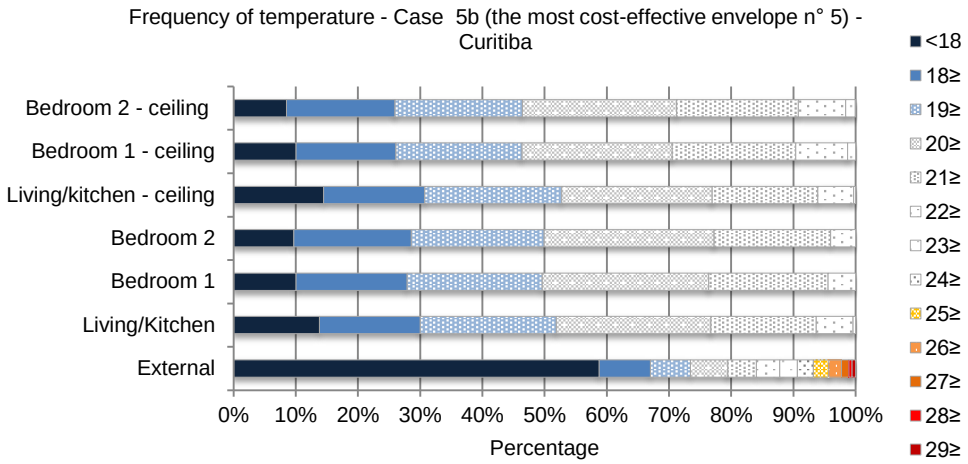


Figure 6-56: Frequency of temperature, Case 5b, Curitiba

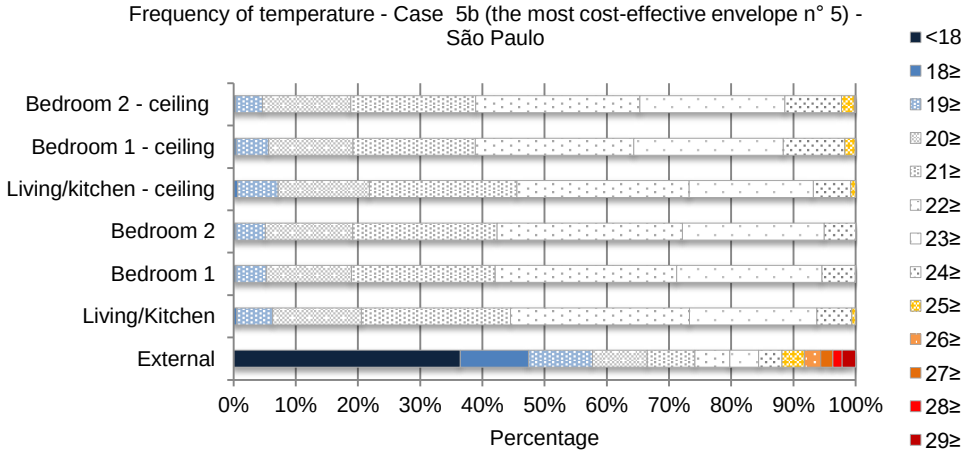


Figure 6-57: Frequency of temperature, Case 5b, São Paulo

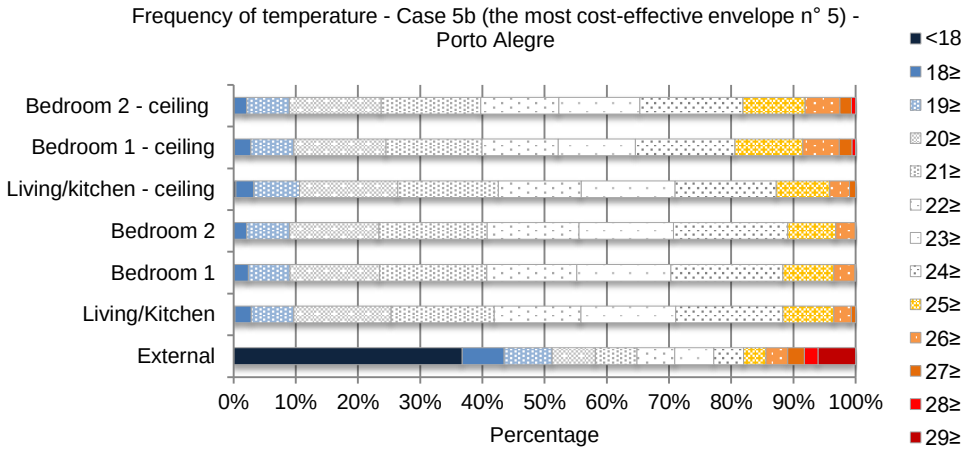
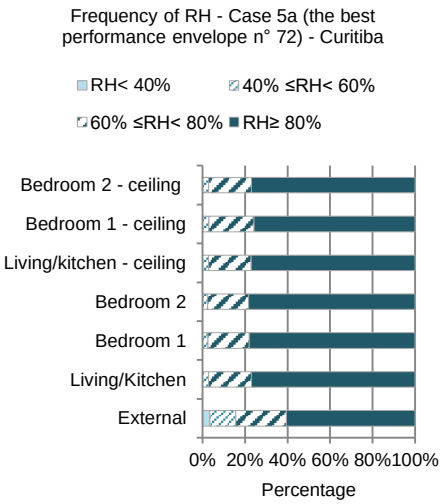


Figure 6-58: Frequency of temperature, Case 5b, Porto Alegre



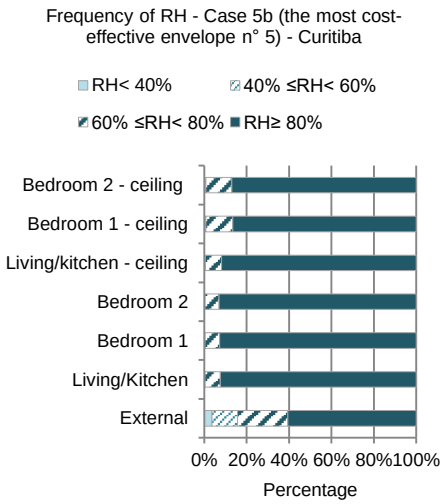
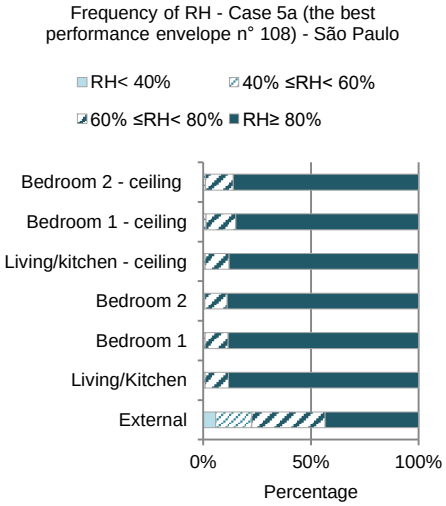


Figure 6-59: Frequency of relative humidity, Case 5a and 5b, Curitiba



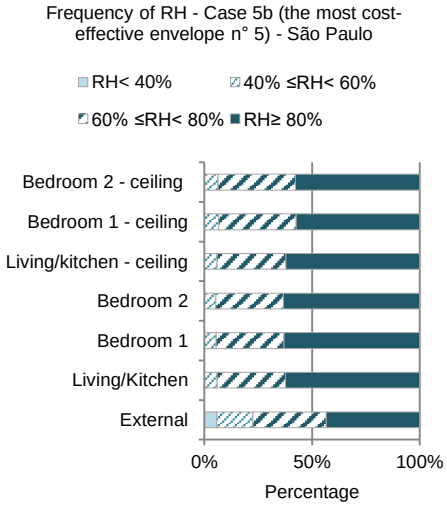
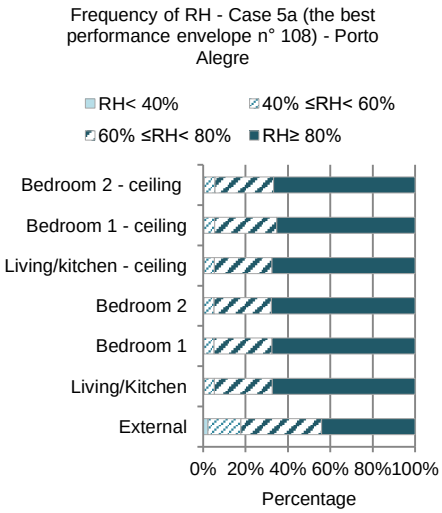


Figure 6-60: Frequency of relative humidity, Case 5a and 5b, Porto Alegre



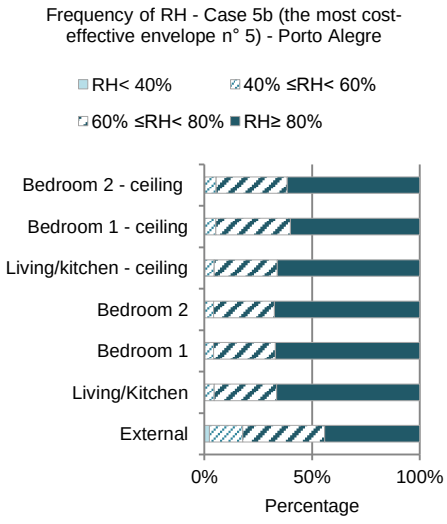


Figure 6-61: Frequency of relative humidity, Case 5a and 5b, Porto Alegre

Case 6 consisted of the adoption of insulated and airtight envelopes, under a regime of natural ventilation.

In Case 6a (Figure 6-62, Figure 6-63 and Figure 6-64), which adopted the best performance envelopes n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, the use of natural ventilation did not impact considerably on the indoor temperatures relative to Case 5a. In Curitiba, the indoor thermal comfort condition remained constant when compared to Case 5a. In São Paulo, the main contribution of ventilation was to reduce the frequency of temperatures in the range between 23 °C and 24 °C and, consequently, increase it to around 22 °C. In Porto Alegre, the indoor temperatures above 25 °C were minimally reduced by less than 0.5% of the time when compared to Case 5a. The main change occurred in the frequency of temperatures around 24 °C, which were reduced and, consequently, the frequency of temperatures in the range between 22 °C and 23 °C were increased.

In Case 6b (Figure 6-65, Figure 6-66 and Figure 6-67), which adopted the most cost-effective envelope n° 5 for all the cities, the use of natural ventilation made a more significant contribution mainly in São Paulo and Porto Alegre when compared to Case 5b. In Curitiba, the indoor thermal comfort condition remained mostly constant when compared to Case 5b. In São Paulo, the frequency of temperatures around 24 °C were reduced to half when compared to Case 5b, being mostly found in the range between 22 °C and 23 °C. In Porto Alegre, the indoor temperatures above 25 °C at occupant level were reduced to up to 7.5% of the year, which suggested an increase of the narrow thermal comfort by about 4% of the year when compared to Case 5b. At ceiling level, as in the case of bedroom 1, the indoor temperatures above 25 °C were reduced from 19.4% to 12.8% of the time relative to Case 5b.

As expected, the adoption of natural ventilation in Case 6 reduced the levels of relative humidity above 80% mainly in São Paulo and Porto Alegre (Figure 6-68, Figure 6-69 and Figure 6-70). In São Paulo and Porto Alegre, the relative humidity levels above 80% were reduced to 84% and 53% of the time for the best performance envelope n° 108 (Case 6a) and to 51% and 48% for the most cost-effective performance n° 5 (Case 6b). This meant that the ventilation reduced the relative humidity above 80% by 6% and 22% for Case 6a and by 18% and 28% in Case 6b for São Paulo and Porto Alegre when compared to Case 5, respectively.

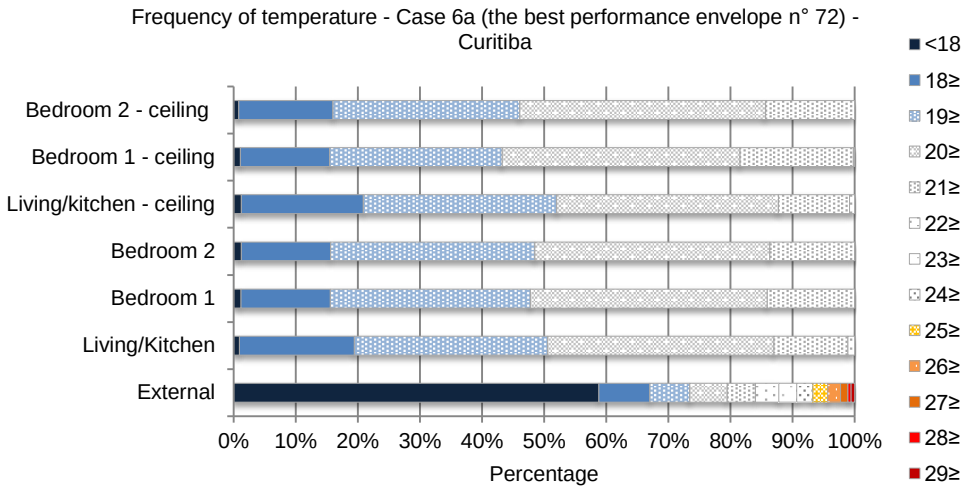


Figure 6-62: Frequency of temperature, Case 6a, Curitiba

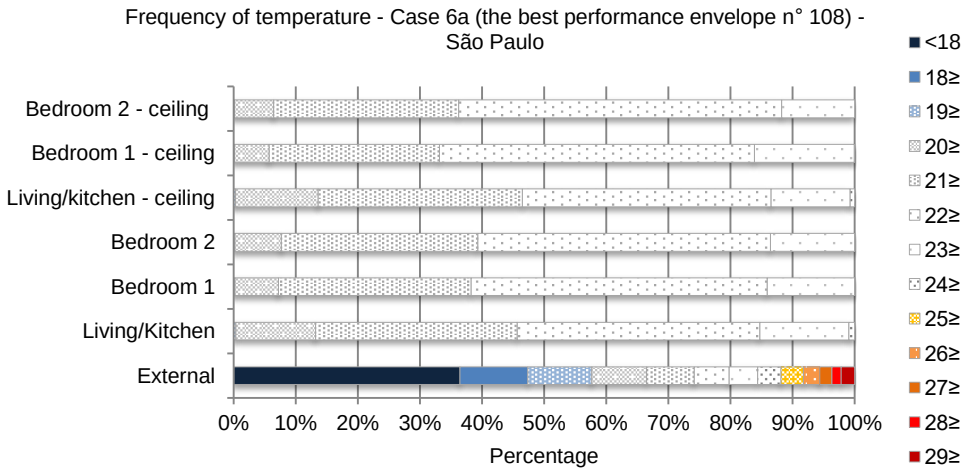


Figure 6-63: Frequency of temperature, Case 6a, São Paulo

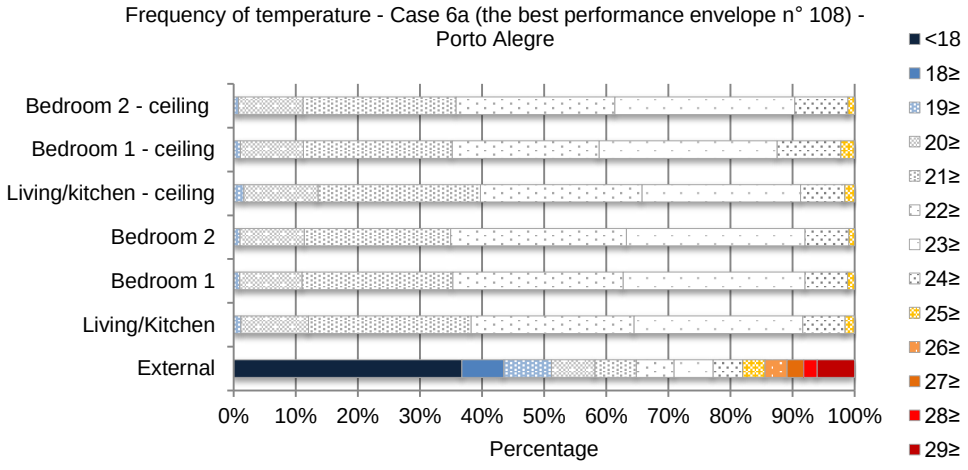


Figure 6-64: Frequency of temperature, Case 6a, Porto Alegre

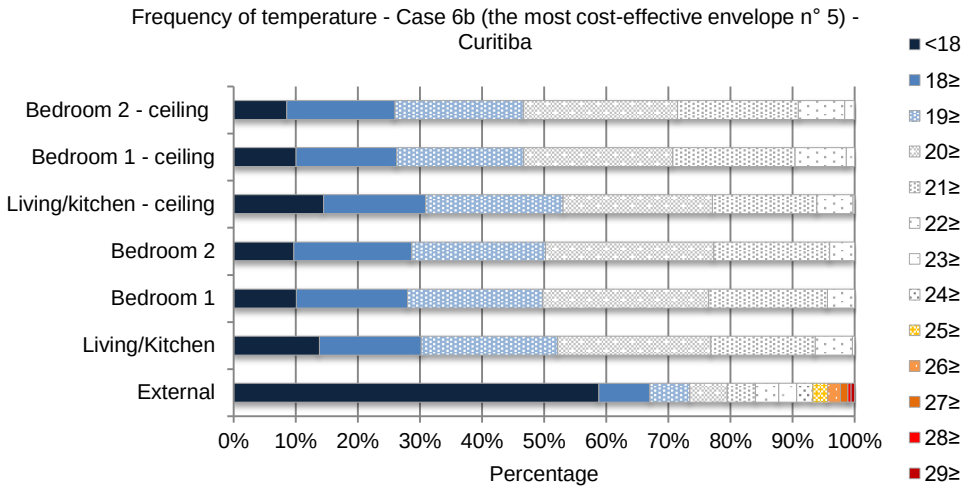


Figure 6-65: Frequency of temperature, Case 6b, Curitiba

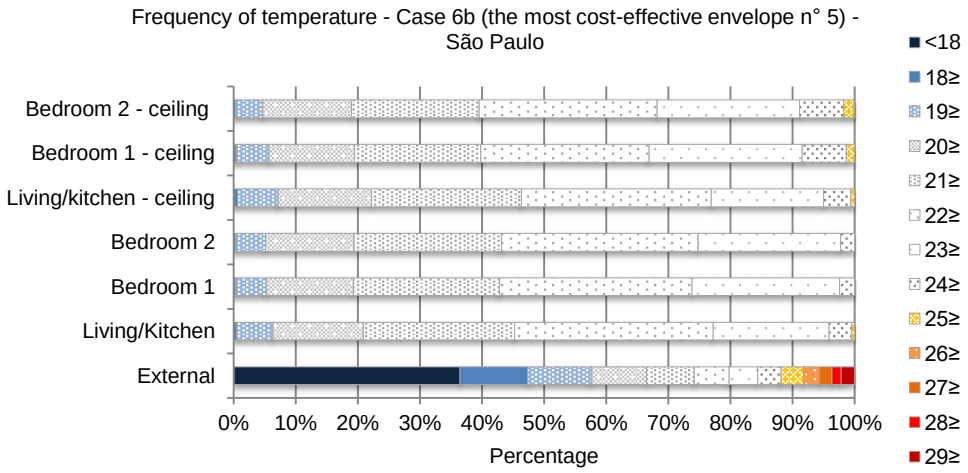


Figure 6-66: Frequency of temperature, Case 6b, São Paulo

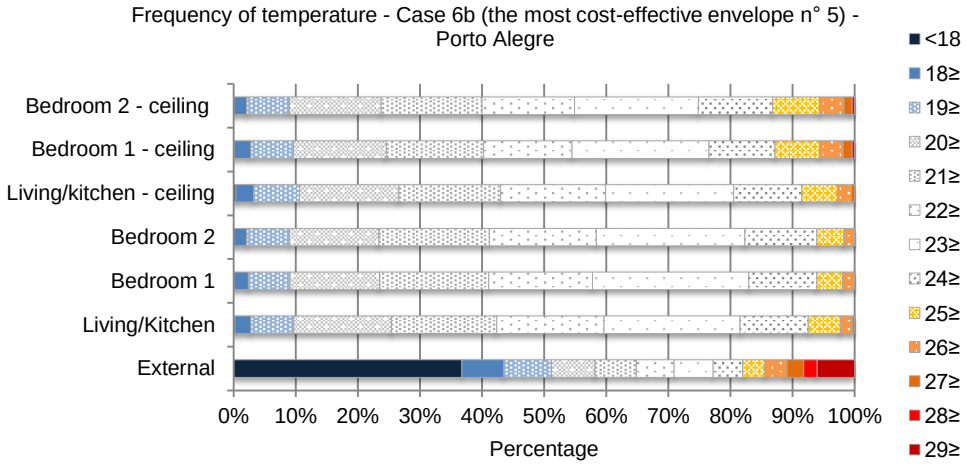


Figure 6-67: Frequency of temperature, Case 6b, Porto Alegre

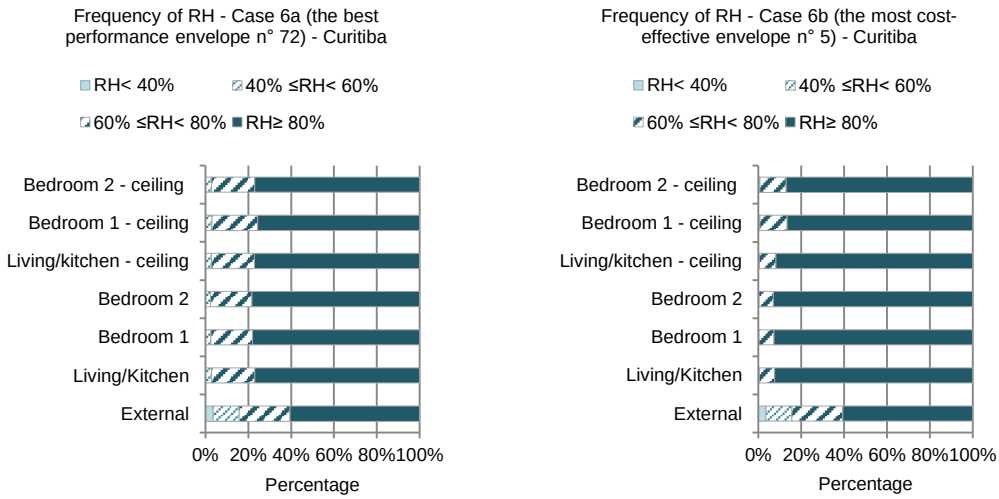


Figure 6-68: Frequency of relative humidity, Case 6a and 6b, Curitiba

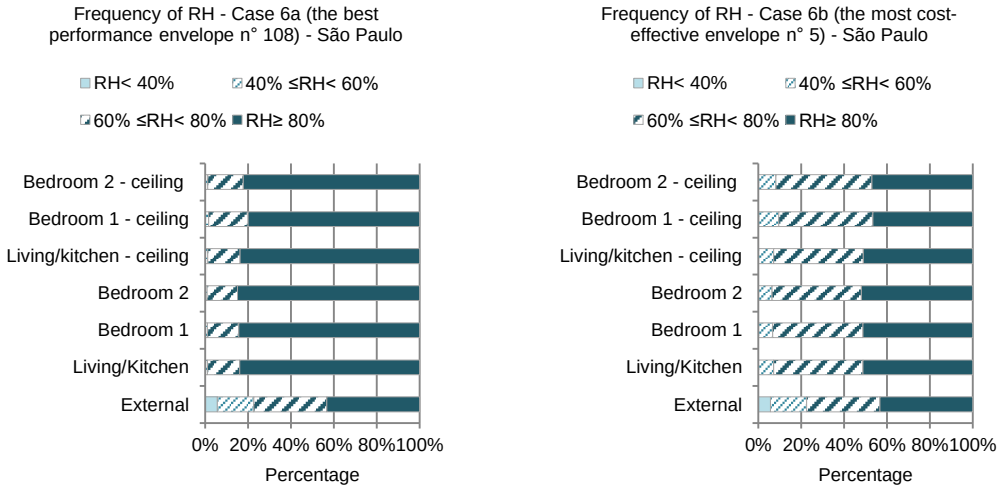


Figure 6-69: Frequency of relative humidity, Case 6a and 6b, São Paulo

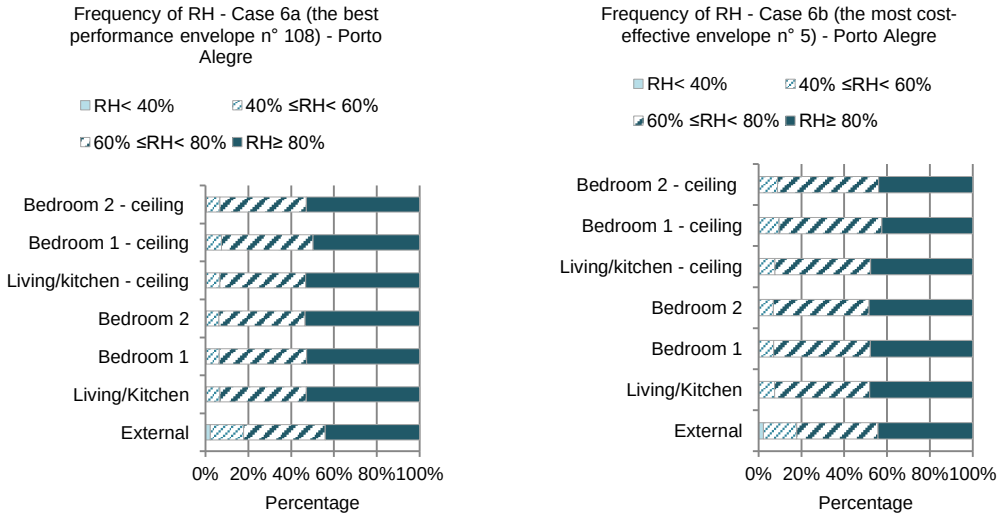


Figure 6-70: Frequency of relative humidity, Case 6a and 6b, Porto Alegre

Table 5-9 shows the thermal comfort percentages achieved for each case investigated.

Table 6-10: Thermal comfort percentage in a year, all cases – Curitiba, São Paulo and Porto Alegre

Thermal comfort – 20-25 °C							
Curitiba	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	30.0%	30.0%	40.0%	34.6%	34.6%	49.6%	49.6%
				Case 3b	Case 4b	Case 5b	Case 6b
				37.6%	37.6%	48.0%	48.0%
São Paulo	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	53.0%	53.0%	58.0%	84.0%	84.0%	100.0%	100.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				77.9%	77.9%	93.1%	93.1%
Porto Alegre	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	42.0%	42.0%	42.0%	72.5%	73.0%	96.8%	97.2%
				Case 3b	Case 4b	Case 5b	Case 6b
				61.0%	64.0%	78.6%	82.8%
Thermal comfort – 18-29 °C							
Curitiba	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	55.0%	55.0%	65.0%	77.5%	77.5%	98.7%	98.7%
				Case 3b	Case 4b	Case 5b	Case 6b
				73.5%	73.5%	86.2%	86.2%
São Paulo	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	83.0%	83.0%	89.0%	100.0%	100.0%	100.0%	100.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				99.0%	99.0%	100.0%	100.0%
Porto Alegre	Base Case	Case 1	Case 2	Case 3a	Case 4a	Case 5a	Case 6a
	76.0%	76.0%	81.0%	98.0%	98.0%	100.0%	100.0%
				Case 3b	Case 4b	Case 5b	Case 6b
				95.0%	95.0%	99.8%	99.8%

Base Case: as built + unoccupied; Case 1: Base Case + shading; Case 2: Case 1 + internal gains; Case 3: Case 2 + increase of insulation; Case 4: Case 3 + ventilation; Case 5: Case 3 + reduction of infiltration; Case 6: Case 5 + ventilation.

Figure 6-71, Figure 6-72 and Figure 6-73 show heating degree-hours for the base temperature of 18 °C, while Figure 6-74, Figure 6-75, Figure 6-76 depict it for the base temperature of 20 °C for Curitiba, São Paulo and Porto Alegre, respectively. The Figures revealed the effect of each strategy on the temperature's magnitude and different envelope optimisation scenarios ('a' and 'b') were comparatively analysed. The major reductions of heating demands were achieved by the internal gains (Case 2), the optimisation of the envelope (Case 3) and the reduction of infiltration (Case 5).

Curitiba showed a benefit by adopting insulated and airtight envelopes from the temperature point of view. For the base temperature of 18 °C, at occupant level, the heating degree-hours of the Alvorada House as built and with internal gains (Case 2) were reduced from about 6000 degree-hours to negligible levels in Case 5a (envelope n° 72, insulated and airtight) and to less than 700 degree-hours in Case 5b (envelope n° 5, insulated and airtight). This represented a reduction of degree-hours by more than 88% and 99%, respectively. Similarly, in São Paulo and Porto Alegre, at occupant level, the degree-hours of the Alvorada House corresponded to around 1000 and 2000 degree-hours and for both cities and for both scenarios of insulated and airtight envelope (5a and 5b), the degree-hours were reduced to negligible levels, respectively.

In Curitiba, for the base temperature of 20 °C, at occupant level, the degree-hours of the Alvorada House as built and with internal gains (Case 2) were reduced from around 14000 degree-hours to less than 4000 degree-hours in scenario 5a (envelope n° 72) and to about 6000 degree-hours in scenario 5b (envelope n° 5). This meant a reduction of degree-hours by more than 71% and 57%, respectively. In São Paulo, the degree-hours were reduced from around 4000 degree-hours to negligible levels in scenario 5a (envelope n° 108) and to less than 200 degree-hours in scenario 5b (envelope n° 5), which corresponded to a reduction of degree-hours by more than 99% and 95%, respectively. Similarly, in Porto Alegre, the degree-hours were reduced from around 6000 degree-hours to negligible levels in scenario 5a (envelope n° 108) and less than 600 degree-hours in scenario 5b (envelope n° 5). This represented a reduction of degree-hours by almost 100% and by more than 90%, respectively.

Figure 6-77, Figure 6-78 and Figure 6-79 illustrate cooling degree-hours for the base temperature of 25 °C in Curitiba, São Paulo and Porto Alegre, respectively. Figure 6-80 shows cooling degree-hours for the base temperature of 29 °C exclusively for Porto Alegre, as the other cities were not found to have degree-hours above this base temperature. The different envelope optimisation scenarios (‘a’ and ‘b’) were also comparatively analysed side by side.

Differently from the heating degree-hours, which had in general similar degree-hours at occupant and ceiling levels, the cooling degree-hours at occupant and ceiling levels varied significantly. As mentioned previously, the temperatures at ceiling level were generally higher and, consequently, the cooling degree-hours were as well. In paticular, the bedrooms had higher cooling degree-hours as they have a small ceiling area when compared to the living room/kitchen.

Whilst the internal gains (Case 2) were responsible for increasing the temperatures above the upper comfort limit, the envelope optimisation (Case 3) and the reduction of infiltration (Case 5) were able to substantially reduce the temperatures above the upper comfort limit and in most of the cases they were able to fully mitigate it.

Porto Alegre had by far the most cooling degree-hours when compared to the other cities. For the base temperature of 25 °C, at occupant level, the cooling degree-hours of the Alvorada House as built and with internal gains (Case 2) were reduced from about 5000 degree-hours to less than 60 degree-hours in Case 5a (envelope n° 108) and to about 800 degree-hours in Case 5b (envelope n° 5). This meant a reduction of the cooling degree-hours by 99% and 84%, respectively. For the base temperature of 29 °C, at both occupant and ceiling levels, the cooling degree-hours in Porto Alegre were reduced from a maximum of 1000 degree-hours to negligible levels for both scenarios of Case 5a and Case 5b.

