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The Case of Villa Benfica: Retrofitting a Multifamily Building in a Hot and Humid Climate For Energy Efficiency

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The Case of Villa Benfica:

Retrofitting a Multifamily Building in a Hot and Humid Climate

For Energy Efficiency

by

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The thesis “The case of Villa Benfica: Retrofitting a Multifamily Building in a Hot and Humid Climate for Energy Efficiency” by Carolina Kühner Câmara dos Santos has been examined and approved by the following Examination Committee:

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Abstract

Buildings and constructions occupy 50% or more of a city's land area and impact the environment with their elevated energy consumption. The current debates involving alternatives to limit the impacts of climate change have informed decision makers, architects, and engineers on design alternatives addressing energy efficiency in new constructions, but the existing building stock requires adaptation. Existing buildings are locked in an inefficient typology. In this context, this work presents energy efficient strategies to retrofit a typical residential building in Recife, Brazil. The study involves the application of three retrofit strategies concerning the building envelope to a baseline building, and their evaluation regarding thermal performance, electricity efficiency and payback calculations. The results of this investigation show that reductions of 3%, 8% and 11% in energy consumption can be achieved with the proposed strategies, but not all are economically viable. The most efficient alternatives would require financial incentives from the local government to become viable options. The value of these strategies is proven when visualizing the entire city and evaluating the significant benefits of 11% reductions in one building replicated in many others.

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List of Abbreviations

AQUA - High Environmental Quality Label

ASHRAE - American Society of Heating, Refrigerating, and Air-Conditioning Engineers

EPE - Empresa de Pesquisa Energética (Association for Research on Energy)

GNI - Gross National Income

HVAC - Heating, Ventilation and Air-Conditioning

LEED - Leadership in Energy and Environmental Design

NBR - Norma Brasileira (Brazilian Norm)

OTTV - Overall Thermal Transfer Value

PBE - Programa Brasileiro de Etiquetagem (Brazilian Program for Labeling)

PROCEL - Programa Nacional de Conservação de Energia Elétrica (National Program for Electricity Conservation)

Qw - Wall's heat gains

Qg - Windows heat gains

Qs - Solar Radiation gains

UCLA - University of California, Los Angeles

WRI - World Resources Institute

1. Introduction

The building stock is large all around the world and keeps growing at a fast rate, along with the population of cities. In 2014, the worldwide building stock was 151.8 billion square meter (1.6 trillion square feet) and is expected to rise to 171.6 billion square meters (1.8 trillion square feet) by 2024 (Freas & Goldstein, 2015). According to the World Resources Institutes, cities are expected to add 3 billion people between the years of 2008 and 2050, almost doubling the global urban population in a short time and increasing the necessity of effective urban development.

Today, the debates revolve around firming commitments and investments in alternatives to stop the disruptive rate in which nations are going beyond the environment's carrying capacity. Information on consequences of each action and alternatives for prevention are widely available and contributes in changing policies and regulations involving several activity sectors, including buildings and constructions. Therefore, developers have available information and technologies to produce buildings that are able to reduce their impact on the environment, and this can be applied to recent and future developments. However, how to address to the existing building stock, completed years ago but that continues impacting the environment with their inefficiency? Are there adaptations to the building's systems, materials, and even design, that can stop or reduce their negative environmental impact?

The density of urban centers weights heavily in environmental impacts and configure an important target for sustainable measures to be urgently adopted. In cities around the world, buildings occupy 50% or more of the land area and are responsible for 60% of electricity use, 12% of water use, 40% of waste and 40% of material resource use (WRI, 2016). In large metropolitan areas, this density generates an elevated level of unwanted emissions, contributing to health problems within the population. In 2014, residential buildings represented 75% of the existing building stock worldwide (Freas & Goldstein, 2015). In Brazilian denser population centers, these residential buildings are frequently mid to high-rise developments constructed on a small site. Developers promote the construction of these buildings in large quantities, replicating the same typology and floor plan layout wherever possible. These types of developments do not take advantage of climate responsive strategies in their designs, being therefore locked into to a pattern that does not evolve, generating decades of inefficiencies. Addressing building efficiency has the potential to cut the growth of energy demand by more than half by 2020 (WRI, 2016), so what are the available options to retrofit this existing residential building stock and achieve energy efficiency?

Recife’s current situation falls within the presented characterization of urban centers. A large number of residential high-rise buildings have been built with low regard for the use of natural elements in favor of convenience. Most residential buildings have expensive and inefficient mechanical air conditioning systems to combat the excessive heat absorbed by poorly laid out spaces. A study on energy efficient solutions is necessary to provide cost-effective and sustainable alternatives that still provide comfort and convenience to inhabitants. Similar to other places in the world, Brazil suffers from ever increasing electricity consumption, that is quickly surpassing current infrastructure capabilities.

1.1. Objectives & Methodology

The objective of this research is to study alternative solutions to be applied in existing residential buildings in Recife to improve their energy efficiency while maintaining comfort levels for the residents. A comparative analysis is conducted between the different retrofit alternatives and their energy efficiency in relation to a baseline, through a building energy simulation and basic thermal calculations. A cost-based analysis is conducted as well, to identify the feasibility of each solution. The final outcomes will answer the hypothesis formulated at the beginning of the study: are the solutions improving thermal comfort and energy efficiency? Are they attainable, cost efficient and replicable?

Three basic steps define the methodology of this research. The initial step involves an extensive research on climate responsive approaches to architecture in hot and humid climates, identifying strategies in direct correlation to the local climate that contribute to the use of passive systems, and information regarding possible retrofit strategies that increase thermal comfort and reduce energy consumption. This research will help narrow down viable options to be applied in the baseline building design. As a second step, three scenarios are developed and studied in relation to their thermal performance and reduced energy footprint. The final step presents results on the outcomes of each solution, payback periods and the thermal performance of each building envelope.

1.2. Thesis Organization

Chapter 2 provides context for the economic, geographical and climate characteristics of Brazil and its regions, with a particular focus on the city of Recife. This information situates the reader in the context of this research, and into specific and important factors to be considered when designing for Recife. The current situation in terms of country's energy mix and consumption, and how Brazil is facing the challenges of global warming and other environmental impacts are also presented.

Chapter 3 provides information regarding the urban characteristics of residential high-rise architecture, in addition to current typologies for this type of design. Commonly used materials and challenges associated with these typologies are also explained. The chapter also includes local codes and energy guidelines currently available in Recife, Brazil which serve as parameters for the final proposals.

Chapter 4 focuses on recommended design solutions associated with a hot and humid climate in which the building is inserted. The chapter provides an overview of climate-related design strategies and serves as a guide to start selecting options applicable to the baseline building.

Chapter 5 presents the correlation of the previously explained design guidelines and their application in a retrofit case. The chapter presents a literature review regarding possible options involving building envelope and natural ventilation strategies, the topics selected to be studied.

Chapter 6 presents parameters and metrics used in this research for evaluating the baseline building and each retrofit strategy. In addition, the baseline building is described in relation to its location, building configuration, materials, thermal transmittance and simulation results. Each retrofit case is also presented, including thermal performance and simulation of the first two retrofit scenarios.

Chapters 7 and 8 present a comparison of all simulated cases, and their improvements compared to each other and to the baseline building. The final chapter answers the research questions previously raised, and provides recommendations based on the comparative results.

2. Recife, Brazil in Context

2.1. Location, Geography & Climate

In relation to the world's economy, Brazil is considered a developing nation according to the United Nations report of 2014[1] (United Nations, 2014) and classified as an upper-middle-income economy[2] by the World Bank (The World Bank, 2016) based on measurements of gross national income (GNI) per capita. It is an extensive country, marked by a diverse population in terms of ethnicities, and by a large disparity between high and low income families.

Brazil is the third largest country in the Americas, with a territory of approximately 8.515.767 km² (2,104.10 acres), only behind Canada (first position) and United States (second position). In terms of population, Brazil appears in the second position with close to 205,758,106 residents, after only the United States, and with 84% of this population living in urban centers (IBGE, 2010).

The country is divided into five macro-regions, North, Northeast, Central-West, Southeast and South, and into twenty-seven states. This is shown in the map below (Figure 1).

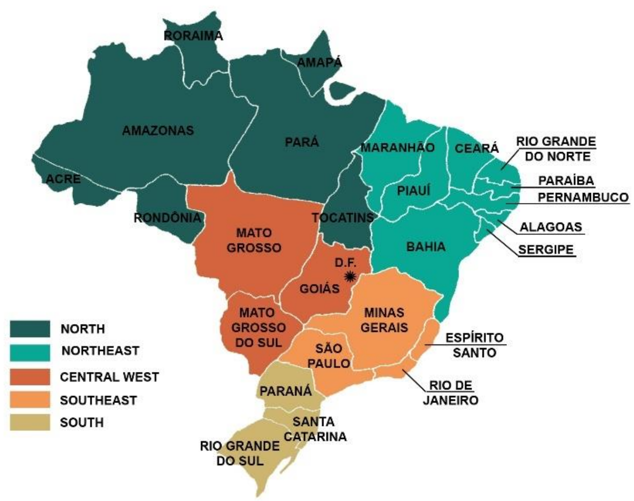

Figure 1- Brazil: regions and states - Adapted from www.infoescola.com.

[1] As a part of a classification between developed economies, economies in transition and developing economies
[2] As a part of a four income classification: low, lower-middle, upper-middle, and high

Given its territorial extension, Brazil has differences in climate conditions throughout its different regions. The country extends from latitude 5.27° N to latitude 33.75° S (IBGE, 2012), with 93% of its territory located in the south hemisphere and 7% in the north hemisphere. Most of the country is located between the Equator line and the Tropic of Capricorn (figure 2), thus being considered to have a Tropical climate (with the exception of the South Region) and characterized by elevated temperatures and rainy seasons.

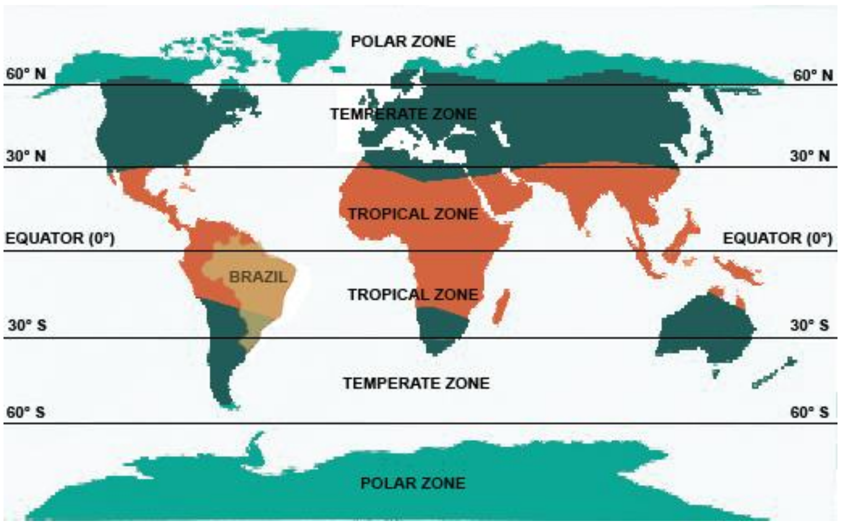

Figure 2 - World's climate zones - Adapted from www.webquest.hawaii.edu.

The Northeast region corresponds to 18% of Brazil's total territory extension and has the highest coastal extension when compared to the other regions. The region also has the lowest index of human development[3], followed by the North region, with the South and Southeast regions in the first and second positions. The north and northeast regions are the least developed in the country, with major problems involving poverty, inequity, poor infrastructure and diseases.

Recife is one of the largest cities in the Northeast region. It is the capital city of Pernambuco (Figure 3), and according to the United Nations database, its population was 3,690,547 inhabitants[4] in 2010, 41.7% of the entire state's population, and the sixth larger metropolitan area of the country. The city can also be characterized as a very dense city (IBGE, 2010), with a density of 7,039.64 habitants per square kilometers (17,600 people/mi^2), close to São Paulo's density of 7.398,26 habitants per square kilometers (18,496 people/mi^2). Similarly to other coastal cities,

[3] Correlation between three main elements of development: longevity, education and income
[4] Considering the metropolitan area

Recife grew and continues to grow from the coast in the west direction, experiencing rapid industrialization and urban growth. Problems such as air and noise pollution, crime, overcrowding and traffic congestion increase more and more each year (Cohen, 2011).

Figure 3 - Map of Pernambuco - Adapted from www.viagemdeferias.com.

The city is located in the latitude 8.05° south, longitude 34.92° west, is predominantly flat and at sea level, increasing altitude as it progresses towards the west (to around 7 meters above sea level or 23 feet). Due to its location near the Atlantic Ocean, Recife has a particular set of climate characteristics, generally compatible with the tropical climate zone but with influences from the proximity to the sea.

In terms of temperature, the mean temperature ranges from 26°C (80°F) to 28°C (84°F) during spring and summer, and from 25°C (77°F) to 26°C (80°F) during the fall and winter, with the hottest month being March (28°C - 84°F) and the coolest being June and July (25°C - 77°F). Overall, the annual temperature remains around 27°C (82°F). Figure 4 represents the temperature ranges for Recife and the comfort zones from the Adaptive Comfort method (left) and the ASHRAE Standard 55 PMV method (right). The Standard 55 PMV method considers the combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate and clothing insulation to define a zone of comfort in indoor spaces. The Adaptive Comfort method, as the name implies, in an adaptation of the previous method, considering outdoor climate causing influences on indoor conditions and the human adaptation to these differences, taking into consideration psychological and behavioral aspect. In comparison to the ASHRAE method, the

Adaptive Comfort considers the influence of natural ventilation, elevating therefore the temperatures associated to comfort sensations.

In the Adaptive method, the temperatures are within the comfort zone, but close to the maximum limits during the summer months. In the ASHRAE Standard 55 method the temperatures are above the line of comfort during the entire year, which indicates the necessity of cooling strategies, especially when natural ventilation is not effective.

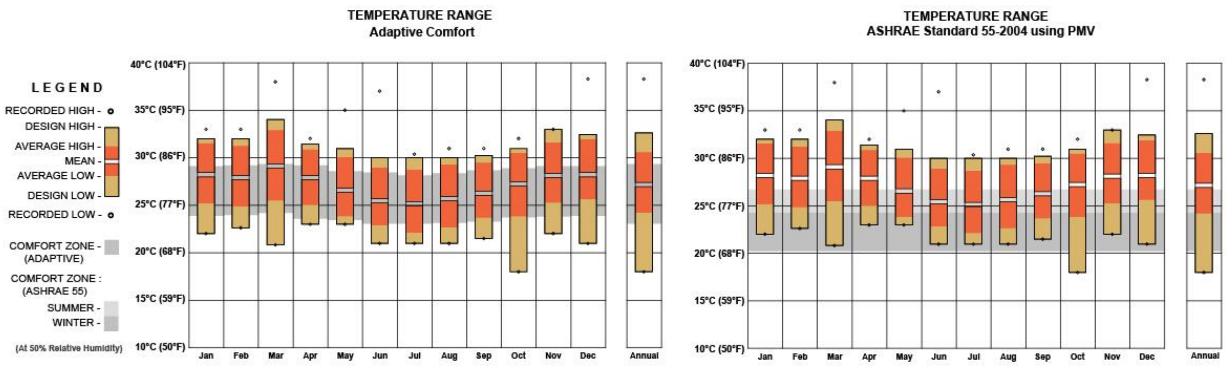

Figure 4 - Recife's temperature range - Adapted from Climate Consultant 6.0.

As shown in figure 4, the temperature change is small between seasons, and the same occurs during the day. The following table (Table 1) shows Cooling and Heating Degree Days based on several thresholds. Cooling and Heating Degree Days represent the quantity of cooling or heating degrees that a space needs to reach comfortable conditions based on daily averages, therefore representing the predominance of cooling or heating necessities. The values are based on the difference between outdoor temperatures (daily average) and the indoor temperature considered as comfortable. As can be seen, there are no heating necessities or Heating Degree Days in Recife, since temperatures are always elevated even during winter seasons.

Cooling Degree Days		Heating Degree Days	
Threshold	**Value**	**Threshold**	**Value**
18°C (65°F)	6286	18°C (65°F)	0
21°C (70°F)	4461	16°C (60°F)	0
24°C (75°F)	2636	13°C (55°F)	0
27°C (80°F)	8888	10°C (50°F)	0

Table 1 – Recife's Cooling and Heating Degree Days – From Green Building Studio.

Recife is privileged by its location on the coast when it relates to wind frequency and speed characterizing, therefore, an opportunity for strategically placing openings to take advantage of this natural feature. As shown in figure 5 the frequent winds originate mainly from the southeast direction, varying along the year between the south and east orientations. The annual wind speed is 3 m/s (7 mph), varying between 2 m/s (5 mph) and 4 m/s (9 mph) through the year. The wind velocity is higher during the hottest month as noticeable in March, as well as during hottest hours of the day, contributing to the adoption of natural ventilation as a cooling strategy in this city (Lôbo & Bittencourt, 2003).

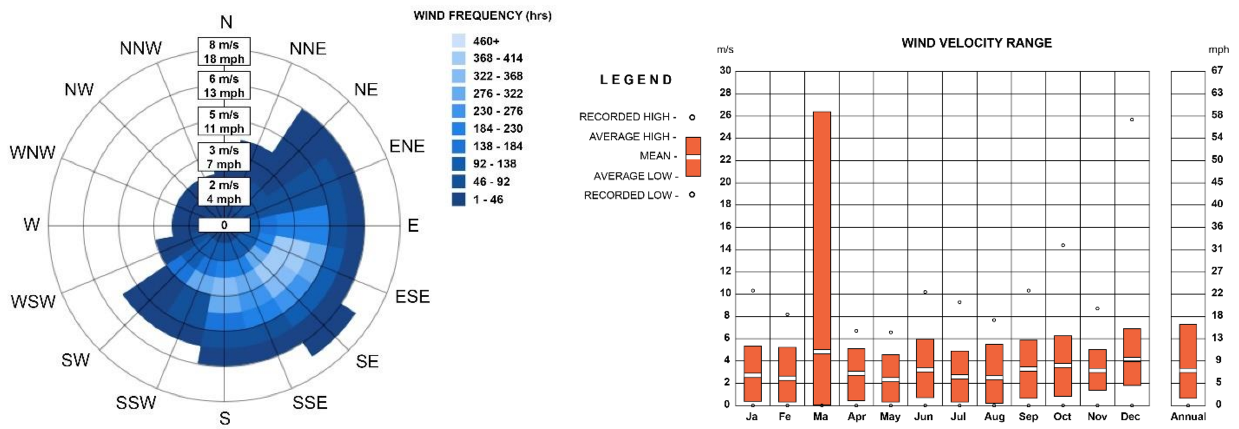

Figure 5 - Recife's wind direction and frequency (left), and intensity (right).

In addition, the proximity to the sea also contributes to a high percentage of relative humidity, varying between 70% and 83% throughout the year. During the winter, higher humidity percentages provoke higher precipitation levels, this being the main differentiating characteristic between winter and summer seasons in this location.

The climate can, therefore, be summarized as hot and humid. A sustainable design must be in direct correlation to these characteristics. The elevated temperatures require shading and heat gain controls associated with the predominant winds to lower body temperatures and cool spaces. The climate possesses a regularity in its characteristics throughout the year that facilitates the use of passive systems as main mechanisms. The use of passive systems associated with active systems serving as backup alternatives contributes to significant reductions in energy use, therefore minimizing carbon and other emissions related to the production and distribution or energy. A climate responsive architecture is fundamental for lowering impacts caused from buildings in cities and in the world.

2.2. Sustainability

In present days, all people share the notions of sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs"[5] (Brundtland Commission, 1987). This belief is universally shared, but problems faced by developed and developing countries are distinct. The major effects felt by developed countries relate to wealthy economies, such as acid rains, an excess of landfills, diseases and health issues associated with excessive consumption of sugary food and drinks. Developing countries, on the other hand, are mostly affected by the lack of infrastructure and fragile economy. The problems involve malnutrition of large portions of the population, lack of treated water and infrastructure for maintaining people's health, lack of health care as well as problems with drugs and alcohol consumption (Lima, 1997). Social problems strongly mark these countries and are major challenges to overcome.

Brazil falls into the aforementioned characterization of developing countries, where the social aspect represents the most critical pillar of its sustainable development but is also a major contributor to the world's climate change. The country imports goods as well as behavior patterns from North America or Europe, which are regions that appear as leaders of environmental problems in the past and current decade. These patterns of behavior are centered in elevated energy consumption and high use of natural resources (Pádua, 1999) and developed themselves to become harmful to the environment. Actions are therefore necessary to change this behavior, especially in developing nations and economies that still have the opportunity to take a different path.

According to data from the World Research Institute, Brazil appears as the 7th top emitter of greenhouse gas in the world, including emissions from land use and forestry, as shown in Figure 6. It is amongst the ten countries that produce approximately 70% of the world's total GHG emission (Ge, Friedrich, & Damassa, 2016).

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[5] as described in the report Our Common Future and published by the World Commission on Environment and Development

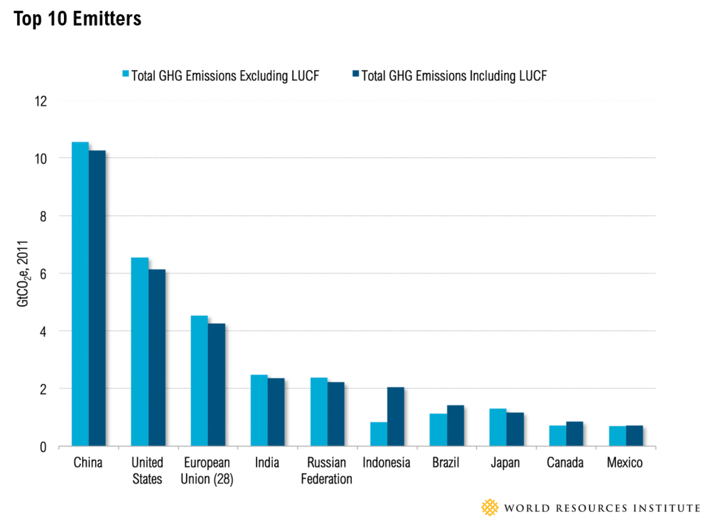

Figure 6 - World top Green House Gas emitters - From www.wri.org.

It is estimated by the same institute that 55% of Brazil's emissions result from deforestation and 22% is associated with energy, transportation, residues and buildings (Oliveira, Pereira, Silva, & Nascimento, 2013). The aggressive pattern that the country's economy has taken so far has been exploratory and without care for the abundant natural resource, resulting in Brazil taking the first position on global deforestation. In the past decades, approximately 98 million acres of forested lands have been destroyed (Padovezi, 2016). Recent commitments (2015) as a direct result of the Paris agreement involving the states of São Paulo, Espírito Santo, and Mato Grosso do Sul revolve around restoring approximately 7 million acres of land as well as eradicating illegal deforestation in one of the three mentioned states. These actions are a part of the Initiative 20x20, to restore 50 million acres of degraded land in Latin America and the Caribbean by 2020 (WRI, 2016).

Efforts in reducing deforestation have increased and become significant, but the reliance more and more on fossil fuels as sources of energy is tracing an alarming path into the future of the country and its growing contribution to climate change. The rapid growth of urban areas causes impacts in the cities' infrastructures and the environment itself. Therefore, sustainable actions are necessary to prevent major damages. In its development process, Brazil went from being 36% urban in 1950 to 81% urban in 2000, and these figures keep increasing each year (Cohen, 2011). Transportation, buildings, and constructions sectors are at the center of these issues, worsening with the rapid urbanization.

In most Brazilian cities, the transportation system is not effective and encourages, along with unhealthy urbanization processes, the intensive use of private vehicles by most the population. Problems with traffic jams and poor mobility have become major issues, affecting heath, environment, and security. In 2012, there were approximately 4.2 million of cars in São Paulo (WRI, 2016), corresponding to approximately 1 car for each 3 habitants. According to the World Resources Institute, in large Brazilian cities transportation accounted for 23% of Green House Gas Emissions and for 70% of air pollution (WRI, 2016). Investing therefore in better mobility in cities has a large influence in reducing impacts on the environment, as well as providing social and economic benefits.

Buildings and constructions are another contributing segment to climate change and environmental impacts in Brazil. According to the International Energy Agency, the building sector is responsible for 48.5% of the country's energy use, and this consumption is rising with the increases in global temperatures and urbanization. The construction industry and the products associated with products are responsible for generating around 40% of all human produced residues (Vahan, Vanderley, & Vanessa, 2001), as well as responsible for a significant amount of emissions during the entire building lifecycle. As an example, around 6% of all CO^2 emissions in Brazil comes from processes of producing cement.

So far, there are no regulations or mandatory standard to reduce the sector's impact on the environment. There is still the need to establish official guidelines for reducing lifecycle impacts, energy consumption, and stimulating reduced and renewable resource consumptions. Apart from the PBE Edifica, an optional certification related to energy efficiency as will be explained in Chapter 3, Brazil does not have any other certification when it relates to sustainable performance. The building legislation does not focus on building performance, but only determines basic standards related to items such as minimum floor area per type of space, accessibility, simple opening dimensioning, and finishing materials specification.

In light of all the difficulties and consequences from this exploratory path, Brazil has been committing to a series of quantitative and qualitative improvements in recent engagements in the Paris agreement. The country has committed to reducing greenhouse gas emissions by 37% below 2005 levels by 2025. The specific objectives to this target involve many sectors and relate to increasing the share of biofuels in the energy mix by close to 18%, improving policies and actions to reduce deforestation as well as restoring and reforesting millions of acres of land, expanding the use of renewable resources other than hydropower in the energy mix by 28 % to 33% by 2030, increase the use of non-fossil fuel domestically and achieve 10% efficiency gains in the electricity sector. In addition, Brazil proposes straightening the Low Carbon Emission Agriculture as a strategy for sustainable agriculture development, promoting new standards for clean technologies and energy efficiency in the industry sector, and improving infrastructure for public transportation in urban centers (Federative Republic of Brazil, 2016). These initiatives will need to involve all sectors currently impacting the environment. Although not directly mentioned in the report, the building sector has its significant participation percentage in greenhouse gas emissions, and both new constructions and the building stock can contribute towards the 37% target. In new buildings, considering lifecycle analysis and impacts when making decisions can prevent a large participation in these emissions. In existing buildings, the retrofit for energy efficiency can reduce the amount of energy use, and therefore scale down the associated emissions.

When addressing sustainable development, Brazil has major challenges to overcome. In one hand, the social pillar, involving problems of poverty, lack of infrastructure, and strong inequity. On the other, the effects on the environment caused by deforestation of extensive areas, poor transportation systems overstimulating individual vehicles, and buildings and constructions, consuming natural resources, generating residues and excessively using energy. The following section will explain Brazil's current energy mix and the participation of the building sector in the overconsumption of resources.

2.3. Energy Sources and Consumption

In terms of sustainable primary energy sources, despite the strong reliance on petroleum and its derivate, Brazil has been in a leading position. Approximately 43.5% of all primary energy derives from renewable sources, leaving 56.5% from non-renewable ones[6]. This still maintains the country above the world's average of 13.2% renewable energy, according to data from 2012 from the International Energy Agency. This contribution of renewable primary energy source originates primarily from hydropower and sugar cane sources.

[6] Based on data from 2014

As shown in Figure 7 (left), when it relates to primary energy sources in the country, fossil fuels play a major role in comparison to other energy sources. Petroleum and its derivates alone are responsible for 42.7% of total primary energy, with this percentage mainly associated with the transportation sector (Lucena). Sugarcane products are also significant and are associated with the transportation sector as well as the energy sector. Natural gas and coal percentages are mainly associated with their use by industries, generating electricity. As shown in Figure 7 (right), when it relates to sources that generate electricity, hydraulic power appears in a leading position, generating 65.2% of Brazil's total domestic electricity generation.

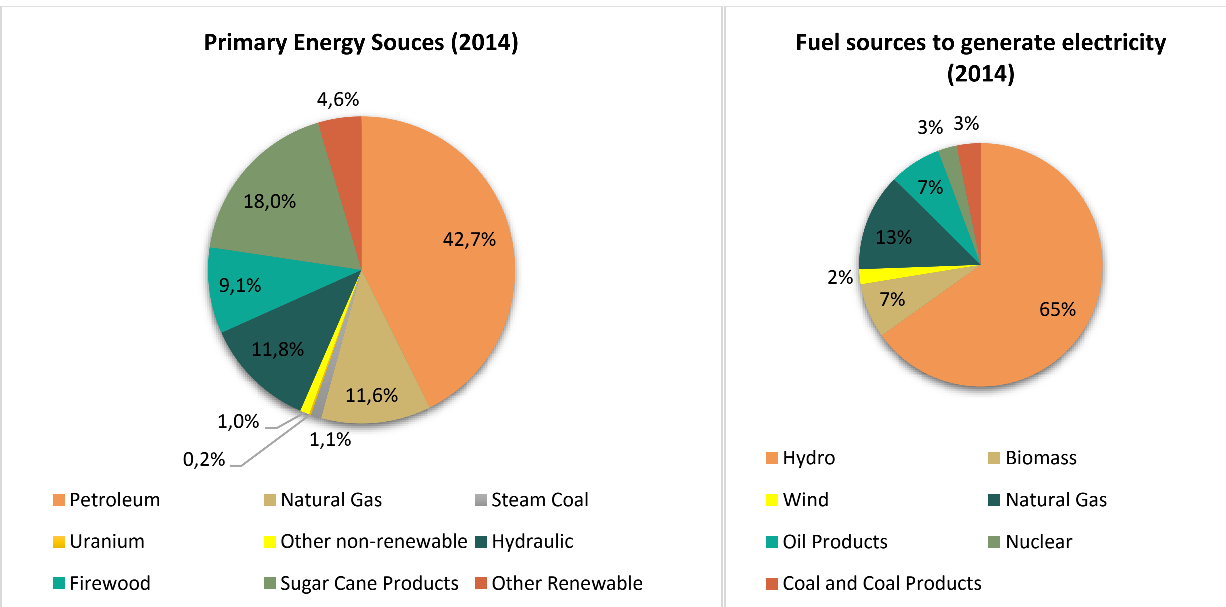

Figure 7 - Brazil's primary energy sources (left) and electricity sources (right) - From BNE 2015.

The industrial and residential sector are responsible for more than 50% of Brazil's total electricity consumption, as shown in the diagram below (Figure 8). The losses in transmission have a significant participation in the overall use, bigger than the commercial and the public sector use, representing the inefficiency of the system.

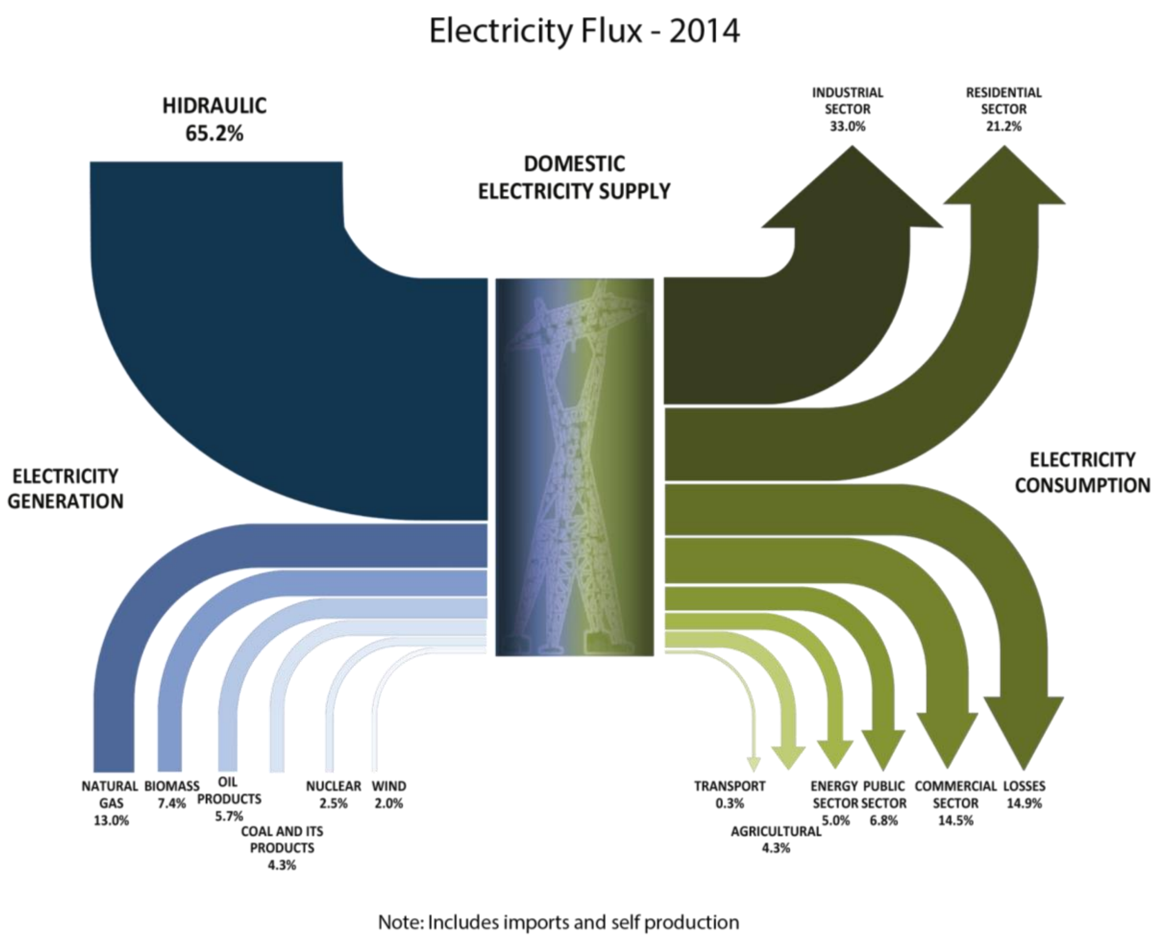

Figure 8 - Brazil's energy flow - Adapted from BEN 2015.