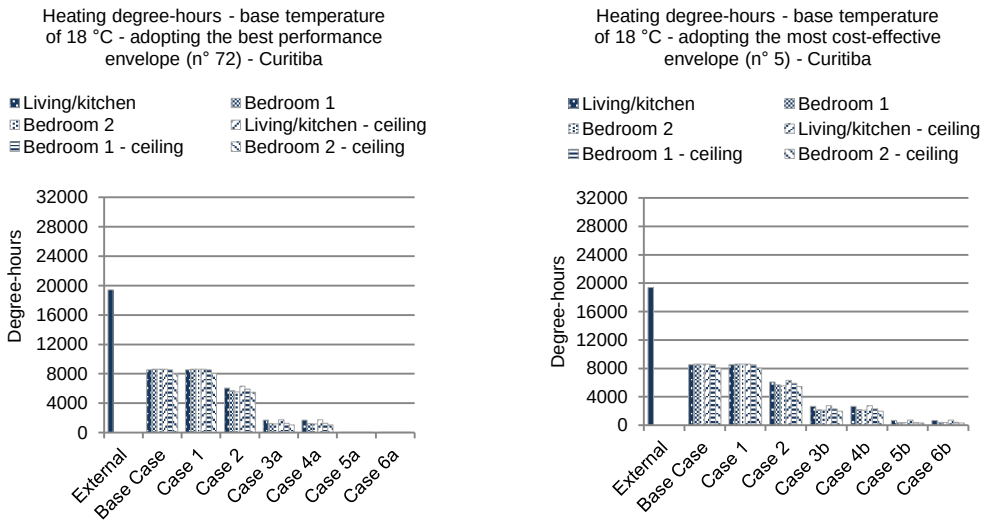


Figure 6-71: Comparison of heating degree-hours, base temperature of 18 °C, all cases, Curitiba

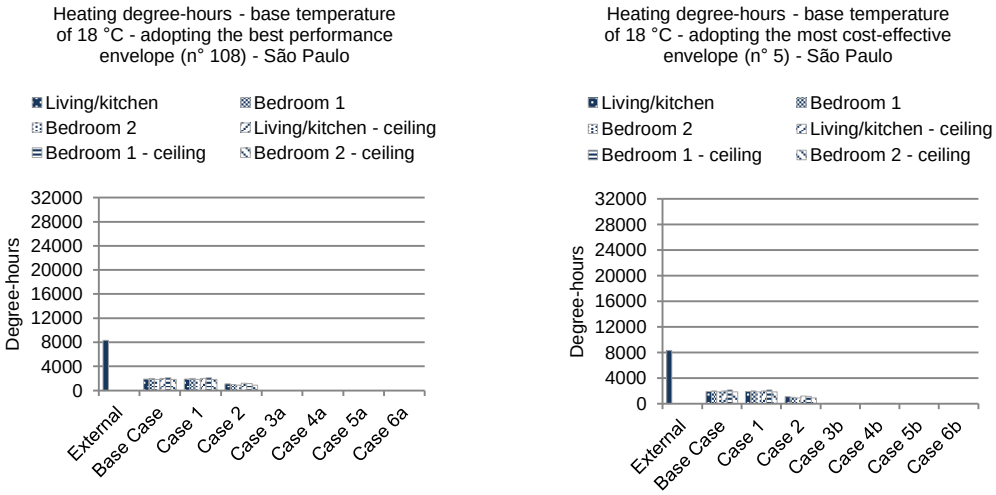


Figure 6-72: Comparison of heating degree-hours, base temperature of 18 °C, all cases, São Paulo

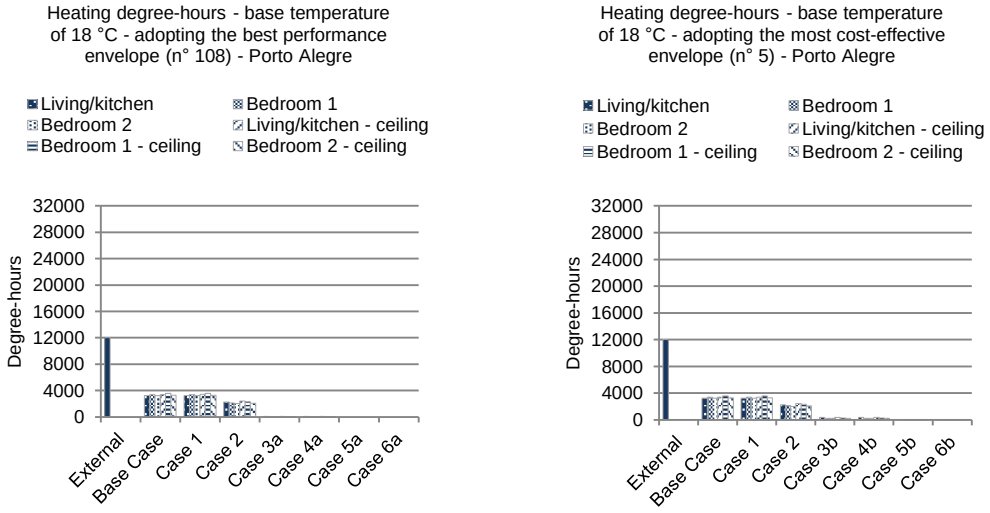
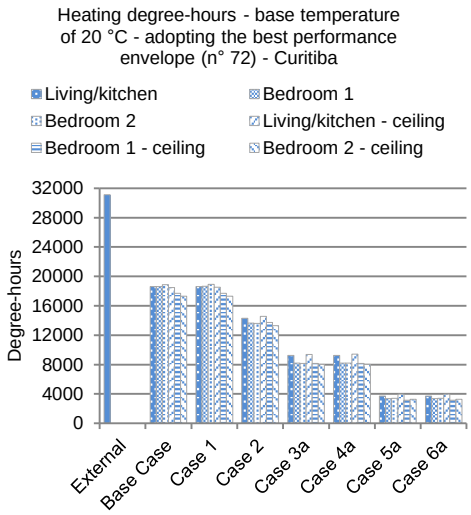


Figure 6-73: Comparison of heating degree-hours, base temperature of 18 °C, all cases,Porto Alegre



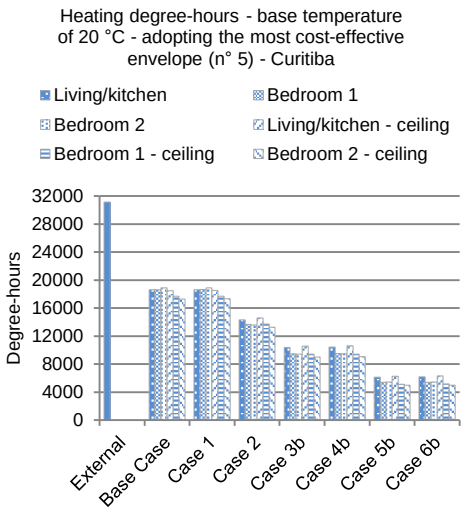
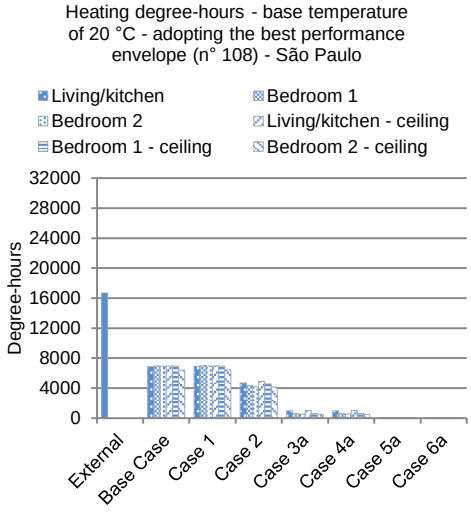


Figure 6-74: Comparison of heating degree-hours, base temperature of 20 °C, all cases, Curitiba



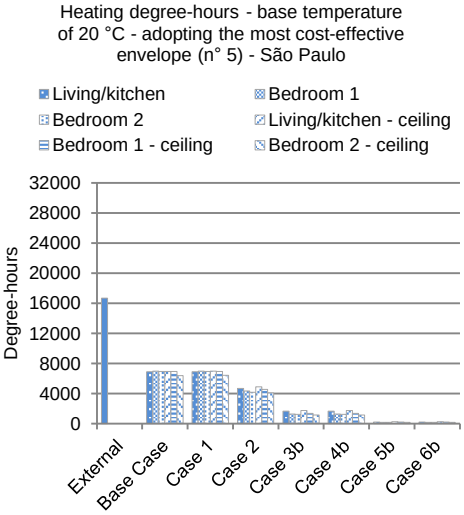
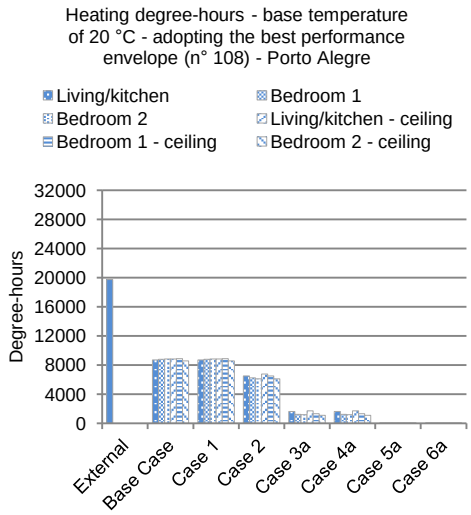


Figure 6-75: Comparison of heating degree-hours, base temperature of 20 °C, all cases, São Paulo



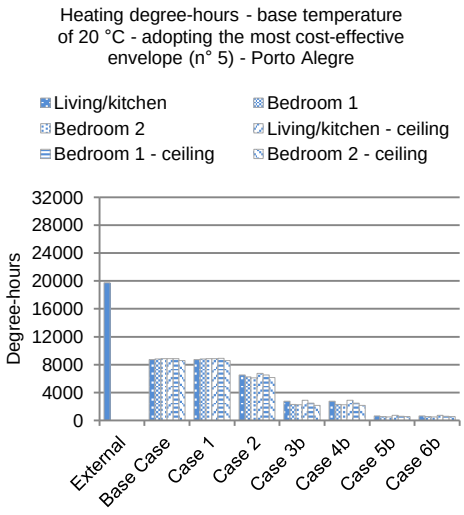


Figure 6-76: Comparison of heating degree-hours, base temperature of 20 °C, all cases,Porto Alegre

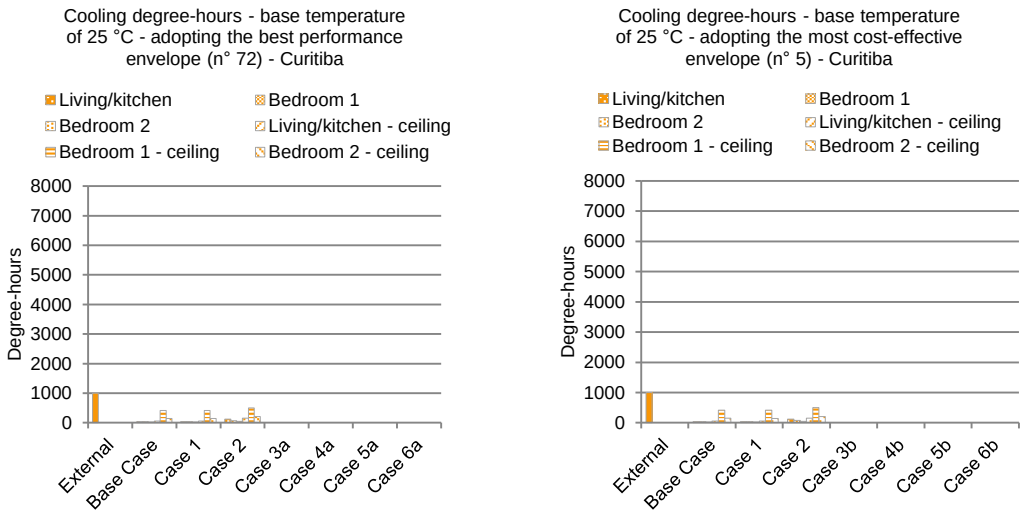


Figure 6-77: Comparison of heating degree-hours, base temperature of 25 °C, all cases, Curitiba

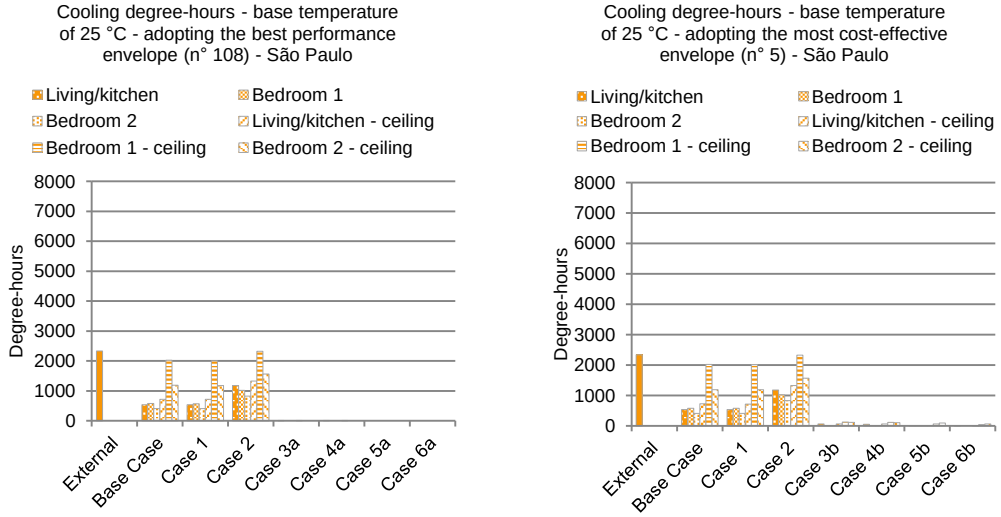


Figure 6-78: Comparison of heating degree-hours, base temperature of 25 °C, all cases, São Paulo

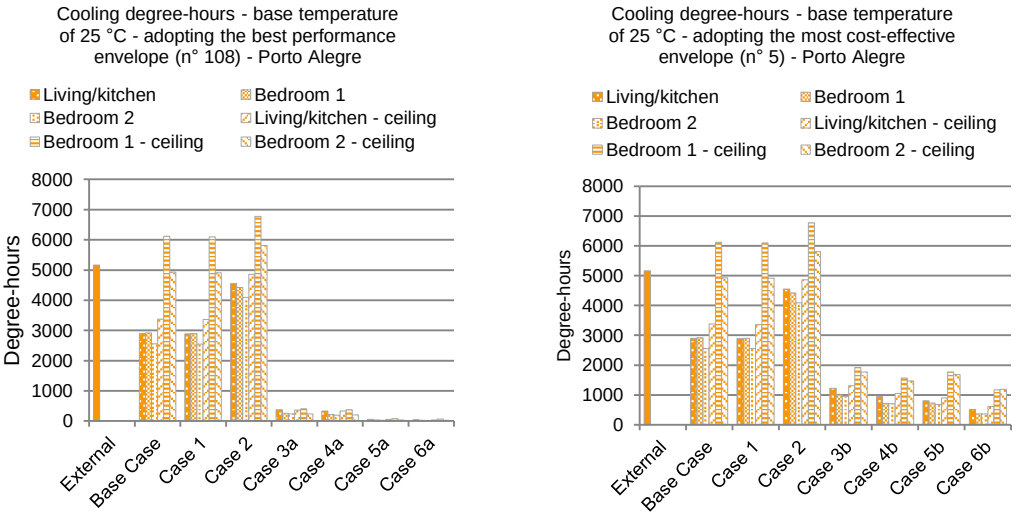


Figure 6-79: Comparison of heating degree-hours, base temperature of 25 °C, all cases,Porto Alegre

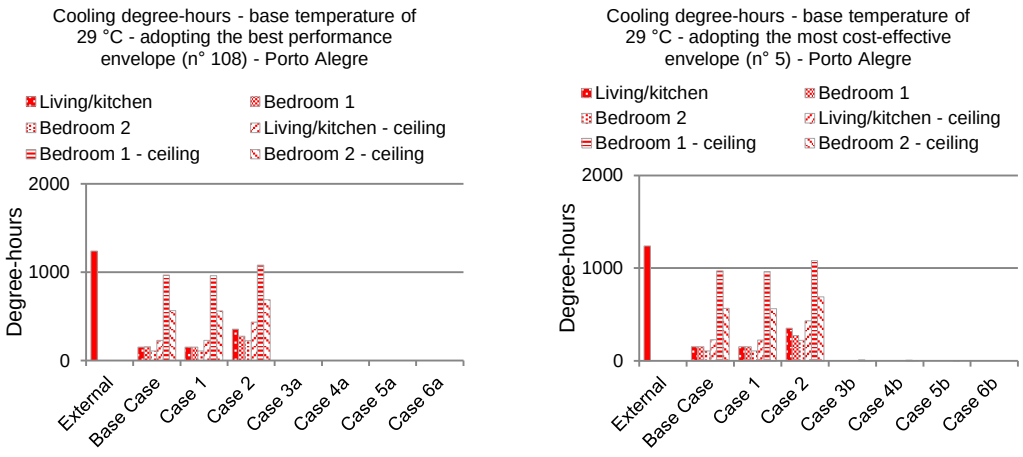


Figure 6-80: Comparison of heating degree-hours, base temperature of 29 °C, all cases,Porto Alegre

Figure 6-81, Figure 6-82 and Figure 6-83 illustrate the peak temperatures for Curitiba, São Paulo and Porto Alegre for all cases, respectively. The Alvorada House as built and occupied in Case 2 is used as a comparison with the optimised envelopes in Case 3 and 5.

In Curitiba, the occupied areas of the house in Case 2 had a maximum temperature of 28.2 °C in the living room/ kitchen. In the scenario of Case 3a (the best performance envelope n° 72) and Case 3b (the most cost-effective envelope n° 5) the indoor peak temperature was reduced by almost 5 K and 4 K when compared to Case 2, respectively. In the scenario of Case 5a and Case 5b, in which the infiltration was reduced, the adoption of the best performance and the most cost-effective envelopes had indoor peak temperatures of 1 K and almost 1 K lower than in Case 3a and Case 3b, respectively.

In São Paulo, the occupied areas of the house in Case 2 had a peak temperature of 29.55 °C in the living room/ kitchen. In the scenario of Case 3a (the best performance envelope n° 108) and Case 3b (the most cost-effective envelope n° 5) the indoor peak temperature was reduced by around 4.3 K and 3.2 K when compared to Case 2, respectively. In the scenario of Case 5a and Case 5b, in which the infiltration was reduced, the adoption of the best performance and the most cost-effective envelopes had the indoor peak temperatures reduced by 5 K and 4 K relative to Case 2, which was less than 1 K lower than in Case 3a and 3b, respectively.

In Porto Alegre, the occupied areas of the Alvorada House in Case 2 had a peak temperature of 32.82 °C in the living room/ kitchen. In the scenario of Case 3a (the best performance envelope n° 108) and Case 3b (the most cost-effective envelope n° 5) the indoor peak temperature was reduced by about 5.5 K and 4 K relative to Case 2. In the scenario of Case 5a and Case 5b, the adoption of the limited infiltration had the indoor

peak temperatures of the best performance and the most cost-effective envelopes 1.5 K and 1 K lower than in Case 3a and Case 3b, respectively.

It should be noted that the benefit of the shading was already delivered by the eaves and, hence, its positive impact on reducing the peak temperatures couldn't be evaluated in depth.

Surprisingly, as shown in the Figures, even though the internal gains in Case 2 had raised the indoor temperatures, they did not impact significantly on the peak temperatures. It would suggest that the high thermal mass of the internal and external walls helped stabilize the indoor temperature by absorbing some of the heat.

Ventilation did not have much influence on reducing the peak temperatures because the highest temperatures occurred mainly when the building was closed. It should be remembered that the ventilation assumptions presupposes that when the external temperatures were higher than indoor, the windows would be kept closed in order to avoid undesirable warm air coming into the building.

Case 7 and Case 8 assumed the Alvorada House as fully space conditioned in order to maintain the indoor temperatures within the thermal comfort interval of 20-25 °C. The cases estimated the potential energy demand for space conditioning and the results were expressed in kWh/m^2. As mentioned, Case 7 considered the envelope as optimised at a standard infiltration of 1 ach, while Case 8 assumed the envelope as optimised and with a reduced infiltration of 0.15 ach. Both Case 7 and Case 8 evaluated scenario 'a' (the best performance envelope n° 72 or 108) and scenario 'b' (the most cost-effective envelope n° 5).

Case 7 and Case 8 are shown comparatively in Figure 6-84, Figure 6-85 and Figure 6-86 against the energy demand of the Alvorada House (as built and occupied) for Curitiba, São Paulo and Porto Alegre, respectively. The breakdown of energy demand in each of those cases can be found in Appendix C. Overall, the findings indicated that optimised envelopes were able to deliver much more energy efficiency when compared to the Alvorada House envelope as built.

In Curitiba, the Alvorada House as built had the highest annual energy demand among the cases investigated, estimated to be 57.52 kWh/m^2. In scenario 'a', only with the adoption of the best performance envelope n° 72 in Case 7a, the energy demand was reduced to 20.56 kWh/m^2. Then, with the reduction of infiltration in Case 8a, the energy demand was reduced to 7.26 kWh/m^2. In scenario 'b', with the adoption of the most cost-effective envelope n° 5 in Case 7b, the energy demand was reduced to 26.03 kWh/m^2 and then, with the reduction of infiltration in Case 8b, the energy demand was reduced to 12.43 kWh/m^2.

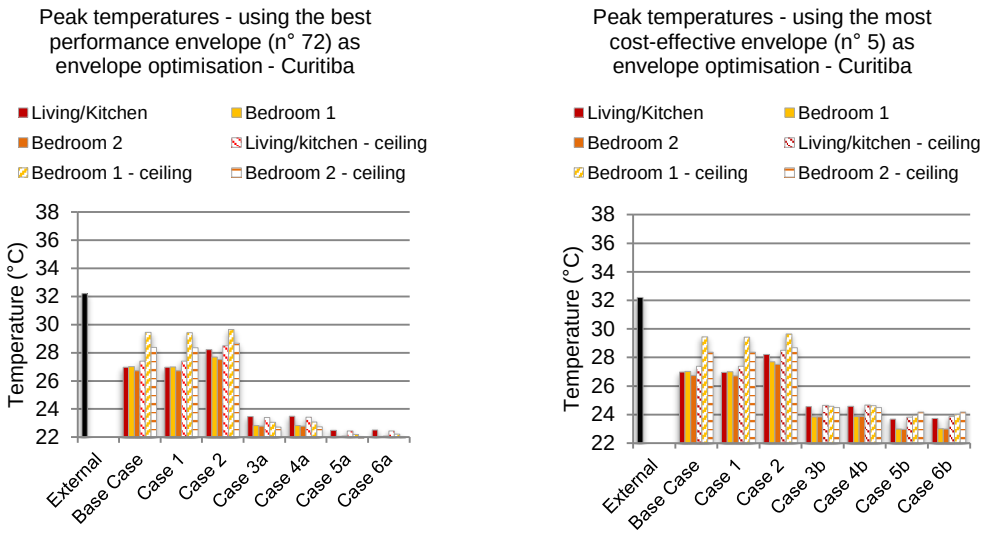


Figure 6-81: Comparison of peak temperatures, all cases, Curitiba

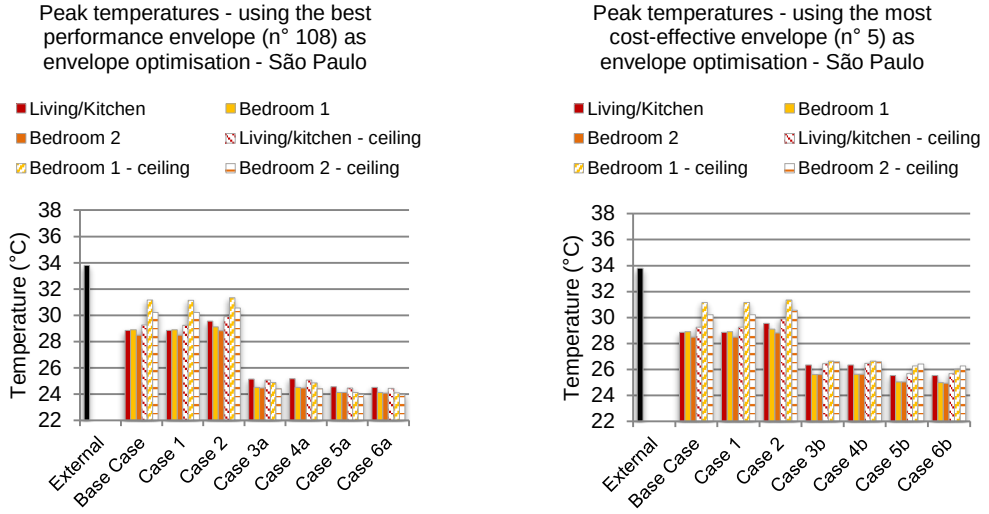


Figure 6-82: Comparison of peak temperatures, all cases, São Paulo

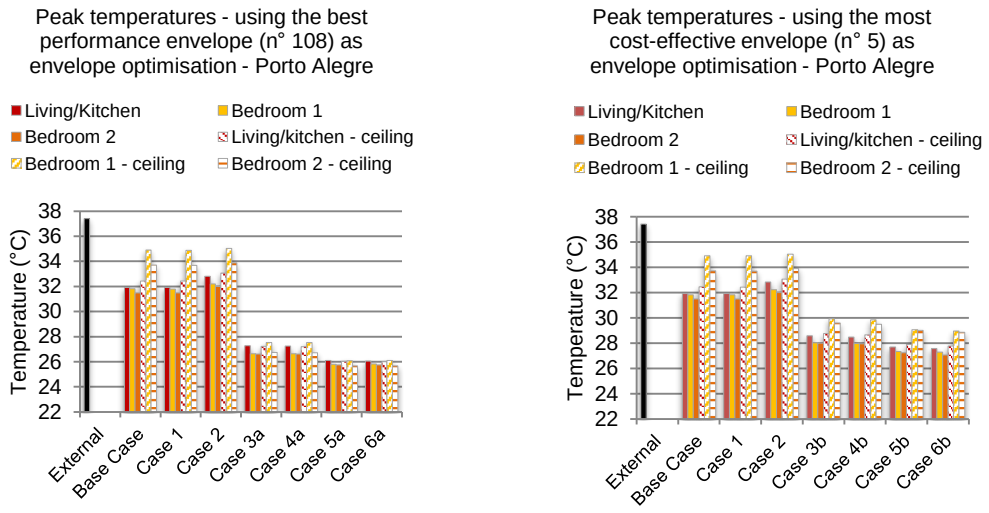


Figure 6-83: Comparison of peak temperatures, all cases, Porto Alegre

Comparatively, this meant that the best performance envelope n° 72 and the most cost-effective envelope n° 5 at standard infiltration of 1 ach (Case 7a and 7b) had the annual energy consumption reduced by 64.25% and 54.75% when compared to the Alvorada House envelope as built for delivering the same levels of indoor thermal comfort, respectively. Lower energy demand than that achieved in Case 7 can be achieved by adopting optimised envelopes at limited infiltration (Case 8) and the energy demand would be reduced by 93% for the best performance envelope n° 72 (Case 8a) and 78.4% for the most cost-effective envelope n° 5 (Case 8b) when compared to the Alvorada House envelope as built.

In São Paulo, the Alvorada house as built had the annual energy demand calculated to be 24.54 kWh/m^2. In scenario 'a', only with the adoption of the best performance envelope n° 108 in Case 7a, the energy demand was reduced to 2.45 kWh/m^2. Then, with the reduction of infiltration in Case 8a, the energy demand could be considered as negligible. In scenario 'b', with the adoption of the most cost-effective envelope n° 5 in Case 7b, the annual energy demand was reduced to 4.77 kWh/m^2 and then, with the reduction of infiltration in Case 8b, the energy demand was reduced to less than 1 kWh/m^2. To sum up, the annual energy consumption of the optimised envelope at standard infiltration of 1 ach would be reduced by 90.02% in Case 7a and 80.56% in Case 7b when compared to the Alvorada House envelope as built. By adopting optimised envelopes at limited infiltration (Case 8), the energy demand would be reduced by 100% for the best performance envelope n° 108 (Case 8a) and 98.50% for the most cost-effective envelope n° 5 (Case 8b) when compared to the Alvorada House envelope as built.

In Porto Alegre, the traditional Alvorada House envelope reached the annual energy demand of 45.39 kWh/m^2. In scenario 'a', only with the adoption of the best performance envelope n° 108 in Case 7a, the energy demand was reduced to 5.35 kWh/m^2. Then, with the reduction of infiltration in Case 8a, the energy demand was reduced to less than 1 kWh/m^2. In scenario 'b', with the adoption of the cost-effective envelope n° 5 in Case 7b, the energy demand was reduced to 11.46 kWh/m^2 and then, with the reduction of infiltration in Case 8b, the energy demand was reduced to 4.37 kWh/m^2. In other words, this meant that the best performance envelope n° 108 and the most cost-effective envelope n° 5 at standard infiltration levels (Case 7a and 7b) had an annual energy consumption 88.21% and 74.75% lower than the original Alvorada House envelope for delivering the same levels of indoor thermal comfort, respectively. For the optimised and airtight envelopes in Case 8, the energy demand of the best performance envelope n° 108 (Case 8a) and the most cost-effective envelope n° 5 (Case 8b) would be 99.3% and 90.4% lower than the Alvorada House envelope as built, respectively.

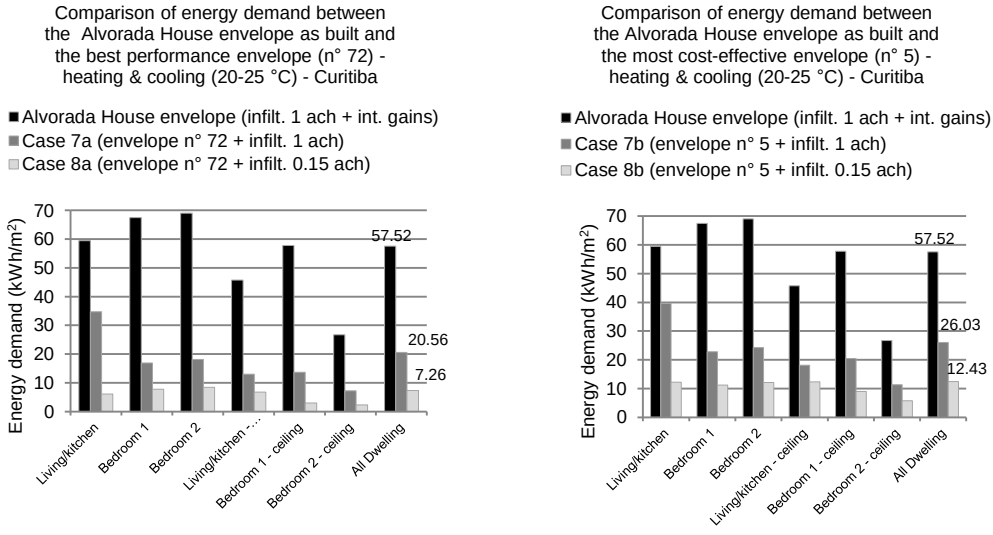


Figure 6-84: Comparison of annual energy demand, Case 7a, 7b, 8a and 8b, Curitiba

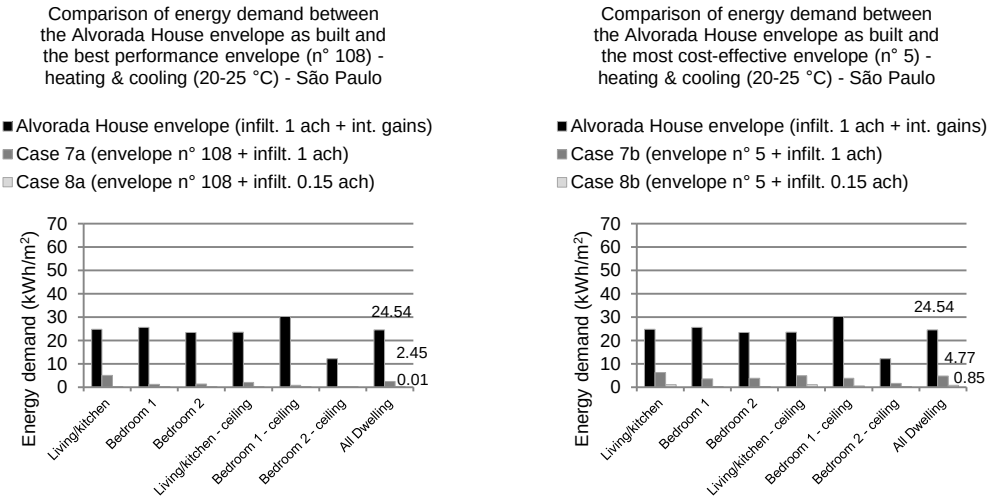


Figure 6-85: Comparison of annual energy demand, Case 7a, 7b, 8a and 8b, São Paulo

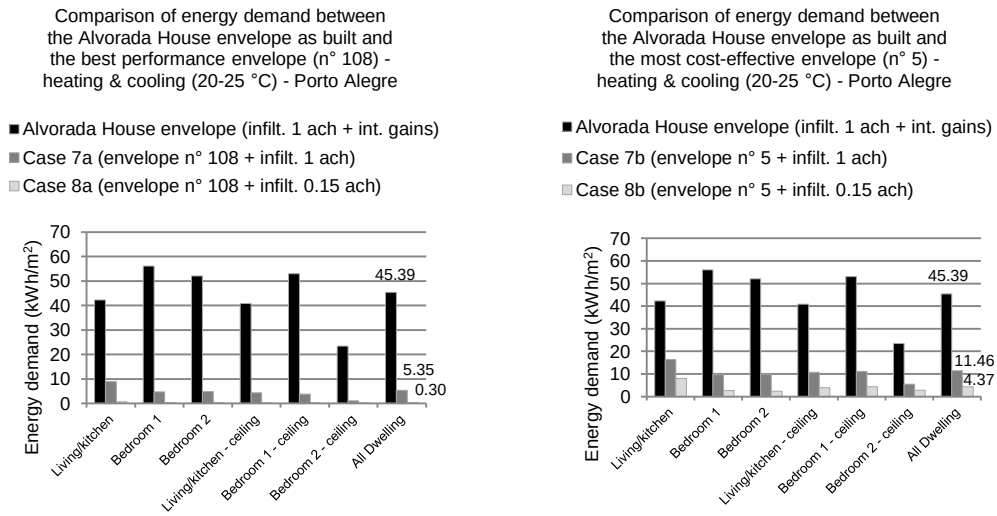


Figure 6-86: Comparison of annual energy demand, Case 7a, 7b, 8a and 8b, Porto Alegre

As expected, the analyses suggested that the best performance envelope (n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre) was shown to deliver more thermal comfort and energy efficiency than the most cost-effective envelope (n° 5 in all the cities). However, both optimised envelope cases showed a significant improvement when compared to the Alvorada House as built and occupied. Hence, in order to make an appropriate comparison of these envelopes, a running cost evaluation was conducted.

Table 6-11 show a running cost evaluation of the Alvorada House for the different envelopes investigated. The energy costs were estimated per square metre and per housing, in both Brazilian reais and US dollars currencies. The costs of housing were calculated for a 1- and 50-year period. A 50-year period was considered as being the lifespan of the house, as suggested by the Brazilian standard NBR 15575 (ABNT, 2013a, p. 53). Also, for a 50-year period, an inflation of 6% per year was assumed as this is the average value found in Brazil in recent years (Banco Central do Brasil, 2014a), as mentioned in Chapter 2.

As can be seen from Table 6-11, for a 50-year period and considering the inflation on the energy tariffs, the costs for running the Alvorada House as built were immensely higher than the optimised envelopes. The best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, at standard infiltration rate of 1 ach (Case 7a) had a running cost approximately 2.8, 10 and 8.5 times lower than the Alvorada House as built during its lifespan, respectively. The most cost-effective envelope n° 5 also at standard infiltration rate of 1 ach (Case 7b) had a running cost approximately 2.2, 5.1 and 4 times lower than the Alvorada House as built in Curitiba, São Paulo and Porto Alegre, respectively.

At limited infiltration rate of 0.15 ach, the Alvorada running costs were much lower than the Alvorada House as built. The best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre (Case 8a) had a running cost approximately 7.9, 2,454.0 and 151.3 times lower than the Alvorada House as built during its lifespan, respectively. The most cost-effective envelope n° 5 also at infiltration rate of 0.15 ach (Case 8b) had a running cost approximately 4.6, 28.9 and 10.4 times lower than the Alvorada House as built in Curitiba, São Paulo and Porto Alegre, respectively.

The next section estimates the costs for building an Alvorada House based on the envelopes investigated and this will allow a comparison with the costs for running the house.