Despite being in a good position in terms of renewable resources use, Brazil is also increasing its energy consumption as a result of economic growth and industry developments, as well as a result of moving towards providing energy access to larger parcels of the population. In comparison to developed countries, Brazil has a significant total annual electricity consumption[7], representing therefore an urgent need for efficiency measures. The table in Appendix A represents Brazil's total electricity consumption in relation to 22 other countries in the world, and the percentage of energy consumption associated with each sector during the year of 2013 (Arnau, 2015). When compared to other countries, Brazil appears in the 8th position in relation to total electricity consumption with values larger than countries such as Spain and the United Kingdom but significantly lower than China, Canada, and the United States. When looking at the contribution from the residential sector, Brazil appears in the 15th position, with an associated

[7] Data from 2013

electricity consumption higher than countries such as China and Italy but lower than the United Kingdom, Canada, and the United States.

The elevated urbanization rate in Brazilian cities, associated with bad consumption habits, increases the demand for electricity over the years, and the infrastructure for hydroelectric power cannot expand at the same rate as the demand. As an example, between the years of 2009 and 2014, a shortage of rain associated with the increased consumption generated almost a permanent use of thermoelectric plants. This shift contributed to an increase in emission from 0.029t/MWh of CO2 in 2009 to 0.158 t/MWh in 2014 (CBCS, 2014). The tendency is that the reliance on environmental harmful energy sources will continue increasing.

Hydroelectric power is nearing its maximum potential, with the excessive energy consumption surpassing supply. The need for expanding the energy resources is leading the country towards non-renewable and carbon-intensive resources (Lucena). Apart from the large investments required for the construction of hydropower stations, Brazil no longer has viable locations for these constructions, with the remaining potential locations inserted in spaces under environmental protection or indigenous territories.

In 2001 a significant energy crisis impacted the entire country, with its causes being a direct correlation to low water levels in the hydraulic power plants and the overconsumption of electricity. Measures for reducing electric energy consumption were put in places, such as the establishment of a maximum amount of electricity use per geographic location, with the non-compliance implicating in elevated charges and energy cuts that could last as long as 3 days. The north and northeast regions were the most impacted by these measures, resulting in severe energy rationing, that changed (albeit temporarily) consumption patterns of the population. This exemplifies that even with renewable resources, with the changing climate, energy consumption patterns must be reevaluated.

The building sector in Brazil is responsible for 48.5% of total electric energy consumption and, according to a prediction from the International Energy Agency, the sector will need to reduce its consumption by 77% in order to keep global warming under 2°C. The entire life cycle of the building, from resource extraction to materials production and transportation, building construction, operation, management and building demolition consume energy intensively and must be included in the equation.

In 2001, during the energy crisis, a federal law (10.295/2001) was established to regulate maximum values of energy consumption for equipment fabricated or commercialized in the country (including household equipment such as refrigerators, televisions, air-conditioners), in an attempt of reducing energy consumption associated with equipment in buildings[8]. To address the whole building efficiency, in 2005 was established the "PBE Edifica" (PBE = Programa Brasileiro de Etiquetagem), a label that defines efficiency levels for public, residential and service buildings. Although voluntary, this is the closest step taken towards improvements of buildings energy performance that Brazil has taken. After a regulation passed in 2014, all public buildings (new and retrofit) need to achieve at least level "A" of efficiency, according to standards defined by this label. Both initiatives promoted by the government represent an initial step towards reducing electricity demands in the building sector, but are both on a voluntary basis, requiring an acknowledgment of its importance by the population.

As shown in this section, despite having clean energy sources, Brazil has an elevated consumption rate when it relates to other countries in the world, with the consumption surpassing the capacities of all renewable sources of energy. Brazil's strategic energy planning must, therefore, focus on improving the energy efficiency of all systems and sectors involved, instead of focusing on finding alternative (and pollutant) sources of energy to supply a demand that does not reduce its rhythm. The contribution of the residential sector is important and represents a sector where conscious architecture can serve in favor of reducing and preventing inefficiencies. The following chapter will describe the residential sector's current characteristics, impacts, and challenges.

[8] Called PROCEL Label – Established Levels A, B, C, D and E of efficiency.

3. Urban Residential Architecture

What currently happens in most capital cities in Brazil, Recife included, is that residential buildings are treated mostly as merchandise by the developers and do not evolve in terms of typology, increasingly compacting and reducing their areas to obtain maximum profits at lower development costs. Developing this type of residential buildings is justified by their economic viability and the fact that they fulfill the necessities of their users. In large cities, production of this type of buildings has been standardized and typified with the goal of reducing costs (Villa, 2004). Each year, thousands of this type of buildings are approved for construction: buildings without a qualitative architectural character, with small apartments and disregard for insolation patterns. The design has become more a product of marketing strategies than of architecture itself.

This vertical solution (Figure 9) for apartment buildings has emerged in the 1920s in large Brazilian cities, producing a new form of living for a developing society following living styles from the United States, the so-called “American way of life”. In the consecutive years, this apartment typology became each time more accepted by the market and started to be considered as an investment. Nowadays, tall and compact apartment buildings have become a staple of middle-income families, with a single access to the living unit, living room sized for two spaces (living and dining), kitchen, service area, service bathroom, two or three bedrooms and a bathroom.

Figure 9 - Aerial view from Recife exemplifying the vertical solution - From www.ebrasilenergia.com.br.

In 1970 developers started investing in adding common areas to buildings to compensate for the apartment's small area and fill a gap in this "urban" type of living. Most apartment buildings nowadays include common pools, playgrounds, party spaces, and small sports fields.

3.1. Typologies and Characteristics

The typologies of this type of residential building do not vary much, concentrating mostly on area and number of bedrooms. Four main typologies can be defined as:

- Zero to one bedroom apartment;
- Two to three bedroom apartment;
- Four or more bedroom apartment

The building floor plans are in direct correlation with the area available for construction, location and income family level targeted. Areas dedicated to recreational activities as well as the apartment areas are also associated with those factors, especially in relation to the family's income. The configuration of the apartment floor plan aims to maximize East exposure but is limited to the site's dimensions. The majority of urban sites have a small frontage and are longer towards the interior of the block. Therefore, the building tower configuration correlates with this available space.

The overall minimalistic aesthetics is a reflection of cost-reduction strategies. Facades are differentiated only by color pattern and by use and disposition of balconies, when possible. The following section presents examples of the different typologies currently found in Recife.

3.1.1. Zero to One Bedroom Apartment

Figure 10 - Golden Wave typical floor plan (left) and exterior 3D view (right) - From www.construtoradallas.com.br.

The typical floor shown in the figure above (Figure 10) is an example of a called "Home Service" apartment. In this type of building, services similar to ones offered at a hotel are provided, such as room service involving daily cleaning and bed changing, restaurant with breakfast, lunch and dinner menus, as well as laundry spaces and services. This type of apartment is usually for people living alone or for corporate employees. This typology shows examples of apartments with bedrooms separated from the living room only by a closet (to be installed after the apartment is purchased), and options with two bedrooms. There are no "service" areas[9] since the building administration offers this type of service.

[9] Space for washing and drying clothes

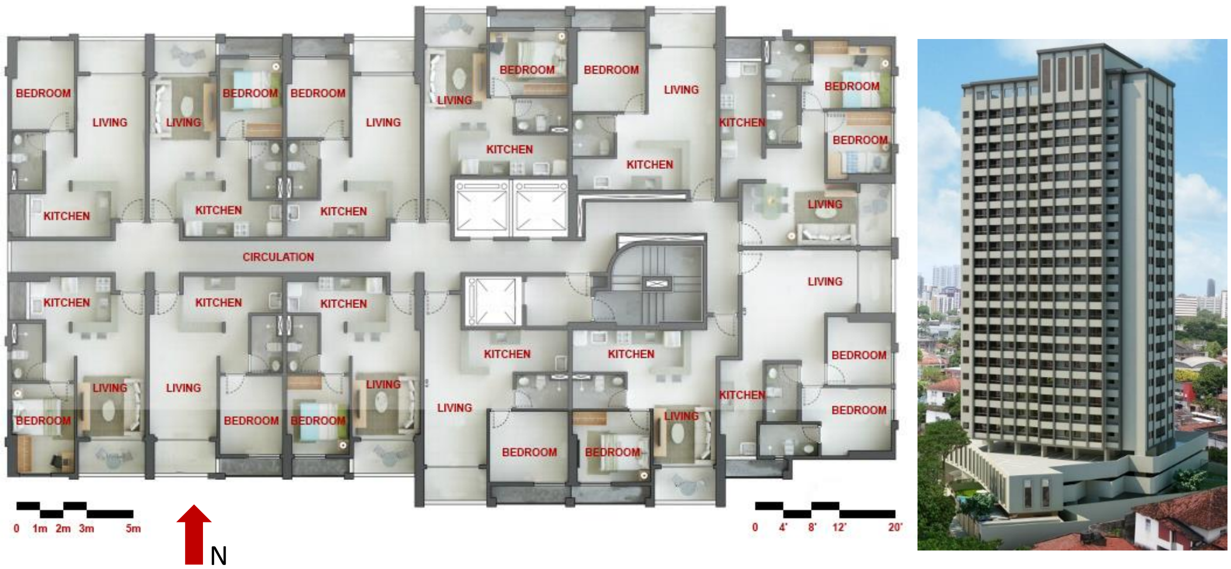

Figure 11 - Boa Vista floor plan (left) and 3D exterior view (right) - From www.construtoraconic.com.br.

In the example above (Figure 11), the apartment area is similar to the previous one, but the building's administration does not offer any services, and therefore these apartments have a dedicated laundry area for washer and dryer, next to the kitchen. Living areas have small balconies, that help to protect against direct sunlight. The distribution of apartments in the building floor plan create a situation with an apartment in both sides of a corridor, a challenge to achieve cross ventilation through the apartments.

3.1.2. Two or Three-Bedroom Apartment

Figure 12 - Torre Amélia floor plan (left) and elevation (right) - From ww.gabrielbacelar.com.br.

When the apartment increases due to the addition of extra bedrooms, floor plans start to have a lower number of units per floor, varying from four to two units. In a three-bedroom apartment, as the one exemplified in Figure 12, the third bedroom is positioned such as to be able to become a reversible space. Owners sometimes decide to open this space to the living room or transform it into a small office. This type of apartment also has a dedicated laundry space and an extra room[10] and bathroom for employees working in the apartment (cooking and cleaning). The number of apartments per floor determines price: the lower the number of apartments in a floor, the higher are their prices.

[10] sometimes used as a storage

3.1.3. Four or More Bedroom Apartment

Figure 13 - Cais da Aurora floor plan (left) and exterior view (right) - From www.construtoraconic.com.br.

Apartments with four or more bedrooms are marketed for high-income families and can have similar floor areas to a house. As shown in Figure 13, living rooms are larger and kitchens are enclosed in their own spaces since usually an employee is preparing the food. This apartment also has a full-service area similar to the one presented previously. Due to the size of the total floor plan with two apartments per floor, the majority of units are north or south faced. High-income buildings with apartments of four or more bedrooms can also have a single unit per floor, as in the following example (Figure 14).

Figure 14 - Lincoln floor plan (left) and exterior 3D view (right) - From www.rioave.com.br.

In the example above, each apartment has its own floor. This configuration benefits from cross ventilation, with winds entering through bedrooms and living space and exiting through kitchen and service areas.

In all examples, the building configuration and the façade elements evolve following the same logic of maximum simplification to lower associated cost. The building's façades are almost a direct result of the plan, without the use of elements to create shade over windows and vertical panes, or arrangements to maximize natural cross ventilation.

3.2. Construction Materials

As discussed, the development of the urban residential typology has become focused on maximizing profit and sales, balancing construction time and cost. The materials used in structural elements and finishes are in direct correlation to these objectives: the systems involve the use of well-known techniques, non-specialized workforce and materials easily available from big-chain suppliers.

The structure is made of reinforced concrete columns and beams, with interior and exterior finishes. Exterior walls are made of 9cm (3 ½") perforated ceramic blocks, finished with gypsum plaster in the interior face and ceramic tile of varying sizes in the exterior face (Figure 15).

Figure 15 - Perforated ceramic brick (left), 10cm x10cm ceramic tile (center), and 5cmx5cm ceramic tile (right).

Interior walls are usually of 9cm (3 ½") or 7cm (2 ¾") perforated ceramic, finished on both sides with gypsum plaster. In locations such as kitchen walls (where the sink is installed) and bathrooms, the interior face is finished with ceramic tiles as well. Ceramic tiles used in walls of interior spaces are larger than the ones used on the exterior, with sizes such as 33cm x 33cm (1'-1"), 33cm x 45cm (1'-1" x 1'-5 ¾"), or sizes that match joint alignment with the tile used on the floor.

Ceramic tiles are also used over the reinforced concrete floors as a finishing material, generally with tiles of 45cm x 45cm (1'-5 ¾" x 1'-5 ¾"). This material is used for its easy maintenance, ease of cleaning, and cooling capabilities. For the ceilings, the usual material is drywall, installed at about 2,65m (8'-9") from the floor and dropped to hide mechanical systems.

3.3. Hot Water and Air Conditioning Systems

The available systems for water heating are electric showers, electric tankless water heaters, electric boilers, gas-fired tankless water heaters, gas-fired water heater (gas boilers), and solar water heating (Figure 16). The majority of middle to low-income residential buildings use electric showers as source for water heating, due to its low initial cost and maintainability (easy to replace). Electric showers work by running electricity through a high resistance heating element, that releases heat and warms the water. Since the water is heated in each unit, they never run out of hot water but have a high consumption of electricity.

Figure 16 - Electric shower, electric water heater, electric boiler, gas-fired heater, and solar heater, in sequence.

In terms of usage, electric showers are followed by gas-fired tankless water heaters, installed in service areas and supplying hot water to showers in the apartment. This system is used higher by income residences since it requires central gas supply and piping distribution around the apartment. In this system, water is heated when passing through the equipment and is later distributed. The energy source is mainly Liquefied Petroleum Gas or Natural Gas when the city's infrastructure allows. This system started to be more adopted after the energy crisis in 2001 as a way of rationalizing electricity.

In relation to cooling and ventilation systems, those commonly used in residential buildings are window air conditioners (single unit) and multiple zone ductless split systems. Both require electricity to function, but the split system provides cooling and ventilation more efficiently. This system became widely used after the energy crisis of 2001 and the implementation of the PROCEL labeling. In middle-income units, the only cooled spaces are bedrooms. In an apartment of families with higher incomes, it is common to consider a cooling unit for the living room and even in enclosed balconies (ceiling mounted units). The split system outdoor unit (condenser) is commonly located close to the kitchen, in the service area, outside the apartment itself.

3.4. Energy Consumption

Residential buildings in 2014 were responsible for approximately 24% of total electric energy consumption in Brazil. Without efficiency measures, this number is likely to increase in coming years. Looking at the whole building level, a variety of aspects can influence a building's final energy consumption, as represented by the diagram below (Figure 17).

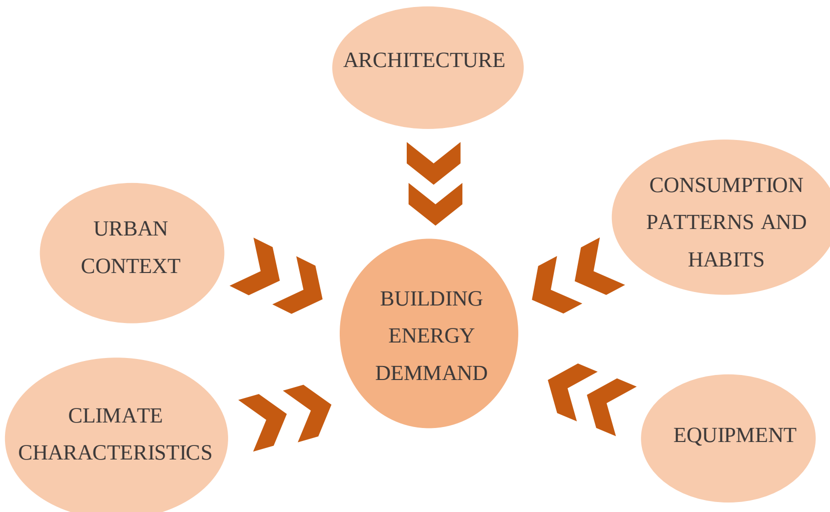

Figure 17 - Influences over a building's energy demand - Adapted from EPE.

Climate characteristics specify cooling and heating necessities based on natural conditions, and the urban context contributes creating shade and protecting the building from the sun and wind. In addition, urban contexts generate microclimates that worsen climate characteristics locally, such as heat islands. Architecture, consumption patterns, habits, and equipment are related to personal decisions, and therefore are elements possible to manipulate for better performances.

The increase in energy consumption in the residential sector is a function of the increasing population number, reduction of the number of inhabitants per household and financial improvements of families. In 2014, according to reports (CBCS, 2014), there were 63 million households in Brazil with a total consumption of 120 TWh of electricity. If things continue on the same path, it is estimated that there will be 98 million households in 2050, representing 336 TWh of electric consumption. Hydropower alone cannot expand at the same rate as consumption, requiring, therefore, a selection of efficient systems and improved building configuration to reduce this consumption.

In an apartment located in the Northeast region of Brazil, the majority of electricity use is associated with refrigerators, electric showers, and artificial lighting. As shown in Figure 18, air conditioning corresponds to 27% of the energy consumption, but with only 11.9% of housing units owning cooling systems. As income increases and global temperature rises, more and more units will start to adopt artificial cooling and for longer times in a day, increasing their share of the total electricity consumption in the residential sector.

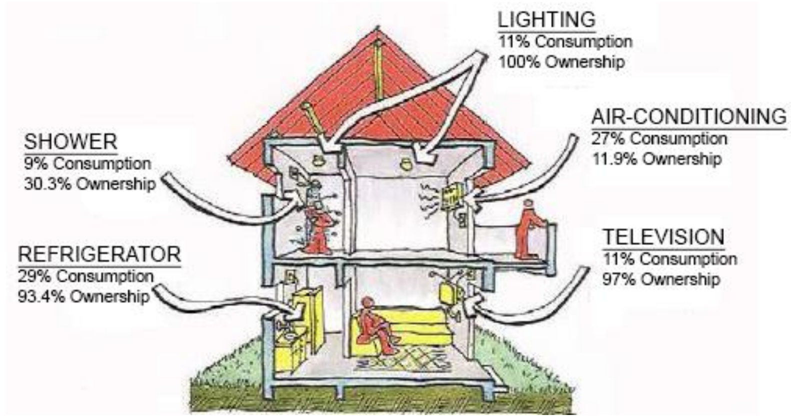

Figure 18 - End-use electric energy in apartments - Adapted from Lamberts, based on 2014 data.

In addition to harming the environment by encouraging disruptive sources of energy, high electricity consumption also increases household utility expenses. According to the EPE, the average consumption of a household in Pernambuco in 2014 was of 131KWh/month. Considering a national average price of $0.20/KWh[11], the total monthly energy cost would be $26.2, is equivalent to approximately R$87[12]. In comparison with Brazil's minimum wage of R$880 (2016), utility bills are equivalent to 10% of a minimum wage monthly income. A poll conducted by the EPE in 2014 inquired households in the Northeast region as to the weight of the energy bill on their monthly budget. Approximately 58% responded that utility costs are too high.

When compared to other countries, Brazil is amongst the ones with higher prices for electricity in the residential sector, as shown in Figure 19 bellow. Factors such as number of available resources, capital involved, workforce, efficiency in processes, market characteristics, and regulations imposed by governments affect the difference in energy prices and productions.

[11] Data from 2013
[12] Considering a conversion rate of 3.3

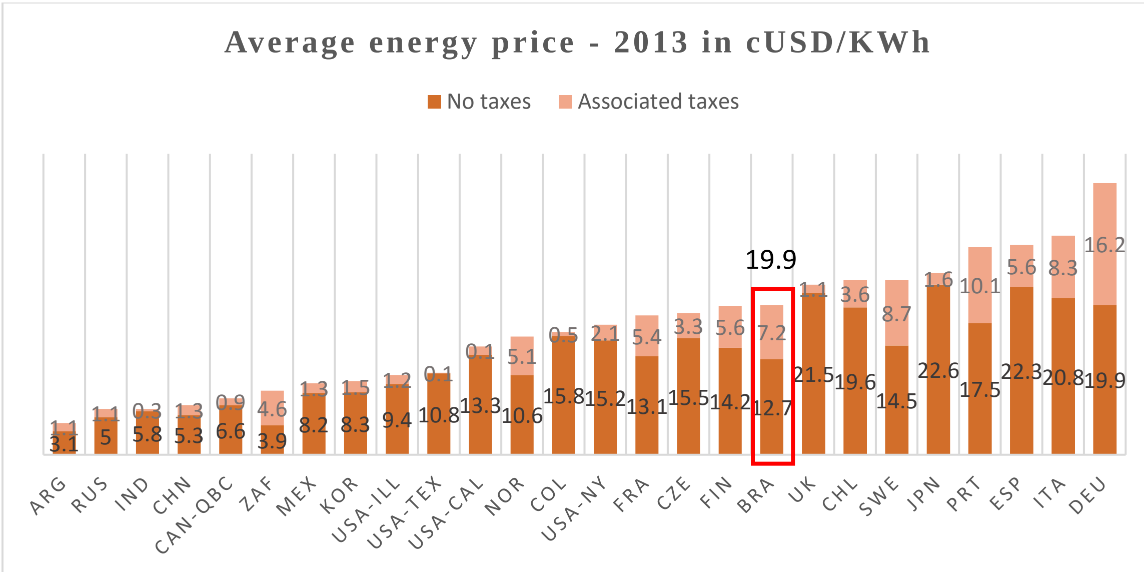

Figure 19 - Average energy prices around the world – From Arnau, 2015.

As mentioned, energy use in the residential sector consumes a significant part of the total electricity generated in Brazil. As time passes, the consumption is increasing and the options of a clean supply are reducing. At the household level, the use of mechanical systems to cools spaces is increasing and becoming a normal reaction to climate change. Actions to reduce this consumption are therefore necessary but does not exist in Brazil in relation to building and construction. The next chapter presents a brief overview of existing and applicable codes and energy standards.

3.5. Local Codes and Energy Standards

The implementation of codes and standards on energy efficiency marks a fundamental shift in approach from increasing energy production to reducing and optimizing consumption. Brazil does not have mandatory standards to improve the energy efficiency of buildings and construction, nor does it provide incentives for sustainable strategies.

Five codes and guidelines are briefly described in the next section, focusing on their energy performance related requirements. Only two codes are currently mandatory: NBR 15575, mandated at the national level, and Recife’s Building Code, at the city level. The Casa Azul, PBE

Edifica, and Acqua are standards aligned to Brazil's particular reality at the national level, but function on a voluntary basis.

3.5.1. NBR 15575

This Brazilian regulation is the first to address building performance requirements for residential buildings and became mandatory in 2014. The norm establishes performance prerequisites, criteria, and related measurement methods to regulate the performance of each system in the building. It is divided into 6 parts, each addressing one of the systems: part 1 addresses general prerequisites, part 2 prerequisites for structural systems, part 3 prerequisites for floorings, part 4 for exterior and interior walls, part 5 for roofs, and part 6 for MEP[13] systems. The evaluation criteria include mechanic, fire safety, use and operation, leak-tightness, thermal and acoustic, lighting, hygiene and air quality, functionality and accessibility, durability, maintenance, and environmental adequacy. The following paragraphs address to sections related to the building's thermal performance.

NBR 15575 uses the same division of Brazil into bioclimatic zones as norm NBR 15220[14] (Figure 20). According to the map, Recife and most of the North region and East coast are located in Zone 8.

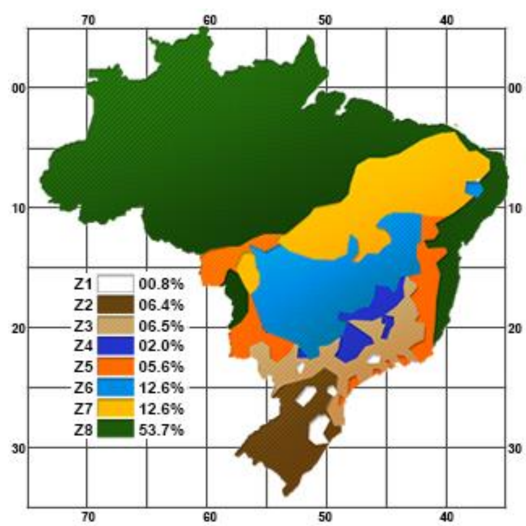

Figure 20 - Brazil's bioclimatic zones – Adapted from NBR 15575.

[13] Mechanical, electrical and plumbing.
[14] Brazilian Regulation for building thermal performance

The norm establishes three approaches for evaluating the thermal performance of a building: calculating thermal transmittance and thermal capacity of the building's envelope and comparing to the baselines established by the norm; simulating using the software Energy Plus; or through on-site measurements (real situation or prototypes). NBR 15575 recommends starting by determining U values and Thermal Capacity of the envelope first to achieve level "M" equivalent to the minimum. With simulations or on-site measurements, it is possible to achieve level "I" (intermediate) or level "S" (superior). The table below represents the baseline levels as defined by the norm.

Thermal Transmittance (U) W/m².C	
Zones 3, 4, 5, 6, 7 and 8	
α ≤ 0.6	α > 0.6
U ≤ 3.7 (0.65 Btu/hft²°F)	U ≤ 2.5 (0.44 Btu/hft²°F)
α: radiation absorbance from the outside surface	

Table 2 - Baseline values for thermal transmittance - Translated from NBR 15575.

In relation to the thermal capacity values accepted, the norm does not specify a minimal value for Zone 8, only for Zones 1 to 7, accepting any values for this measurement. NBR 15575 also establishes metrics related to roofs, but since this work considers typical apartments, the roof will not be considered a variable. Regarding ventilation, the norm defines values for situations where local building codes do not take precedence, which is not the case for Recife.

The norm also establishes maximum interior temperatures for typical summer and winter days. Table 3 shows exterior characteristics in a typical day in summer and winter, and Table 4 shows performance levels in relation to interior temperatures required by the norm.

Recife – Typical summer and winter days				
	Maximum daily temperature	Maximum daily amplitude	Solar radiation	Nebulosity
Typical summer day	31.4°C (88.52°F)	7.4°C (13.32°F)	5105 Wh/m²	0.6
Typical winter day	18.8°C (65.84°F)	6.7°C (12.06°F)	4562 Wh/m²	0.6

Table 3 - Recife’s typical summer and winter days - Translated from NBR 15575.

Performance Level	Criteria (Zone 8) Summer	
Minimum	Ti,max. ≤ Te,max.	Ti,max: maximum interior temperature Te,max: maximum exterior temperature Ti,min: minimum interior temperature Te,min: minimum exterior temperature
Intermediate	Ti,max. ≤ (Te,max. – 1°C)	
Superior	Ti,max. ≤ (Te,max. – 2°C) Ti,min. ≤ (Te,min. + 1°C)	

Table 4 - Required interior and exterior temperatures for the summer - Translated from NBR 15575.

For Zone 8, there are no requirements related to temperature during the winter. This norm represents the first step taken for establishing parameters for building performance but is not rigorous when determining minimum performances.

3.5.2. Recife's Building Code

Recife's building code was developed in 1997 and hasn't been revised since. It provides general guidelines for wall, ceiling and floor finishes, as well as foundations and roof constructions. The code defines minimum areas for each space base on the occupancy type, general accessibility parameters, sizing parameters for horizontal and vertical circulation, minimum specifications for pools, as well as opening sizes in regards to ventilation and natural lighting. The code also specifies regulations for parking (sizes and configuration of each space) and baselines for plumbing, telecommunication, fire safety, and special equipment.

The table below represents requirements for openings.

Opening requirements	
Space Type	**Fraction of floor area**
Living room	1/6
Bedroom	1/6
Kitchen	1/6
Service area	1/6
Bathroom	1/10

Table 5 - Building openings requirement.

Openings for lighting and ventilation are the only parameters related to the building envelope mentioned in this local code, evidencing the need for future revisions. Proper sizing is defined, but do not relate to building orientation nor require shading.

3.5.3. Selo Casa Azul

The Casa Azul label is the first system completely developed in Brazil, being adapted to local problems. The Labeling guidebook provides strategies for sustainability in constructions to be voluntarily adopted in projects financed by the Brazilian's national bank CAIXA. It also serves as a general sustainable guideline for other developments, but only developments financed by CAIXA can submit the documentation and receive the final label. Initial evaluation occurs upon analysis of the technical viability study for the development, followed by constant monitoring of the requirements during execution. The label is conceded at the end of construction, and there is no high cost associated with the application process.

The following table shows the requirements associated with each level of accreditation. In addition to these requirements, limitations in the final equivalent unit price are also established, especially related to the lowest level of certification. Figure 21 shows the certification labels and its variations.

Label	Minimum requirements
Bronze	Comply with mandatory criteria
Silver	Comply with mandatory criteria and other 6 criteria of their choice
Gold	Comply with mandatory criteria and other 12 criteria of their choice

Table 6 - Label requirement equivalency - From Selo Casa Azul.

Figure 21 - Available labels - From Selo Caixa Azul.

There are six main categories revolving around the label: urban quality, design and comfort, energy efficiency, resources, water, and social practices. The following paragraphs will address the guidelines that apply to this research: thermal performance, and energy efficiency.

Casa Azul defines the same bioclimatic zones as NBR 15575 when determining thermal performance and classifies Recife into Zone 8. As done by NBR 15575, the norm also defines the required maximum U-value coefficients for exterior walls.

Thermal Transmittance (U) W/m².C	
Zones 3, 4, 5, 6, 7 and 8	
α < 0.6	α ≥ 0.6
U ≤ 3.7 (0.65 Btu/hft²°F)	U ≤ 2.5 (0.44 Btu/hft²°F)
α: absorbance of radiation from the outside surface	

Table 7 - Exterior walls thermal requirements - From Selo Casa Azul.

Casa Azul is, however, stricter in that regard, requiring for a surface absorbance of 0.6 a minimum of 2.5 W/m²C of U-value instead of 3.7 W/m²C. The same guidelines for roofs also apply. As for thermal performance, Casa Azul determines guidelines for opening in the exterior walls shown in Table 8.

Minimum opening requirements for ventilation		
Living Room	**Bedroom**	**Kitchen**
≥ 20% of floor area	≥ 15% of floor area	≥ 20% of floor area

Table 8 - Opening requirements - From Selo Casa Azul.

Additionally, the norm presents a series of standard approaches to managing thermal performance for each bioclimatic zone, requiring compliance to at least one. For Zone 8 the approaches are: permanent cross ventilation in bedrooms and living rooms, shading over facades and openings, and no west-facing windows in bedrooms and living areas. Shades are mandatory when west-facing windows are considered necessary.

In relation to energy efficiency, requirements vary between mandatory and optional. Mandatory items require the use of efficient light bulbs in private areas, motion-sensitive and efficient lighting in common areas and presence of dedicated sensors for measuring gas consumption. Optional items require the use of solar water heating, gas water heating, use of efficient elevators, use of efficient household equipment, and the use of alternative sources of energy.

When it relates to energy performance, Casa Azul presents similar considerations as those found in NBR 15575. A positive aspect is the consideration of bioclimatic design strategies, that could be easily introduced into a mandatory local or national standard.

3.5.4. PBE Edifica

PBE Edifica is a part of the Brazilian Labeling Program (PBE - Programa Brasileiro de Etiquetagem) and is a conformity label whose purpose is to make it clear when a building is compliant with a set number of performance standards. It evaluates a building's energy efficiency. The label varies from A (most efficient) to E (least efficient) and can evaluate commercial, services, and public buildings, as well as multifamily buildings and common areas. Figure 22 below shows the final label conceded to the building.

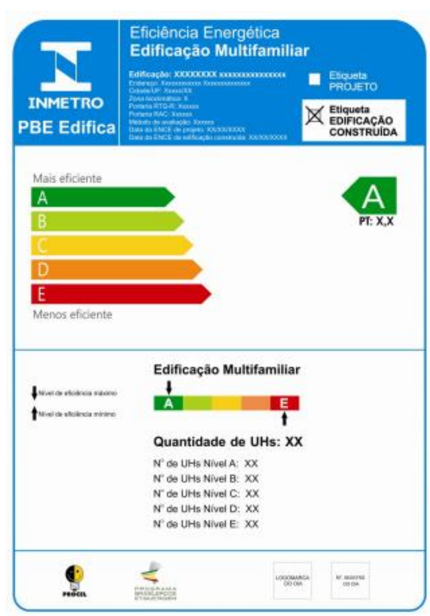

Figure 22 - Final energy efficiency label - From PBE Edifica.

The system associates points to each of its requirements and compares the total score with the efficiency levels as listed in Table 9. In the case of multifamily buildings, the total points are calculated based on the average of points received by each residential unit, divided by the total area. The prerequisites are, therefore, related to the habitational unit.

Efficiency level	Total equivalent points
A	≥ 4.5
B	≥ 3.5 and < 4.5
C	≥ 2.5 and < 3.5
D	≥ 1.5 and < 2.5
E	<1.5

Table 9 - Efficiency level and equivalent points - From PBE Edifica.

The system evaluates the building envelope and the building's water heating system giving additional points for improved performances. In relation to the building envelope, elements evaluated are thermal performance and the solar absorbance of surfaces, natural ventilation, and natural lighting, each room being evaluated individually.

Once again, requirements are specific to each of the bioclimatic zone presented in the first subtopic of this chapter, being the same as those defined by NBR 15575. Non-compliance with any requirement results in an automatic "C" rate evaluation. When it relates to openings for lighting and ventilation, PBE Edifica requires that living rooms and bedrooms have 10% of their floor areas open for ventilation.

As for cross ventilation, the norm requires that the total surface area of wind-facing openings be at least 25% greater than the total surface area of all other openings. For natural lighting, the requirement is that window area must be equal or superior to 12,5% of the floor area in bedrooms and living rooms. Failing to comply to either of those results in a 'C' level rating for the topic in question.

The evaluation of the efficiency of a building envelope is one of the most important aspects of this certification and can be calculated step-by-step as described in the specification of this norm or by means of software simulations following the base assumptions determined by the manual. In the calculation method, the score for each individual space is calculated separately and the final average is then computed for the entire unit. The following factors are considered for naturally ventilated buildings or for conditioned areas: area, orientation, ventilation coefficient and thermal transmittance of windows, exterior walls and roofs; total floor area; room height and volume. For the simulation method, the norm requires the simulation of the spaces when naturally ventilated and when artificially conditioned, and defines predefined elements to be used as standards in the software, such as occupancy patterns, lighting schedule, equipment loads and soil temperatures.

In relation to the water heating system, the certification evaluates solar water heating, gas heating, heat pumps, electric heating and oil-fired boilers. Procedures for calculating the efficiency of each system are described in the manual, and in most cases the equipment used must have the PROCEL label for efficiency.