Table 6-11: Estimated running cost of the Alvorada House according to the envelope type and infiltration rate - Curitiba, São Paulo and Porto Alegre

		Energy demand & costs	Curitiba	São Paulo	Porto Alegre
		Cost of kWh/m², in Brazilian reais (R$)	0.74592	0.50305	0.63570
		Cost of kWh/m², in US dollars (US$)	0.24536	0.16547	0.20911
Case 7a envelope n° 72 or 108 infiltration 1 ach	R$	Energy demand (kWh/m²)	20.56	2.45	5.35
		Cost per m² per annum (R$/m²a)	15.34	1.83	3.99
		Estimated cost for 1-year (R$)	593.05	70.67	154.32
		Estimated cost for 50-year (R$)	29,652.38	3,533.48	7,715.96
		Estimated cost for 50-year (R$), with inflation of 6% per year	**172,183.00**	**20,517.92**	**44,804.43**
	US$	Energy demand (kWh/m²)	20.56	2.45	5.35
		Cost per m² per annum (US$/m²a)	5.04	0.60	1.31
		Estimated cost for 1-year (US$)	195.08	23.25	50.76
		Estimated cost for 50-year (US$)	9,754.07	1,162.33	2,538.15
		Estimated cost for 50-year (US$), with inflation of 6% per year	**56,639.15**	**6,749.31**	**14,738.30**
Case 7b envelope n° 5, infiltration 1 ach	R$	Energy demand (kWh/m²)	26.03	4.77	11.46
		Cost per m² per annum (R$/m²a)	19.42	3.56	8.55
		Estimated cost for 1-year (R$)	750.83	137.59	330.56
		Estimated cost for 50-year (R$)	37,541.41	6,879.47	16,528.03
		Estimated cost for 50-year (R$), with inflation of 6% per year	**217,992.39**	**39,947.13**	**95,973.60**
	US$	Energy demand (kWh/m²)	26.03	4.77	11.46
		Cost per m² per annum (US$/m²a)	6.39	1.17	2.81
		Estimated cost for 1-year (US$)	246.98	45.26	108.74
		Estimated cost for 50-year (US$)	12,349.15	2,262.98	5,436.85
		Estimated cost for 50-year (US$), with inflation of 6% per year	**71,708.02**	**13,140.50**	**31,570.26**
Case 8a envelope n° 72 or 108, infiltration 0.15 ach	R$	Energy demand (kWh/m²)	7.26	0.01	0.30
		Cost per m² per annum (R$/m²a)	5.42	0.01	0.22
		Estimated cost for 1-year (R$)	209.41	0.29	8.65
		Estimated cost for 50-year (R$)	10,470.64	14.42	432.67
		Estimated cost for 50-year (R$), with inflation of 6% per year	**60,800.03**	**83.75**	**2,512.40**
	US$	Energy demand (kWh/m²)	7.26	0.01	0.30
		Cost per m² per annum (US$/m²a)	1.78	0.00	0.07
		Estimated cost for 1-year (US$)	68.89	0.09	2.85
		Estimated cost for 50-year (US$)	3,444.29	4.74	142.33
		Estimated cost for 50-year (US$), with inflation of 6% per year	**20,000.01**	**27.55**	**826.45**
Case 8b envelope n° 5, infiltration 0.15 ach	R$	Energy demand (kWh/m²)	12.43	0.85	4.37
		Cost per m² per annum (R$/m²a)	9.27	0.63	3.26
		Estimated cost for 1-year (R$)	358.54	24.52	126.05
		Estimated cost for 50-year (R$)	17,927.00	1,225.90	6,302.57
		Estimated cost for 50-year (R$), with inflation of 6% per year	**104,097.02**	**7,118.46**	**36,597.26**
	US$	Energy demand (kWh/m²)	12.43	0.85	4.37
		Cost per m² per annum (US$/m²a)	3.05	0.21	1.07
		Estimated cost for 1-year (US$)	117.94	8.07	41.46
		Estimated cost for 50-year (US$)	5,897.04	403.26	2,073.21
		Estimated cost for 50-year (US$), with inflation of 6% per year	**34,242.44**	**2,341.60**	**12,038.57**
Alvorada House envelope as built, infiltration 1 ach, internal gains	R$	Energy demand (kWh/m²)	57.52	24.54	45.39
		Cost per m² per annum (R$/m²a)	42.91	18.30	33.86
		Estimated cost for 1-year (R$)	1659.15	707.85	1309.26
		Estimated cost for 50-year (R$)	82,957.43	35,392.48	65,463.11
		Estimated cost for 50-year (R$), with inflation of 6% per year	**481,710.43**	**205,514.15**	**380,125.81**
	US$	Energy demand (kWh/m²)	57.52	24.54	45.39
		Cost per m² per annum (US$/m²a)	14.11	6.02	11.14
		Estimated cost for 1-year (US$)	545.77	232.85	430.68
		Estimated cost for 50-year (US$)	27,288.63	11,642.26	21,533.92
		Estimated cost for 50-year (US$), with inflation of 6% per year	**158,457.38**	**67,603.34**	**125,041.38**

Exchange rate: R$ 3.04 ~ US$ 1.00[74].
Prices estimated for 2015.

[74] BANCO CENTRAL DO BRASIL. 2015. Dólar americano [Online]. Available: http://www4.bcb.gov.br/pec/taxas/batch/taxas.asp?id=txdolar [Accessed 08 May 2015.

6.9 Cost Analysis

The cost analysis of the Alvorada House consisted of a comparison between the costs of the main envelope elements as built and optimised (for the scenario of the best performance envelope and the most cost-effective). The purpose of this analysis was to explore the difference in the envelope prices due to the replacement of the traditional envelope by the optimised envelopes and thus, explore the envelopes' cost viability. It has been assumed that the costs for the other building elements would be the same between the original and the optimised Alvorada House envelope.

The estimation of the costs for constructing each envelope was based on the TCPO's web database (PINI, 2015b). As mentioned in Chapter 4 and 5, TCPO is a reliable database with more than 5 thousand typical construction composition prices for the capitals of each Brazilian state (PINI, 2015a).

Table 6-12 summarizes the estimated costs of the envelopes investigated. Table 6-13, Table 6-14 and Table 6-15 show the cost estimation of the main elements of the traditional Alvorada House envelope. Table 6-16, Table 6-17 and Table 6-18 show the cost estimation of the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre, respectively. Table 6-19, Table 6-20 and Table 6-21 show the cost estimation of the most cost-effective envelope n° 5 in Curitiba, São Paulo and Porto Alegre, respectively. The table's data is show in Brazilian reais currency and data converted to US dollars currency can be found in Appendix C. The data was based on May 2015 prices.

Table 6-12: Summary of the main envelope costs – Curitiba, São Paulo and Porto Alegre

Envelope	Currency	Curitiba	São Paulo	Porto Alegre
Typical MCMV Envelope	R$	13,046.65	13,736.87	12,222.84
	US$	4,291.66	4,518.71	4,020.67
The best performance envelope	R$	52,475.61	52,386.49	49,916.34
	US$	17,261.71	17,232.40	16,419.85
The most cost-effective envelope	R$	17,730.25	17,244.50	17,457.06
	US$	5,832.32	5,672.53	5,742.45

The fenestrations of the Alvorada House were assumed as simplified in order to estimate their costs more realistically according to the available housing database. It should be stressed that the fenestrations of the original Alvorada house were built with a high degree of complexity and also a high percentage of frame that might differ slightly from the most common practices in affordable houses.

Table 6-13: Estimated costs of the Alvorada House envelope as built, in Brazilian Reais - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Solid ceramic brick wall 11 cm (11x5x22cm)	98.53[75]	0.91 1.52	Servant 4.73 Brick layer 6.67	Brick 21.65 Mortar 15.82	2.43	14.44	37.47	m^2	239.43	1,423.04	1,820.78	3,691.92	6,935.74	13,046.65
Roof	Aluminium foil	42.90	0.22 0.22	R. Servant 5.12 Roofer 6.67	295.90 /roll of 50m^2	0.44	2.59	295.90	m^2	18.88	111.27	142.38	295.90	549.55	
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00 2.00 5.15 5.15	Servant 4.73 Brick layer 6.67 W. servant 5.12 W.worker 6.67	Window 260.42 Other 2.69	14.3	83.52	263.11	m^2	81.22	474.39	606.98	1494.46	2,575.83	
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00 3.00 8.00 8.00	Servant 4.73 Brick layer 6.67 W. servant 5.12 W.worker 6.67	Window 337.44 Other 105.56	22	128.52	443.00	un	22	128.52	164.44	443.00	735.96	
Window glazing	Single glazing	7.10	-	Installation 15.81	Glass 40.89	-	15.81	40.89	m^2	-	112.25	-	290.32	402.57	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40 1.40 3.75 3.75	Servant 4.73 Brick layer 6.67 W. servant 5.12 W.worker 6.67	Door 461.37 Other 324.97	10.3	60.17	786.34	un	20.6	120.35	153.98	1,572.68	1,847.01	

[75] As built - Per layer: single layer: 81.37 m^2; double layer: 8.58 m^2. Per façade: south: 19.64 m^2, 2.99m^2; north: 25.80 m^2; west: 5.17 m^2, 7.07 m^2, 8.58 m^2 (double layer); east: 19.47 m^2, 1.23 m^2.

Table 6-14: Estimated costs of the Alvorada House envelope as built, in Brazilian Reais – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R/m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 129.34% (R$)	Material (R$)		
Wall	Solid ceramic brick wall 11 cm (11x5x22cm)	98.53	0.91 1.52	Servant 5.64 Brick layer 6.86	Brick 20.16 Mortar 15.62	2.43	15.56	35.78	m^2	239.43	1,533.09	1,982.90	3,525.40	7,041.39	13,736.87
Roof	Aluminium foil	42.90	0.22 0.22	R. Servant 5.64 Roofer 6.86	293.88 /roll of $50m^2$	0.44	2.75	293.88	m^2	18.88	117.98	152.59	293.88	564.44	
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00 2.00 5.15 5.15	Servant 5.64 Brick layer 6.86 W. servant 5.64 W.worker 6.86	Window 308.43 Other 2.45	14.3	89.38	310.88	m^2	81.22	507.65	656.59	1,765.80	2,930.04	
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00 3.00 8.00 8.00	Servant 5.64 Brick layer 6.86 W. servant 5.64 W.worker 6.86	Window 399.65 Other 106.65	22	137.50	506.30	un	22	137.50	177.84	506.30	821.64	
Window glazing	Single glazing	7.10	-	Installation 15.00	Glass 41.33	-	15.00	41.33	m^2	-	106.50	-	293.44	399.94	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40 1.40 3.75 3.75	Servant 5.64 Brick layer 6.86 W. servant 5.64 W.worker 6.86	Door 499.34 Other 342.73	10.3	64.38	842.07	un	20.6	128.75	166.53	1,684.14	1,979.42	

Table 6-15: Estimated costs of the Alvorada House envelope as built, in Brazilian Reais – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Solid ceramic brick wall 11 cm (11x5x22cm)	98.53	0.91 1.52	Servant 4.00 Brick layer 5.40	Brick 19.41 Mortar 17.40	2.43	11.85	36.81	m^2	239.43	1,167.38	1,493.67	3,626.89	6,287.94	12,222.84
Roof	Aluminium foil	42.90	0.22 0.22	R. Servant 4.42 Roofer 5.40	300.90 /roll of 50m^2	0.44	2.16	300.90	m^2	18.88	92.68	118.59	300.90	512.17	
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00 2.00 5.15 5.15	Servant 4.00 Brick layer 5.40 W. servant 4.42 W.worker 5.40	Window 260.42 Other 2.87	14.3	69.37	263.29	m^2	81.22	394.04	504.17	1,495.49	2,393.70	
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00 3.00 8.00 8.00	Servant 4.00 Brick layer 5.40 W. servant 4.42 W.worker 5.40	Window 337.44 Other 94.19	22	106.76	431.63	un	22	106.76	136.60	431.63	674.99	
Window glazing	Single glazing	7.10	-	Installation 12.80	Glass 37.86	-	12.80	37.86	m^2	-	90.88	-	268.81	359.69	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40 1.40 3.75 3.75	Servant 4.00 Brick layer 5.40 W. servant 4.42 W.worker 5.40	Door 530.31 Other 352.93	10.3	49.99	883.24	un	20.6	99.97	127.91	1,766.48	1,994.36	

Table 6-16: Estimated costs of the best performance Alvorada House envelope (n° 72), in Brazilian Reais - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	193.60[76]	1.81	Servant 4.73	Brick 49.78	4.23	24.70	83.19	m^2	818.93	4,782.44	6,119.14	16,105.58	27,007.16	52,475.61
			2.42	Brick layer 6.67	Mortar [77] 33.41										
	EPS 30 cm	95.34	0.30	Servant 4.73	Insulat. 105.36	0.60	3.42	116.11	m^2	57.20	326.06	417.20	11,069.93	11,813.19	
			0.30	Brick layer 6.67	Other 10.75										
Roof	Mineral wool panels bet. Roof structure	42.90	0.66	R. Servant 5.12	75.18	1.32	7.78	75.18	m^2	56.63	333.82	427.13	3,225.22	3,986.17	
			0.66	Roofer 6.67											
Window frame	PVC frame - Awning (9un varied size)	5.68	1.00	Servant 4.73	Window 616.84	2.00	11.40	638.76	m^2	11.36	64.75	82.85	3,628.16	3,775.76	
			1.00	Brick layer 6.67	Other 21.92										
	PVC frame - Sliding + shutter (1un119x119cm)	1.42	1.00	Servant 4.73	Window 1,091.65	2.50	14.74	1,113.57	m^2	3.55	20.92	26.77	1,581.27	1,628.96	
			1.50	Brick layer 6.67	Other 21.92										
Window glazing	Double uncoated glazing	7.10	-	Installation 15.81	Glass 140.00	-	15.81	994.0	m^2	-	112.25	-	994.0	1,106.25	
Door	PVC (2un varied size)	2.00	3.00	Servant 4.73	Door 1,489.09	6.00	34.20	1,501.10	un	12.00	68.40	87.52	3,002.20	3,158.12	
			3.00	Brick layer 6.67	Other 12.01										

[76] Best performance envelope - Per layer: internal layer: 88.28 m^2; external layer: 105.32 m^2.

[77] It assumes 10 mm thick joints.

Table 6-17: Estimated costs of the best performance Alvorada House envelope (n° 108), in Brazilian Reais – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 129.34% (R$)	Material (R$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	193.60	1.81	Servant 5.64	Brick 46.34	4.23	26.81	79.33	m^2	818.93	5,190.34	6,713.18	15,358.29	27,261.81	52,386.49
			2.42	Brick layer 6.86	Mortar 32.99										
	EPS 30 cm	95.34	0.30	Servant 5.64	Insulat. 95.39	0.60	3.75	102.50	m^2	57.20	357.53	462.42	9,772.35	10,592.30	
			0.30	Brick layer 6.86	Other 7.11										
Roof	Mineral wool panels bet. Roof structure	42.90	0.66	R. Servant 5.64	80.64	1.32	8.25	80.64	m^2	56.63	353.93	457.77	3,459.46	4,271.15	
			0.66	Roofer 6.86											
Window frame	PVC frame - Awning (9un varied size)	5.68	1.00	Servant 5.64	Window 559.27	2.00	12.5	585.33	m^2	11.36	71.00	91.83	3,324.67	3,487.51	
			1.00	Brick layer 6.86	Other 26.06										
	PVC frame - Sliding + shutter (1un119x119cm)	1.42	1.00	Servant 5.64	Window 989.76	2.50	15.93	1,015.82	m^2	3.55	22.62	29.26	1,442.46	1,494.34	
			1.50	Brick layer 6.86	Other 26.06										
Window glazing	Double coated glazing	7.10	-	Installation 15.00	Glass 320.00	-	15.00	320.00	m^2	-	106.50	-	2,272.00	2,378.50	
Door	PVC (2un varied size)	2.00	3.00	Servant 5.64	Door 1,350.10	6.00	37.5	1,364.44	un	12.00	75.00	97.01	2,728.88	2,900.89	
			3.00	Brick layer 6.86	Other 14.34										

Table 6-18: Estimated costs of the best performance Alvorada House envelope (n° 108), in Brazilian Reais – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	193.60	1.81	Servant 4.00	Brick 44.63	4.23	20.31	81.37	m^2	818.93	3,931.63	5,030.52	15,753.23	24,715.38	49,916.34
			2.42	Brick layer 5.40	Mortar 36.74										
	EPS 30 cm	95.34	0.30	Servant 4.00	Insulat. 105.36	0.60	2.82	116.08	m^2	57.20	268.86	344.00	11,067.07	11,679.93	
			0.30	Brick layer 5.40	Other 10.72										
Roof	Mineral wool panels bet. Roof structure	42.90	0.66	R. Servant 4.42	75.18	1.32	6.48	75.18	m^2	56.63	278.04	355.76	3,225.22	3,859.02	
			0.66	Roofer 5.40											
Window frame	PVC frame - Awning (9un varied size)	5.68	1.00	Servant 4.00	Window 526.37	2.00	9.40	544.39	m^2	11.36	53.39	68.32	3,092.14	3,213.84	
			1.00	Brick layer 5.40	Other 18.02										
	PVC frame - Sliding + shutter (1un119x119cm)	1.00	1.00	Servant 4.00	Window 931.54	2.50	12.10	949.56	m^2	3.55	17.18	21.98	1,348.38	1,387.54	
			1.50	Brick layer 5.40	Other 18.02										
Window glazing	Double coated glazing	7.10	-	Installation 12.80	Glass 320.00	-	12.80	320	m^2	-	90.88	-	2,272.00	2,362.88	
Door	PVC (2un varied size)	2.00	3.00	Servant 4.00	Door 1,270.69	6.00	28.2	1,284.59	un	12	56.4	72.16	2,569.18	2,697.74	
			3.00	Brick layer 5.40	Other 13.90										

Table 6-19: Estimated costs of the most cost-effective Alvorada House envelope (n° 5), in Brazilian Reais - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R/m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm)	91.21	0.51	Servant 4.73	Brick 44.80	1.30	7.68	53.08	m^2	118.57	700.64	896.47	4,841.43	6,438.53	17,730.25
			0.79	Brick layer 6.67	Mortar 8.28										
	EPS 10 cm	95.26	0.30	Servant 4.73	Insulat. 35.84	0.60	3.42	46.59	m^2	57.16	325.79	416.85	4,438.16	5,180.80	
			0.30	Brick layer 6.67	Other 10.75										
Roof	Aluminium foil	42.90	0.22	R. Servant 5.12	295.90 /roll of $50m^2$	0.44	2.59	295.90	m^2	18.88	111.27	142.38	295.90	549.55	
			0.22	Roofer 6.67											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 4.73	Window 260.42	14.3	83.52	263.11	m^2	81.22	474.39	606.98	1,494.46	2,575.83	
			2.00	Brick layer 6.67											
			5.15	W. servant 5.12	Other 2.69										
			5.15	W.worker 6.67											
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00	Servant 4.73	Window 337.44	22	128.52	443.00	un	22	128.52	164.44	443.00	735.96	
			3.00	Brick layer 6.67											
			8.00	W. servant 5.12	Other 105.56										
			8.00	W.worker 6.67											
Window glazing	Single glazing	7.10	-	Installation 15.81	Glass 40.89	-	15.81	40.89	m^2	-	112.45	-	290.32	402.57	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Servant 4.73	Door 461.37	10.3	60.17	786.34	un	20.6	120.35	153.98	1,572.68	1,847.01	
			1.40	Brick layer 6.67											
			3.75	W. servant 5.12	Other 324.97										
			3.75	W.worker 6.67											

Table 6-20: Estimated costs of the most cost-effective Alvorada House envelope (n° 5), in Brazilian Reais – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 129.34% (R$)	Material (R$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29 cm)	91.21	0.51	Servant 5.64	Brick 38.92	1.30	8.30	46.99	m^2	118.57	756.66	978.66	4,285.96	6,021.28	17,244.50
			0.79	Brick layer 6.86	Mortar 8.07										
	EPS 10 cm	95.26	0.30	Servant 5.64	Insulat. 31.82	0.60	3.75	38.93	m^2	57.16	357.23	462.03	3,708.47	4,527.73	
			0.30	Brick layer 6.86	Other 7.11										
Roof	Aluminium foil	42.90	0.22	R. Servant 5.64	293.88 /roll of 50m^2	0.44	2.75	293.88	m^2	18.88	117.98	152.59	293.88	564.44	
			0.22	Roofer 6.86											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 5.64	Window 308.43	14.3	89.38	310.88	m^2	81.22	507.65	656.59	1,765.80	2,930.04	
			2.00	Brick layer 6.86											
			5.15	W. servant 5.64	Other 2.45										
			5.15	W.worker 6.86											
	Eucalyptus Timber frame - Sliding + shutter (1un 119x119cm)	1.00	3.00	Servant 5.64	Window 399.65	22	137.50	506.30	un	22	137.50	177.84	506.30	821.64	
			3.00	Brick layer 6.86											
			8.00	W. servant 5.64	Other 106.65										
			8.00	W.worker 6.86											
Window glazing	Single glazing	7.10	-	Installation 15.00	Glass 41.33	-	15.00	41.33	m^2	-	106.50	-	293.44	399.94	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Servant 5.64	Door 499.34	10.3	64.38	842.07	un	20.6	128.75	166.53	1,684.14	1,979.42	
			1.40	Brick layer 6.86											
			3.75	W. servant 5.64	Other 342.73										
			3.75	W.worker 6.86											

Table 6-21: Estimated costs of the most cost-effective Alvorada House envelope (n° 5), in Brazilian Reais – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (R$)	Total cost (R$)
			Labour (hour)	Labour (R$/h)	Material (R$/$m^2$)	Labour (hour)	Labour (R$)	Material (R$)	unit	Labour (hour)	Labour (R$)	Labour taxes 127.95% (R$)	Material (R$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm	91.21	0.51	Servant 4.00	Brick 48.16	1.30	6.31	56.61	m^2	118.57	575.17	735.93	5,163.40	6,474.50	17,457.06
			0.79	Brick layer 5.40	Mortar 8.45										
	EPS 10 cm	95.26	0.30	Servant 4.00	Insulat. 35.84	0.60	2.82	46.56	m^2	57.16	268.63	343.72	4,435.31	5,047.65	
			0.30	Brick layer 5.40	Other 10.72										
Roof	Aluminium foil	42.90	0.22	R. Servant 4.42	300.90 /roll of 50m^2	0.44	2.16	300.90	m^2	18.88	92.68	118.59	300.90	512.17	
			0.22	Roofer 5.40											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 4.00	Window 260.42	14.3	69.37	263.29	m^2	81.22	394.04	504.17	1,495.49	2,393.70	
			2.00	Brick layer 5.40											
			5.15	W. servant 4.42	Other 2.87										
			5.15	W.worker 5.40											
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00	Servant 4.00	Window 337.44	22	106.76	431.63	un	22	106.76	136.60	431.63	674.99	
			3.00	Brick layer 5.40											
			8.00	W. servant 4.42	Other 94.19										
			8.00	W.worker 5.40											
Window glazing	Single glazing	7.10	-	Installation 12.80	Glass 37.86	-	12.80	37.86	m^2	-	90.88	-	268.81	359.69	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Servant 4.00	Door 530.31	10.3	49.99	883.24	un	20.6	99.97	127.91	1,766.48	1,994.36	
			1.40	Brick layer 5.40											
			3.75	W. servant 4.42	Other 352.93										
			3.75	W.worker 5.40											

According to the Tables, the costs of the best performance envelope n° 72 in Curitiba and n° 108 in São Paulo and Porto Alegre were shown to be 4.0, 3.8 and 4.1 times more than the cost of the Alvorada House envelope as built, respectively. It should be noted that the main envelope elements responsible for raising the costs were the masonry replacement. A cross-analysis of the costs of the envelope and costs for running the housing (for a standard infiltration rate of 1 ach) revealed that the payback period would be estimated to be approximately 21, 27 and 19 years in Curitiba, São Paulo and Porto Alegre, respectively.

The costs of the most cost-effective envelope n° 5 were shown to be only 1.4 times more in Curitiba and Porto Alegre and 1.3 times more in São Paulo than the cost of the original Alvorada House envelope. A cross-analysis of the costs of the envelope and costs for running the housing (for standard infiltration rate of 1 ach) revealed that the payback period would be estimated to be 5 years in Curitiba and Porto Alegre and 6 years in São Paulo. The estimated payback period according to the envelope type is shown in Figure 6-87.

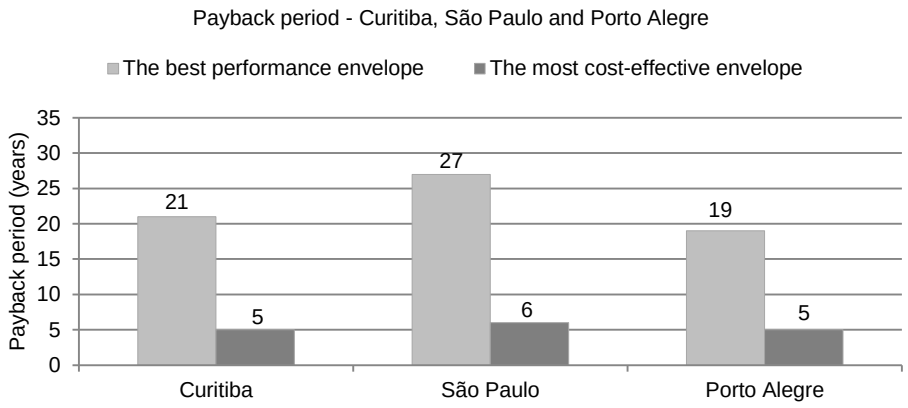


Figure 6-87: Estimated payback period of the MCMV House according to the envelope type - Curitiba, São Paulo and Porto Alegre

Comparatively, a closer look at the optimised envelopes revealed that the cost of the most cost-effective n° 5 was 66%, 67% and 65% lower than the best performance envelope n° 72 or n° 108 in Curitiba, São Paulo and Porto Alegre, respectively. The analyses seem to suggest that despite the fact that the best performance envelope increased indoor thermal comfort and energy efficiency as shown in the analysis, this envelope might not be the most appropriate envelope for the Brazilian context because it adds a significant cost to the typical Brazilian envelope. The analyses also showed that small changes on the envelope, such as those that adopted the most cost-effective envelope n° 5, can significantly reduce the energy demand while only increasing the

cost by moderate levels. Adopting the most cost-effective envelope would be an initial step forward for more thermally comfortable and energy efficient affordable homes.

The estimated cost of the Alvorada House as built was compared with its real costs during the housing construction. For this comparison, the house was classified according to its standard level, established by the Brazilian standard NBR 12721 (ABNT, 2006). As mentioned in Chapter 5, the standard classifies the housing standard level according to its typology, size, quality of material and finishing. For instance, the Alvorada House was classified as a low standard single-family house (R1-B) mainly due to its 1 floor-2-bedroom typology. However, the house materials and finishing of the Alvorada House gave to the housing construction a certain higher standard when compared to the MCMV House typology.

Table 6-22 shows the unit cost per square metre of a R1-B house typology estimated for each city investigated, using the CUB methodology, as described in Chapter 5. The contribution of each construction activity to the overall construction cost is illustrated in Table 6-23.

Table 6-22: CUB of low standard single-family house – R1-B, based on May 2015 (SINDUSCON-PR, 2015, SINDUSCON-SP, 2015, SINDUSCON-RS, 2015, p. 2).

	CUB/PR - Curitiba	CUB/SP - São Paulo	CUB/RS - Porto Alegre
R$/m^2	1,233.64	1,190.85	1,180.08
US$/m^2	405.80	391.73	388.18
Exchange rate: R$ 3.04 ~ US$ 1.00			

Table 6-23: Share of contribution of each construction activity on the overall CUB of low standard single-family house – R1-B, based on May 2015 (SINDUSCON-PR, 2015, SINDUSCON-SP, 2015, SINDUSCON-RS, 2015, p. 2)

Activity	CUB/PR - Curitiba	CUB/SP - São Paulo	CUB/RS - Porto Alegre
Workforce	52.69%	53.59%	45.14%
Material	38.15%	40.35%	44.18%
Administrative Expenses	8.96%	6.06%	9.93%
Equipment Expenses	0.20%	Not Informed	0.75%

According to the CUB methodology (Table 5-24), the estimated costs of the overall Alvorada House with a built area of 49.43 m^2 would be equivalent to 60.9, 58.8 and 58.3 thousand Brazilian reais (approximately 20.0, 19.3 and 19.1 thousand US dollars) for the cities of Curitiba, São Paulo and Porto Alegre, respectively.

Table 6-24: Estimation of the Alvorada House cost through the CUB methodology

Currency	Curitiba	São Paulo	Porto Alegre
R$	60,978.82	58,863.71	58,331.35
US$	20,058.82	19,363.06	19,187.94
Based on a built area of 49.43 m^2			

Back in 2006 when the house construction cost was evaluated, the real cost of the construction of the Alvorada House was found to be higher than those estimated costs of other affordable houses of similar size (Kuhn, 2006). This was because the Alvorada House construction took into account constructive solutions and strategies that differed

from those already consolidated in the affordable houses (e.g. roof typology, porches and structure).

The Alvorada House construction cost was calculated to be 345.67 Brazilian reais per square metre for the reference period of January 2006, which was equivalent to 31.94%[78] of the CUB[79] of the reference period (Kuhn, 2006, p. 139,171). As mentioned, the Alvorada House cost did not include labour cost because the house was built with self-construction. However, this cost cannot be directly compared to the current CUB due to the change of the methodology calculation that occurred with the publication of the Brazilian standard NBR 12721 (ABNT, 2006) in 2006.

In order to obtain a comparable value of the Alvorada House cost, the calculated cost of the house was adjusted according to the annual Brazilian inflation rates from 2006 to 2014[80]. The adjusted value was calculated to be 553.50 Brazilian reais (approximately 182.07 US dollars), which corresponded to 46.90% of the CUB for a low standard house in Porto Alegre. Indeed, this percentage of the CUB seemed to be realistic, because it appeared to be slightly higher than the current share of 44.18% of the CUB due to the materials (see Table 6-23).

It should be highlighted that the roof was the building element that made the highest contribution to the cost, being 39.60% of the house materials cost (Kuhn, 2006, p. 139). However, a high percentage of the roof costs were due to the concrete beams. The walls and the windows contribution to the cost were equivalent to 21.67% and 20.48%, respectively (Kuhn, 2006, p. 139).

A cross-analysis of the estimated costs of the main envelope elements (Table 6-13 to Table 6-18) and the estimated total cost of the Alvorada House (Table 5-24) suggested that the best performance envelope would add 65% to the overall typical Alvorada House cost in Curitiba and Porto Alegre and 66% in São Paulo, respectively. However, the most cost-effective envelope would add only 8%, 6% and 9% to the overall typical Alvorada House cost for Curitiba, São Paulo and Porto Alegre, respectively.

However, the cost for building an optimised Alvorada House envelope might be higher than it appears to be if considering the expenses of design and construction

[78] The cost would represent 39.57% of the CUB if foundations were considered.

[79] CUB of January of 2006 was R$873.50/m^2. SINDUSCON-RS 2013b. Evolução do CUB/RS NBR 12721/1999 em R$ m² – Jan/1970 – Mar/2009. Sindicato da Indústria da Construção Civil no Estado do Rio Grande do Sul (SINDUSCON-RS).

[80] Annual Inflation: 2006: 3.14%; 2007: 4.46%; 2008:5.90%; 2009:4.31%; 2010: 5.91%; 2011: 6.50%; 2012: 5.84%; 2013: 5.91%; 2014: 6.41%. BANCO CENTRAL DO BRASIL. 2014a. *Histórico de Metas para a Inflação no Brasil* [Online]. Banco Central do Brasil. Available: https://www.bcb.gov.br/Pec/metas/TabelaMetaseResultados.pdf [Accessed 16 February 2015.

management. Both these expenses might be able to cover the potential costs with limited infiltration, as in an airtight construction the design would need to be more detailed and the construction management would also need to be more meticulous.

As mentioned in Chapter 5, the costs of the architectural design were estimated using the methodology suggested by CAU (CEAU, 2014a). According to the methodology, buildings with the same built areas can have different degrees of complexity, which varies from a low to a high degree of complexity. Detailed calculation of the architectural design cost can be found in Appendix C. Table 5-25 shows the estimated architectural design costs for the Alvorada House as built and optimised, which have low and high degree of design complexity, respectively. Both the optimised envelopes design were assumed to have a high degree of design complexity as both required a careful design to deliver the expected performance.

Table 6-25: Estimated cost of the architectural design

	Currency	Curitiba	São Paulo	Porto Alegre
Traditional envelope	R$	4,469.75	4,314.71	4,275.69
	US$	1470.31	1419.31	1406.48
Optimised envelope	R$	6,707.67	6,475.01	6,416.45
	US$	2206.47	2129.94	2110.67

The costs of construction management were also estimated according to CAU methodology (CEAU, 2014b, p. 15) and were considered to be 17% of the overall construction cost. Hence, the management of the construction of the optimised envelopes (best performance and the most-effective envelopes) would add cost to the Alvorada House because the overall house cost would be increased.

In constructing an optimised housing envelope, it would be expected that the costs be increased initially due to the innovativeness of the strategies in the current Brazilian market. It is estimated that the time for designing and constructing would also be much higher due to the uncertainties of the construction process. In addition, the construction of these buildings might require more trained professionals and experienced workers involved in the design and construction of these buildings, which may add some more labour cost to the overall housing construction. However, as soon as the worker and professionals involved acquire the knowledge required to design and construct these house buildings properly, it would be expected that these costs would return back to standard levels.

The estimated costs for design and constructing the Alvorada House as built would be calculated through Equation 5-1 for the cities investigated. Please note that self-build method was disregarded on these equations. The estimated costs of the Alvorada House best performance envelope would be calculated through Equation 5-5, Equation 5-6 and Equation 5-7 for Curitiba, São Paulo and Porto Alegre, respectively. The

estimated costs of the Alvorada House most-effective envelope would be calculated through Equation 6-5, Equation 6-6 and Equation 6-7, according to each city.

Equation 6-1: Estimated cost of the Alvorada House envelope as built – Curitiba, São Paulo and Porto Alegre

$$C_{as\ built,\ Cur,\ Sp,\ Poa} = p \times 1.17 + 0.733\ d_{as\ built}$$

Equation 6-2: Estimated cost of the Alvorada House best performance envelope - Curitiba

$$C_{best\ perf.\ Cur} = (p \times 1.65) \times 1.17 + 0.11\ d_{best\ perf.\ Cur}$$

Equation 6-3: Estimated cost of the Alvorada House best performance envelope - São Paulo

$$C_{best\ perf.\ Sp} = (p \times 1.66) \times 1.17 + 0.11\ d_{best\ perf.\ SP}$$

Equation 6-4: Estimated cost of the Alvorada House best performance envelope - Porto Alegre

$$C_{best\ perf.\ Poa} = (p \times 1.65) \times 1.17 + 0.11\ d_{best\ perf.\ Poa}$$

Equation 6-5: Estimated cost of the Alvorada House most-effective performance envelope - Curitiba

$$C_{cost-effect.\ Cur} = (p \times 1.08) \times 1.17 + 0.11\ d_{cost-effect.\ Cur}$$

Equation 6-6: Estimated cost of the Alvorada House most-effective performance envelope - São Paulo

$$C_{cost-effect.\ Sp} = (p \times 1.06) \times 1.17 + 0.11\ d_{cost-effect.\ SP}$$

Equation 6-7: Estimated cost of the Alvorada House most-effective performance envelope - Porto Alegre

$$C_{cost-effect.\ Poa} = (p \times 1.09) \times 1.17 + 0.11\ d_{cost-effect.\ Poa}$$

Where,

C = cost of the Alvorada House construction, in Brazilian reais.
p = standard price of the house construction, calculated through the multiplication of the CUB by the built area of the house, in Brazilian reais.
d = cost of the architectural design. For a typical affordable housing, this is obtained through the multiplication of the CUB by the built area of the house, as shown in Table 5-25.