Overall, the standards established in this labeling process are the only ones related directly to the building’s energy performance and involve a comprehensive analysis of building envelopes. Attention to the evaluated elements in this norm can improve the building’s thermal performance.

3.5.5. Aqua – High Environmental Quality (Alta Qualidade Ambiental)

This certification resulted from a collaboration between the University of São Paulo and a French corporation that certifies the quality of housings. It is based on French parameters but adapted to the Brazilian situation.

Similarly to a LEED[15] system, the Aqua certification evaluates major categories related to a building's environmental quality:

- Site and construction: a building's relationship with the context, integrative selection of products and systems, low impact during construction.
- Management: energy management, water management, residues and building's operations, building maintenance.
- Comfort: thermal comfort, acoustic comfort, visual comfort, smells.
- Quality: sanitation, air quality, and water quality.

[15] Leadership in Energy and Environmental Design

Each subtopic in a category is evaluated according to three levels: good, corresponding to the minimum acceptable level; superior, corresponding to good practices; and excellent, corresponding to maximum performance. Certification is given when a development achieves a minimum of 3 excellent ratings and a maximum of 7 good ratings. The following paragraphs will focus on the recommendations regarding thermal performance, natural ventilation and energy efficiency.

Category 4 addresses to energy management, with the following recommendations:

- 4.1 - Reduction of energy consumption through building design, by complying with the maximum U-values dictated by norm NBR 15575 or with levels A, B or C for building envelope performance in the PBE Label.
- 4.3 - Reduce energy consumption of air conditioning, ventilation, and exhaustion systems by using equipment with PROCEL label for efficiency.

Category 8 treats of thermal comfort, and the following topics are recommended:

- 8.2 - Provide thermal comfort during summer, by complying with thermal transmittance values for exterior walls, as values established in NBR 15575 and controlling heat gains from windows located in North, East and West facades, using Solar Factor $\leq$ 0.45.
- 8.3 – Provide thermal comfort during winter by complying with the interior temperatures established for the bioclimatic zone 8, following requirements in NBR 15575.

The additional requirement below is specified for ventilation:

- 13.1 - Provide efficient ventilation by using openings with an area equivalent to 10% or more of a spaces’ floor area and ventilation or strategies related to pressure differences.

When comparing the five standards described in this session it is possible to identify PBE Edifica as having stricter and comprehensive analysis of the building envelope. Casa Azul, Aqua and NBR 15575 all relate to the same simple thermal performances, and Recife’s building code do not address to thermal properties at all. Brazil lacks therefore of energy efficiency codes to regulate buildings and constructions.

3.6. Challenges

Recife's urban residential typology has become a result of market strategies instead of architectural expressions and has a fairly well-established and unchanging process that optimizes speed, price and construction techniques. However, consumption patterns are changing, with a reliance more and more on artificial air conditioning systems. In association, climate change is increasing global temperatures each year worsening external conditions, and the increase in urbanization produces an escalation on heat island effects. Residential buildings are not responding to those changes, and this typology is continuously being repeated.

Concepts of climate responsive architecture are not a priority and the lack of mandatory energy conservation measures is not contributing to guiding decision-makers towards a sustainable path for residential architecture. Any factor that deviates from the existing process and template is seen as an extra cost added to the development instead of a benefit to the typology. The challenge for architects is proving the benefits that can be aggregated when using a different approach to this urban residential typology, an approach that is conscious of climate conditions and considers the entire lifecycle of the building, improving its overall performance.

This scenario proves the necessity of two urgent actions. First is implementing building policies that establish parameters to measure building performance as well as provide economic incentives for retrofitting the existing building stock. The second is the investment in training and conferences to educate professionals and decision makers in the construction business on the urgency of adopting sustainable solutions and the paybacks associated with those solutions.

4. Climate-Responsive Architecture

Despite the lack of regulations, the ever-changing nature of cities has lead renowned Brazilian architects in the last century to develop a new bioclimatic architectural paradigm in which local climate and natural conditions play a major role. This can be clearly seen in the projects developed by Lucio Costa during the modernist period in Brazil, between the years of 1930 and 1960. Lucio highlighted the importance of understanding local climate conditions and solar positions when designing and used multiple shading features such as brise-soleil (overhangs and side fins) and “cobogó” (Figure 23) as a response to Brazil’s hot climate.

Figure 23 - Brise-soleil at the Ministry of Education and Heath (Lucio Costa)(left) and cobogós at the Bristol Building (Lucio Costa)(right) - From www.archdaily.com.br and www.arquiteturaetc.worldpress.com.

Unfortunately, these principles were not carried through to the regular multifamily housing market during the rapid urbanization process of cities in Brazil, as discussed in the previous chapter. Market and profit started to predominate in the typical residential buildings, and important characteristics such as comfort associated with energy efficiency were set aside, with developers making a business out of the housing deficit in urban centers, constructing and selling condensed and stacked apartment buildings that rely on artificial solutions.

It is necessary to return to concepts of bioclimatic architecture developed by modernist architects in order to provide better comfort levels to the users using the least amount of energy. This chapter provides a brief explanation of fundamental strategies for the development of a climate-responsive architecture, focused on strategies for Recife’s hot and humid climate.

The psychometric chart shown in Figure 24 is a graphical representation of weather data in the region, superimposed with limits of comfort, and provides information on adequate passive strategies. The percentages indicate the number of comfortable hours reached by a specific approach. The chart below (Figure 24) represents conditions in Recife, extracted from the Climate Consultant 6.0 software, designed by the UCLA Energy Design Tools Group.

The chart is reflecting parameters of comfort established by ASHRAE Standard 55, indicated in blue, and parameters of comfort considering the ASHRAE Standard adapted to a situation with natural ventilation, indicated in green. According to the data presented, without considerations of natural ventilation a person would only feel comfortable during 2 hours of a year in an enclosed space in Recife. Ventilation strategies have therefore a significant impact, responsible for providing 60.8% of comfort hours, and must be considered in all situations. Sun shading of windows and dehumidification also appear as fundamental strategies to reach improved comfort. In general, the necessary strategies focus on cooling, preventing heat gains, and facilitating dehumidification.

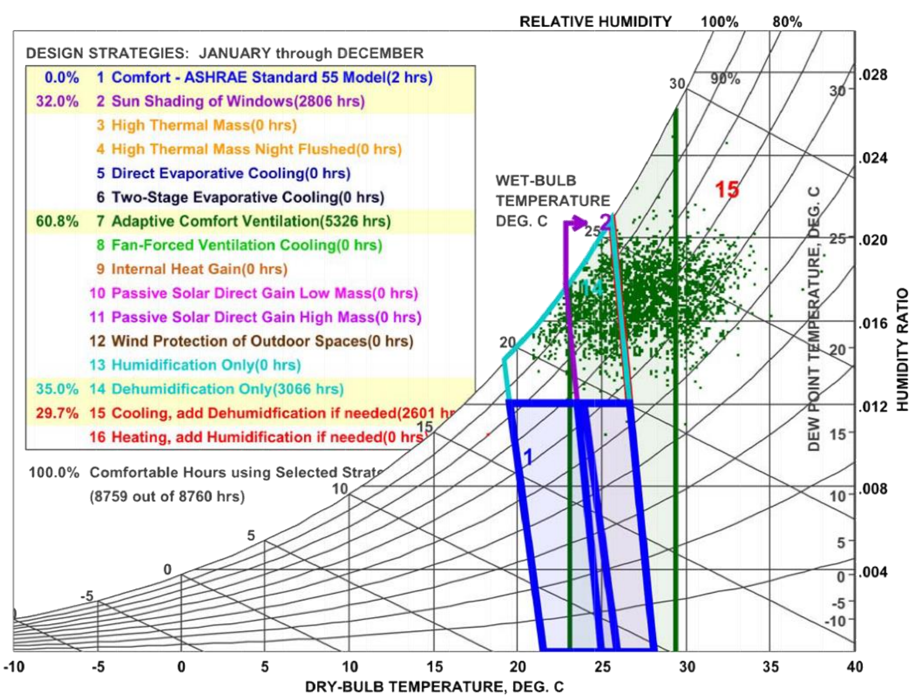

Figure 24 - Recife's Psychometric chart - From Climate Consultant 6.0.

Despite efforts involving window shading and natural ventilation, the psychometric chart indicates that 29.7% of hours will most likely still require the use of active cooling systems. In response to these elements, the following design strategies are suggested by Climate Consultant to minimize the climate's negative impact, and to take advantage of natural elements:

- Use doors with louvers and screens, ceiling fans and design for cross ventilation.
- Use of window overhangs or operable sunshades.
- Use plant materials to minimize heat gain.
- Prevent or eliminate west-facing glazing.
- Use of high performance glazing.
- Reduce the building's contact with the ground, to minimize dampness and maximize ventilation underneath.
- Design long narrow building floorplan to maximize cross ventilation.
- Produce stack ventilation, maximizing vertical height between the air inlet and outlet.
- Use of light colors in building materials and roofs to minimize conducted heat gain.

In tropical regions, it is a challenge to provide thermal comfort without depending on active solutions such as air conditioning to combat the excessive heat, characteristic of the location. These guidelines are not recent and were understood as fundamental by architects even before 1950 when climate change was not a prevailing topic.

Armando de Holanda graduated in 1964 with a bachelor degree in architecture in Recife and understood problems and potentialities of the interaction between climate and architecture in the Northeast. In 1976, the architect published with the Federal University of Pernambuco (UFPE) a book entitled "A guide to building in the Northeast" (Roteiro para Construir no Nordeste (Holanda, 1976)), which consisted on a gathering of his classes contents and experience as an architect, with valuable concepts for designing in the Northeast. The combination of his concepts with the ones explored by Johan van Lengen in his book "The Barefoot Architect" (Van Legen, 2004) are described in the next topics, reinforcing strategies proposed by the software, as a base for conscious architecture adapted to Recife's climate and location.

4.1. Shading

In a hot and humid climate, one of the most important concepts involves protecting windows and walls from the sun. It is important to use terraces, balconies, pergolas to promote to allow sunlight to enter without the excessive heat gain. The use of large overhangs, trees, and another vegetation to protect from the sun incidence in walls is also recommended, to protect from excessive heat, rain, and humidity. The use of balconies and terraces around the house is an effective way to create shades.

Figure 25 - Shading - From Holanda, 1976.

4.2. Windows and Door Protection

It is important to study sun paths and insolation patterns to design a proper window shade for each location and situation. Glass allows light to pass but also a large amount of heat, that is transferred to the interior spaces. Creating shades with correct dimensions and positions will reduce the heat transmitted through these transparent elements. It is also recommended the use of protections that allow the air to circulate and light to penetrate into the spaces even raining, promoting both heat reduction from direct sunlight and allowing winds to flow through at all times.

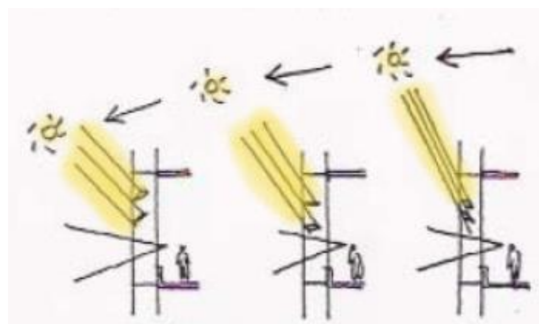

Figure 26 - Window shades - From Holanda, 1976.

Protecting doors can provide benefits as well, allowing them to be kept open to allow winds to continuously pass through.

4.3. Ventilation

Wind circulation through spaces is essential to reduce body temperatures and improve comfort conditions. It is recommended that to circulate the wind effectively, the exit opening is equal or larger that the entry opening. It is recommended as well to create fluid spaces, using lower walls and communicating areas between floors, to allow ventilation throughout the entire building both horizontally and vertically.

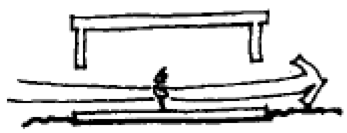

Figure 27 - Cross ventilation - From Van Legen 2004.

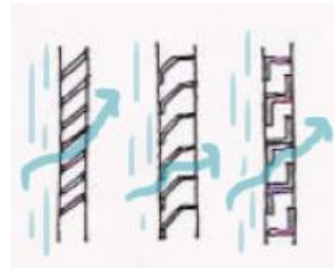

Figure 28 - Cobogó and rain - From Holanda 1976.

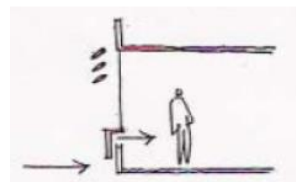

Figure 29 - Ventilated Sills - from Holanda 1976

The use of permeable walls is also beneficial, with the use of elements such as "cobogós", that allow light and winds to pass through (Figure 28). It is a simple, resistant and economic material, easy to repeat and reproduce. It is adequate to Recife’s climate conditions and contributes as a northeastern aesthetic element. Ventilated window sills (Figure 29) are also elements that allow ventilation through, entering spaces while blocking the rain.

4.4. Humidity Protection

In locations with high humidity levels, it is recommended to elevate floors from the soil, to prevent humidity inside the building, from ruining walls and creating mold. Sloped roofs are important as well to make water run faster and away from the building, in addition to lowering the amount of heat absorbed by the roof, since reduces perpendicular surfaces from the direct sun incidence.

All the presented elements provide passive solutions to achieve comforts in interior spaces in the Northeast region and Recife, and when considered during schematic design, contribute to an efficient and comfortable building. Adoption of these strategies reduce the amount of active cooling systems used with the building’s operation and are urgently needed to the design process of condensed apartment buildings of current Brazilian urban centers.

When considering the existing building stock, these design strategies must be revisited and adapted to provide viable possibilities in building retrofits. The following chapter provides existing examples and possibilities of strategies applied when adapting an existing building.

5. Retrofit Strategies

As previously explained, urban centers are expanding increasingly, and new constructions have the potential to integrate sustainable elements that might have been previously disregarded. Rating systems are being developed and constantly improved to help guide new constructions. All this can and is being implemented in newly constructed buildings or in future developments. However, these options are not all available for the existing building stock. They require a level of adaptation to stop contributing negatively to the environment.

Retrofitting a building has many advantages that go beyond preventing a demolition and its associated impacts to the environment. Retrofitting constructions can be performed while the building is still functioning, without impacting in the building's activities. In addition, renovations have lower costs in comparison to whole building demolitions and new constructions, many times taking advantaged of pre-existing elements that when restored have the potential to contribute to the efficiency. Existing buildings have also the advantage of being inserted in an existing and functioning infrastructure involving transportation and services.

Going back to the elements that impact in the buildings' energy demand, climate characteristics, urban context, architecture, consumption patterns and habits and equipment, not all can be modified when considering existing buildings. Urban context and climate characteristics cannot be altered during a process of retrofitting, neither building orientation and geometry. The figure bellow represents possible modification options for a retrofitting case, with opportunities that focus on strategies related to reducing the energy use in a hot and humid climate. When talking about improving any systems, it is important to address two factors listed in the figure bellow: in a first moment, improve the efficiency of the system reducing the demand, and in a second moment, arrange alternative sources to add to the efficiency.

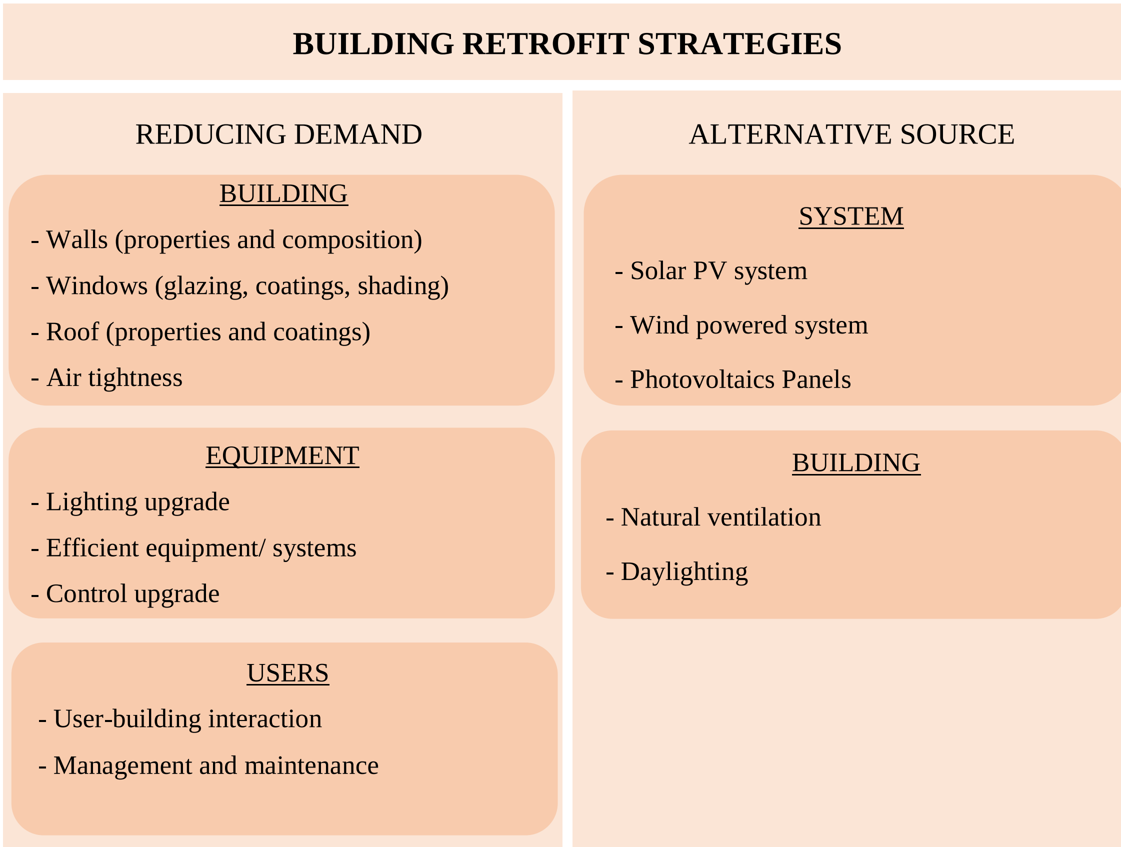

Figure 28 - Retrofit strategies - Adapted from EPE.

As shown above, there are five categories that can influence in building energy consumption, varying from demand reduction to providing alternative sources of energy. The combination and integration of all elements represent the maximum potential for improvements, and when designing, thinking about all systems as integrated is fundamental. Each category impacts in the energy use in different aspects: strategies that target reducing heat gains from the exterior to the interior, strategies that directly reduce the electricity used, and strategies that provide alternative sources of electricity.

Strategies that fall into the reducing heat gains category relate to the building itself: reduce demand by changing walls, windows, roofs, air tightness, lighting upgrade, and providing natural ventilation as an alternative source. Modifying these factors implicates in lowering cooling loads necessities and therefore reducing the use of air-conditioning systems. Lighting upgrade can implicate in electricity reduction as well when targeting changes in the fixtures.

A study conducted in Hong Kong simulated a 25 story residential building with eight units per floor, typical of local dense residential buildings, to identify heat gain components in the building. The research shows that heat gains through windows are responsible for 45% of the building cooling load, and external wall conduction represents 24%. As shown in Figure 29, 70% of the air conditioning electricity consumption is used to remove heat gain through the building envelope (Lam, 2000). During summer, Hong Kong's climate is considered tropical, hot and humid with occasional showers or thunderstorms. Afternoon temperatures frequently exceed 32°C (90°F) with a mean temperature around 27-29°C (80-84°F). This season in Hong Kong presents similarities with Recife's annual climate conditions validating, therefore, a comparison.

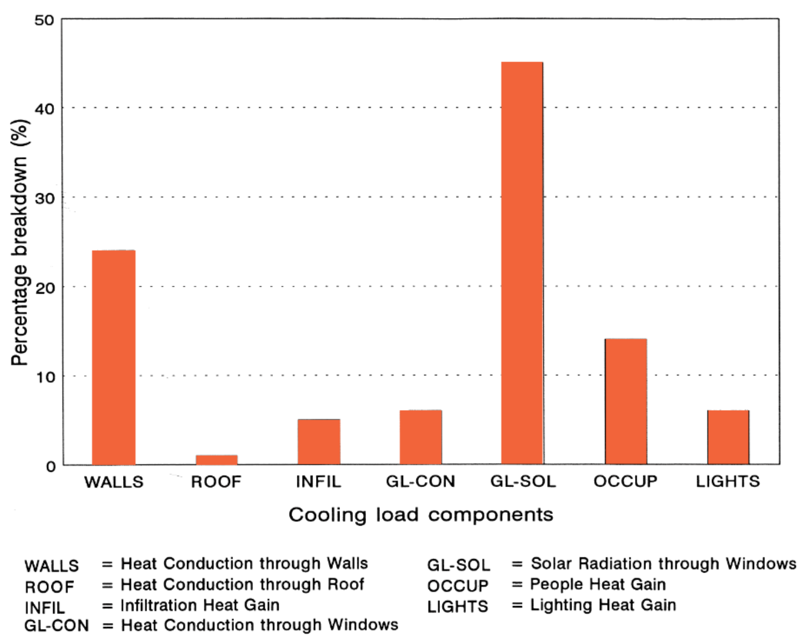

Figure 29 - Participation of building components in cooling loads - From Lam, 2000

The figure above represents the importance of studying building envelope elements to address alternatives for building retrofitting, especially when adapting to reduce heat gains and improve cooling performance. Another research (Cheung, Fuller, & Luther, 2005), also conducted on an existing building in Hong Kong, investigated the effects of wall insulation, glazing types, the color of external walls, window size and external shading on the energy efficiency of buildings. The results showed that up to 40% of annual required cooling energy could be saved with a combination of these strategies. This reinforces the sensitivity and opportunity provided by parameters associated with the building envelope.

In terms of natural ventilation, the same apartment complex in Hong Kong was studied, and results showed that at least 24% of the air-conditioning use was able to be substituted by natural ventilation (Lun & Yik, 2009). This represents a significant element to be considered in a building design strategy and in a building retrofit when the climate characteristics cooperate.

Strategies that fall into the reducing electricity use category are equipment and systems related. Reducing electricity use by replacing light bulbs and light fixtures by more efficient ones (same or better performance, using less electricity), or using certified household equipment such as refrigerators and televisions are examples of this strategy. Providing better controls such as installing lighting sensors integrated with daylight sensors can also generate a significant reduction. When it relates to user aspects, the demand may be reduced by improving maintenance of systems and the user's interaction with the building.

Alternate sources in this category focus on providing another system to substitute the source of energy (such as using solar panel as a source for water heating) or to provide electricity through a sustainable source, such as the case of photovoltaic panels supplying electricity from captured solar radiation, or the case of wind turbines, converting wind power into electricity. Daylighting strategies involve, in a similar sense, utilizing the sun's light to substitute, when possible, the artificial lighting.

As presented, many are the routes when improving the energy consumption of a residential building. Based on the data, building envelope is one of the major impacting elements on this consumption. Preventing heat gains will prevent the excessive use of air conditioning, reducing therefore significantly the energy consumption and improving the users' comfort using passive strategies. Going back to the climate responsive strategies associated to tropical hot and humid climates, the building envelope has the potential to provide additional shading, protect windows from solar gains, protect materials from excessive humidity, as well as contribute with natural ventilation, addressing therefore to key elements associated with this type of climate.

For this reason, the selection of strategies focuses on reducing energy consumption with attention to cooling. The most sensitive strategies focus on the building envelope, presented as opaque and transparent elements in relation to the demand side, and natural ventilation in relation to the alternate source side.

5.1. Opaque Elements

Three thermal effects can be associated to opaque elements: absorbance of the material related to its color (the lighter the material, the less absorbent it is), heat conduction associated to the thermal conductivity of the material itself or layered materials (U value of the components and composition), and heat exchanges with interior spaces (Lamberts, 1997). The difference from exterior and interior temperatures provides a heat flow from hottest to coldest. In Recife, this heat flow occurs from exterior to interior spaces.

The thermal influence of materials and their composition is fundamental for gaining or preventing heat gain from solar radiation. The addition of thermal insulation materials as well as adding other materials to the wall's layers can decrease the thermal transmittance of a wall (Magrini, 2014). Therefore, when considering retrofitting opaque surfaces for hot climates, two main strategies are identified:

a. Adding wall insulation to the existing exterior wall;
b. Changing the façade's composition entirely.

The three main solutions when considering building insulation involve adding internal material, exterior material or adding an air layer to the composition. All three options carry advantages and disadvantages. External insulation is the most effective but also the most expensive (Magrini, 2014), and can only be applied when the building has a façade free of ornaments. The cost associated with this option might be worth if another façade treatment is applied simultaneously, justifying the expenses with equipment. Applying insulation externally contributes to reducing the impact of thermal bridges (Brito, 2010), points in the building envelope where the thermal transmittance is higher in comparison to other exterior walls. This occurs in locations such as columns and beams (Figure 30), and using insulation in the exterior would protect these points.

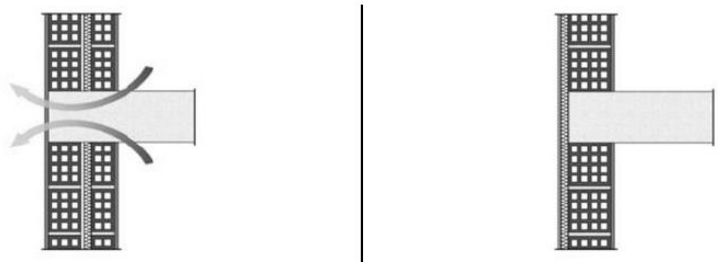

Figure 30 - Thermal bridges without external insulation (left) and with external insulation (right) - From Brito, 2010.

Applying interior insulation is easier in a retrofit situation, since it does not require large equipment such as scaffolders, but it is not efficient when compared to exterior insulation. Interior insulations also have the additional negative aspect of reducing the area of interior spaces. In relation to insulation types, the common material used are extruded polystyrene, expanded polystyrene, and mineral wool.

A computer simulation was performed by a research in a 42 story multifamily building located in Hong Kong (latitude 22° 18'N and longitude 114° 10'E) to study the impacts in consumption of different envelope strategies applied to the building. The apartments in the studied building present similarities to the ones studied in this research, with three bedroom flats with areas of 70m² (753 sf) and two bedroom flats with 60m² (646 sf) (Cheung, Fuller, & Luther, 2005). The study tested different widths of extruded polystyrene insulation in external walls, applying on the exterior face as well as the interior face of the wall. The results showed a reduction of 29.2% in the peak cooling load, with the application of a thick 100mm (4”) insulation placed on the exterior surface. In addition, increasing the thermal capacity of the external wall as a whole also proved to be beneficial to the reduction of annual cooling loads. This option presented the highest contributions in comparison to other alternatives tested.

It is important to note that when increasing the insulation on the exterior walls, internal heat gains and solar gains from transparent surfaces must be controlled in order to avoid internal overheating, as presented in a study developed in residential buildings in Portugal (Chvatal & Corvacho, 2009). The association with constant ventilation is important to avoid internal overheating.

A solution that has been investigated and applied in Brazil in recent years and that combines the advantages of thermal insulation and ventilation, are the ventilated facades. This system involves an exterior finish applied to a backup wall using a secondary structure. A space of at least one inch is left between the finish material and the backup wall, allowing the air to flow throughout the space by natural convection. This solution presents many advantages, such as improving the thermal resistance of the wall's exterior surface, protecting the backup wall from direct solar radiation and serving as a cooling mechanism as well. It also has a good acoustic performance, and is easy to maintain, since a single unit of tile can be replaced instead of a large section of the finishing material. This system has the added advantage of having the possibility of being installed over an existing exterior wall, without the necessity of removing the existing finishing material.

Ventilated facades can also contribute with the aesthetics of the building’s façade since its modularity and variety in terms of finishes allow the creation of many facade compositions. The finishing tiles can be in metal panels (steel, copper or aluminum), ceramic tiles, laminated panels, thin concrete tiles (special concrete, where the water and cement are substituted by a polymer), and cement tiles (Gelinski, 2015).

A study analyzing the effectiveness of a ventilated façade by in site measurements and by computer modeling show that with carefully designed ventilated façades, the energy savings with cooling in summer months can exceed 40% (Ciampi, Leccese, & Tuoni, 2003).

Based on the validity and potential for improvement shown by the studies presented, the use of a ventilated façade with an insulation layer is tested as an alternative for retrofit in the baseline building of this research. The insulation combined with the chimney effect ventilating the air space proved to be an effective combination for hot and humid climates.

5.2. Transparent Elements

Transparent elements are translucent or clear openings that present an added characteristic when compared to opaque surfaces: aside to conducting heat, they allow solar radiation to penetrate interior spaces. Therefore, their specifications must involve three main aspects, that impact on energy efficiency and comfort: heat flow control, protection from solar radiation, and visual connection to the outside with a satisfactory level of natural light (Magrini, 2014).

Windows are the main elements in transparent structures, and replacing it can be the most effective strategy in retrofitting cases, representing the option with most efficient cost/performance ratio (Magrini, 2014). This retrofit can be as simple as replacing the windows with new ones leaving the existing frame. Opening orientation, opening size, composition of the window (a type of glass, type of frame, number of layers and space between the layers), and the use of exterior shadings, are elements that impact in transparent surfaces' performance. Therefore, the following options are available for retrofitting cases:

a. Changing Glass/window properties and framing material
b. Adding shading elements
c. Changing sizes
d. Changing positioning

When addressing window properties, three elements define their thermal behavior: the glass panes, the frame (fixed or operable) and the space between panes (multi-glazed windows). The permutation of these elements can create a window with a high transmission coefficient (clear single pane) or a low transmission coefficient (multi-pane systems with coatings and gasses). The frame has its share in the overall performance of the windows, and can be of wood, aluminum or metal with thermal break, PVC or other mixed material. A Mixed solution, such as aluminum in the exterior and wood in the interior also has a good performance, proven to be better than aluminum with thermal break frames (Magrini, 2014).

In relation to glass panes, the variations involve the properties of glass, coatings, and number of glass panes used in the window composition. In relation to the number of window panes, the most common variations involve single pane (single glass pane), double pane (two glass panes) or triple pane (three glass panes), with the thermal resistance increasing in the same order. In terms of types of glass and coatings, the most cited options are:

- *Clear simple glazing*: good for visibility, but highly transmissible of solar radiation. Since the glass is opaque to short wavelengths (ultraviolet), the heat trapped inside causes the interior space to overheat.
- *Tinted glazing*: slightly pigmented glass to reduce transmission of short wavelengths (ultraviolet), and specified for maximum absorption at part of the solar spectrum. The low transmission reduces the amount of daylight through the material. Research shows that

tinted glasses can reduce the thermal loads by 22.4% when compared to clear glasses[16] (Chow, Li, & Lin, 2009).

- *Reflective glazing*: receives coating of thin metallic or metal oxide layers that increase the reflectivity of the glass surface, similarly to a mirror. It can be specific to reflect short wavelengths, long wavelengths or both. The same research shows 44.9% reduction in heat gains when compared to clear glass, and 38.2% reductions when compared to tinted glass. When used excessively, its sun mirror effect may affect nearby buildings or cause disturbances on traffic.
- *Low-emissivity*: reduce emissivity over long wavelengths. The coatings available have a range of solar characteristics. For applications aiming to reduce solar gain, it is recommended to place the coating over the interior face of the window's outer layer. The same cited research shows a reduction of 48% in thermal loads after applying the low emissivity coating.
- *Smart windows*: the use of chromogenic technologies allow the glass to tint in response to external factors. Examples include glasses that change with electrical voltage or charge (electrochromic), glasses that respond to temperature (thermochromic), and glasses that respond to UV light (photochromic).
- *Photovoltaic glazing*: solar cells are laminated in clear glass panes. It provides both sun shading and electricity generation but aggregates an elevated cost. The same research shows it has the potential of reducing 52% of heat gains while simultaneously generating electricity.

In relation to the cost associated with each type of glass, the price increases following complexity of each composition. Low-emissivity coatings have relatively high production costs but appear as an effective solution. Smart window and photovoltaic glazing are still in the process of development, requiring a high upfront cost, are not efficient enough to overcome associated costs.

As mentioned, the space between panes in case of multi-glazed systems also contributes to reducing heat gains in the interior spaces when filled with air, gasses or other materials. The air cavity increases the window insulation significantly when compared to a single glazed unit, and

[16] The overall performance of the window depends on the frame as well

the use of two or three cavities contributes even more with the window's thermal properties, despite not recommended for cooling prevailing climates.

The same research cited in section 5.1, with a building located in Hong Kong (Cheung, Fuller, & Luther, 2005), shows that the combination of proper window types and coatings can represent a reduction in 4.6% of the building's annual cooling loads and reduce the cooling peak demand in 5.4%. These contributions are smaller when compared to the opaque solutions, but when combined, have the potential to provide an important contribution.

Shading elements, as discussed in the Climate Responsive Architecture section of this research, are essential when designing for hot climates. As shown in a research conducted analyzing the impact of four types of window protections[17], solar shading is an essential design feature to avoid overheating inside the building and thus decrease artificial cooling necessities (David, Donn, & Lenoir, 2011). By local measurements and computer simulations, the research demonstrated that the annual cooling energy is almost proportional to the solar shading coefficient (the lower the solar shading coefficient, the lower the annual cooling energy). The effect of solar shading in interior lighting loads was studied as well, the results showing that the increase in lighting loads was not significant in comparison to the reduction of cooling loads. Cooling energy demand was proven to be 20 times higher than the energy consumption of lights.

Window sizes and positioning have a direct impact on heat gains and interior temperature. The increase of window to wall ratio on one hand increment indoor air velocity, but on the other absorbs solar radiation increasing heat gains (Hien & Liping, 2007). The larger the glazing surface, the larger the amount of solar radiation absorbed by the transparent material. In terms of positioning, the orientation of each glazing plays a major role in defining the amount of heat transferred since it defines the amount of solar radiation heating the surface. A glazing positioned in a façade receiving large amounts of insolation will contribute immensely to heat gains into the interior spaces.

Based on the references and results cited, changing window properties associated to window shading solutions have the potential to significantly benefit the building's energy performance. These options can also represent the least amount of work and the least expensive

[17] Simple overhang, overhang with infinite width, simple overhang with rectangular side fins and simple overhang with triangular side fins.

investment in the specific case of a retrofit. Changing window positioning and sizes, when considered in the specific situation of the baseline building selected, although being very effective in preventing heat gains, are difficult to be performed. The apartments are compact and almost all spaces require opening, leaving no wall to be altered. For these reasons, one of the study cases focuses on improving widow performance by changing its characteristics and by providing shading solutions.