6.10 Conclusions

The Alvorada House is an affordable house appropriately designed for the local climate (i.e. diferent from the MCMV House) and it had its thermal performance evaluated using empirical data. In addition, a housing envelope optimisation analysis was undertaken based on the findings of Chapter 4, which suggested the use of insulation and limited infiltration on the housing envelope for increasing its thermal comfort.

The Alvorada House was found to well represent a 1-storey 2-bedroom affordable detached house typology for the southern Brazilian context and its main characteristics are shown in Table 6-26. The house was conceived as an optimised design solution for affordable houses to be implemented in small and medium scales in locations that share cultural, market and climate similarities.

Table 6-26: Alvorada House summary

	Characteristics:
House type	Affordable house for low and lower-middle economic classes
Total internal area	38.67 m^2
Total external area	43.00 m^2 (49.43 m^2 including porches)
Orientation	North-south orientated
Typology	1-storey, 2-bedroom detached house
Features	Rectangular plan, pitched roof and use of porches
Materials	Culturally accepted materials: brick and ceramic roof tiles

The Alvorada House design exploited the use of passive design strategies at affordable costs mainly for the context of Porto Alegre. Some of these strategies were found to be successfully implemented such as the eaves. The eaves on the north facade were found capable of delivering equinox cut-off shading and, consequently, additional shading was shown to be ineffective on this facade.

The house construction used culturally accepted materials of good quality, as traditionally used in most middle-class standard houses. However, even though the house walls were built out of materials of high thermal mass such as solid bricks, the use of low thickness could have impaired the house's thermal performance.

The Alvorada House under a typical occupancy was estimated to have internal gains equivalent to 10.9 W/m^2. The internal gains of the Alvorada House were found to be 5 times higher than the internal gains adopted in the Passivhaus standard for a house that is 2.8 times smaller than the typical size of the German standard house.

The internal gains turned out to play an important role in the thermal comfort balance of the house. They brought moisture inside the building and this seems to be the reason why the Passivhaus standard sets out the use of highly efficient equipment and a very limited occupancy. The internal gains were also responsible for increasing peak

temperatures but the solid nature of the Brazilian construction using bricks on the envelope and on the internal partitions might have reduced its negative effect. The findings suggested that the traditional use of thermal mass in southern Brazilian houses might absorb the heat and release it when the internal temperatures are more favourable.

The Alvorada House performance as built and occupied was compared with optimised envelope scenarios at standard infiltration rate, defined based on the findings of Chapter 4. The super-insulated envelope scenario, which had insulation levels compatible with the Passivhaus standard, increased the narrow thermal comfort by 45% in São Paulo and 73% in Porto Alegre relative to the envelope as built. The most cost-effective envelope scenario increased the narrow thermal comfort by 34% in São Paulo and 45% in Porto Alegre relative to the envelope as built. In Curitiba, for both envelope scenarios, the increase of comfort level was only observed for the wide thermal comfort interval.

The optimised envelope scenarios were also evaluated at limited infiltration rate to increase indoor thermal comfort conditions. Limited infiltration rate showed to be beneficial for the climates investigated at first mainly because it reduced heating demand and cooling demand as it reduced the peak temperatures when the house was closed. The super-insulated envelope scenario increased the thermal comfort by 24%, 72% and 130% in Curitiba, São Paulo and Porto Alegre relative to the Alvorada House envelope as built, respectively. The most cost-effective envelope scenario increased the narrow thermal comfort by 20%, 60.5% and 87% for the cities relative to the envelope as built, respectively.

Despite its evident benefit, airtight envelopes should be handled with care for the Brazilian context. From the temperature point of view, airtight envelopes can keep the indoor temperatures within the thermal comfort zone effectively, but from the relative humidity point of view, they can be counterproductive for the Brazilian context of affordable houses. Airtight housing envelopes had relative humidity levels above 80% almost quadrupled when compared to the Alvorada House as built. This suggests that if airtight envelopes would be adopted at this level, a strategy for dehumidification should be considered.

Therefore, limited infiltration rate requires further investigation as to what level it should be implemented, how it should be implemented and how it could be supported in the Brazilian houses, given its thermal beneficial contribution. Specifically, building energy regulations should be revisited and special attention should be paid to ensure optimised levels of infiltration without compromising the IAQ of the building. Furthermore, from the cost perspective, in order to deliver limited infiltration to the building, the costs and the time in designing and constructing the housing would be increased, which might

not be feasible for the affordable housing context, but might be for other housing typologies.

Disregarding limited infiltration rate, the optimised envelope at standard infiltration rate was able to deliver satisfactory levels of thermal comfort if the wide thermal comfort interval is to be considered. In particular, the most cost-effective envelope would increase the thermal comfort to 73.5%, 99% and 95% of the year, which was 13%, 11% and 17% more thermally comfortable than the occupied typical Alvorada House in Curitiba, São Paulo and Porto Alegre, respectively.

Most of the simulations were conducted considering the building as free-running, as it is mostly found in affordable Brazilian houses. The use of natural ventilation was found to be effective to reduce the temperatures and the relative humidity levels inside the building. However, in order to quantify the running costs of the house under the typical and optimised envelopes, a fully conditioned scenario was evaluated.

Under a fully conditioned scenario, the optimised envelopes showed to consume less energy than the Alvorada House envelope as built. The super-insulated envelope scenario had energy cost savings of 64.25%, 90.02% and 88.21% in Curitiba, São Paulo and Porto Alegre when compared to the typical envelope, respectively. Despite their significant reduction in energy demand, the super-insulated envelope would add 65% 66% and 65% more to the typical construction costs and the payback period would correspond to 21, 27 and 19 years in Curitiba, São Paulo and Porto Alegre, respectively. For a more realistic scenario, the most cost-effective envelope scenario had energy cost savings of 54.75%, 80.56%, 74.75% in Curitiba, São Paulo and Porto Alegre in comparison to the typical envelope, respectively. However, the most cost-effective envelope would add only 8%, 6 and 9% more to the typical construction costs in Curitiba, São Paulo and Porto Alegre and the payback period would correspond to around five years, which makes its implementation more feasible, respectively.

As expected, the analysis of the Alvorada envelope showed that adopting the Fabric First approach principles can be beneficial to a certain extent. However, due to the small size of affordable Brazilian housing, high form factor, high internal gains and also because of the additional costs, the conservative Brazilian construction market and the affordable nature of the house, this would limit the successful use of the approach in the Brazilian context.

CHAPTER 7: CONCLUSION AND FURTHER WORK

This chapter presents the conclusion of the current work and recommendations for further work.

''The ideal project does not exist, each time there is the opportunity to realize an approximation''
Paulo Mendes da Rocha, Brazilian architect (Dushkes, 2012, p. 50)

7 CONCLUSION AND FURTHER WORK

The Brazilian government has set an ambitious target of 24 million new affordable dwellings to be built by 2022 to mitigate the enormous housing shortfall and the inadequate living conditions of dwellings. Moreover, a recent change in the Brazilian energy matrix, with a higher share supplied by fossil fuels, has been implemented to supplement the increasing energy demand, impacting directly on residential energy costs. It is therefore critical that the new affordable homes are energy efficient and provide adequate levels of thermal comfort; otherwise the impact on the energy use will be significant in a long-term housing run.

Despite the fact that most house in Brazil operate in free-running mode, the houses need to be as efficient as possible when they operate in mixed-mode, as they can reduce the energy use.

The literature has suggested that the Fabric First approach is a potential solution to increase thermal comfort and to reduce energy use in houses. The present research consisted of a new take on the Fabric First approach use for the climates of southern Brazil in the context of housing. It also considered the existing cultural, economic and climate differences in the cities investigated and proposed a new deeper investigation about the implementation of the Fabric First approach.

The research originality relied on the fact that there are so far a very limited number of studies that address this matter in different climates and even fewer studies that consider the regional peculiarities that the locations investigated display. The subject-matter is extremely relevant at global levels, in the context of the worldwide current calls by governments for increasing energy efficiency in buildings, climate change and risk of fuel poverty; and at national levels, in the context of changes in the Brazilian energy matrix, the increase in energy prices, and the recent increase of the residential sector for low and low-middle classes that is taking place in Brazil.

The rigour of the present work was achieved by using established methods to explore a new subject: a sensitivity analysis and multiple-case study analysis. The sensitivity analysis, discussed in Chapter 4, had exploratory purposes as it examined the performance of a variety of different envelopes by considering local features of the construction and specific concepts of the Fabric First approach. It also had explanatory purposes as it aimed to understand the physics involved in the results obtained. The case studies, shown in Chapter 5 and 6, were analysed independently through a similar descriptive framework and they showed the same convergence line of results. The case studies investigated the thermal performance of a typical affordable Brazilian

house and an optimised design affordable Brazilian house, through computational simulations underpinned by monitored data. The case studies had in common their typology and size but varied widely in some aspects such as design form and fenestrations. The case studies evaluated the house's original thermal performance in use and examined potential improvements through the adoption of the Fabric First approach for two different envelope optimisation scenarios. The case studies had the method and procedures of analysis replicated, which made the argument and the investigation more persuasive and robust. It should be highlighted, however, that the Alvorada House case study was a step up of the investigation as it adopted a case study built with environmental design strategies to improve thermal comfort and used empirical data to calibrate the simulation model.

7.1 Research Outcome

The research hypothesis assumed that currently most Brazilian housing building envelopes, and those of affordable housing in particular, underperform in terms of thermal comfort and energy efficiency and could be optimised through the use of the fabric first approach. To do so, the hypothesis led to the research question as follow:

Is the application of the fabric first approach suitable to improve thermal comfort and energy efficiency in affordable housing in southern Brazil?

The thesis argued that the Fabric First approach can lead to a substantial increase of thermal comfort and energy efficiency in affordable dwellings but its application should be handled with care as there are cultural and economic limitations. The thesis makes a distinct addition to knowledge as it supports the claim that typical building envelopes of affordable Brazilian dwellings in the cities investigated perform poorly and they consume more energy when compared to other optimised envelopes, based on the Fabric First approach.

The sensitivity analysis evaluated 108 envelope combinations based on the most used Brazilian envelopes, with a varied degree of insulation on different elements of the building envelope. Typical and reduced infiltration rates were also explored. The results were compared against cost estimation of typical affordable dwellings. Typical Brazilian envelopes underperformed by up to 65% in terms of thermal comfort when compared to the super-insulated envelopes investigated. Limited infiltration rates increased the thermal comfort by up to 25% when adopted in typical envelopes. However, they were more beneficial when adopted on super-insulated envelopes, where the thermal comfort increase corresponded to up to 97% in comparison to the typical envelope, in terms of the narrow thermal comfort interval. The outcomes of the investigation

revealed the best performance envelope and the most cost-effective envelope, which were tested in real case studies.

In the case studies, the super-insulated envelope with standard infiltration rate was shown to deliver up to 73-75% more thermal comfort than the typical Brazilian case study envelopes for narrow thermal comfort interval. Comparatively, the most cost-effective envelope was shown to deliver up to 40-45% more thermal comfort in comparison to the typical case study envelopes for the narrow thermal comfort intervals.

With the use of an airtight super-insulated envelope, the thermal comfort would correspond to up to 114-130% more than the typical case study envelopes at standard infiltration rate. The most cost-effective envelope at limited infiltration rate could deliver up to 71-87% more thermal comfort in comparison to the typical case study envelopes at standard infiltration rate. However, the investigation shows that the construction market still needs to adapt to achieve limited infiltration levels.

Despite the thermal benefits, the use of super-insulated envelopes were shown not to be cost-effective, given that in current Brazilian construction practices, it could increase the dwellings' construction costs by about 56-66% and have a payback period of up to 32 years for a fully-conditioned scenario or even much higher for a mixed-mode scenario. This has shown to be immensely higher than in other countries such as the United Kingdom, where a properly certified Passivhaus house (not only building envelope improvements) would have extra costs of about 15-20% (Passivhaus Trust, 2015, p. 11, Newman, 2012, p. 4).

Despite the fact that the research findings showed that currently envelopes do not provide reasonable thermal comfort levels in affordable houses, small changes on the envelope, however, such as those adopted in the most cost-effective envelope would add upfront costs of only 6-12% and have a payback period of 5-11 years, based on a fully conditioned scenario.

It should be stressed that previous work in this field has suggested that airtight and super-insulated houses might not be adequate in terms of thermal comfort and could even lead to indoor overheating. However, the present work has shown that the Fabric First approach can be suitable to a certain extent for the climates investigated, despite the fact that humidity control may need to be considered. However, a limited implementation of this approach seems to be more realistic to improve thermal comfort and energy efficiency in affordable southern Brazilian houses in a cost-effective way.

In summary, the present research has found that the Fabric First approach might not be suitable to be wholly implemented in Brazil. The reason is because there is a social

and economic impact, which might require massive step changes in the design process, construction practice and market. Hence, this might not be a sustainable approach to be implemented in full for affordable houses in Brazil, which display a unique characteristic of being low-rise, spread-out form, small and highly occupied. It is suggested, however, that progressive improvements on their building envelope, can ensure gradually improved levels of indoor thermal comfort and energy efficiency as the construction costs will reduce overtime and also the access to skilled labour will increase over time. Therefore, the implementation of the Fabric First approach in southern Brazil should acquire its own features because there are differences from the original approach that are not adequate for use in Brazil.

It is therefore also crucial the implementation of a holistic approach, which encompasses an optimised house design, with appropriate fenestrations design, orientation, use of ventilation and use of shading. For example, shading is given no attention at all by the people involved in the planning and designing of the affordable houses, as shown by the typical affordable house case study. Fortunately, it is from the common practice of vernacular and local habits of designing and constructing dwellings to consider shading with the use of eaves in the houses, which showed a satisfactory contribution to reducing the risk of overheating. Similarly, the positive effect of ventilation is only achieved if the occupant has a grasp of the variables involved. Ventilation strategies can be widely adjusted and surely adopting different patterns of use do make a huge difference in achieving higher levels of indoor thermal comfort and adequate relative humidity levels. The inappropriate use of ventilation was shown to have a negative impact on the indoor thermal conditions.

The present research identified two key areas, which can contribute to limiting the application of the Fabric First approach in affordable southern Brazilian houses:

i. Cultural: the tradition in which the houses are built and as they are inhabited may restrict the use of the Fabric First approach.
    - The way that affordable dwellings are built in Brazil evolves from the use of cheap masonry materials and custom-made techniques. The present research has identified the best performance envelope among those evaluated as being a super-insulated envelope and the most cost-effective as being a typical Brazilian envelope with insulated walls. Despite the fact that the main envelope materials are similar to those used in affordable houses (i.e. brick), the use of insulation is not part of common practice in constructing dwellings in Brazil and it will require appropriate installation and maintenance to deliver the predicted performance.
    - Brazilian occupancy behaviour mostly keeps the windows opened even when the outdoor temperature is higher than the internal condition. There

seems to be a lack of awareness of the physics involved in buildings which can negatively contribute to the performance of dwellings. Therefore, more understanding by the occupants in better managing the windows would be required and it could be a limitation for poor and less educated households.

- The affordable houses in Brazil showed to be very distinct from the houses where the Fabric First approach was designed and where it is currently being used. The main aspects of affordable Brazilian houses are that they have a spread-out form, a small size and high occupancy, which negatively impacts on the thermal performance and costs, limiting the application of the Fabric First approach for the locations investigated. Affordable Brazilian dwellings are about 2.8-3 times smaller than the typical Fabric First approach house and have heat gains estimated to be about 5-5.5 times higher than values assumed in low-energy houses such as Passivhaus houses. The occupancy rates in the affordable Brazilian dwellings investigated are equivalent to 1 person for each 9-10 m^2, whereas in Passivhaus buildings the occupancy rates represent 1 person for each 35 m^2.

ii. Economic: the nature of the Brazilian construction market would greatly impact on the construction costs, limiting the application of the Fabric First approach.

- There is a lack of skilled labour in the construction sector. The workforce has insufficient training and a lower educational level than workers of other sectors. This may be implicated in the low level of commitment and awareness of the workers regarding the construction aspects such as airtightness and how to make buildings less leaky. It is therefore critical to promote changes in the workforce such as training and use of specialised labour.
- Lack of good quality and detailed architectural design of affordable dwellings which might result in imprecisions and re-work during the construction phase and poor performance in the use phase.
- The Brazilian method of construction is more custom-made rather than prefabricated, which gives a variable quality to the building construction. Due to the particular characteristic of being very handcrafted, rates of re-works are likely to be high. The construction process still uses low innovation and limited pre-fabrication and has low productivity and quality. This might compromise the delivery of the predicted performance to the occupants.
- Lack of innovation in the construction industry regarding high performance materials. As observed in the present research, high performance

materials such as low-e glazing and thick insulation materials are not yet widespread in the dwellings construction market, although they can be found in the construction industry. This may impair the use of these high-performance materials on the dwellings envelope.

- Lack of government subsidies on the use of high performance materials.

All these findings can be used to inform government and industry regarding the benefits of adopting stricter requirements for the building envelopes of dwellings than those currently used and required by the building energy regulations. The findings also evidenced that although the recent implementation of the NBR 15575 has established stricter criteria to the residential buildings than previously adopted, there is a huge capacity to deliver much more, employing changes in the building envelope. This implies that there is a need to revisit the Brazilian standard if energy efficiency is aimed in affordable dwellings.The outcomes suggest that changes in common practices in affordable houses could ensure better levels of thermal comfort and low running costs during the lifespan of these houses.

7.2 Further work

This research has not only focused on affordable homes but also made a significant contribution to help define different characteristics of middle-class standard houses, which corresponds to another massive proportion of Brazilian houses. Middle-class standard housing, however, was left out of the investigation because these kinds of houses vary immensely and, thus, a prior detailed prolonged investigation of existing typologies, typical sizes and areas would be required. Research in middle-class standard housing might show to be more appropriate in implementing the Fabric First approach when compared to affordable houses. This would be because middle-class standard housing uses better performance materials, has less occupancy (less internal gains), has a larger internal area and might also have a more compact typology, which might approximate to the typical houses where the Fabric First approach has been implemented. To sum up, the study of middle-class standard houses could add to the investigation of the application of the Fabric First in Brazilian dwellings and it remains a strong case for further investigation.

The potential impact of an improved design of the affordable house in terms of thermal performance also remains for further investigation, as improvements in the design could ensure much higher levels of thermal performance for the occupants.

Another suggestion for further work is to conduct a similar study as this one, looking into warmer climates in Brazil. The investigation in warmer climates will have different

responses of the envelopes investigated, as the envelopes will impact the energy demand in a different way, suggesting different running costs and payback period.

It is also suggested for further investigation to test the cost equations formulated in the current research for designing and delivering typical and optimised affordable houses in Brazil. The equations can be used to help estimate the cost of, a potentially time-consuming process, in a simplified and an efficient way.

PUBLISHED PAPERS

Published papers at the time of the thesis submission:

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APPENDIX A

Appendix A shows additional information of Chapter 4.

Thermal properties of the envelope elements- parametric study

Location	Material	Density ρ (kg/m^3)	Thermal conductivity λ (W/mK)	Specific heat capacity c (J/kgK)	Source
Walls	Solid Brick	1800	1.0	920	(ABNT, 2005c)
	Hollow Block	1300	0.9	920	(ABNT, 2005b)
	Lime cement plaster (μ:15)	2000	1.15	1000	(ABNT, 2005c)
	Ceramic tile	2000	1.20	850	(CIBSE, 2006b)
	Silicate plaster (μ:35)	1800	0.8	1120	(IBO - Austrian Institute for Healthy and Ecological Building, 2009)
	EPS (μ:30)	30	0.035	1450	
	EPS facade (μ:1)	18	0.040	1450	
Windows	3 mm glass	-	1.0	-	CIBSE, 2006)
	Wood frame	600	0.23	1340	(ABNT, 2005b)
	PVC frame	-	0.176	-	TAS database
Roof	Ceramic roof tiles	2000	1.05	920	(ABNT, 2005c)
	Aluminium foil (μ:1,500,000)	2700	230	880	(ABNT, 2005c)
	Mineral wool (μ:1)	33	0.040	1030	(IBO - Austrian Institute for Healthy and Ecological Building, 2009)
	Open-diffusion PE foil (μ:100)	0.08	0.2	1400	
	Wood fibreboard (μ:5)	270	0.05	2000	
	Vapour barrier (μ:10)	0.2	0.2	1400	
	Wood ceiling	600	0.23	1340	(ABNT, 2005b)
Ground	Soil	1250	1.5	2500	TAS database
	Stone chippings	2000	2	1000	TAS database
	Concrete/Screed concrete (μ:100/ 50)	2200	1.75	1000	(ABNT, 2005b)
	Ceramic floor tiles (μ:150)	2000	1.30	840	(IBO - Austrian Institute for Healthy and Ecological Building, 2009)
Shading	Wood	600	0.23	1340	(ABNT, 2005b)

Schedule of internal gains

0: off; 1: on

Weekdays	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
24 hours period	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Occupancy period	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
95W occupancy	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
130W occupancy	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Lighting 5W/m^2	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0
TV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
Weekend	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
24 hours period	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Occupancy period	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
95W occupancy	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
130W occupancy	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0
Lighting 5W/m^2	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	1	1	1	1	1	1	0
TV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0

95W is compatible with an occupancy regime of a bedroom and 130W is compatible with an occupancy regime of a living room.

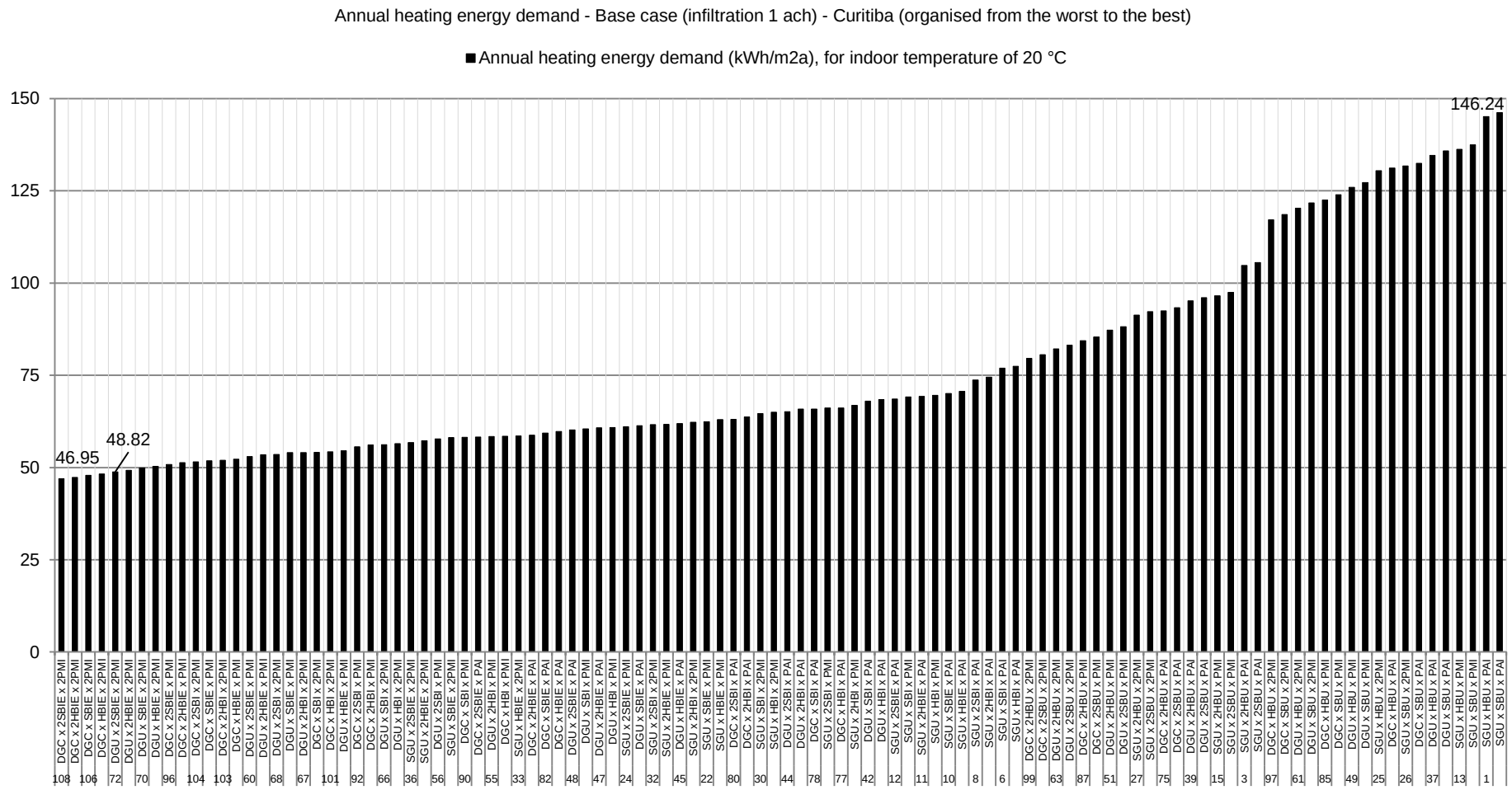
		PAI		PMI		2PMI
				SGU glazing – from 1 to 36		
HBU	**001**	(SGU) Single glazing, (HBU) Hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**013**	(SGU) Single glazing,(HBU) Hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**025**	(SGU) Single glazing, (HBU) Hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
SBU	**002**	(SGU) Single glazing,(SBU) Solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**014**	(SGU) Single glazing, (SBU) Solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**026**	(SGU) Single glazing,(SBU) Solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
2HBU	**003**	(SGU) Single glazing,(2HBU) 2-Layers hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**015**	(SGU) Single glazing,(2HBU) 2-Layers hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**027**	(SGU) Single glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
2SBU	**004**	(SGU) Single glazing,(2SBU) 2-Layers solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**016**	(SGU) Single glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**028**	(SGU) Single glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
HBI	**005**	(SGU) Single glazing,(HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**017**	(SGU) Single glazing, (HBI) Hollow ceramic block wall insulated, (PMI) Mineral wool roof	**029**	(SGU) Single glazing, (HBI) Hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
SBI	**006**	(SGU) Single glazing,(SBI) Solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**018**	(SGU) Single glazing, (SBI) Solid ceramic brick wall insulated, (PMI) Mineral wool roof	**030**	(SGU) Single glazing, (SBI) Solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
2HBI	**007**	(SGU) Single glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**019**	(SGU) Single glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PMI) Mineral wool roof	**031**	(SGU) Single glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
2SBI	**008**	(SGU) Single glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**020**	(SGU) Single glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PMI) Mineral wool roof	**032**	(SGU) Single glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
HBIE	**009**	(SGU) Single glazing, (HBIE) Hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**021**	(SGU) Single glazing, (HBIE) Hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**033**	(SGU) Single glazing, (HBIE) Hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
SBIE	**010**	(SGU) Single glazing, (SBIE) Solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**022**	(SGU) Single glazing, (SBIE) Solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**034**	(SGU) Single glazing, (SBIE) Solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
2HBIE	**011**	(SGU) Single glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**023**	(SGU) Single glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**035**	(SGU) Single glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
2SBIE	**012**	(SGU) Single glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**024**	(SGU) Single glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**036**	(SGU) Single glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof

		PAI		PMI		2PMI
			DGU glazing from 37 to 72			
HBU	**037**	(DGU) Double uncoated glazing, (HBU) Hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**049**	(DGU) Double uncoated glazing, (HBU) Hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**061**	(DGU) Double uncoated glazing, (HBU) Hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
SBU	**038**	(DGU) Double uncoated glazing, (SBU) Solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**050**	(DGU) Double uncoated glazing, (SBU) Solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**062**	(DGU) Double uncoated glazing, (SBU) Solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool pitched roof
2HBU	**039**	(DGU) Double uncoated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (PAI) Aluminium foil pitched roof	**051**	(DGU) Double uncoated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (PMI) Mineral wool pitched roof	**063**	(DGU) Double uncoated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool pitched roof
2SBU	**040**	(DGU) Double uncoated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PAI) Aluminium foil pitched roof	**052**	(DGU) Double uncoated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PMI) Mineral wool pitched roof	**064**	(DGU) Double uncoated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool pitched roof
HBI	**041**	(DGU) Double uncoated glazing,(HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil pitched roof	**053**	(DGU) Double uncoated glazing, (HBI) Hollow ceramic block wall insulated, (PMI) Mineral wool roof	**065**	(DGU) Double uncoated glazing, (HBI) Hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool pitched roof
SBI	**042**	(DGU) Double uncoated glazing,(SBI) Solid ceramic brick wall insulated, (PAI) Aluminium foil pitched roof	**054**	(DGU) Double uncoated glazing, (SBI) Solid ceramic brick wall insulated, (PMI) Mineral wool roof	**066**	(DGU) Double uncoated glazing, (SBI) Solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool pitched roof
2HBI	**043**	(DGU) Double uncoated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PAI) Aluminium foil pitched roof	**055**	(DGU) Double uncoated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PMI) Mineral wool roof	**067**	(DGU) Double uncoated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
2SBI	**044**	(DGU) Double uncoated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**056**	(DGU) Double uncoated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PMI) Mineral wool roof	**068**	(DGU) Double uncoated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
HBIE	**045**	(DGU) Double uncoated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**057**	(DGU) Double uncoated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**069**	(DGU) Double uncoated glazing, (HBIE) Hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
SBIE	**046**	(DGU) Double uncoated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**058**	(DGU) Double uncoated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**070**	(DGU) Double uncoated glazing, (SBIE) Solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
2HBIE	**047**	(DGU) Double uncoated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**059**	(DGU) Double uncoated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**071**	(DGU) Double uncoated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
2SBIE	**048**	(DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**060**	(DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**072**	(DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof

		PAI		PMI		2PMI
			DGC glazing from 73 to 108			
HBU	**073**	(DGC) Double coated glazing, (HBU) Hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**085**	(DGC) Double coated glazing, (HBU) Hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**097**	(DGC) Double coated glazing, (HBU) Hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
SBU	**074**	(DGC) Double coated glazing, (SBU) Solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**086**	(DGC) Double coated glazing, (SBU) Solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**098**	(DGC) Double coated glazing, (SBU) Solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
2HBU	**075**	(DGC) Double coated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**087**	(DGC) Double coated glazing, 2HBU) 2-Layers hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**099**	(DGC) Double coated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
2SBU	**076**	(DGC) Double coated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**088**	(DGC) Double coated glazing, 2SBU) 2-Layers solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**100**	(DGC) Double coated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
HBI	**077**	(DGC) Double coated glazing, (HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**089**	(DGC) Double coated glazing, (HBI) Hollow ceramic block wall insulated, (PMI) Mineral wool roof	**101**	(DGC) Double coated glazing, (HBI) Hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
SBI	**078**	(DGC) Double coated glazing, (SBI) Solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**090**	(DGC) Double coated glazing, (SBI) Solid ceramic brick wall insulated, (PMI) Mineral wool roof	**102**	(DGC) Double coated glazing, (SBI) Solid ceramic brick wall insulated, 2PMI) 2-layers Mineral wool roof
2HBI	**079**	(DGC) Double coated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**091**	(DGC) Double coated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PMI) Mineral wool roof	**103**	(DGC) Double coated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
2SBI	**080**	(DGC) Double coated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**092**	(DGC) Double coated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PMI) Mineral wool roof	**104**	(DGC) Double coated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
HBIE	**081**	(DGC) Double coated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**093**	(DGC) Double coated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**105**	(DGC) Double coated glazing, (HBIE) Hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
SBIE	**082**	(DGC) Double coated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**094**	(DGC) Double coated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**106**	(DGC) Double coated glazing, (SBIE) Solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
2HBIE	**083**	(DGC) Double coated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**095**	(DGC) Double coated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**107**	(DGC) Double coated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
2SBIE	**084**	(DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**096**	(DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**108**	(DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof

Envelope combinations investigated

001	(SGU) Single glazing, (HBU) Hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**013**	(SGU) Single glazing,(HBU) Hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**025**	(SGU) Single glazing, (HBU) Hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
002	(SGU) Single glazing,(SBU) Solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**014**	(SGU) Single glazing, (SBU) Solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**026**	(SGU) Single glazing,(SBU) Solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
003	(SGU) Single glazing,(2HBU) 2-Layers hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**015**	(SGU) Single glazing,(2HBU) 2-Layers hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**027**	(SGU) Single glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
004	(SGU) Single glazing,(2SBU) 2-Layers solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**016**	(SGU) Single glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**028**	(SGU) Single glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
005	(SGU) Single glazing,(HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**017**	(SGU) Single glazing, (HBI) Hollow ceramic block wall insulated, (PMI) Mineral wool roof	**029**	(SGU) Single glazing, (HBI) Hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
006	(SGU) Single glazing,(SBI) Solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**018**	(SGU) Single glazing, (SBI) Solid ceramic brick wall insulated, (PMI) Mineral wool roof	**030**	(SGU) Single glazing, (SBI) Solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
007	(SGU) Single glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**019**	(SGU) Single glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PMI) Mineral wool roof	**031**	(SGU) Single glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
008	(SGU) Single glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**020**	(SGU) Single glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PMI) Mineral wool roof	**032**	(SGU) Single glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
009	(SGU) Single glazing, (HBIE) Hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**021**	(SGU) Single glazing, (HBIE) Hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**033**	(SGU) Single glazing, (HBIE) Hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
010	(SGU) Single glazing, (SBIE) Solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**022**	(SGU) Single glazing, (SBIE) Solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**034**	(SGU) Single glazing, (SBIE) Solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
011	(SGU) Single glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**023**	(SGU) Single glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**035**	(SGU) Single glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
012	(SGU) Single glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**024**	(SGU) Single glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**036**	(SGU) Single glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
037	(DGU) Double uncoated glazing, (HBU) Hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**049**	(DGU) Double uncoated glazing, (HBU) Hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**061**	(DGU) Double uncoated glazing, (HBU) Hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
038	(DGU) Double uncoated glazing, (SBU) Solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**050**	(DGU) Double uncoated glazing, (SBU) Solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**062**	(DGU) Double uncoated glazing, (SBU) Solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool pitched roof
039	(DGU) Double uncoated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (PAI) Aluminium foil pitched roof	**051**	(DGU) Double uncoated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (PMI) Mineral wool pitched roof	**063**	(DGU) Double uncoated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool pitched roof
040	(DGU) Double uncoated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PAI) Aluminium foil pitched roof	**052**	(DGU) Double uncoated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PMI) Mineral wool pitched roof	**064**	(DGU) Double uncoated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool pitched roof
041	(DGU) Double uncoated glazing,(HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil pitched roof	**053**	(DGU) Double uncoated glazing, (HBI) Hollow ceramic block wall insulated, (PMI) Mineral wool roof	**065**	(DGU) Double uncoated glazing, (HBI) Hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool pitched roof
042	(DGU) Double uncoated glazing,(SBI) Solid ceramic brick wall insulated, (PAI) Aluminium foil pitched roof	**054**	(DGU) Double uncoated glazing, (SBI) Solid ceramic brick wall insulated, (PMI) Mineral wool roof	**066**	(DGU) Double uncoated glazing, (SBI) Solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool pitched roof
043	(DGU) Double uncoated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PAI) Aluminium foil pitched roof	**055**	(DGU) Double uncoated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PMI) Mineral wool roof	**067**	(DGU) Double uncoated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
044	(DGU) Double uncoated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**056**	(DGU) Double uncoated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PMI) Mineral wool roof	**068**	(DGU) Double uncoated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
045	(DGU) Double uncoated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**057**	(DGU) Double uncoated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**069**	(DGU) Double uncoated glazing, (HBIE) Hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
046	(DGU) Double uncoated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**058**	(DGU) Double uncoated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**070**	(DGU) Double uncoated glazing, (SBIE) Solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
047	(DGU) Double uncoated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**059**	(DGU) Double uncoated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**071**	(DGU) Double uncoated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
048	(DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**060**	(DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**072**	(DGU) Double uncoated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
073	(DGC) Double coated glazing, (HBU) Hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**085**	(DGC) Double coated glazing, (HBU) Hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**097**	(DGC) Double coated glazing, (HBU) Hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
074	(DGC) Double coated glazing, (SBU) Solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**086**	(DGC) Double coated glazing, (SBU) Solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**098**	(DGC) Double coated glazing, (SBU) Solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
075	(DGC) Double coated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (PAI) Aluminium foil roof	**087**	(DGC) Double coated glazing, 2HBU) 2-Layers hollow ceramic block wall uninsulated, (PMI) Mineral wool roof	**099**	(DGC) Double coated glazing, (2HBU) 2-Layers hollow ceramic block wall uninsulated, (2PMI) 2-layers Mineral wool roof
076	(DGC) Double coated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (PAI) Aluminium foil roof	**088**	(DGC) Double coated glazing, 2SBU) 2-Layers solid ceramic brick wall uninsulated, (PMI) Mineral wool roof	**100**	(DGC) Double coated glazing, (2SBU) 2-Layers solid ceramic brick wall uninsulated, (2PMI) 2-layers Mineral wool roof
077	(DGC) Double coated glazing, (HBI) Hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**089**	(DGC) Double coated glazing, (HBI) Hollow ceramic block wall insulated, (PMI) Mineral wool roof	**101**	(DGC) Double coated glazing, (HBI) Hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
078	(DGC) Double coated glazing, (SBI) Solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**090**	(DGC) Double coated glazing, (SBI) Solid ceramic brick wall insulated, (PMI) Mineral wool roof	**102**	(DGC) Double coated glazing, (SBI) Solid ceramic brick wall insulated, 2PMI) 2-layers Mineral wool roof
079	(DGC) Double coated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PAI) Aluminium foil roof	**091**	(DGC) Double coated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (PMI) Mineral wool roof	**103**	(DGC) Double coated glazing, (2HBI) 2-Layers hollow ceramic block wall insulated, (2PMI) 2-layers Mineral wool roof
080	(DGC) Double coated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PAI) Aluminium foil roof	**092**	(DGC) Double coated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (PMI) Mineral wool roof	**104**	(DGC) Double coated glazing, (2SBI) 2-Layers solid ceramic brick wall insulated, (2PMI) 2-layers Mineral wool roof
081	(DGC) Double coated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**093**	(DGC) Double coated glazing, (HBIE) Hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**105**	(DGC) Double coated glazing, (HBIE) Hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
082	(DGC) Double coated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**094**	(DGC) Double coated glazing, (SBIE) Solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**106**	(DGC) Double coated glazing, (SBIE) Solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof
083	(DGC) Double coated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PAI) Aluminium foil roof	**095**	(DGC) Double coated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (PMI) Mineral wool roof	**107**	(DGC) Double coated glazing, (2HBIE) 2-Layers hollow ceramic block wall extra insulated, (2PMI) 2-layers Mineral wool roof
084	(DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PAI) Aluminium foil roof	**096**	(DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (PMI) Mineral wool roof	**108**	(DGC) Double coated glazing, (2SBIE) 2-Layers solid ceramic brick wall extra insulated, (2PMI) 2-layers Mineral wool roof


Annual heating energy demand - Base case (infiltration 1 ach) - Curitiba (organised from the worst to the best)
Annual heating energy demand (kWh/m2a), for indoor temperature of 20 °C
150
125
100
75
50
25
0
46.95
48.82
146.24
DGC x 2SBIE x 2PMI
DGC x 2HBIE x 2PMI
DGC x SBIE x 2PMI
DGC x HBIE x 2PMI
DGU x 2SBIE x 2PMI
DGU x 2HBIE x 2PMI
DGU x SBIE x 2PMI
DGU x HBIE x 2PMI
DGC x 2SBIE x PMI
DGC x 2HBIE x PMI
DGC x SBIE x PMI
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DGC x HBI x 2PMI
DGU x 2SBI x 2PMI
DGU x 2HBI x 2PMI
DGU x SBI x 2PMI
DGU x HBI x 2PMI
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SGU x SBIE x 2PMI
SGU x HBIE x 2PMI
DGC x 2SBIE x PAI
DGC x 2HBIE x PAI
DGC x SBIE x PAI
DGC x HBIE x PAI
DGU x 2SBIE x PAI
DGU x 2HBIE x PAI
DGU x SBIE x PAI
DGU x HBIE x PAI
SGU x 2SBIE x PMI
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SGU x 2SBU x PAI
SGU x 2HBU x PAI
SGU x SBU x PAI
SGU x HBU x PAI
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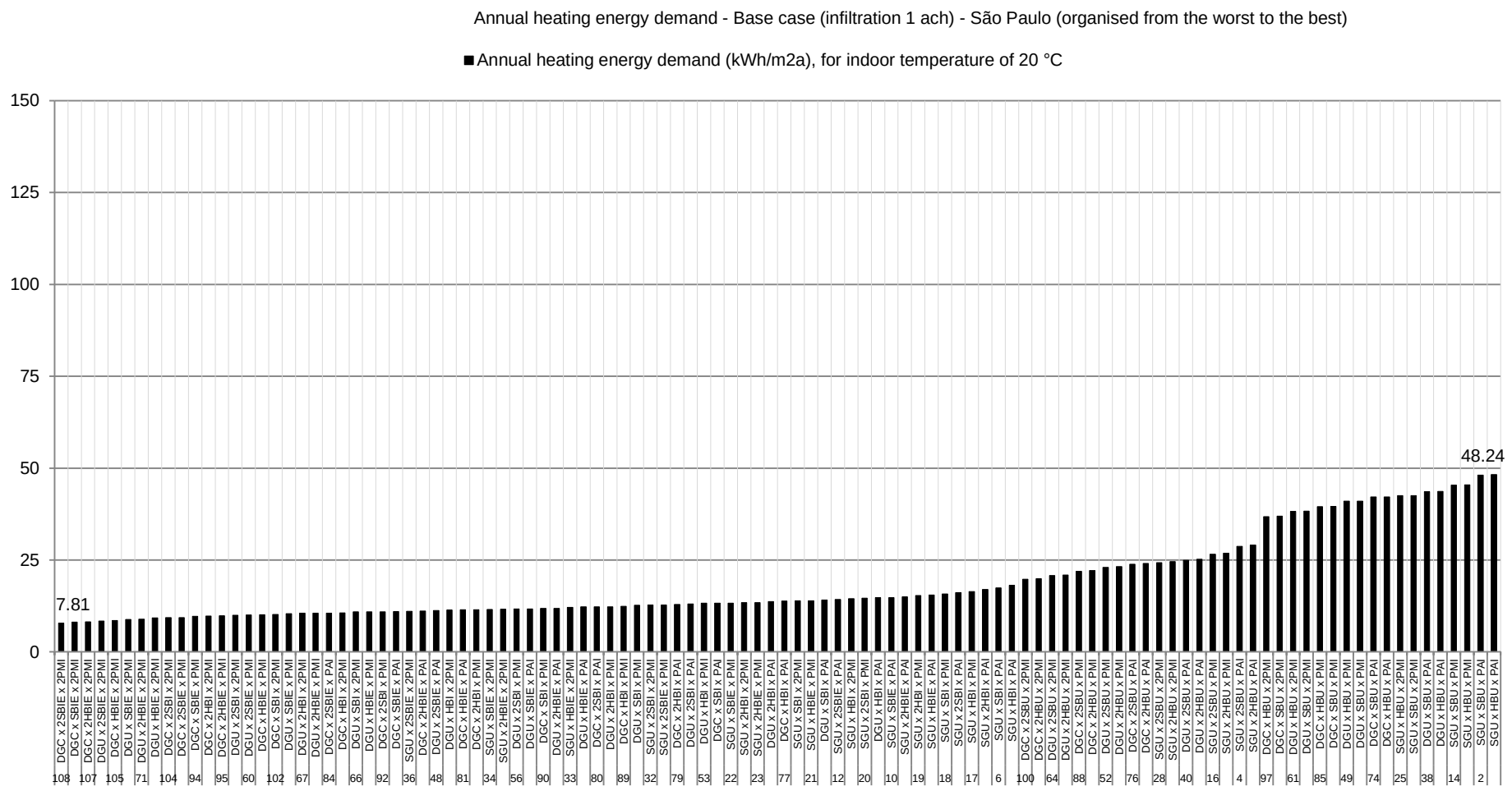
Annual heating energy demand - Base case (infiltration 1 ach) - São Paulo (organised from the worst to the best)
Annual heating energy demand (kWh/m2a), for indoor temperature of 20 °C
150
125
100
75
50
25
0
7.81
48.24
DGC x 2SBIE x 2PMI
DGC x SBIE x 2PMI
DGC x 2HBIE x 2PMI
DGU x 2SBIE x 2PMI
DGC x HBIE x 2PMI
DGU x SBIE x 2PMI
DGU x 2HBIE x 2PMI
DGU x HBIE x 2PMI
DGC x 2SBI x 2PMI
DGC x 2SBIE x PMI
DGC x SBIE x PMI
DGC x 2HBIE x PMI
DGU x 2SBI x 2PMI
DGC x HBIE x PMI
DGU x 2SBIE x PMI
DGU x SBIE x PMI
DGU x 2HBIE x PMI
DGC x 2SBIE x PAI
DGC x HBI x 2PMI
DGU x SBI x 2PMI
DGU x HBIE x PMI
DGC x 2SBI x PMI
DGC x SBIE x PAI
SGU x 2SBIE x 2PMI
DGC x 2HBIE x PAI
DGU x 2SBIE x PAI
DGU x HBI x 2PMI
DGC x HBIE x PAI
DGC x 2HBI x PMI
SGU x SBIE x 2PMI
SGU x 2HBIE x PAI
DGU x SBI x 2PMI
DGC x SBIE x PMI
DGU x 2HBIE x PAI
DGC x 2SBI x PAI
DGC x HBI x PMI
DGU x SBI x PMI
SGU x 2SBI x 2PMI
DGC x 2HBI x PAI
DGU x HBI x PMI
DGC x SBI x PAI
SGU x 2HBI x 2PMI
SGU x SBIE x PMI
DGU x 2HBI x PAI
SGU x SBI x 2PMI
SGU x HBIE x PMI
DGC x HBI x PAI
SGU x SBIE x PAI
SGU x 2HBIE x PMI
DGU x SBI x PAI
SGU x HBI x 2PMI
SGU x 2SBI x PMI
DGU x HBI x PAI
SGU x SBI x PMI
SGU x 2SBI x PAI
SGU x HBI x PMI
SGU x 2HBI x PAI
SGU x SBI x PAI
SGU x HBI x PAI
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DGC x 2HBIE x PMI
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DGU x HBIE x PMI
DGC x 2SBI x PMI
DGC x SBIE x PMI
DGU x 2HBIE x PMI
DGU x SBIE x PMI
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SGU x 2HBIE x PMI
DGU x 2SBI x PMI
DGU x SBIE x PMI
SGU x 2HBI x PMI
SGU x SBIE x PMI
SGU x 2SBI x PMI
SGU x SBI x PMI
DGC x 2SBU x 2PMI
DGC x 2HBU x 2PMI
DGU x 2SBU x 2PMI
DGU x 2HBU x 2PMI
DGC x 2SBU x PMI
DGC x 2HBU x PMI
DGU x 2SBU x PMI
DGU x 2HBU x PMI
DGC x 2SBU x PAI
DGC x 2HBU x PAI
SGU x 2SBU x 2PMI
SGU x 2HBU x 2PMI
DGU x 2SBU x PAI
DGU x 2HBU x PAI
SGU x 2SBU x PMI
SGU x 2HBU x PMI
SGU x 2SBU x PAI
SGU x 2HBU x PAI
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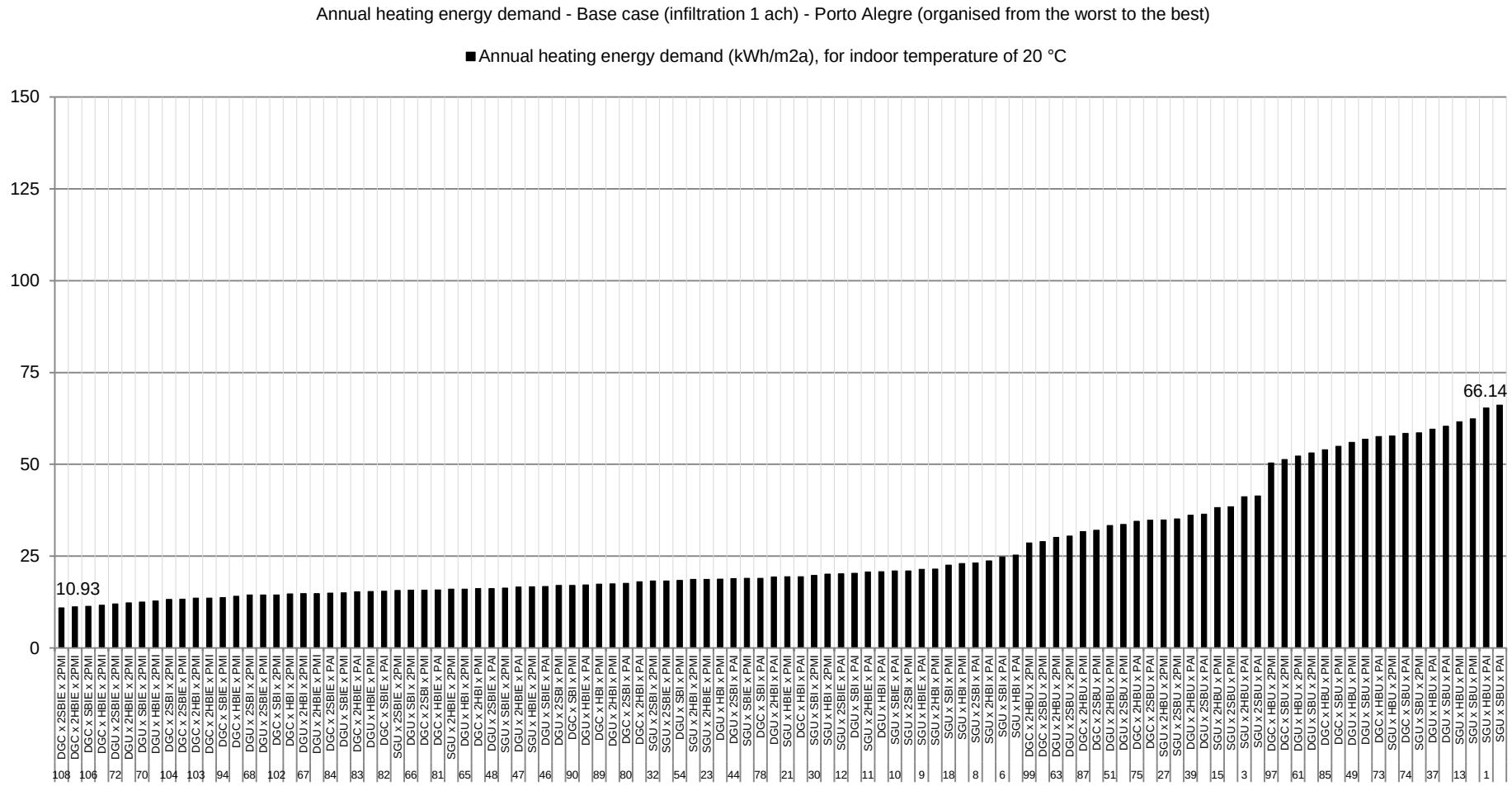
Annual heating energy demand - Base case (infiltration 1 ach) - Porto Alegre (organised from the worst to the best)
Annual heating energy demand (kWh/m2a), for indoor temperature of 20 °C
150
125
100
75
50
25
0
10.93
66.14
DGC x 2SBIE x 2PMI 108
DGC x 2HBIE x 2PMI 106
DGC x SBIE x 2PMI 72
DGC x HBIE x 2PMI 70
DGU x 2SBIE x 2PMI 104
DGU x 2HBIE x 2PMI 103
DGU x SBIE x 2PMI 94
DGU x HBIE x 2PMI 68
DGC x 2SBI x 2PMI 102
DGC x 2HBI x 2PMI 67
DGC x SBI x 2PMI 84
DGC x HBI x 2PMI 83
DGU x 2SBI x 2PMI 82
DGU x 2HBI x 2PMI 66
DGU x SBI x 2PMI 81
DGU x HBI x 2PMI 65
SGU x 2SBIE x 2PMI 48
SGU x 2HBIE x 2PMI 47
SGU x SBIE x 2PMI 46
SGU x HBIE x 2PMI 90
DGC x 2SBIE x PAI 89
DGC x 2HBIE x PAI 80
DGC x SBIE x PAI 32
DGU x 2SBIE x PAI 54
DGU x 2HBIE x PAI 23
DGU x SBIE x PAI 44
SGU x 2SBIE x PAI 78
SGU x 2HBIE x PAI 21
SGU x SBIE x PAI 30
DGC x 2SBI x PMI 12
DGC x 2HBI x PMI 11
DGC x SBI x PMI 10
DGC x HBI x PMI 9
DGU x 2SBI x PMI 18
DGU x 2HBI x PMI 8
DGU x SBI x PMI 6
DGU x HBI x PMI 99
SGU x 2SBI x PMI 63
SGU x 2HBI x PMI 87
SGU x SBI x PMI 51
SGU x HBI x PMI 75
DGC x 2SBIE x PAI 27
DGC x 2HBIE x PAI 39
DGC x SBIE x PAI 15
DGU x 2SBIE x PAI 3
DGU x 2HBIE x PAI 97
DGU x SBIE x PAI 61
SGU x 2SBIE x PAI 85
SGU x 2HBIE x PAI 49
SGU x SBIE x PAI 73
DGC x 2SBI x PAI 74
DGC x 2HBI x PAI 37
DGC x SBI x PAI 13
DGC x HBI x PAI 1
DGU x 2SBI x PAI
DGU x 2HBI x PAI
DGU x SBI x PAI
DGU x HBI x PAI
SGU x 2SBI x PAI
SGU x 2HBI x PAI
SGU x SBI x PAI
SGU x HBI x PAI
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SGU x 2SBU x 2PMI
SGU x 2HBU x 2PMI
SGU x SBU x 2PMI
SGU x HBU x 2PMI
DGC x 2SBU x PMI
DGC x 2HBU x PMI
DGC x SBU x PMI
DGC x HBU x PMI
DGU x 2SBU x PMI
DGU x 2HBU x PMI
DGU x SBU x PMI
DGU x HBU x PMI
SGU x 2SBU x PMI
SGU x 2HBU x PMI
SGU x SBU x PMI
SGU x HBU x PMI
DGC x 2SBU x PAI
DGC x 2HBU x PAI
DGC x SBU x PAI
DGC x HBU x PAI
DGU x 2SBU x PAI
DGU x 2HBU x PAI
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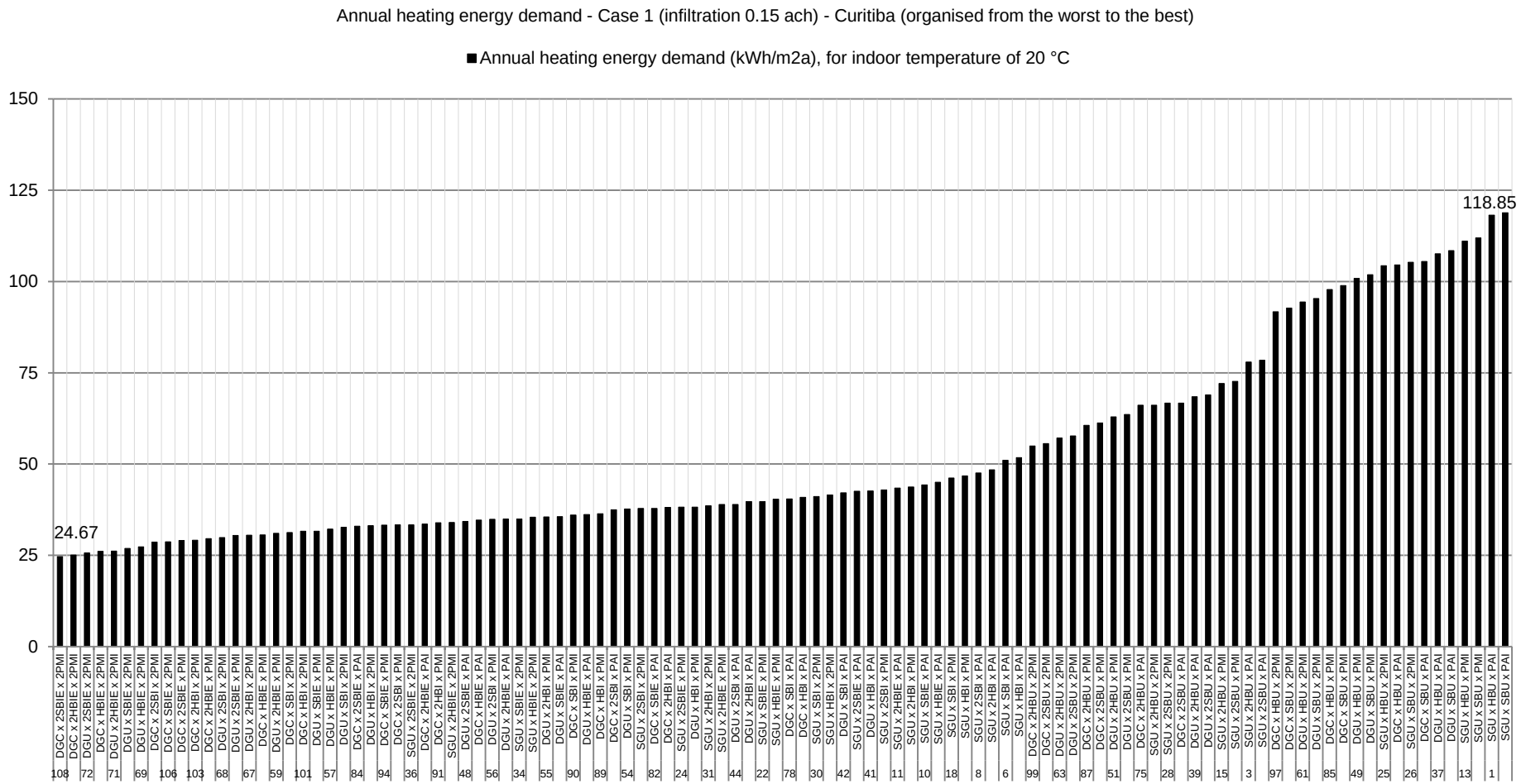
Annual heating energy demand - Case 1 (infiltration 0.15 ach) - Curitiba (organised from the worst to the best)
Annual heating energy demand (kWh/m2a), for indoor temperature of 20 °C
150
125
100
75
50
25
0
24.67
118.85
DGC x 2SBIE x 2PMI
DGC x 2HBIE x 2PMI
DGU x 2SBIE x 2PMI
DGC x HBIE x 2PMI
DGU x 2HBIE x 2PMI
DGU x SBIE x 2PMI
DGU x HBIE x 2PMI
DGC x 2SBI x 2PMI
DGC x SBIE x 2PMI
DGC x 2SBIE x PMI
DGC x 2HBI x 2PMI
DGC x 2HBIE x PMI
DGU x 2SBI x 2PMI
DGU x 2SBIE x PMI
DGU x 2HBI x 2PMI
DGC x HBIE x PMI
DGU x 2HBIE x PMI
DGC x SBI x 2PMI
DGC x HBI x 2PMI
DGU x SBIE x PMI
DGU x HBI x 2PMI
DGU x SBI x 2PMI
DGC x 2SBI x PMI
DGC x 2SBIE x PAI
DGU x HBI x PMI
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SGU x 2HBIE x PMI
DGU x 2SBI x PAI
DGU x 2HBI x PMI
DGC x SBIE x PMI
SGU x HBIE x PMI
DGC x SBI x PAI
SGU x SBI x 2PMI
SGU x HBI x 2PMI
DGU x SBI x PAI
DGU x HBI x PAI
SGU x 2SBI x PMI
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SGU x SBIE x PMI
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DGU x SBU x PMI
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DGC x SBU x PAI
DGC x HBU x PAI
DGU x SBU x PAI
DGU x HBU x PAI
SGU x SBU x PMI
SGU x HBU x PMI
SGU x SBU x PAI
SGU x HBU x PAI
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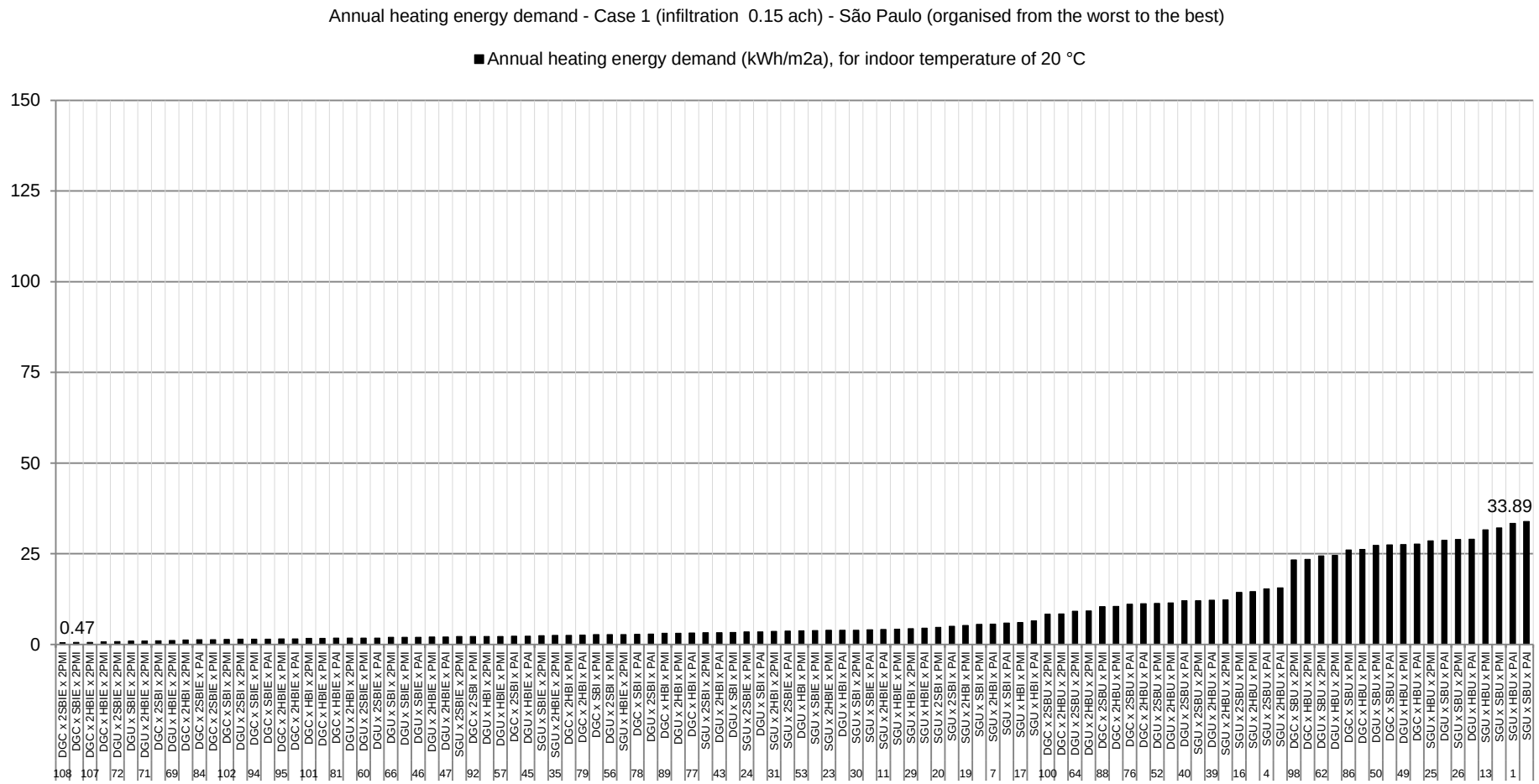
Annual heating energy demand - Case 1 (infiltration 0.15 ach) - São Paulo (organised from the worst to the best)
Annual heating energy demand (kWh/m2a), for indoor temperature of 20 °C
150
125
100
75
50
25
0
0.47
33.89
DGC x 2SBIE x 2PMI
DGC x SBIE x 2PMI
DGC x 2HBIE x 2PMI
DGC x HBIE x 2PMI
DGU x 2SBIE x 2PMI
DGU x SBIE x 2PMI
DGU x 2HBIE x 2PMI
DGC x 2SBI x 2PMI
DGU x HBIE x 2PMI
DGC x 2HBI x 2PMI
DGC x 2SBIE x PA
DGC x 2SBIE x PMI
DGU x 2SBI x 2PMI
DGC x SBI x 2PMI
DGC x SBIE x PMI
DGC x SBIE x PAI
DGC x 2HBIE x PMI
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SGU x HBIE x 2PMI
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DGU x SBU x 2PMI
DGC x SBU x PMI
DGC x HBU x PMI
DGU x SBU x PMI
DGU x HBU x PMI
DGC x SBU x PAI
DGC x HBU x PAI
DGU x SBU x PAI
DGU x HBU x PAI
SGU x HBU x 2PMI
SGU x SBU x PMI
SGU x HBU x PMI
SGU x SBU x PAI
SGU x HBU x PAI
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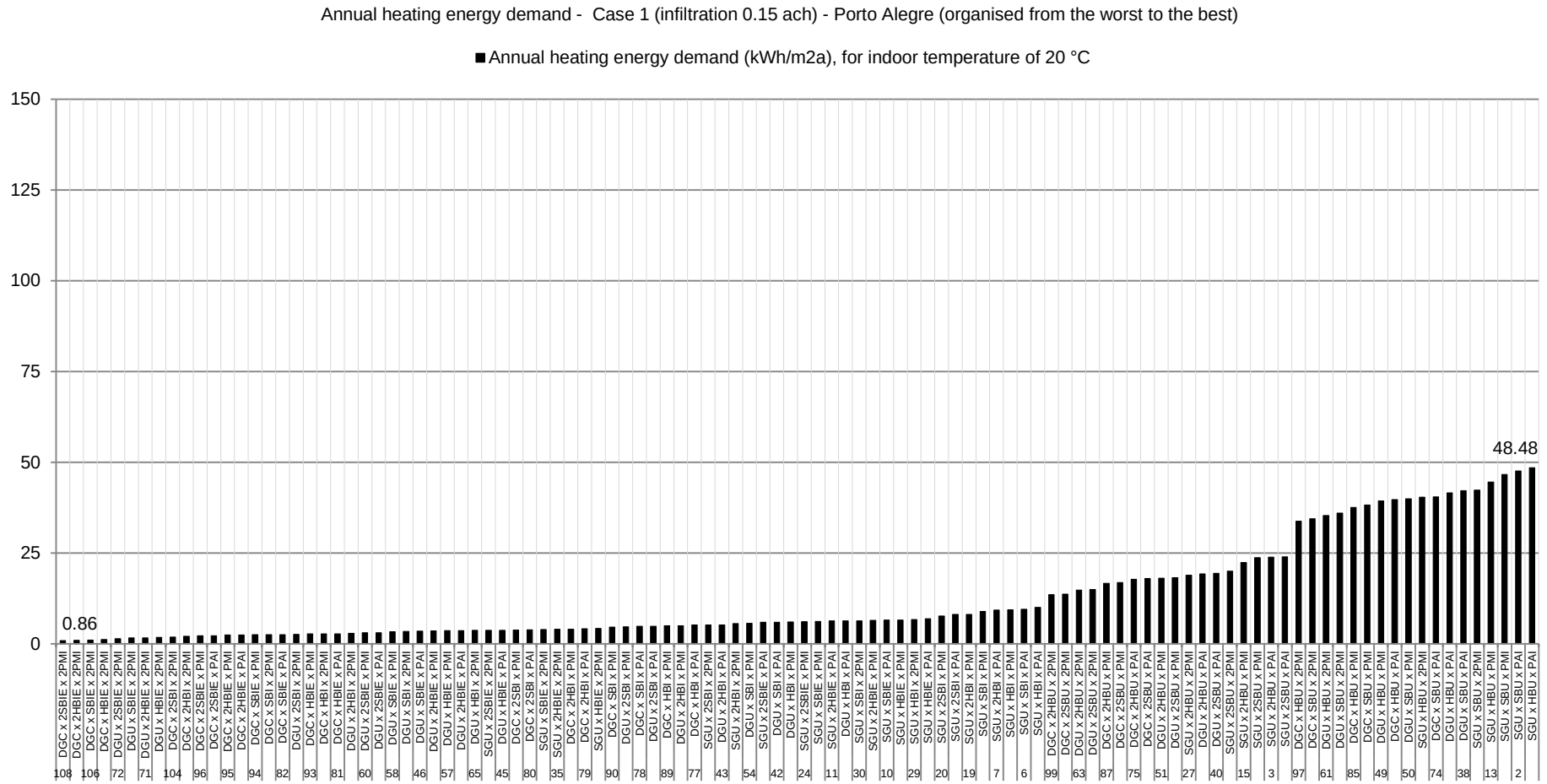
Annual heating energy demand - Case 1 (infiltration 0.15 ach) - Porto Alegre (organised from the worst to the best)
Annual heating energy demand (kWh/m2a), for indoor temperature of 20 °C
150
125
100
75
50
25
0
0.86
48.48
DGC x 2SBIE x 2PMI 108
DGC x 2HBIE x 2PMI 106
DGC x SBIE x 2PMI 72
DGC x HBIE x 2PMI 71
DGU x 2SBIE x 2PMI 104
DGU x SBIE x 2PMI 96
DGU x 2HBIE x 2PMI 95
DGU x HBIE x 2PMI 94
DGC x 2SBI x 2PMI 82
DGC x SBI x 2PMI 93
DGC x 2HBI x 2PMI 81
DGC x HBI x 2PMI 60
DGU x 2SBI x 2PMI 58
DGU x SBI x 2PMI 46
DGU x 2HBI x 2PMI 57
DGU x HBI x 2PMI 65
SGU x 2SBIE x 2PMI 45
DGC x 2SBI x PMI 80
DGC x 2SBI x PAI 35
SGU x SBIE x 2PMI 79
SGU x 2HBIE x 2PMI 90
DGC x SBI x PMI 78
DGU x 2SBI x PMI 89
DGC x HBI x PMI 77
DGC x HBI x PAI 43
SGU x 2SBI x 2PMI 54
DGU x 2HBI x PMI 42
DGU x SBI x PMI 24
SGU x 2SBIE x PAI 11
SGU x 2HBIE x PMI 30
DGU x HBI x PAI 10
SGU x SBI x 2PMI 29
SGU x SBIE x PMI 20
SGU x HBIE x 2PMI 19
SGU x HBIE x PAI 7
SGU x 2HBI x PMI 6
SGU x SBI x PAI 99
SGU x HBI x PAI 63
DGC x 2HBU x 2PMI 87
DGC x 2SBU x 2PMI 75
DGC x 2SBU x PMI 51
DGC x 2HBU x PAI 27
DGU x 2SBU x PMI 40
DGU x 2HBU x PAI 15
SGU x 2SBU x 2PMI 3
SGU x 2HBU x PMI 97
SGU x 2SBU x PAI 61
DGC x HBU x 2PMI 85
DGC x SBU x 2PMI 49
DGU x HBU x 2PMI 50
DGU x SBU x 2PMI 74
SGU x HBU x 2PMI 38
SGU x SBU x 2PMI 13
DGC x HBU x PMI 2
DGC x SBU x PMI
DGC x HBU x PAI
DGC x SBU x PAI
DGU x HBU x PMI
DGU x SBU x PMI
DGU x HBU x PAI
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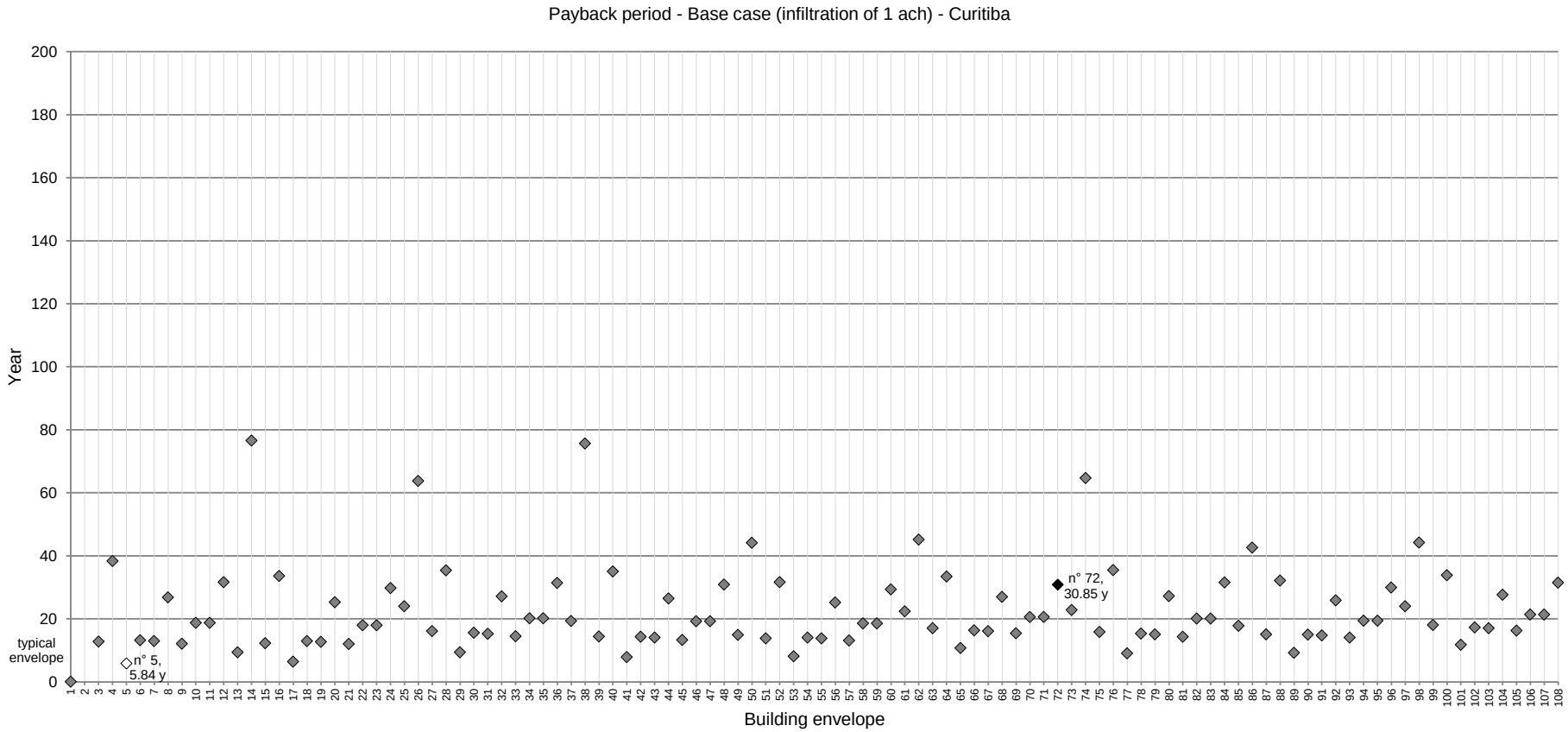
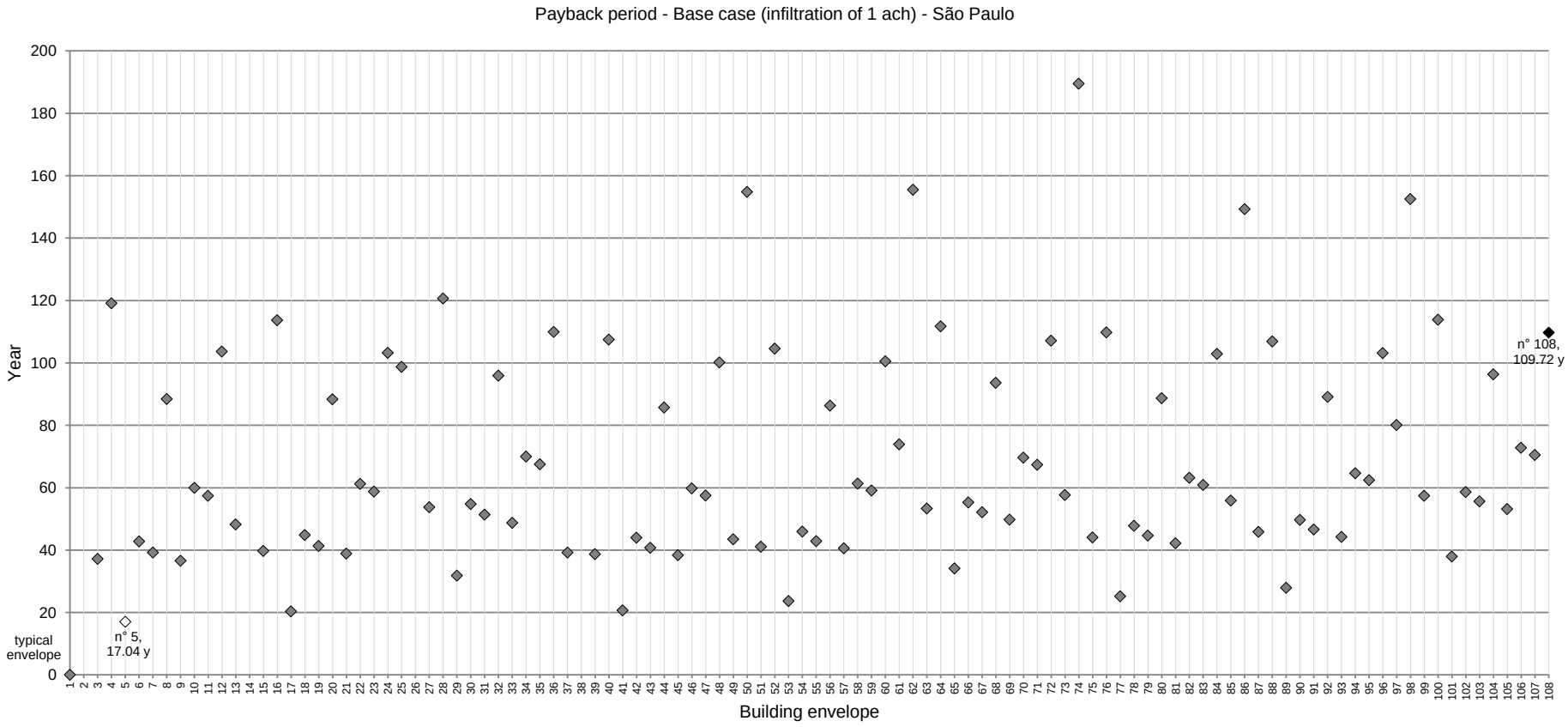
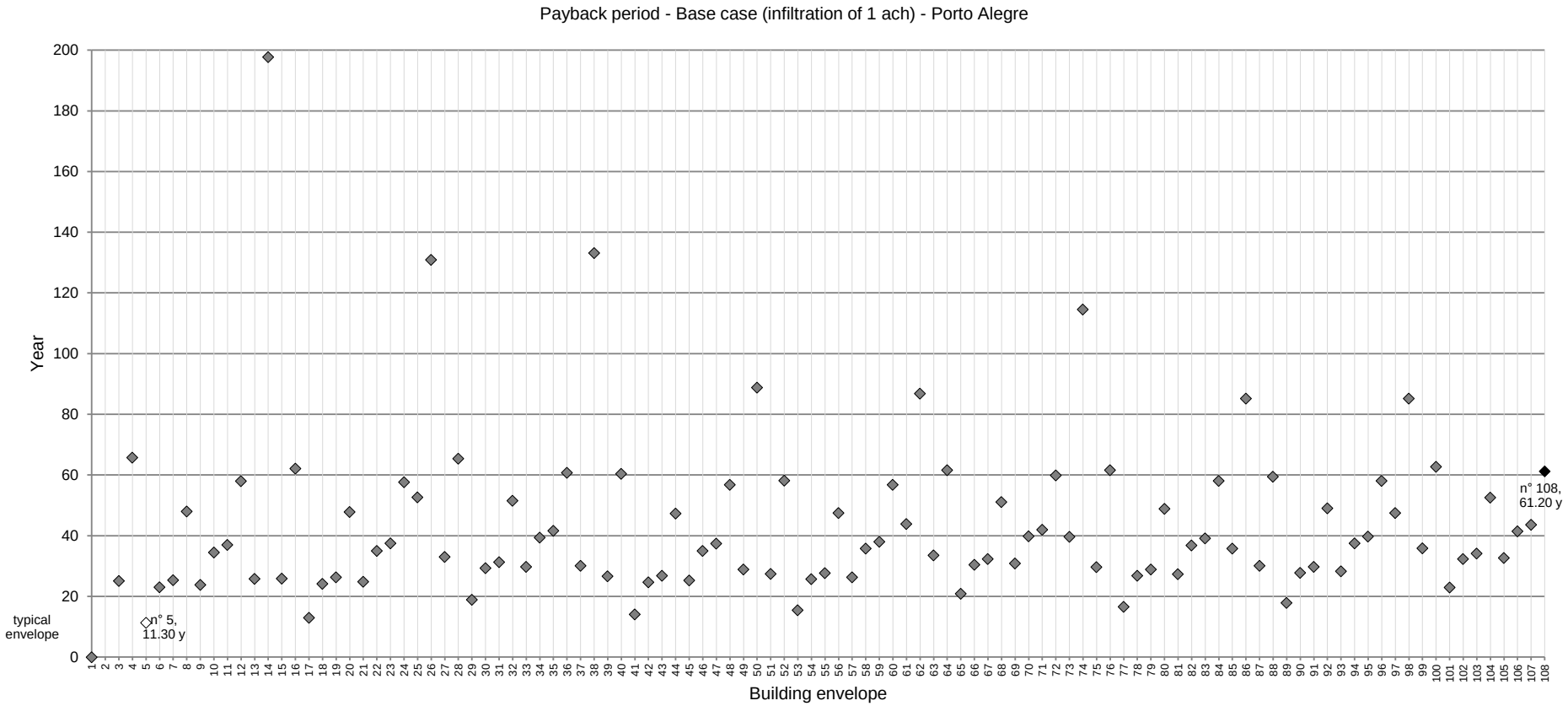
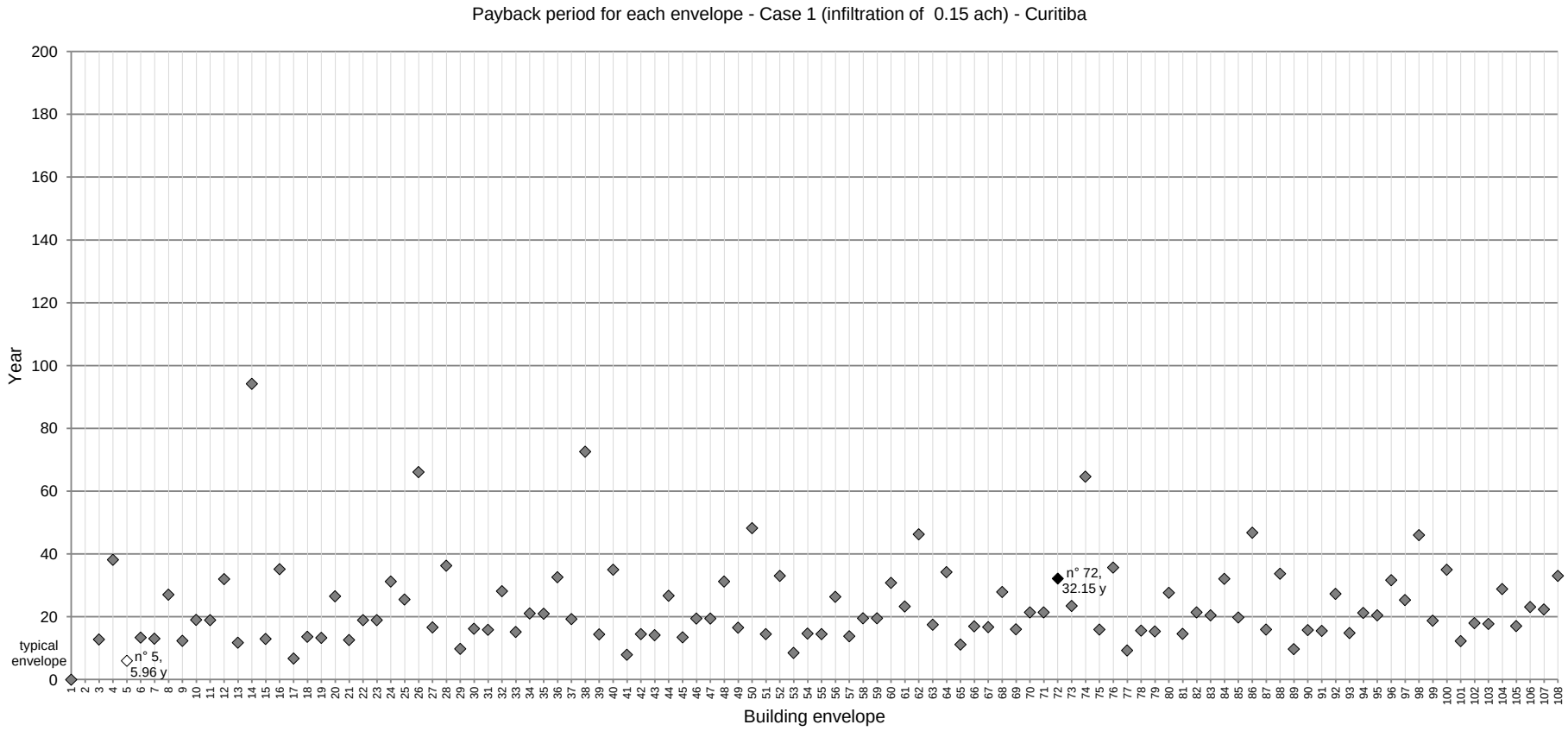
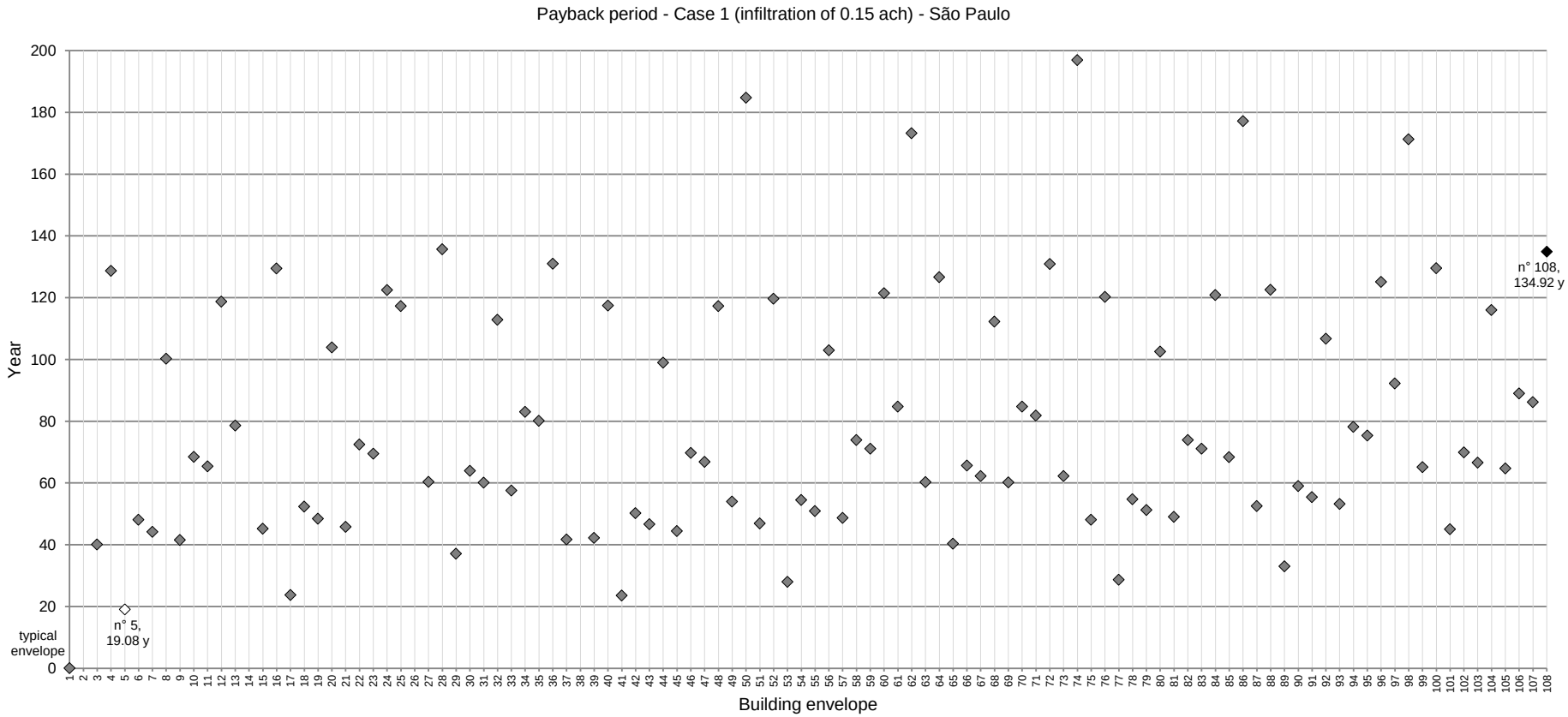
SGU x HBU x PMI
SGU x SBU x PMI
SGU x HBU x PAI
SGU x SBU x PAI