5.3. Natural Ventilation

Natural ventilation in buildings is associated with indoor air quality control, and to thermal comfort. When bringing outside air into interior spaces, natural ventilation dilutes indoor air pollution concentration, if the air is unpolluted. In addition, the air flow in higher velocities will increase the evaporation rate of the skin, enhancing the cooling sensation, as well as reduce or prevent internal heat gains, managing interior temperatures. An interior air speed of 0.8m/s (1.8mph) allow the interior temperature to be 2°C warmer (at 60% relative humidity) and still maintain optimal comfort (Allard, 1998).

Wind distributions occur due to pressures that result from the interaction of wind directions and building elements (wind-driven ventilation) or as a result of temperature differences (buoyancy-driven ventilation), the second happening in the vertical direction (stack ventilation). These elements can also be combined for best efficiency when natural climate conditions allow. In relation to wind-driven ventilation, the following situations are commonly found in isolated spaces, where the only significant openings are direct to the exterior:

- Cross ventilation
- Single-sided ventilation

Cross ventilations approaches involve the strategic positioning and dimensioning of openings to increase ventilation by providing a way in (inlet) and a way out (outlet) through different walls, allowing the wind to circulate from areas with positive pressure to negative pressure. Single-sided ventilation occurs when inlet and outlet are located on the same wall, and require a larger effort to increase ventilation rates.

Strategies related to cross ventilations involve locating inlets oriented towards predominant winds direction and dimensioning to maximize wind capturing effects. When compared with the effects of perpendicular winds, oblique winds (at 45 degrees in relation to a perpendicular line from the window) promote a more efficient ventilation in all cases (Allard, 1998). In relation to the openings' size, for cross ventilations and perpendicular wind, the maximum performance occurs when the inlet to wall ratio is 2/3 and the outlet wall ratio is 2/3. In the case of oblique wind direction, maximum ventilation occurs when the inlet wall ration is 1/3 and outlet wall ratio is 1 (Allard, 1998). When modifying openings, it is important to balance their ventilation effects with their contribution in adding heat gains through solar radiation.

Strategies for single-sided ventilation involve the use of barriers generating zones with different pressures, and promoting air flow, as shown in Figure 31. Wing walls and overhangs are examples of this strategy conducting air flows.

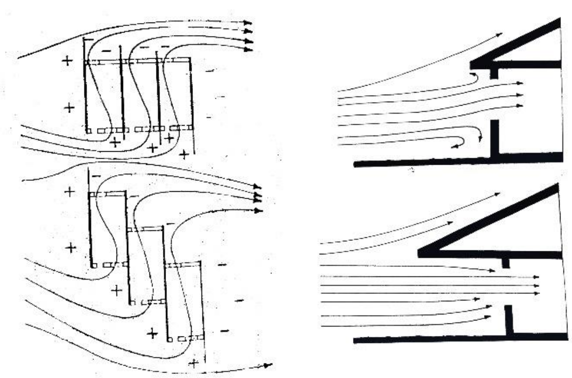

Figure 31 – Wing walls (left) and large overhangs (right) – From Allard, 1998

Types of windows also have an impact, maximizing or controlling the amount of ventilation entering a space. Single openings, such as single hung, double hung and horizontal sliding, do not generally affect the velocity or the direction of the wind flow. Vertical-vane openings, such as side-hinged casement, folding casement, and vertical pivot, generate different influences on pattern and velocity, addressing especially the horizontal distribution of winds. The sashes can block or direct wind flows to the intended direction, as well as create turbulences in the wind pattern inside the space. Horizontal-vane openings, defined as windows pivoting on a horizontal axis, influence winds movements in the horizontal direction, directing the airflow upwards or downwards (Allard, 1998). In relation to strategies applicable to a building retrofit, changing the windows' positioning might not be viable due to floor plan arrangements remaining, therefore, the use of wing walls, overhangs, dimensioning and type of opening as main alternatives.

Single-sided ventilation can also happen by buoyancy, this effect being especially important when the spaces' openings are located in leeward positions (downwind position) and wind-driven ventilation is not effective since the space is capturing slow wind speeds at low frequencies. A research with model simulations was conducted in 2008 to identify dominant effects on single sided ventilation cases and showed that the dominating force, either wind effect or buoyancy, changes as a function of incidence angle as well as the air rates inside a space (Heiselberg & Larsen, 2008). Since winds directions and velocities vary throughout a day or a year, it is effective to address to both forces in all openings.

In relation to buoyancy ventilation, the following options are commonly found and are applied to connected spaces, which make use of the building height to enhance buoyancy-induced ventilation.

- Solar chimney
- Atrium and courtyards
- Double skin façade

In a solar chimney, a vertical shaft is created on the building's exterior to promote ventilation. The sun's radiation incident on the chimney heats the air inside the space, generating a difference in temperatures from its interior to adjacent spaces connected. Cool air enters the chimney as the heated air escapes at the top, promoting a wind circulation. In the case of courtyards and atriums, a similar process occurs, with a smaller participation from solar radiation, since centrally located. In this situation the enclosed space formed by atriums, and courtyards channels and direct air flow. The same process happens in a double skin façade, where the sun's incidence in the façade will generate an air flow inside the system by stack effect (buoyancy), contributing to cooling the façade. Solar chimneys, atriums and courtyards are difficult to be applied in existing buildings since requires vertical connections that were not previously designed. Particularly in residential buildings, the communication between different floors might encounter problems such as noise, fire regulations, and user privacy issues.

A study simulated stack effect in a computational and physical model, using natural process and mechanically forced process. For the natural process model, the exit surface was painted in black to increase the heat absorption and consequently increase the temperature difference. In this case, the temperature difference measured was 10°C, which proved to be insufficient to generate an efficient stack ventilation in a height of 3m (10 feet). In the case of forced ventilation model, higher velocity was achieved (Cheong, Priyadarsini, & Wong, 2004). Another research analyzed the impact of stack ventilation in high-rise residential buildings between 37 and 60 floors. Problems with pressure differences between the bottom and the highest floors were identified, represented by significant difficulties when opening apartment doors. These researched represent difficulties associated to stack effect ventilation options that are therefore not effective when considering the retrofit of an apartment building.

Given the configuration of apartment buildings, with rooms on the same level and no usable roof space, cross ventilation and single sided ventilation are practically the only effective natural ventilation options to be used (Allard, 1998). Stack ventilation can be possible if the building is considered as a whole, but limitations involve problems associated with acoustics and fire protection. Communicating all floors and allowing the wind to circulate between apartments and common areas also implicates in allowing sounds to be transmitted along this path, causing problems with acoustics and the user's privacy. In this context, the presented information showed the inapplicability of using solar chimneys, atriums, and wind towers as retrofit strategies for the baseline building. Single sided and cross ventilation, associated with the proposed solar shading elements used in other case studies and the ventilated façade are proposed in the retrofit case three.

6. Methodology

This research consists of the application of retrofit strategies to a selected baseline building, and the analysis of its results in terms of improvements in energy efficiency and payback periods. In a first moment, a baseline building is presented, representing a frequent typology of a multifamily residential building currently in Recife. In the sequence, justified by studies presented, three retrofit cases are proposed to be applied in the baseline building: Case 1 involves modifying transparent surfaces, Case 2 involves modifying wall properties (opaque surfaces) and Case 3 involves improving natural ventilation conditions. To evaluate the positive and negative aspects of each study case, three steps are performed: step one determines the Overall Thermal Transfer Value of each building façade, step two involves a simplified computer simulation to identify total building loads and performance, and step three determines payback period for the retrofit measures. For the study case on natural ventilation, a qualitative evaluation is performed, based on the available literature on the subject. In this particular retrofit case, Overall Thermal Transfer Value, energy simulation and payback calculations are not performed.

In residential buildings, heat gains from internal sources are less intensive, and therefore the building's envelope dominates the cooling loads. Hence, calculating the thermal transfer of each wall is applicable in these situations to reflect each walls contribution in relation to those heat gains. The simulation of the study cases provides percentages of improvements of each solution, and serve as a step to determine the payback period. Payback calculation is one of the most impacting factors when considering the viability of performing a building retrofit, with the identification of total costs providing a sense of reality to the studies.

6.1. Metrics

The following parameters and formulas are considered as a basis for calculations for the Overall Thermal Transfer Value of each façade and situation, as well as determining thermal properties of materials and payback calculation.

6.1.1. OTTV - Overall Thermal Transfer Value

OTTV is the measurement of heat transferred through a building envelope, developed by ASHRAE for new building design, introduced in Standard 90-75, and later revised into Standard 90A-1980 (Wan & Yik, 2005). The smaller the OTTV, the smaller is the heat gain through the building envelope, and therefore less cooling is required. The OTTV involve three main elements that relate to materials and local climate conditions: conduction through walls, conduction through windows, and solar radiation through glass (Lam, Tsang, & Yang, 2008). OTTV are calculated for walls and for roofs, separately. In this research, the roof's OTTV was not calculated since it impacts mostly on the top unit, not impacting a "typical floor unit".

The formula for calculating OTTV used in this research is presented below (Vijayalaxmi, 2010). The first equation in parenthesis represents the calculation of conduction through walls, the second represents the calculation of conduction through windows, and the third represents the calculation of solar radiation through window glass.

$$OTTV = \frac{(Aw\ x\ Uw\ x\ \Delta Ts) + (Ag\ x\ Ug\ x\ \Delta T) + (Ag\ x\ I\ x\ \theta)}{Ai}$$

Where, Aw is the area of opaque surfaces, Uw is the thermal transmittance of the wall (U-value), ΔTs is the equivalent temperature difference, Ag is the glass surface area (window area), Ug is the window's U-value, ΔT is the temperature difference (difference between outside and inside temperatures), I is the incident solar radiation, θ is the window solar gain factor, and Ai the total wall area (opaque + transparent areas). The window solar gain factor is the window's shading coefficient x external shading factor, and the equivalent temperature difference is calculated by:

$$\Delta Ts = \left(To + I\ x\ \frac{\propto}{fo}\right) - Ti$$

Where, To is the outside air temperature, I is the radiation intensity, $\propto$ is the surface absorbance, fo is the surface conductance outside, and Ti is the inside air temperature. The unit for the OTTV is W/m^2.

The determination of each wall (varying by orientation) of the baseline building shows which orientation and parameter of the building's envelope have highest contributions to cooling necessities. This indicates which elements when changed, have the potential to provide the highest efficiency when it relates to the building's envelope. This calculation is understood as a step towards efficiency but does not represent its totality. According to research (Wan & Yik, 2005) OTTV alone does not ensure energy efficiency and cost effective design, and needs to be associated with other elements such as air leakage, selection of efficient HVAC systems and equipment, building energy management, and daylight optimization.

6.1.2. Equivalent Temperature Difference, Temperature Difference, Exterior and Interior Temperatures

ASHRAE 55 Standard when defining Design Equivalent Temperature Differences considers an average indoor temperature of 23.8°C (75°F) as a basis for calculation (Grondzik, 2010), based on a value of temperature related to the user’s comfort. This base assumption is not valid for location in hot and humid climate such in the northeast region of Brazil, and has its incoherencies when applied to buildings that use mainly natural ventilation as a source of passive cooling, as demonstrated in a research developed for defining thermal comfort in passively ventilated buildings in Natal – RN, Brazil (Negreiros, 2010). According to the authors’ researches, users in naturally ventilated spaces can adapt to a larger set of conditions that balances with the outside settings, and air movement impacting in the temperature felt as comfortable in that space. Negreiros identifies, based on literature review, four models for quantifying a comfortable or neutral temperature, based on adaptive models that consider natural ventilation, type of activity and clothing into the equation. The most recent one mentioned, dated from 2006, is explained as adequate for naturally ventilated housing constructed in hot and humid climate and was utilized to define a comfortable temperature for this simulation. It is also proposed a variation of 2.5°C (more or less) to consider adaptations. The equation is as follow:

$$Tn = 0.534 \times Tm + 11.90$$

Where Tn is the comfort temperature (in Celsius) and Tm is the mean monthly outside temperature (in Celsius).

For the OTTV calculations in this research, two months are identified for study, representing the highest amounts of solar radiation (as explained in topic 6.1.3.): December (summer) and June (winter). The following equations represent the final temperature considered for each month:

December: $0.534 \times 28 + 11.9 = 26.8°C$ [80.24 °F]

June: $0.534 \times 25 + 11.90 = 25.25°C$ [77.45°F]

6.1.3. Surface Absorbance, Surface Conductance and Incident Solar Radiation

The baseline building exterior finish is in ceramic tiles, its majority in the color white with details in blue. The total surface absorbance considered in the calculations is 0.3 (α), equivalent to white colored surfaces, as shown in Table 10 (Frota & Schiffer, 2001). In Case 2, the same value is used, since the use of a light color influences in the heat absorption from the wall.

Color	α
White	0.2 - 0.2
Yellow, orange, light red	0.3 - 0.5
Dark red, light green, light blue	0.5 - 0.7
Light brown, dark green, dark blue	0.7 - 0.9
Dark brown, black	0.9 - 1.0

Table 10 - Surface absorbance value by color - From Frota & Schiffer, 2001.

The surface conductance used in the calculation is equivalent to $25 w/m^2 °C$. This value corresponds to the inverse value of the surface resistance, defined in the Brazilian norm NBR 15220 for thermal performances of buildings. The following table was extracted from the norm and represents the surface resistance value recommended, based on heat flow directions.

Interior surface resistance (m^2C/W)			**Exterior surface resistance (m^2C/W)**		
Heat flow direction			**Heat flow direction**		
Horizontal	Upwards	Downwards	Horizontal	Upwards	Downwards
⇨ |	⇧	⇩	⇨ |	⇧	⇩
0.13 (0.73 $hft^2°F/Btu$)	0.10 (0.57 $hft^2°F/Btu$)	0.17 (0.96 $hft^2°F/Btu$)	0.04 (0.23 $hft^2°F/Btu$)	0.04 (0.23 $hft^2°F/Btu$)	0.04 (0.23 $hft^2°F/Btu$)

Table 11 - Interior and exterior surface resistance values - From NBR 15220.

The maximum values of solar radiation used for the calculations are the ones relative to 3pm during summer (December 22^{nd}) and relative to 3pm during winter (June 22^{nd}). As shown in

Appendix B, this time and day exhibits the most intensive radiation values, representing therefore the worst situations.

6.1.4. Wall U-Values

For the baseline building, the final U-value of each multilayered wall was calculated based on the recommendations from the NBR 15220, considering the U-value equivalent as the inverse of the R-value. The norm recommends the following formula for calculating thermal resistance in multilayered walls:

$$Rt = \frac{Aa + Ab + \cdots + An}{\frac{Aa}{Ra} + \frac{Ab}{Rb} + \cdots + \frac{An}{Rn}}$$

Where Rt is the wall's total resistance, An are the areas of each sections and Rn are the resistance from each material in the section. In addition, the values of exterior and interior thermal resistance (from Table 11) are added in the total, for the final resistance value, as shown in the equation:

$$RT = Rsi + Rt + Rse$$

Where RT is the final total resistance, Rsi is the interior resistance, Rt is the wall's resistance and Rse is the exterior resistance. Each material's resistance was extracted from table B2, of the same norm. In Appendix C are the calculations performed for each wall type in the baseline.

For the U-values of the ventilated façade, the value provided in a study (Gagliano, Galesi, Ferlito, Nocera, & Patania, 2010) was used as a base for calculation of the final wall types. The value of R = 1.98 m^2C/W (11.11 $hft^2°F/Btu$) was considered for the base assembly (finish material + air space + insulation + existing perforated block wall) and to serve as a basis for the definition of the other assemblies. A percentage improvement is calculated in comparison to the baseline wall value, and this percentage is applied to the other assemblies to generate their final U-values.

6.1.5. Window Properties

The windows property values used in the OTTV calculations were extracted from the extensive library of window types and properties existing in the Autodesk Revit software, the same software (and values) used in the simulations.

For the effect of shadings, the value considered was based on table 4.8 of the book Energy Efficiency in Architecture (Lamberts, 1997). The reference establishes a factor of 25% applied to the incident radiation, representing that 75% of the incident radiation is blocked by the shading device.

6.1.6. Payback Calculations

Payback calculation serves as an understanding of a time frame in which the initial investment in the retrofit alternative will be paid back by the reduced electricity consumption and consequently the reduced utility bills. It has the ability to show the apartment owner if the retrofit will be a short or a long term investment.

The payback calculation follows the equation:

$$Ni\ (years) = \frac{total\ investment\ in\ retrofitting\ (R\$)}{\left(annual\ energy\ baseline\ \left(\frac{kWh}{year}\right) - annual\ energy\ case\left(\frac{kWh}{year}\right)\right)\ x\ electricity\ cost\ \left(\frac{R\$}{kWh}\right)}$$

The annual energy baseline is calculated using an existing example of energy consumption: an energy bill from an apartment with the same characteristics as the baseline building, also located in Recife, as shown in Appendix D. The annual energy baseline is equivalent to the monthly consumption presented in the example's energy bill, multiplied by 12 months and 72 apartments[18]. The annual energy from the case is the total baseline multiplied by the relative percentage of reduction identified from the simulations.