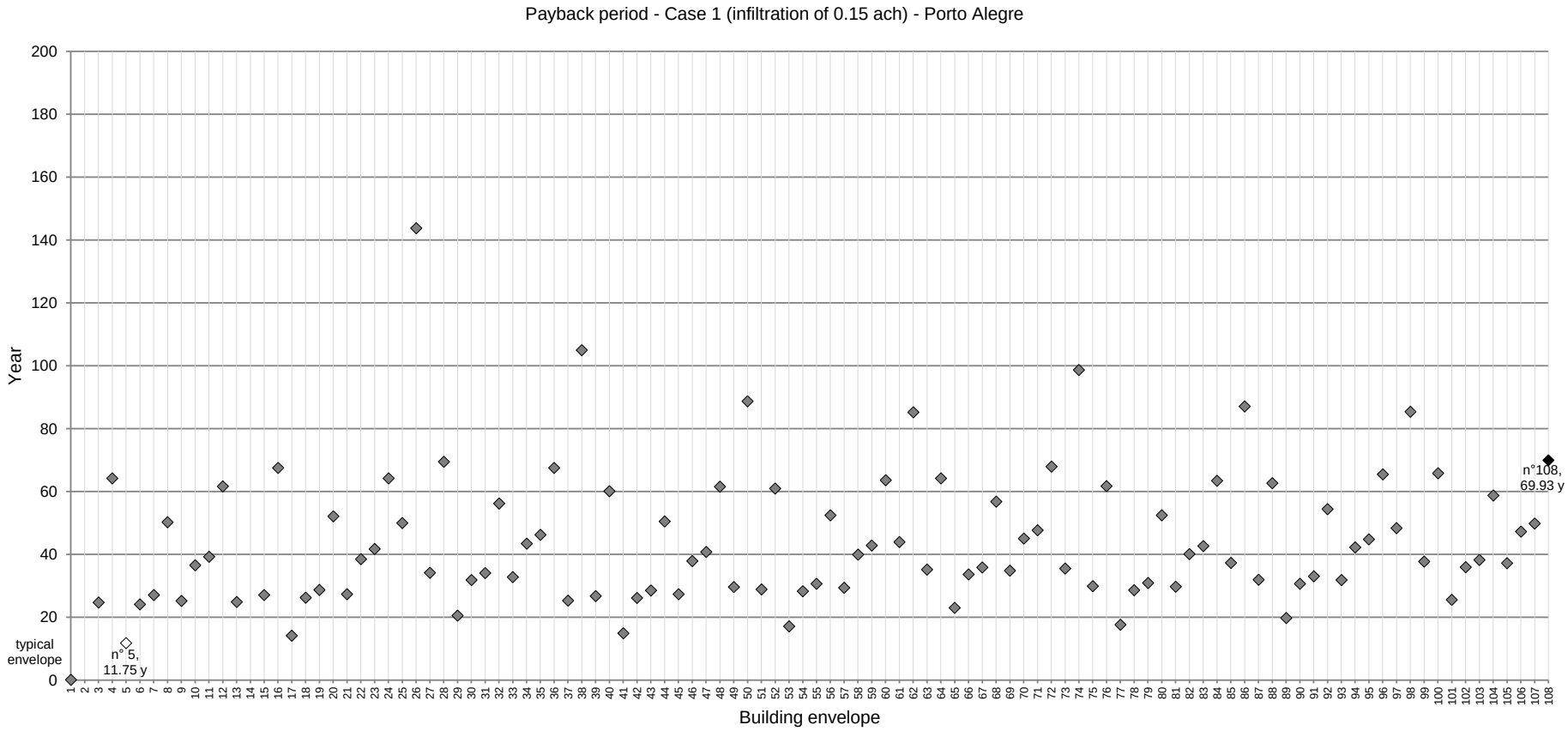

Payback period - Base case (infiltration of 1 ach) - Curitiba
Year
Building envelope
typical envelope
n° 5, 5.84 y
n° 72, 30.85 y


Payback period - Base case (infiltration of 1 ach) - São Paulo
Year
Building envelope
typical envelope
n° 5, 17.04 y
n° 108, 109.72 y


Payback period - Base case (infiltration of 1 ach) - Porto Alegre
Year
Building envelope
typical envelope
n° 5, 11.30 y
n° 108, 61.20 y


Payback period for each envelope - Case 1 (infiltration of 0.15 ach) - Curitiba
Year
Building envelope
typical envelope
n° 5, 5.96 y
n° 72, 32.15 y


Payback period - Case 1 (infiltration of 0.15 ach) - São Paulo
Year
Building envelope
typical envelope
n° 5, 19.08 y
n° 108, 134.92 y


Payback period - Case 1 (infiltration of 0.15 ach) - Porto Alegre
Year
Building envelope
typical envelope
n° 5, 11.75 y
n°108, 69.93 y

APPENDIX B

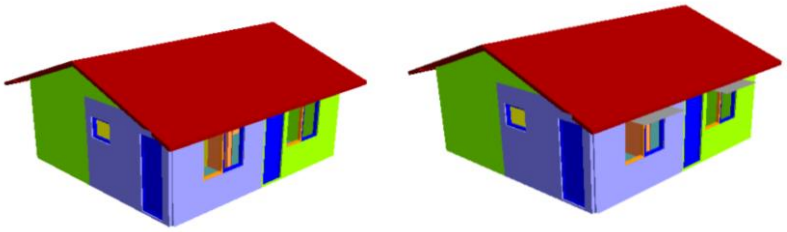
Appendix B shows additional information of Chapter 5.

Examples of sliding windows

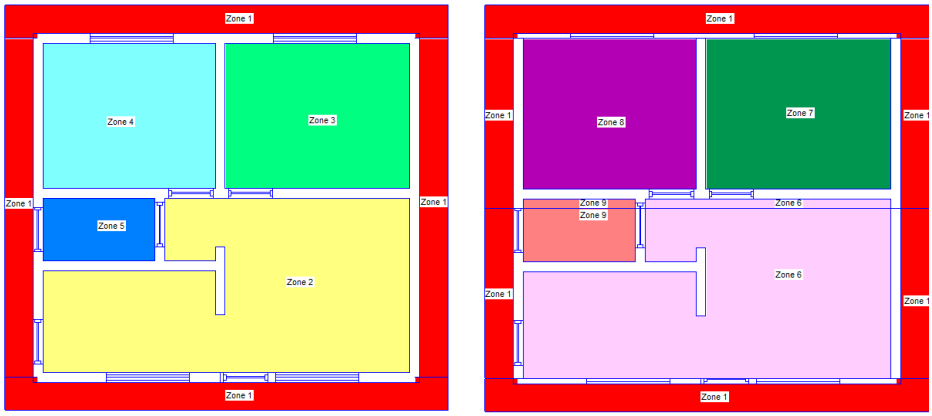
Example of awning window

Examples of doors

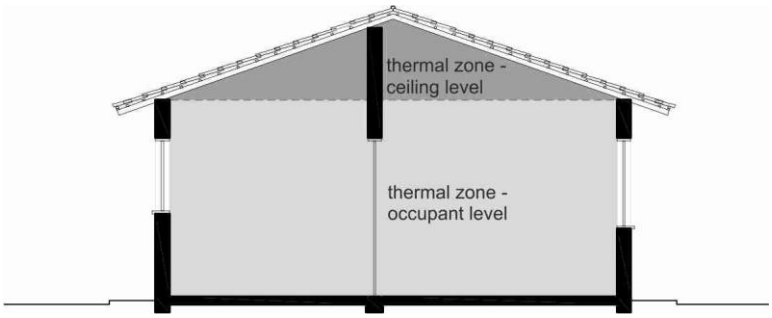
Examples of typical affordable fenestrations. Based on Trifel (2009, p. 16-25)



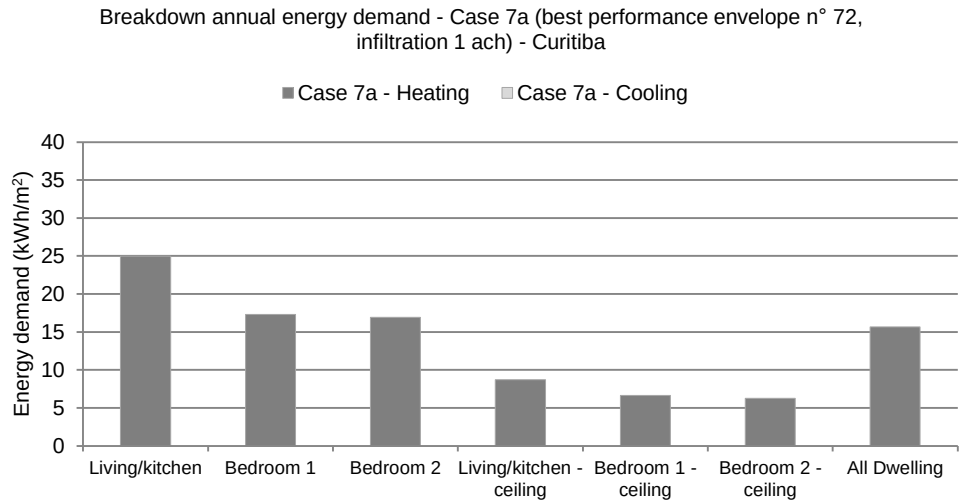
3D TAS model of the MCMV house: Base Case (left) and Case 1 to 8 (right)



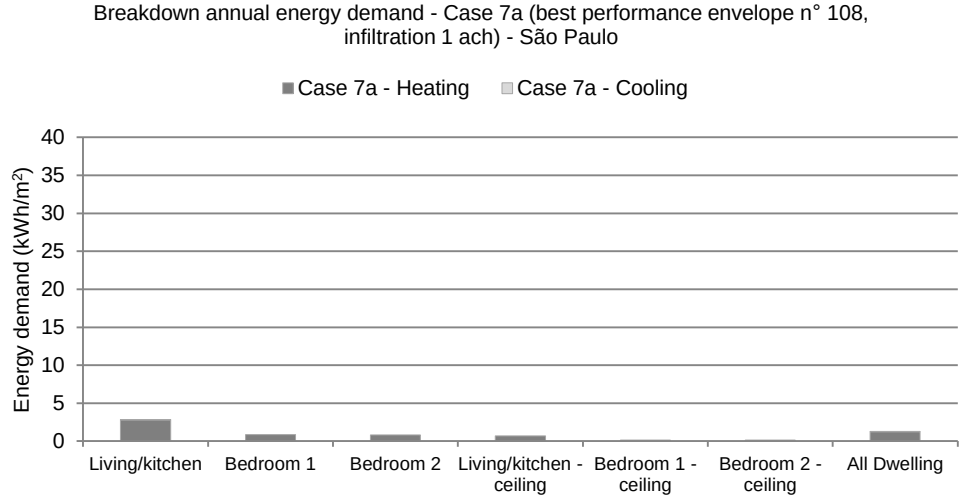
Thermal zones of the MCMV house - plan: occupant level (left) and ceiling level (right)



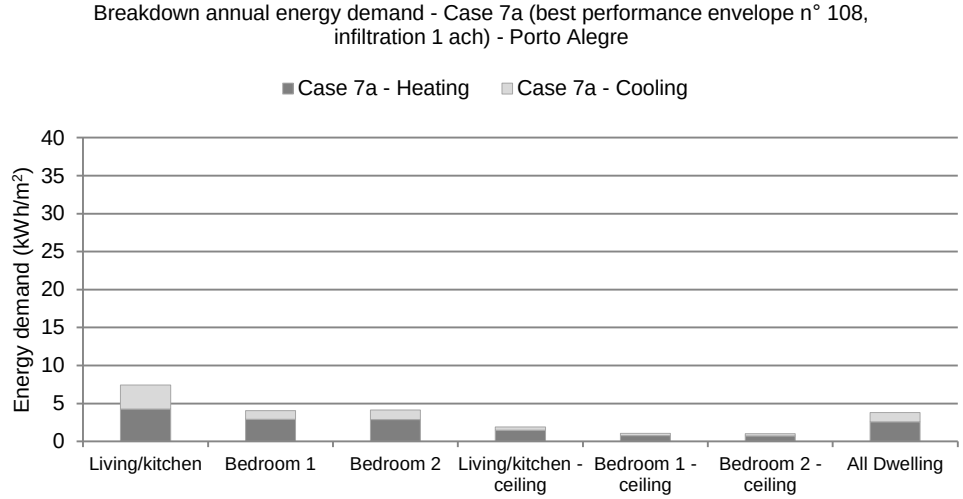
Thermal zones of the MCMV house - section: occupant and ceiling levels



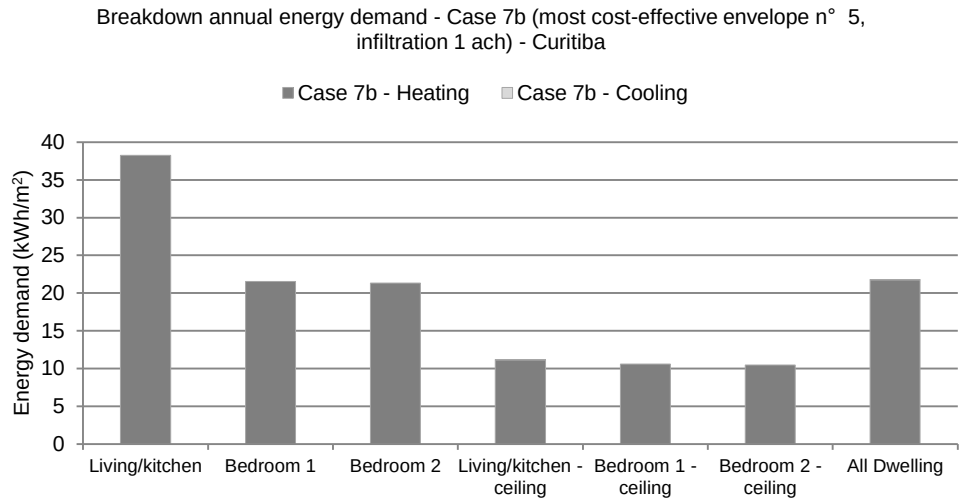
Breakdown annual energy demand, Case 7a, Curitiba



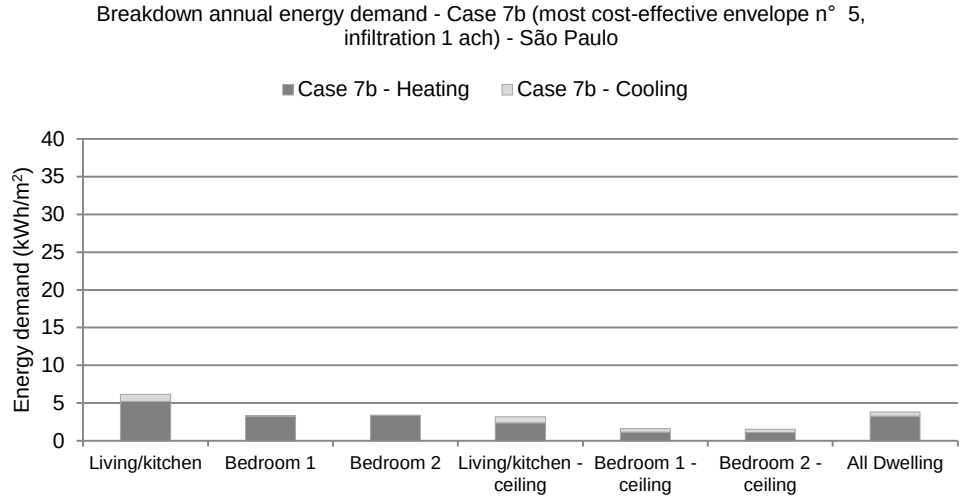
Breakdown annual energy demand, Case 7a, São Paulo



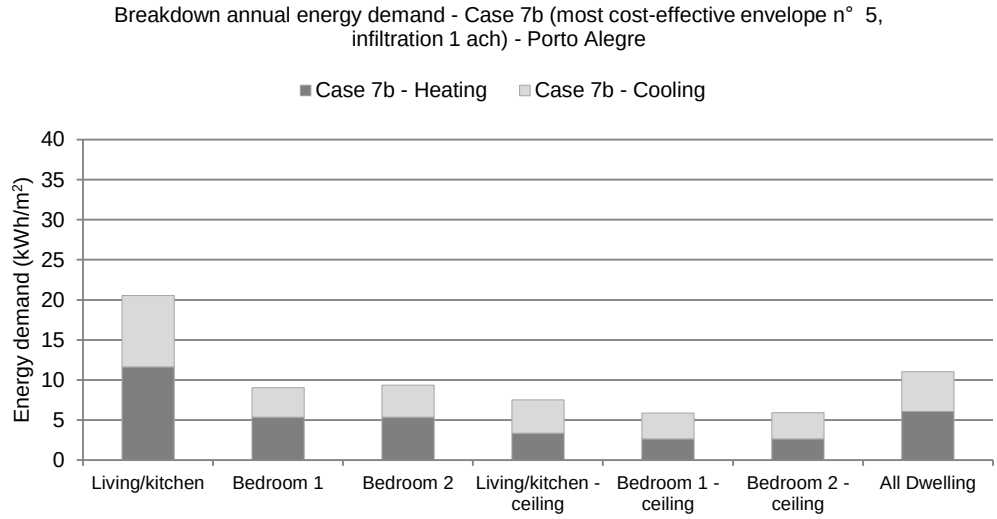
Breakdown annual energy demand, Case 7a, Porto Alegre



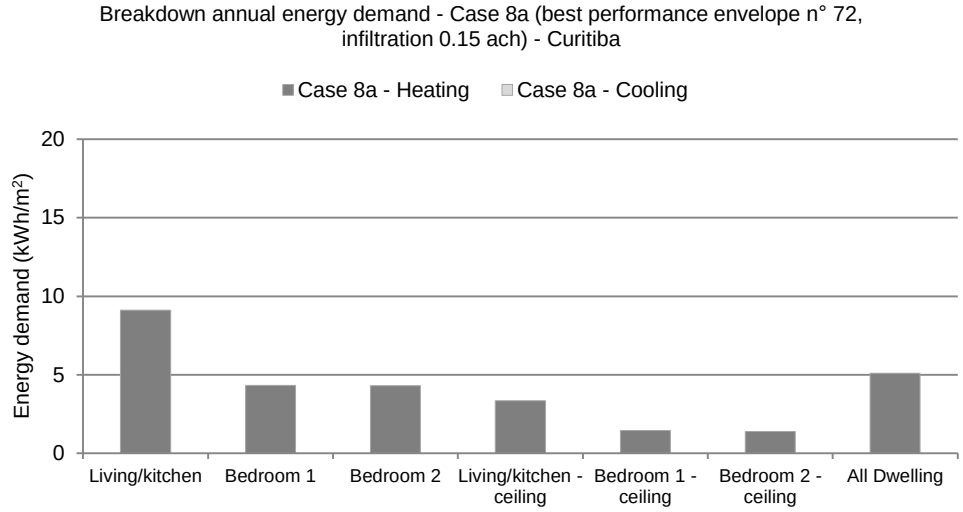
Breakdown annual energy demand, Case 7b, Curitiba



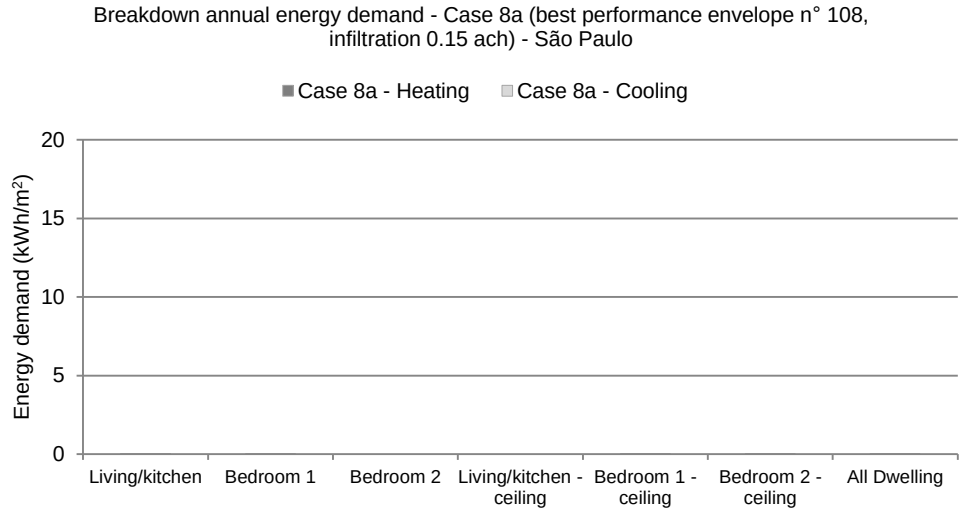
Breakdown annual energy demand, Case 7b, São Paulo



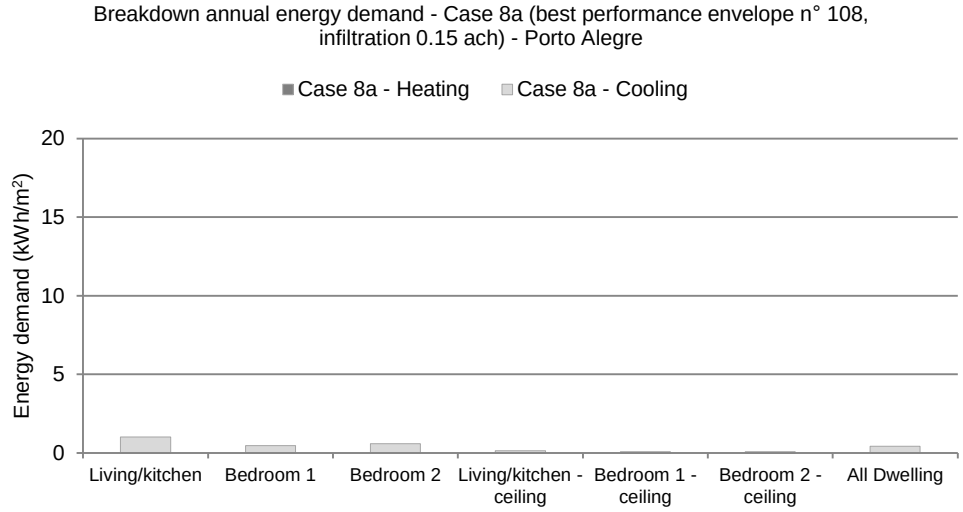
Breakdown annual energy demand, Case 7b, Porto Alegre



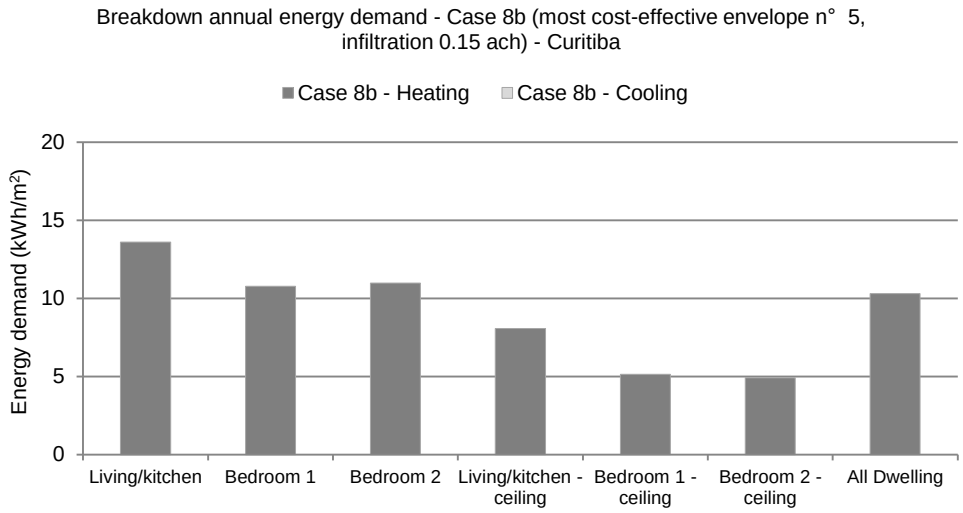
Breakdown annual energy demand, Case 8a, Curitiba



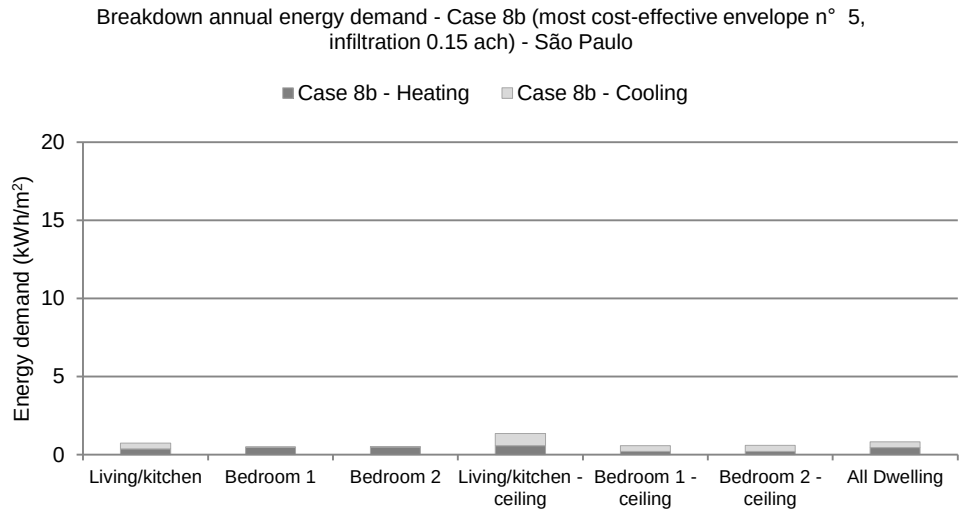
Breakdown annual energy demand, Case 8a, São Paulo



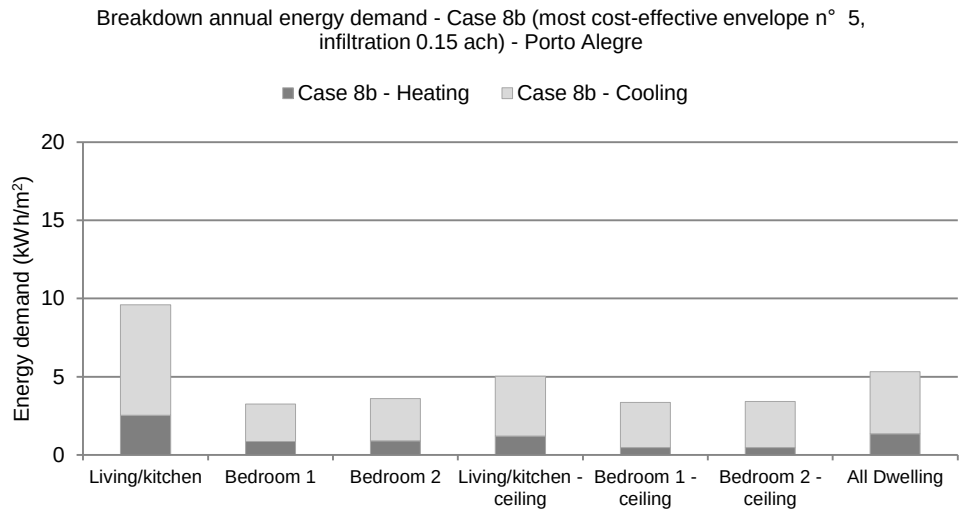
Breakdown annual energy demand, Case 8a, Porto Alegre



Breakdown annual energy demand, Case 8b, Curitiba



Breakdown annual energy demand, Case 8b, São Paulo



Breakdown annual energy demand, Case 8b, Porto Alegre

Estimated costs of the typical MCMV House envelope, in US dollars - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Hollow ceramic block wall 14 cm (14x19x29cm)	66.51	0.47	Servant 1.56	Block 14.21	1.22	2.38	16.44	m^2	81.14	158.08	202.27	1,093.26	1,453.61	3,654.76
			0.75	Brick layer 2.19	Mortar 2.23										
Roof	Aluminium foil	43.95	0.22	R. Servant 1.68	97.34/ roll of 50m^2	0.44	0.85	97.34	m^2	19.34	37.50	47.98	97.34	182.82	
			0.22	Roofer 2.19											
Window frame	Aluminium frame - Awning (1un 80x60cm)	0.48	1.00	Servant 1.56	Window 160.77	2.50	4.85	161.32	m^2	1.20	2.33	2.98	77.43	82.74	
			1.50	Brick layer 2.19	Others 0.55										
	Aluminium frame - Sliding (2un150x100cm) (2un150x120cm)	6.60	1.00	Servant 1.56	Window 173.16	2.50	4.85	173.71	m^2	16.50	31.99	40.93	1,146.51	1,219.43	
			1.50	Brick layer 2.19	Others 0.55										
Window glazing	Single glazing	7.08	-	Installation 5.20	13.45	-	5.20	13.45	m^2	-	36.82	-	95.23	132.05	
Door	Aluminium (2un 80x210cm)	3.36	2.00	Servant 1.56	Door 156.08	4.00	7.50	156.75	m^2	13.44	25.20	32.24	526.67	584.11	
			2.00	Brick layer 2.19	Others 0.66										

Estimated costs of the typical MCMV House envelope, in US dollars - São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 129.34% (US$)	Material (US$)		
Wall	Hollow ceramic block wall 14 cm (14x19x29cm)	66.51	0.47 0.75	Servant 1.86 Brick layer 2.26	Block 12.35 Mortar 2.17	1.22	2.57	14.52	m^2	81.14	170.56	220.60	965.49	1,356.65	3,626.83
Roof	Aluminium foil	43.95	0.22 0.22	R. Servant 1.86 Roofer 2.26	96.67/ roll of 50m^2	0.44	0.90	96.67	m^2	19.34	39.76	51.42	96.67	187.85	
Window frame	Aluminium frame - Awning (1un 80x60cm)	0.48	1.00 1.50	Servant 1.86 Brick layer 2.26	Window 160.77 Others 0.52	2.50	5.24	161.29	m^2	1.20	2.52	3.25	77.42	83.19	
	Aluminium frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.00 1.50	Servant 1.86 Brick layer 2.26	Window 173.16 Others 0.52	2.50	5.24	173.68	m^2	16.50	34.59	44.73	1,146.29	1,225.61	
Window glazing	Single glazing	7.08	-	Installation 4.93	13.60	-	4.93	13.60	m^2	-	34.93	-	96.26	131.19	
Door	Aluminium (2un 80x210cm)	3.36	2.00 2.00	Servant 1.86 Brick layer 2.26	Door 171.59 Others 0.73	4.00	8.22	172.31	m^2	13.44	27.63	35.74	578.97	642.34	

Estimated costs of the typical MCMV House envelope, in US dollars - Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Hollow ceramic block wall 14 cm (14x19x29cm)	66.51	0.47 0.75	Servant 1.32 Brick layer 1.78	Block 15.28 Mortar 2.27	1.22	1.95	17.55	m^2	81.14	129.74	166.00	1,167.21	1,462.94	3,446.35
Roof	Aluminium foil	43.95	0.22 0.22	R. Servant 1.45 Roofer 1.78	98.98/ roll of 50m^2	0.44	0.71	98.98	m^2	19.34	31.23	39.96	98.98	170.18	
Window frame	Aluminium frame - Awning (1un 80x60cm)	0.48	1.00 1.50	Servant 1.32 Brick layer 1.78	Window 163.48 Others 0.57	2.5	3.98	164.05	m^2	1.20	1.91	2.44	78.74	83.10	
	Aluminium frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.00 1.50	Servant 1.32 Brick layer 1.78	Window 176.08 Others 0.57	2.5	3.98	176.64	m^2	16.50	26.30	33.61	1,165.86	1,225.74	
Window glazing	Single glazing	7.08	-	Installation 4.21	12.45	-	4.21	12.45	m^2	-	29.81	-	88.17	117.98	
Door	Aluminium (2un 80x210cm)	3.36	2.00 2.00	Servant 1.32 Brick layer 1.78	Door 100.18 Others 0.73	4.00	6.18	100.90	m^2	13.44	20.78	26.59	339.04	386.40	

Estimated costs of the best performance MCMV House envelope (n° 72), in US dollars - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	144.49	1.81	Servant 1.56	Brick 16.38	4.23	8.13	27.37	m^2	611.19	1,174.11	1,502.27	3,953.99	6,630.37	13,692.17
			2.42	Brick layer 2.19	Mortar 10.99										
	EPS 30 cm	72.25	0.30	Servant 1.56	Insulat. 34.66	0.60	1.13	38.19	m^2	43.35	81.28	104.00	2,759.52	2,944.80	
			0.30	Brick layer 2.19	Other 3.54										
Roof	Mineral wool panels bet. Roof structure	43.95	0.66	R. Servant 1.68	24.73	1.32	2.56	24.73	m^2	58.01	112.50	143.94	1,086.89	1,343.33	
			0.66	Roofer 2.19											
Window frame	PVC frame - Awning (1un 80x60cm)	0.48	1.00	Servant 1.56	Window 202.91	2.00	3.75	210.12	m^2	0.96	1.80	2.30	100.86	104.96	
			1.00	Brick layer 2.19	Others 7.21										
	PVC frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.50	Servant 1.56	Window 178.40	3.00	5.63	179.14	m^2	19.80	37.13	47.50	1,182.36	1,266.98	
			1.50	Brick layer 2.19	Others 0.75										
Window glazing	Double uncoated glazing	7.08	-	Installation 5.20	46.05	-	5.20	46.05	m^2	-	36.82	-	326.05	362.87	
Door	PVC (2 un 80x210cm)	2.00	3.00	Servant 1.56	Door 489.83	6.00	11.25	493.78	un	12.00	22.50	28.79	987.57	1,038.86	
			3.00	Brick layer 2.19	Other 3.95										

Estimated costs of the best performance MCMV House envelope (n° 108), in US dollars - São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 129.34% (US$)	Material (US$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	144.49	1.81	Servant 1.86	Brick 15.24	4.23	8.82	26.10	m^2	611.19	1,274.25	1,648.12	3,770.52	6,692.89	13,769.59
			2.42	Brick layer 2.26	Mortar 10.85										
	EPS 30 cm	72.25	0.30	Servant 1.86	Insulat. 31.38	0.60	1.23	33.72	m^2	43.35	89.13	115.27	2,436.06	2,640.46	
			0.30	Brick layer 2.26	Other 2.34										
Roof	Mineral wool panels bet. Roof structure	43.95	0.66	R. Servant 1.86	26.53	1.32	2.71	26.53	m^2	58.01	119.27	154.27	1,165.83	1,439.37	
			0.66	Roofer 2.26											
Window frame	PVC frame - Awning (1un 80x60cm)	0.48	1.00	Servant 1.86	Window 183.97	2.00	4.11	192.54	m^2	0.96	1.97	2.55	92.42	96.95	
			1.00	Brick layer 2.26	Others 8.57										
	PVC frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.50	Servant 1.86	Window 161.75	3.00	6.17	162.44	m^2	19.80	40.71	52.65	1,072.13	1,165.49	
			1.50	Brick layer 2.26	Others 0.70										
Window glazing	Double coated glazing	7.08	-	Installation 4.93	105.26	-	4.93	105.26	m^2	-	34.93	-	745.26	780.20	
Door	PVC (2 un 80x210cm)	2.00	3.00	Servant 1.86	Door 444.11	6.00	12.34	448.83	un	12.00	24.67	31.91	897.66	954.24	
			3.00	Brick layer 2.26	Other 4.72										

Estimated costs of the best performance MCMV House envelope (n° 108), in US dollars - Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	144.49	1.81	Servant 1.32	Brick 14.68	4.23	6.68	26.77	m^2	611.19	965.23	1,235.01	3,867.48	6,067.73	13,111.25
			2.42	Brick layer 1.78	Mortar 12.09										
	EPS 30 cm	72.25	0.30	Servant 1.32	Insulat. 34.66	0.60	0.93	38.18	m^2	43.35	67.02	85.75	2,758.81	2,911.59	
			0.30	Brick layer 1.78	Other 3.53										
Roof	Mineral wool panels bet. Roof structure	43.95	0.66	R. Servant 1.45	24.73	1.32	2.13	24.73	m^2	58.01	93.70	119.89	1,086.89	1,300.48	
			0.66	Roofer 1.78											
Window frame	PVC frame - Awning (1un 80x60cm)	0.48	1.00	Servant 1.32	Window 173.15	2.00	3.09	179.13	m^2	0.96	1.48	1.90	85.98	89.37	
			1.00	Brick layer 1.78	Others 5.99										
	PVC frame - Sliding (4un150x100cm) (2un150x120cm)	6.60	1.50	Servant 1.32	Window 152.23	3.00	4.64	153.00	m^2	19.80	30.61	39.17	1,009.82	1,079.60	
			1.50	Brick layer 1.78	Others 0.77										
Window glazing	Double coated glazing	7.08	-	Installation 4.21	105.26	-	4.21	105.26	m^2	-	29.81	-	745.26	775.07	
Door	PVC (2 un 80x210cm)	2.00	3.00	Servant 1.32	Door 417.99	6.00	9.28	422.56	un	12.00	18.55	23.74	845.13	887.41	
			3.00	Brick layer 1.78	Other 4.57										

Estimated costs of the most cost-effective MCMV House envelope (n° 5), in US dollars - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm)	66.63	0.51	Servant 1.56	Brick 14.74	1.30	2.53	17.46	m^2	86.62	168.37	215.42	1,163.39	1,547.18	5,263.61
			0.79	Brick layer 2.19	Mortar 2.72										
	EPS 10 cm	69.95	0.30	Servant 1.56	Insulat. 11.79	0.60	1.13	15.33	m^2	41.97	78.69	100.69	1,072.03	1,251.41	
			0.30	Brick layer 2.19	Other 3.54										
Roof	Aluminium foil	43.95	0.22	R. Servant 1.68	97.34 /roll of 50m^2	0.44	0.85	97.34	m^2	19.34	37.50	47.98	97.34	182.82	
			0.22	Roofer 2.19											
Window frame	Timber frame - Awning (1un 80x60cm)	0.48	2.00	Servant 1.56	Window 85.66	14.30	27.47	86.55	m^2	6.86	13.19	16.87	41.54	71.61	
			2.00	Brick layer 2.19											
			5.15	W. servant 1.68	Other 0.88										
			5.15	W.worker 2.19											
	Timber frame - Sliding + shutter (2un150x100cm) (2un150x120cm)	6.60	2.00	Servant 1.56	Window 125.86	14.30	27.47	160.25	m^2	94.38	181.32	232.00	1,057.65	1,470.98	
			2.00	Brick layer 2.19											
			5.15	W. servant 1.68	Other 34.39										
			5.15	W.worker 2.19											
Window glazing	Single glazing	7.08	-	Installation 5.20	Glass 13.45	-	5.20	13.45	m^2	-	36.82	-	95.23	132.05	
Door	Timber (2un 80x210cm)	2.00	1.40	Servant 1.56	Door 151.77	10.30	19.79	258.66	un	20.6	39.59	50.65	517.33	607.57	
			1.40	Brick layer 2.19											
			3.75	W. servant 1.68	Other 106.90										
			3.75	W.worker 2.19											

Estimated costs of the most cost-effective MCMV House envelope (n° 5), in US dollars – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 129.34% (US$)	Material (US$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29 cm)	66.63	0.51	Servant 1.86	Brick 12.80	1.30	2.73	15.46	m^2	86.62	181.83	235.17	1,029.91	1,446.91	4,965.55
			0.79	Brick layer 2.26	Mortar 2.65										
	EPS 10 cm	69.95	0.30	Servant 1.86	Insulat. 10.47	0.60	1.23	12.81	m^2	41.97	86.29	111.60	895.77	1,093.66	
			0.30	Brick layer 2.26	Other 2.34										
Roof	Aluminium foil	43.95	0.22	R. Servant 1.86	96.67 /roll of 50m^2	0.44	0.90	96.67	m^2	19.34	39.76	51.42	96.67	187.85	
			0.22	Roofer 2.26											
Window frame	Timber frame - Awning (1un 80x60cm)	0.48	2.00	Servant 1.86	Window 101.46	14.30	29.40	102.26	m^2	6.86	14.11	18.25	49.09	81.45	
			2.00	Brick layer 2.26											
			5.15	W. servant 1.86	Other 0.81										
			5.15	W.worker 2.26											
	Timber frame - Sliding + shutter (2un150x100cm) (2un150x120cm)	6.60	2.00	Servant 1.86	Window 100.92	14.30	29.40	140.66	m^2	94.38	194.04	250.97	928.34	1,373.35	
			2.00	Brick layer 2.26											
			5.15	W. servant 1.86	Other 39.74										
			5.15	W.worker 2.26											
Window glazing	Single glazing	7.08	-	Installation 4.93	Glass 13.60	-	4.93	13.60	m^2	-	34.93	-	96.26	131.19	
Door	Timber (2un 80x210cm)	2.00	1.40	Servant 1.86	Door 164.26	10.30	21.18	277.00	un	20.6	42.35	54.78	553.99	651.13	
			1.40	Brick layer 2.26											
			3.75	W. servant 1.86	Other 112.74										
			3.75	W.worker 2.26											

Estimated costs of the most cost-effective MCMV House envelope (n° 5), in US dollars – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm	66.63	0.51	Servant 1.32	Brick 15.84	1.30	2.08	18.62	m^2	86.62	138.21	176.85	1,240.76	1,555.82	5,439.69
			0.79	Brick layer 1.78	Mortar 2.78										
	EPS 10 cm	69.95	0.30	Servant 1.32	Insulat. 11.79	0.60	0.93	15.32	m^2	41.97	64.89	83.02	1,071.34	1,219.25	
			0.30	Brick layer 1.78	Other 3.53										
Roof	Aluminium foil	43.95	0.22	R. Servant 1.45	98.98 /roll of 50m^2	0.44	0.71	98.98	m^2	19.34	31.23	39.96	98.98	170.18	
			0.22	Roofer 1.78											
Window frame	Timber frame - Awning (1un 80x60cm)	0.48	2.00	Servant 1.32	Window 85.66	14.30	22.82	86.61	m^2	6.86	10.95	14.02	41.57	66.54	
			2.00	Brick layer 1.78											
			5.15	W. servant 1.45	Other 0.94										
			5.15	W.worker 1.78											
	Timber frame - Sliding + shutter (2un150x100cm) (2un150x120cm)	6.60	2.00	Servant 1.32	Window 156.39	14.30	22.82	198.57	m^2	94.38	150.61	192.71	1,310.56	1,653.88	
			2.00	Brick layer 1.78											
			5.15	W. servant 1.45	Other 42.18										
			5.15	W.worker 1.78											
Window glazing	Single glazing	7.08	-	Installation 4.21	Glass 12.45	-	4.21	12.45	m^2	-	29.81	-	88.17	117.98	
Door	Timber (2un 80x210cm)	2.00	1.40	Servant 1.32	Door 174.44	10.30	16.44	290.54	un	20.6	32.88	42.08	581.08	656.04	
			1.40	Brick layer 1.78											
			3.75	W. servant 1.45	Other 116.10										
			3.75	W.worker 1.78											

Calculation of the architectural design costs of the MCMV House – Curitiba, São Paulo and Porto Alegre

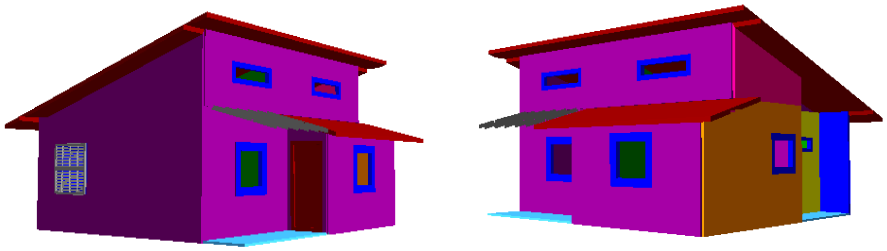
Variables of the calculation	*Calculation description*
The values were obtained from CEAU (2014a, p. 40-44, 64-69). $Sc = 43.83\ m2$ $BH = R\$\ 1{,}233.64\ Curitiba$ $BH = R\$\ 1{,}190.85\ Sao\ Paulo$ $BH = R\$\ 1{,}180.08\ Porto\ Alegre$ $Fp = 7.33\%\ \ for\ low\ standard\ typology\ and\ for\ the\ corresponding\ area\ \ Due\ to\ the\ increase\ of\ complexity\ of\ the\ design, this\ index\ can\ achieve\ 11.00\%\ for\ this\ corresponding\ area\ .$ $R = \frac{Sp}{Sc} = 1$ $Sp = Snr + (Sr\ \times r) = 43.83 + (0\ \times 100) = 43.83\ m2$	*Traditional MCMV House architectural design* $PV = Sc\ \times BH\ \times (Fp\ \times R)$ $PV = 43.83\ \times\ CUB\ of\ each\ city\ \times 0.0733$ $\boldsymbol{PV_{Curitiba}\ =\ R\$\ 3,963.36}$ $\boldsymbol{PV_{Sao\ Paulo}\ = R\$\ 3,825.89}$ $\boldsymbol{PV_{Porto\ Alegre}\ = R\$\ 3,791.29}$ *Optimised MCMV House architectural design* $PV = Sc\ \times BH\ \times (Fp\ \times R)$ $PV = 43.83\ \times\ CUB\ of\ each\ city\ \times 0.11$ $\boldsymbol{PV_{Curitiba}\ = R\$\ 5,947.75}$ $\boldsymbol{PV_{Sao\ Paulo}\ = R\$\ 5,741.44}$ $\boldsymbol{PV_{Porto\ Alegre}\ = R\$\ 5,689.52}$

Where,

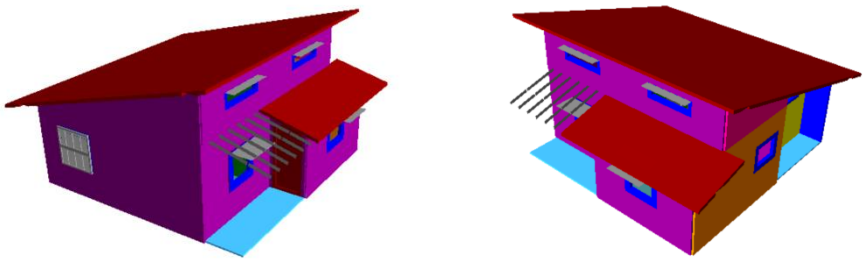
PV= price of the architectural design, in R$ Brazilian Reais
Sc = estimated built area of the building, in m^2
BH = fees basis, in R$ Brazilian Reais. For low standard typology, this value is equal to the corresponding CUB.
F_p = percentage factor, in %. This is defined by the area of the building and its typology.
R = Ratio of *Sp* to *Sc*, where *Sp = Snr + (Sr x r)*. Sp consists of a relationship between the area of the building that has repetitions (*Sr*) in the design and those that do not (*Srn*). *r* is the factor of reduction due to the repetition.

APPENDIX C

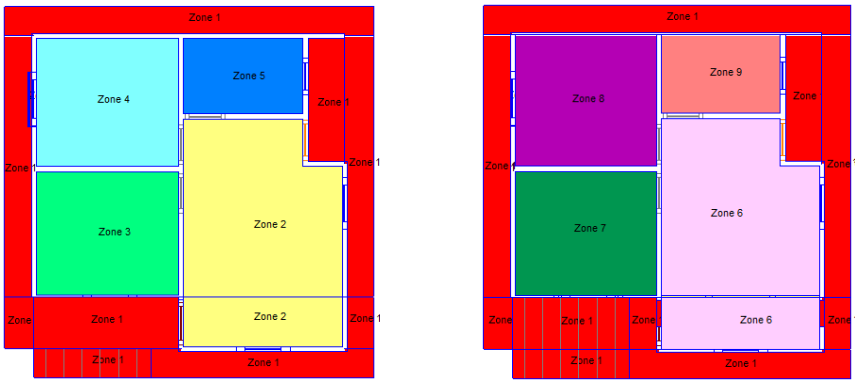
Appendix C shows additional information of Chapter 6.



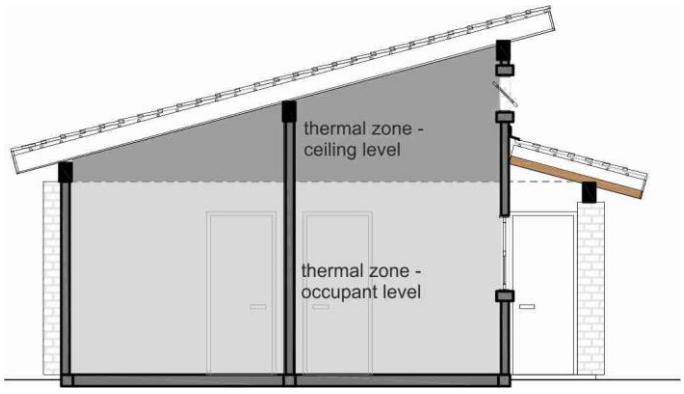
3d TAS model of the Alvorada House: Base Case



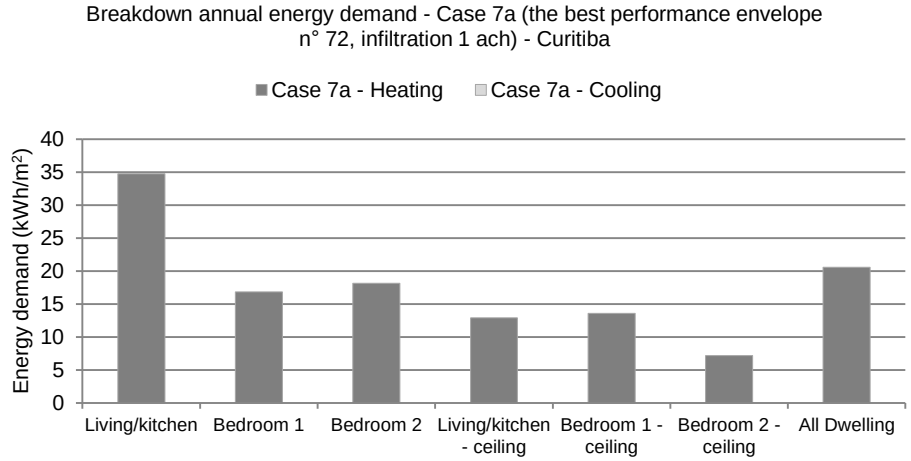
3d TAS model of the Alvorada House: Case 1 to 8



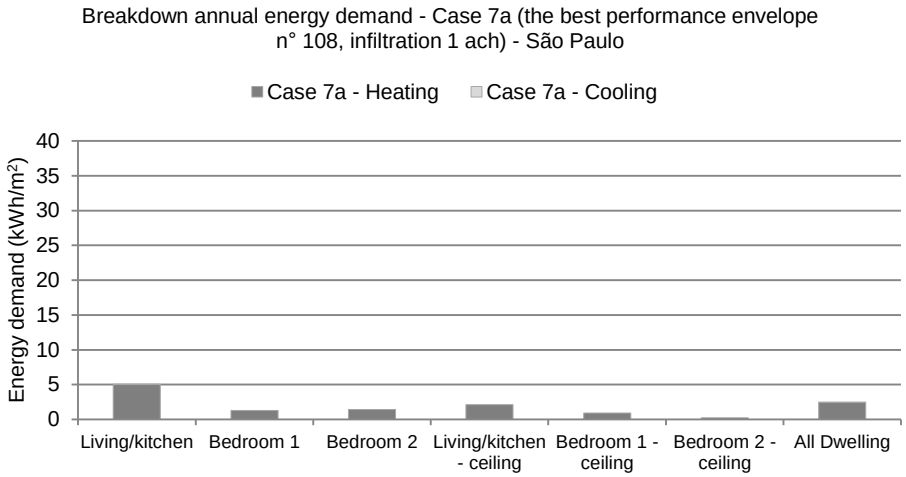
Thermal zones of the Alvorada House - plan: occupant level (left) and ceiling level (right)



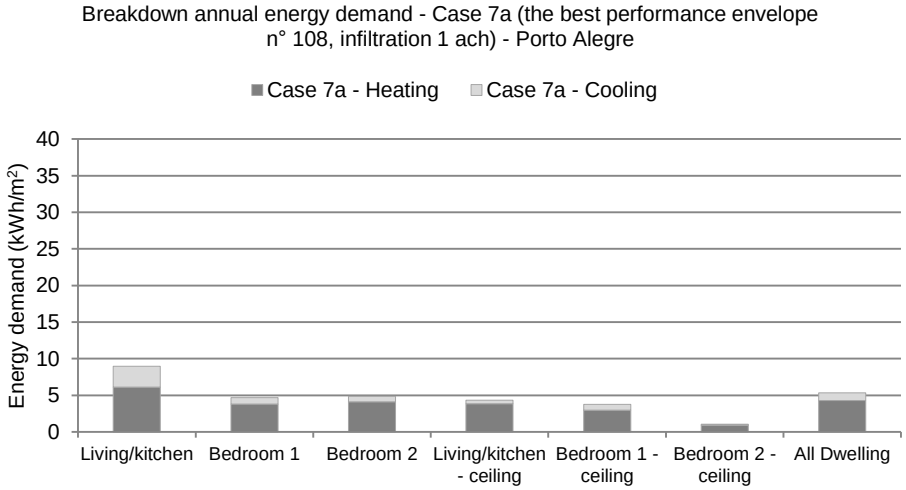
Thermal zones of the Alvorada House - section: occupant and ceiling levels



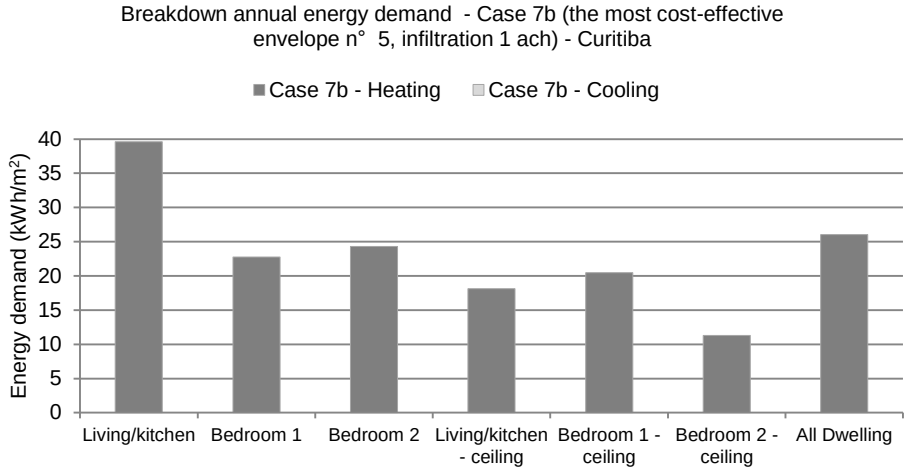
Breakdown annual energy demand, Case 7a, Curitiba



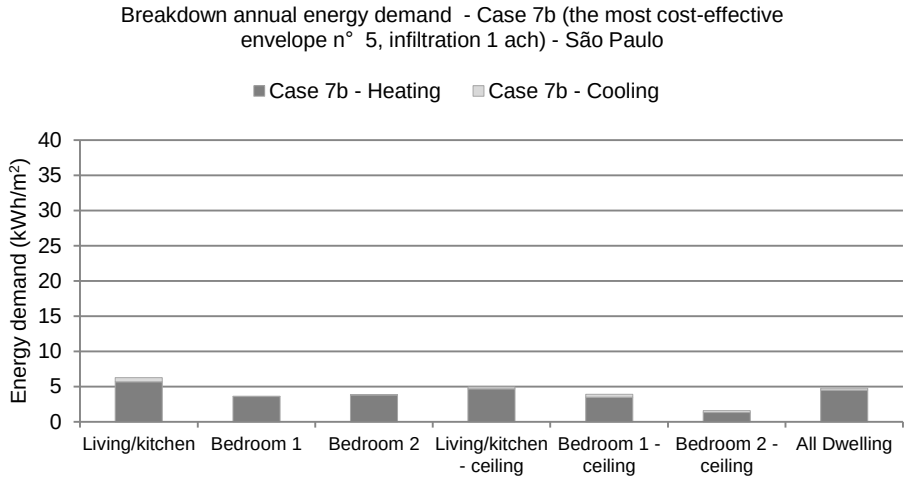
Breakdown annual energy demand, Case 7a, São Paulo



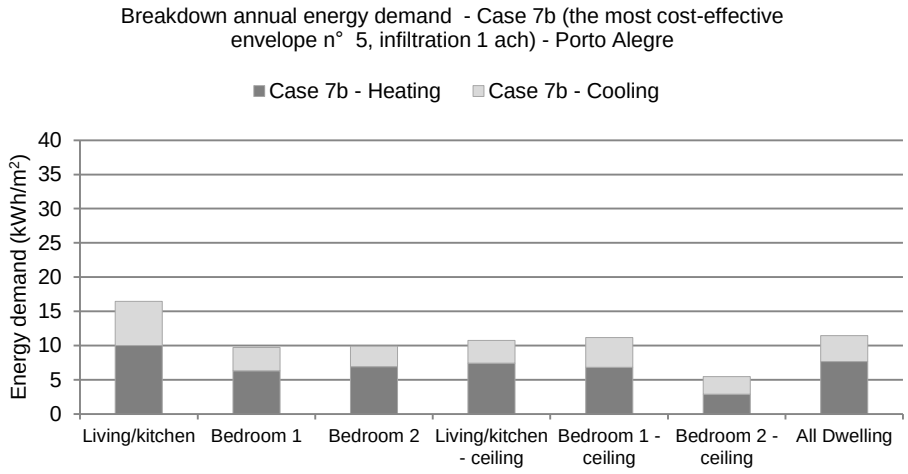
Breakdown annual energy demand, Case 7a, Porto Alegre



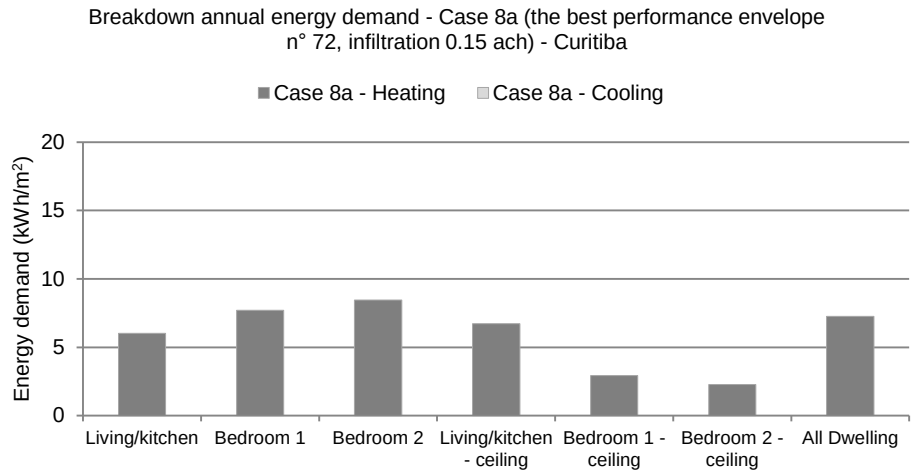
Breakdown annual energy demand, Case 7b, Curitiba



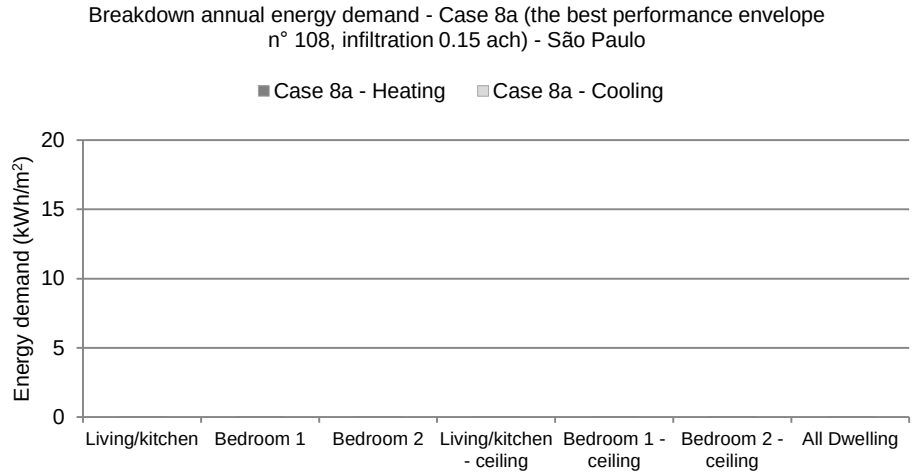
Breakdown annual energy demand, Case 7b, São Paulo



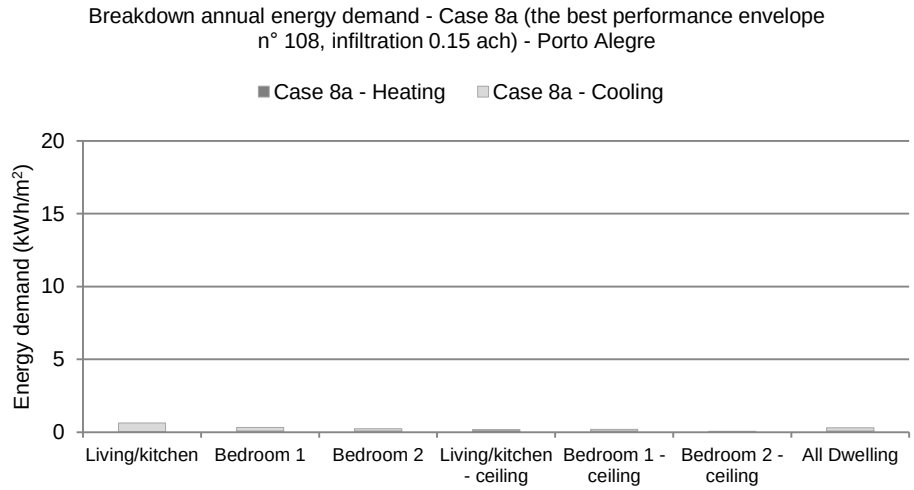
Breakdown annual energy demand, Case 7b, Porto Alegre



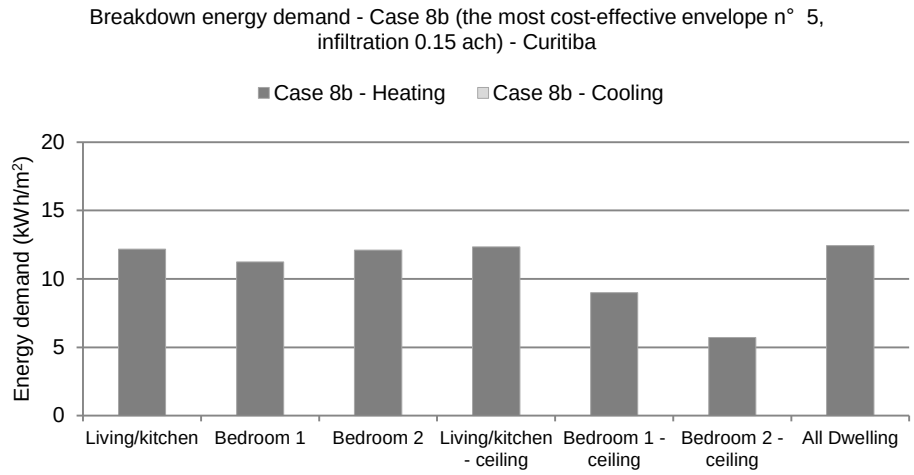
Breakdown energy demand, Case 8a, Curitiba



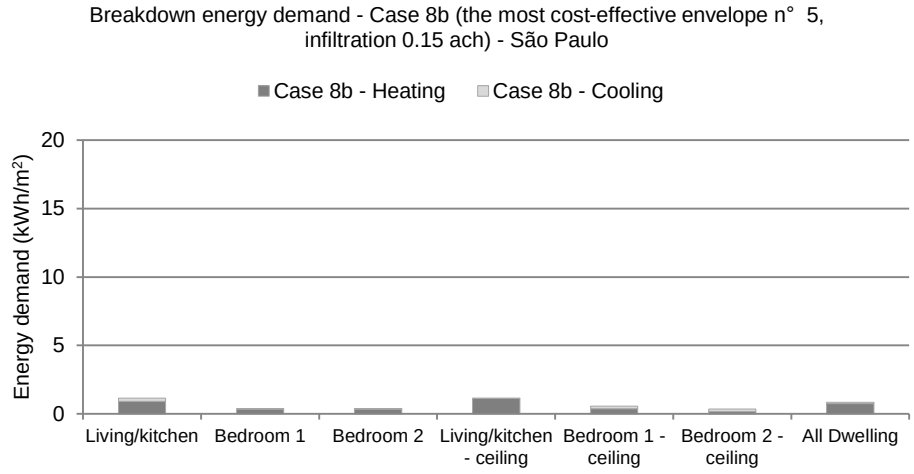
Breakdown annual energy demand, Case 8a, São Paulo



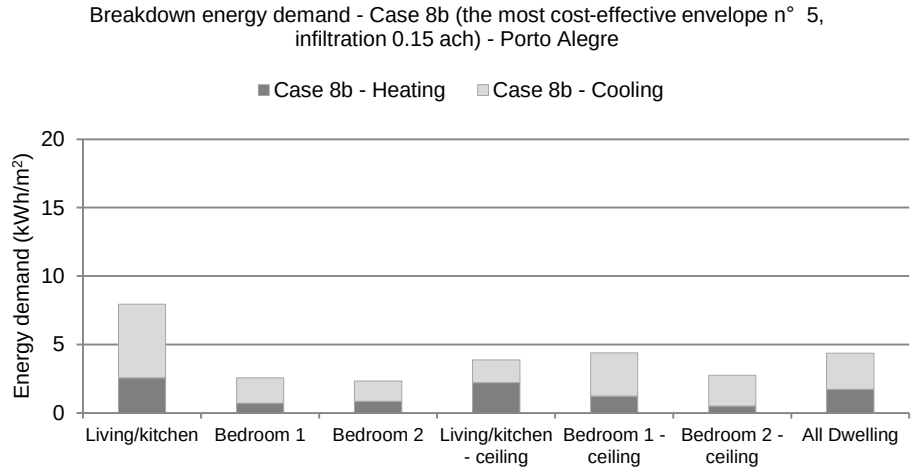
Breakdown annual energy demand, Case 8a, Porto Alegre



Breakdown energy demand, Case 8b, Curitiba



Breakdown energy demand, Case 8b, São Paulo



Breakdown energy demand, Case 8b, Porto Alegre

Estimated costs of the Alvorada House envelope as built, in US dollars - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Solid ceramic brick wall 11 cm (11x5x22cm)	98.53	0.91 1.52	Servant 1.56 Brick layer 2.19	Brick 7.12 Mortar 5.20	2.43	4.75	12.33	m^2	239.43	468.11	598.94	1,214.45	2,281.49	4,291.66
Roof	Aluminium foil	42.90	0.22 0.22	R. Servant 1.68 Roofer 2.19	97.34 /roll of 50m^2	0.44	0.85	97.34	m^2	18.88	36.60	46.84	97.34	180.77	
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00 2.00 5.15 5.15	Servant 1.56 Brick layer 2.19 W. servant 1.68 W.worker 2.19	Window 85.66 Other 0.88	14.3	27.47	86.55	m^2	81.22	156.05	199.66	491.60	847.31	
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00 3.00 8.00 8.00	Servant 1.56 Brick layer 2.19 W. servant 1.68 W.worker 2.19	Window 111.00 Other 34.72	22	42.28	145.72	un	22	42.28	54.09	145.72	242.09	
Window glazing	Single glazing	7.10	-	Installation 5.20	Glass 13.45	-	1.71	13.45	m^2	-	36.92	-	95.50	132.42	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40 1.40 3.75 3.75	Servant 1.56 Brick layer 2.19 W. servant 1.68 W.worker 2.19	Door 151.77 Other 106.90	10.3	19.79	258.66	un	20.6	39.59	50.65	517.33	607.57	

Estimated costs of the Alvorada House envelope as built, in US dollars – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 129.34% (US$)	Material (US$)		
Wall	Solid ceramic brick wall 11 cm (11x5x22cm)	98.53	0.91 1.52	Servant 1.86 Brick layer 2.26	Brick 6.63 Mortar 5.14	2.43	5.12	11.77	m^2	239.43	504.31	652.27	1,159.67	2,316.25	4,518.71
Roof	Aluminium foil	42.90	0.22 0.22	R. Servant 1.86 Roofer 2.26	96.67 /roll of 50m^2	0.44	0.90	96.67	m^2	18.88	38.81	50.19	96.67	185.67	
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00 2.00 5.15 5.15	Servant 1.86 Brick layer 2.26 W. servant 1.86 W.worker 2.26	Window 101.46 Other 0.81	14.3	29.40	102.26	m^2	81.22	166.99	215.98	580.86	963.83	
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00 3.00 8.00 8.00	Servant 1.86 Brick layer 2.26 W. servant 1.86 W.worker 2.26	Window 131.46 Other 35.05	22	45.23	166.55	un	22	45.23	58.50	166.55	270.28	
Window glazing	Single glazing	7.10	-	Installation 4.93	Glass 13.60	-	1.62	13.60	m^2	-	35.03	-	96.53	131.56	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40 1.40 3.75 3.75	Servant 1.86 Brick layer 2.26 W. servant 1.86 W.worker 2.26	Door 164.26 Other 112.74	10.3	21.18	277.00	un	20.6	42.35	54.78	553.99	651.13	

Estimated costs of the Alvorada House envelope as built, in US dollars – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Solid ceramic brick wall 11 cm (11x5x22cm)	98.53	0.91	Servant 1.32	Brick 6.38	2.43	3.90	12.11	m^2	239.43	384.01	491.34	1,193.06	2,068.40	4,020.67
			1.52	Brick layer 1.78	Mortar 5.72										
Roof	Aluminium foil	42.90	0.22	R. Servant 1.45	98.98 /roll of 50m^2	0.44	0.71	98.98	m^2	18.88	30.49	39.01	98.98	168.48	
			0.22	Roofer 1.78											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 1.32	Window 85.66	14.30	22.82	86.61	m^2	81.22	129.62	165.85	491.94	787.40	
			2.00	Brick layer 1.78											
			5.15	W. servant 1.45	Other 0.94										
			5.15	W.worker 1.78											
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00	Servant 1.32	Window 111.00	22.00	35.12	141.98	un	22.00	35.12	44.93	141.98	222.04	
			3.00	Brick layer 1.78											
			8.00	W. servant 1.45	Other 30.98										
			8.00	W.worker 1.78											
Window glazing	Single glazing	7.10	-	Installation 4.21	Glass 12.45	-	1.38	12.45	m^2	-	29.89	-	88.42	118.32	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Servant 1.32	Door 174.44	10.3	16.44	290.54	un	20.6	32.88	42.08	581.08	656.04	
			1.40	Brick layer 1.78											
			3.75	W. servant 1.45	Other 116.10										
			3.75	W.worker 1.78											

Estimated costs of the best performance Alvorada House envelope (n° 72), in US dollars - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	193.60	1.81	Servant 1.56	Brick 16.38	4.23	8.13	27.37	m^2	818.93	1,573.17	2,012.88	5,297.89	8,883.93	17,261.71
			2.42	Brick layer 2.19	Mortar 10.99										
	EPS 30 cm	95.34	0.30	Servant 1.56	Insulat. 34.66	0.60	1.13	38.19	m^2	57.20	107.26	137.24	3,641.42	3,885.92	
			0.30	Brick layer 2.19	Other 3.54										
Roof	Mineral wool panels bet. Roof structure	42.90	0.66	R. Servant 1.68	24.73	1.32	2.56	24.73	m^2	56.63	109.81	140.50	1,060.93	1,311.24	
			0.66	Roofer 2.19											
Window frame	PVC frame - Awning (9un varied size)	5.68	1.00	Servant 1.56	Window 202.91	2.00	3.75	210.12	m^2	11.36	21.30	27.25	1,193.47	1,242.03	
			1.00	Brick layer 2.19	Other 7.21										
	PVC frame - Sliding + shutter (1un119x119cm)	1.42	1.00	Servant 1.56	Window 359.10	2.50	4.85	366.31	m^2	3.55	6.88	8.81	520.15	535.84	
			1.50	Brick layer 2.19	Other 7.21										
Window glazing	Double uncoated glazing	7.10	-	Installation 5.20	Glass 46.05	-	1.71	326.97	m^2	-	36.92	-	326.97	363.90	
Door	PVC (2un varied size)	2.00	3.00	Servant 1.56	Door 489.83	6.00	11.25	493.78	un	12.00	22.50	28.79	987.57	1,038.86	
			3.00	Brick layer 2.19	Other 3.95										

Estimated costs of the best performance Alvorada House envelope (n° 108), in US dollars – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 129.34% (US$)	Material (US$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	193.60	1.81	Servant 1.86	Brick 15.24	4.23	8.82	26.10	m^2	818.93	1,707.35	2,208.28	5,052.07	8,967.70	17,232.40
			2.42	Brick layer 2.26	Mortar 10.85										
	EPS 30 cm	95.34	0.30	Servant 1.86	Insulat. 31.38	0.60	1.23	33.72	m^2	57.20	117.61	152.11	3,214.59	3,484.31	
			0.30	Brick layer 2.26	Other 2.34										
Roof	Mineral wool panels bet. Roof structure	42.90	0.66	R. Servant 1.86	26.53	1.32	2.71	26.53	m^2	56.63	116.42	150.58	1,137.98	1,404.98	
			0.66	Roofer 2.26											
Window frame	PVC frame - Awning (9un varied size)	5.68	1.00	Servant 1.86	Window 183.97	2.00	4.11	192.54	m^2	11.36	23.36	30.21	1,093.64	1,147.21	
			1.00	Brick layer 2.26	Other 8.57										
	PVC frame - Sliding + shutter (1un119x119cm)	1.42	1.00	Servant 1.86	Window 325.58	2.50	5.24	334.15	m^2	3.55	7.44	9.63	474.49	491.56	
			1.50	Brick layer 2.26	Other 8.57										
Window glazing	Double coated glazing	7.10	-	Installation 4.93	Glass 105.26	-	1.62	105.26	m^2	-	35.03	-	747.37	782.40	
Door	PVC (2un varied size)	2.00	3.00	Servant 1.86	Door 444.11	6.00	12.34	448.83	un	12.00	24.67	31.91	897.66	954.24	
			3.00	Brick layer 2.26	Other 4.72										

Estimated costs of the best performance Alvorada House envelope (n° 108), in US dollars – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	2-layer solid ceramic brick wall 19 cm (9x5.7x19cm)	193.60	1.81	Servant 1.32	Brick 14.68	4.23	6.68	26.77	m^2	818.93	1,293.30	1,654.78	5,181.98	8,130.06	16,419.85
			2.42	Brick layer 1.78	Mortar 12.09										
	EPS 30 cm	95.34	0.30	Servant 1.32	Insulat. 34.66	0.60	0.93	38.18	m^2	57.20	88.44	113.16	3,640.48	3,842.08	
			0.30	Brick layer 1.78	Other 3.53										
Roof	Mineral wool panels bet. Roof structure	42.90	0.66	R. Servant 1.45	24.73	1.32	2.13	24.73	m^2	56.63	91.46	117.03	1,060.93	1,269.41	
			0.66	Roofer 1.78											
Window frame	PVC frame - Awning (9un varied size)	5.68	1.00	Servant 1.32	Window 173.15	2.00	3.09	179.08	m^2	11.36	17.56	22.47	1,017.15	1,057.18	
			1.00	Brick layer 1.78	Other 5.93										
	PVC frame - Sliding + shutter (1un119x119cm)	1.00	1.00	Servant 1.32	Window 306.43	2.50	3.98	312.36	m^2	3.55	5.65	7.23	443.55	456.43	
			1.50	Brick layer 1.78	Other 5.93										
Window glazing	Double coated glazing	7.10	-	Installation 4.21	Glass 105.26	-	1.38	105.26	m^2	-	29.89	-	747.37	777.26	
Door	PVC (2un varied size)	2.00	3.00	Servant 1.32	Door 417.99	6.00	9.28	422.56	un	12	18.55	23.74	845.13	887.41	
			3.00	Brick layer 1.78	Other 4.57										

Estimated costs of the most cost-effective Alvorada House envelope (n° 5), in US dollars - Curitiba

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm)	91.21	0.51	Servant 1.56	Brick 14.74	1.30	2.53	17.46	m^2	118.57	230.47	294.89	1,592.58	2,117.94	5,832.32
			0.79	Brick layer 2.19	Mortar 2.72										
	EPS 10 cm	95.26	0.30	Servant 1.56	Insulat. 11.79	0.60	1.13	15.33	m^2	57.16	107.17	137.12	1,459.92	1,704.21	
			0.30	Brick layer 2.19	Other 3.54										
Roof	Aluminium foil	42.90	0.22	R. Servant 1.68	97.34 /roll of 50m^2	0.44	0.85	97.34	m^2	18.88	36.60	46.84	97.34	180.77	
			0.22	Roofer 2.19											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 1.56	Window 85.66	14.3	27.47	86.55	m^2	81.22	156.05	199.66	491.60	847.31	
			2.00	Brick layer 2.19											
			5.15	W. servant 1.68	Other 0.88										
			5.15	W.worker 2.19											
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00	Servant 1.56	Window 111.00	22	42.28	145.72	un	22	42.28	54.09	145.72	242.09	
			3.00	Brick layer 2.19											
			8.00	W. servant 1.68	Other 34.72										
			8.00	W.worker 2.19											
Window glazing	Single glazing	7.10	-	Installation 5.20	Glass 13.45	-	1.71	13.45	m^2	-	36.99		95.50	132.42	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Serv. 4.73	Door 151.77	10.3	19.79	258.66	un	20.6	39.59	50.65	517.33	607.57	
			1.40	Brick layer 2.19											
			3.75	W. servant 1.68	Other 106.90										
			3.75	W.worker 2.19											

Estimated costs of the most cost-effective Alvorada House envelope (n° 5), in US dollars – São Paulo

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (US$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 129.34% (US$)	Material (US$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29 cm)	91.21	0.51	Servant 1.86	Brick 12.80	1.30	2.73	15.46	m^2	118.57	248.90	321.93	1,409.86	1,980.68	5,672.53
			0.79	Brick layer 2.26	Mortar 2.65										
	EPS 10 cm	95.26	0.30	Servant 1.86	Insulat. 10.47	0.60	1.23	12.81	m^2	57.16	117.51	151.98	1,219.89	1,489.38	
			0.30	Brick layer 2.26	Other 2.34										
Roof	Aluminium foil	42.90	0.22	R. Servant 1.86	96.67 /roll of 50m^2	0.44	0.90	96.67	m^2	18.88	38.81	50.19	96.67	185.67	
			0.22	Roofer 2.26											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 1.86	Window 101.46	14.3	29.40	102.26	m^2	81.22	166.99	215.98	580.86	963.83	
			2.00	Brick layer 2.26											
			5.15	W. servant 1.86	Other 0.81										
			5.15	W.worker 2.26											
	Eucalyptus Timber frame - Sliding + shutter (1un 119x119cm)	1.00	3.00	Servant 1.86	Window 131.46	22	45.23	166.55	un	22	45.23	58.50	166.55	270.28	
			3.00	Brick layer 2.26											
			8.00	W. servant 1.86	Other 35.08										
			8.00	W.worker 2.26											
Window glazing	Single glazing	7.10	-	Installation 4.93	Glass 13.60	-	1.62	13.60	m^2	-	35.03	-	96.53	131.56	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Serv. 1.86	Door 164.26	10.3	21.18	277.00	un	20.6	42.35	54.78	553.99	651.13	
			1.40	Brick layer 2.26											
			3.75	W. servant 1.86	Other 112.74										
			3.75	W.worker 2.26											

Estimated costs of the most cost-effective Alvorada House envelope (n° 5), in US dollars – Porto Alegre

Envelope element		Quantity (m^2) (un)	Detailed unit cost			Unit cost				Calculated cost				Cost per element (US$)	Total cost (US$)
			Labour (hour)	Labour (us$/h)	Material (US$/$m^2$)	Labour (hour)	Labour (US$)	Material (US$)	unit	Labour (hour)	Labour (US$)	Labour taxes 127.95% (US$)	Material (US$)		
Wall	Hollow ceramic brick wall 19 cm (19x19x29cm	91.21	0.51	Servant 1.32	Brick 15.84	1.30	2.08	18.62	m^2	118.57	189.20	242.08	1,698.49	2,129.77	5,742.45
			0.79	Brick layer 1.78	Mortar 2.78										
	EPS 10 cm	95.26	0.30	Servant 1.32	Insulat. 11.79	0.60	0.93	15.32	m^2	57.16	88.37	113.07	1,458.98	1,660.41	
			0.30	Brick layer 1.78	Other 3.53										
Roof	Aluminium foil	42.90	0.22	R. Servant 1.45	98.98 /roll of 50m^2	0.44	0.71	98.98	m^2	18.88	30.49	39.01	98.98	168.48	
			0.22	Roofer 1.78											
Window frame	*Eucalyptus* Timber frame - Awning (9un varied size)	5.68	2.00	Servant 1.32	Window 85.66	14.3	22.82	86.61	m^2	81.22	129.62	165.85	491.94	787.40	
			2.00	Brick layer 1.78											
			5.15	W. servant 1.45	Other 0.94										
			5.15	W.worker 1.78											
	Eucalyptus Timber frame - Sliding + shutter (1un119x119cm)	1.00	3.00	Servant 1.32	Window 111.00	22	35.12	141.98	un	22	35.12	44.93	141.98	222.04	
			3.00	Brick layer 1.78											
			8.00	W. servant 1.45	Other 30.98										
			8.00	W.worker 1.78											
Window glazing	Single glazing	7.10	-	Installation 4.21	Glass 12.45	-	1.38	12.45	m^2	-	29.89	-	88.42	118.32	
Door	*Eucalyptus* Timber (2un varied size)	2.00	1.40	Serv. 1.32	Door 174.44	10.3	16.44	290.54	un	20.6	32.88	42.08	581.08	656.04	
			1.40	Brick layer 1.78											
			3.75	W. servant 1.45	Other 116.10										
			3.75	W.worker 1.78											

Calculation of the architectural design costs of the Alvorada House – Curitiba, São Paulo and Porto Alegre

Variables of the calculation	*Calculation description*
The values were obtained from CEAU (2014a, p. 40-44, 64-69). $Sc = 49.43\ m2$ $BH = R\$\ 1{,}233.64\ Curitiba$ $BH = R\$\ 1{,}190.85\ Sao\ Paulo$ $BH = R\$\ 1{,}180.08\ Porto\ Alegre$ $Fp = 7.33\%\ \ for\ low\ standard\ typology\ and\ for\ the\ corresponding\ area\ \ Due\ to\ the\ increase\ of\ complexity\ of\ the\ design, this\ index\ can\ achieve\ 11.00\%\ for\ this\ corresponding\ area\ .$ $R = \frac{Sp}{Sc} = 1$ $Sp = Snr + (Sr\ \times r) = 43.83 + (0\ \times 100) = 43.83\ m2$	*Alvorada House as built architectural design* $PV = Sc\ \times BH\ \times (Fp\ \times R)$ $PV = 43.83\ \times\ CUB\ of\ each\ city\ \times 0.0733$ $\boldsymbol{PV_{Curitiba}\ =\ R\$\ 4{,}469.75}$ $\boldsymbol{PV_{Sao\ Paulo}\ = R\$\ 4{,}314.71}$ $\boldsymbol{PV_{Porto\ Alegre}\ = R\$\ 4{,}275.69}$ *Optimised Alvorada House architectural design* $PV = Sc\ \times BH\ \times (Fp\ \times R)$ $PV = 43.83\ \times\ CUB\ of\ each\ city\ \times 0.11$ $\boldsymbol{PV_{Curitiba}\ = R\$\ 6{,}707.67}$ $\boldsymbol{PV_{Sao\ Paulo}\ = R\$\ 6{,}475.01}$ $\boldsymbol{PV_{Porto\ Alegre}\ = R\$\ 6{,}416.45}$

Where,

PV= price of the architectural design, in Brazilian Reais
Sc = estimated built area of the building, in m^2
BH = fees basis, in Brazilian Reais. For low standard typology, this value is equal to the monthly CUB.
F_p = factor, in %. This is defined by the area of the building and its typology.
R = Ratio of *Sp* to *Sc*, where *Sp = Snr + (Sr x r)*. Sp consists of a relationship between the area of the building that has repetitions (*Sr*) in the design and those that do not (*Srn*). *r* is the factor of reduction due to the repetition.