6.2. Simulation Software & Parameters

The software used in the simulations is the Autodesk Revit 2016, with the use of energy analysis tools embedded in the software. This function also provides a list of results in an online platform entitled Green Building Studio.

The following parameters are set as default in the simulation software:

Location	**Recife, PE**
Weather Station	1216915
Building Type	Multi Family
Outdoor Temperature	Max 34°C/Min 22°C (93°F/71°F)
Average Lighting Power	6.46W/m²

[18] Number of apartments in the baseline building

Average Equipment Power Density:	5.38W/m²	
Occupancy	21 m² (222.05ft²) per person[19]	
Schedule	24/7 facility	
Occupancy schedule	12am - 5am: 90% 6am: 70% 7am - 8am: 40% 9am - 2pm: 20% 3pm: 30%	4pm - 6pm: 50% 7pm - 8pm: 70% 9pm: 80% 10pm - 11pm: 90%
Lighting schedule	12am - 4am: 10% 5am: 30% 6am - 9am: 45% 10am - 5pm: 30% 18pm: 60%	7pm: 80% 8pm: 90% 9pm: 80% 10pm: 60% 11pm: 30%
Spaces	Cooled: Naturally ventilated: Unconditioned:	Bedrooms Living rooms Kitchens Service areas Restrooms Stairs Corridors
HVAC Equipment	PSZ, 14 SEER, 90% AFUE Residential System	

Table 12 - Simulation parameters

The HVAC selection presented in this table is the closest to the existing in reality in this type of apartment. For hot water systems, Revit does not provide an option for electric heating, and therefore the results consider fuel heating.

The simulation is performed using a model developed in Revit, with only the "tower" of the building, considering 18 typical floors stacked. The total amount of energy used and the numbers related to the simulation do not reflect the reality of the entire building. The simulations will serve in a comparison base, to identify percentages of gains and losses when applying one solution or the other, in comparison with the baseline building simulated.

6.3. Baseline Building

The building selected to serve as a baseline for the modifications is called Villa Benfica and is a typical example of a residential multifamily building for a middle-income family. The design was developed by a local architecture company in 2011, and the construction is almost

[19] Calculated based on the total floor area and the overall floor occupancy (3 persons per apartment = 12 persons per floor).

finished, with predictions of been completed by the end of 2016. It is a recent development, which exemplifies the lack of sustainable solutions adopted in the present days.

6.3.1. Location and Context

The building is located in the city of Recife and in the neighborhood called Madalena, as shown in figure 32. This neighborhood is considered the 6^{th} of the 10 most expensive neighborhoods in the city, with a price of R$6,000 per square meter (around $1,876/m² - $188/sf²), a region with medium to high-income families. The proximity to the river also adds to the neighborhood's valorization, following a pattern that happens in the city, where neighborhoods located close to the beach and at the margins of the rivers are considered more expensive.

Figure 32 - Madalena's location map (left) and aerial view (right) - From Wikipedia and Skyscrapercity.

The neighborhood is expanding, but already presents many similar middle to high-rise multifamily buildings such as the Villa Benfica. As shown in figure 32 it is a dense area with an urban character.

6.3.2. Building Configuration

The selected building has 18 typical apartment floors, one floor for common recreational spaces, and three floors dedicated to parking (parking garage). Both pedestrian and car entrances are located on the ground floor, accessed through the street Arnaldo Bastos. As shown in Figure 34 the first floor is mostly dedicated to parking spaces, with a small controlled entrance, a waiting area for elevators, and mechanical spaces. The green areas are restricted to residual spaces, to comply with the maximum land coverage area/percentage established by the local code.

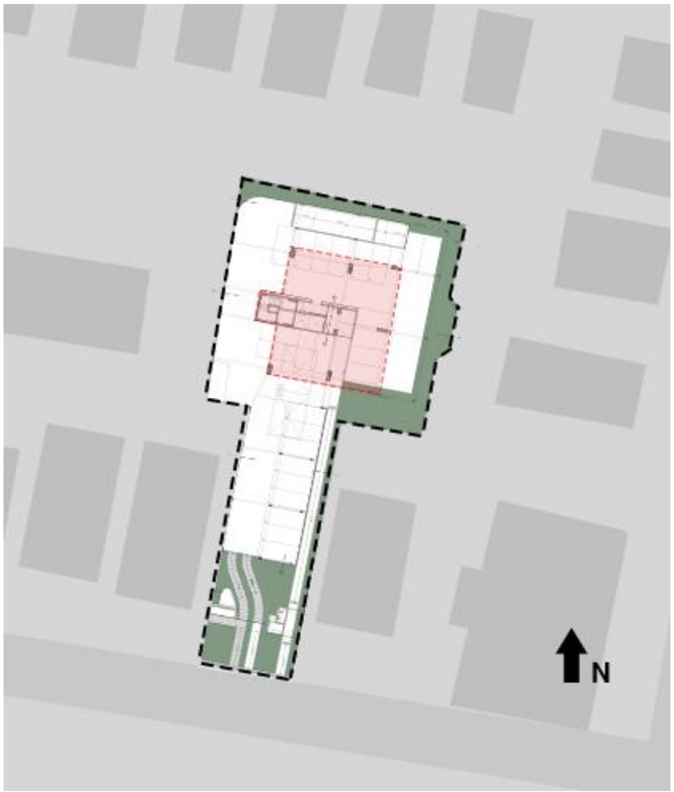

Figure 33 - First floor in context with surrounding buildings.

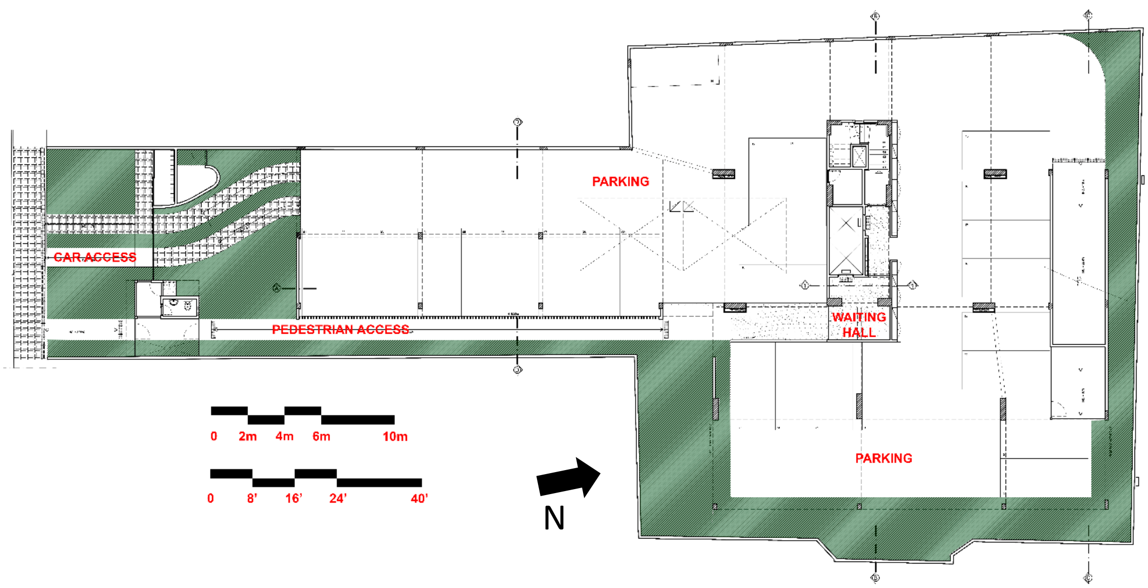

Figure 34 - Villa Benfica first floor plan.

The second and third floor are completely dedicated to parking spaces, with only a small waiting area for the elevators, as shown in Figures 35 and 36. The walls surrounding this floor do not go up to the ceiling, maintaining wind circulation and allowing for natural light to get in.

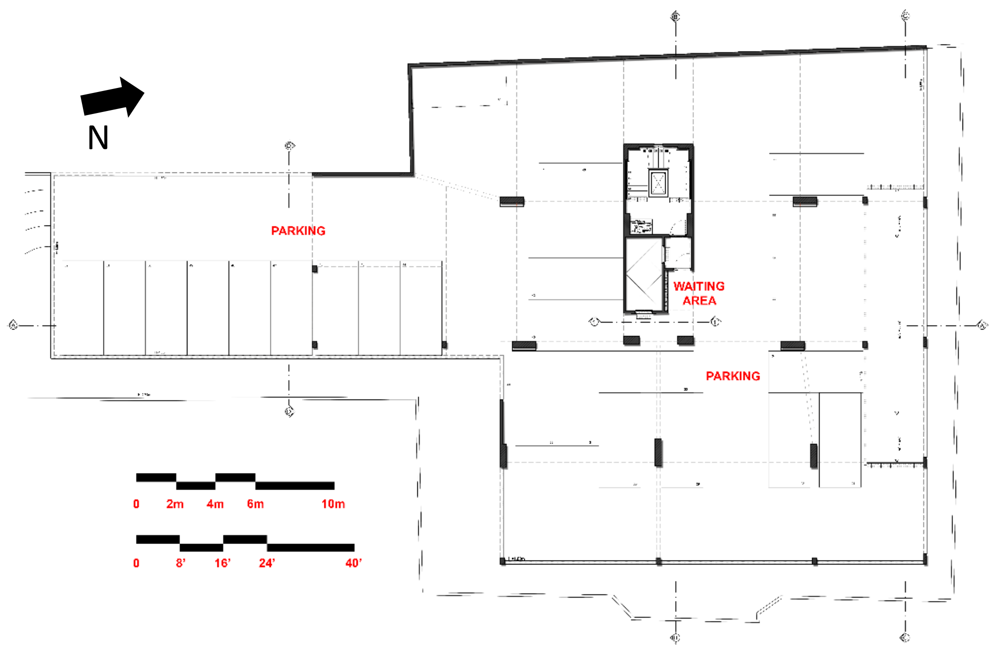

Figure 35 - Villa Benfica second floor plan.

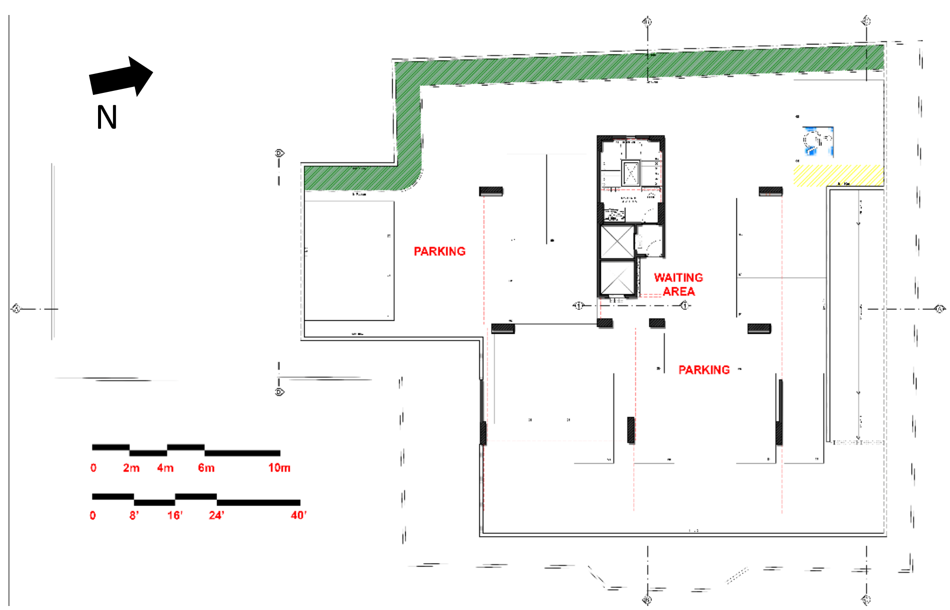

Figure 36 - Villa Benfica third floor plan.

The fourth floor is where common and recreational areas are located. The floor is the exact size as a typical apartment floor and has a small pool with an open terrace, two event spaces ("party space" used for gatherings such as birthday parties and barbecues), a game room and a small gym. This floor also has bathrooms and spaces to serve the entire floor.

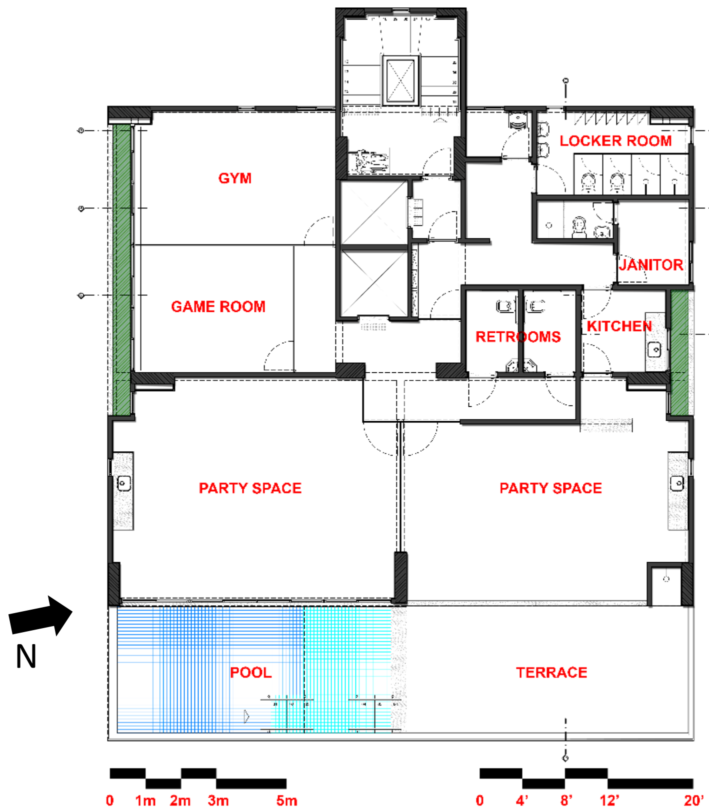

Figure 37 - Villa Benfica fourth floor plan.

The typical apartment floor goes from the fifth to the twenty-second floor, with a configuration of four apartments per floor, and one hall for the elevator area directing to each apartment door, as shown in Figure 38. Each apartment has only one entrance door, two bedrooms, two bathrooms (one exclusive for the "master" bedroom), a living and dining room, a kitchen and a service space (with a sink and space for a clothes washer). The apartments number 01 and 04 are slightly smaller than the apartments 02 and 03: the first two have 48.84 m² (525.71 square feet) and the other two 52.90 m² (569.41 square feet).

Figure 38 - Villa Benfica typical floor plan.

The building tower is oriented with apartments 02 and 03 facing east, with a small rotation of 8.91 degrees in direction to the south. Therefore, the majority of windows in apartments 02 and 03 are oriented to the east, apartment 01 is oriented to the north, and apartment 04 is oriented to the south. In the typical apartment, social areas are located closest to the facades and service areas are aggregated (due to technical and economic efficiency) and located towards the center of the floor or in the worst orientations. An example is the service areas of apartments 01 and 04, which are aggregated and located closest to the west façade. The vertical circulation is also strategically located in the worst orientation since heat gains are not a concern.

The elevations are simple and straight, using only the change of ceramic tile colors to provide a different pattern, as shown in Figure 39.

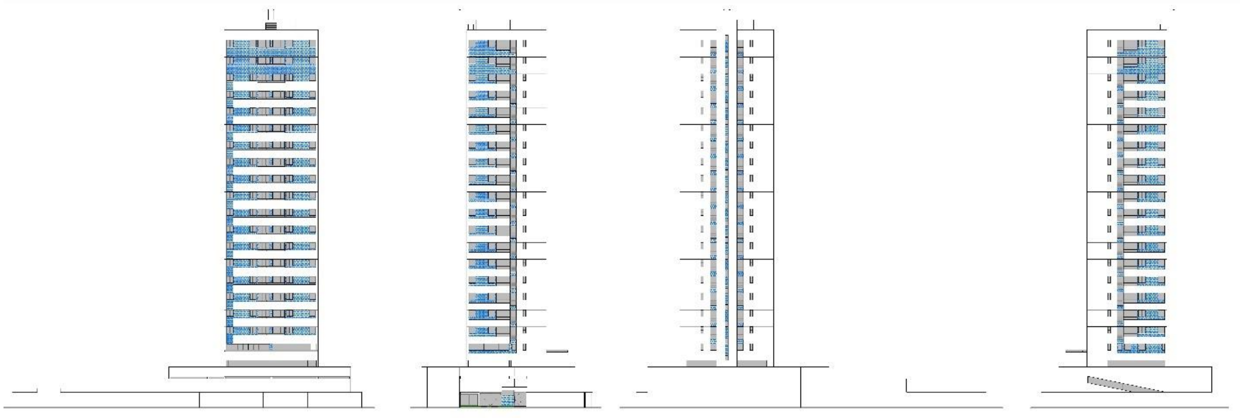

Figure 39 - Villa Benfica elevations: east, north, west and south.

6.3.3. Materials

In similarity to most constructions in Brazil, the main construction materials used in this project are reinforced concrete and ceramic perforated blocks. The structure of this building is a set of columns, beams and floors made of reinforced concrete, and the building envelope of nonbearing ceramic perforated blocks. The façade has ceramic tiles of different dimensions and colors as the finish material. The table below shows the composition of each wall and the thermal values calculated.

Building construction materials specifications			
Material	**Thickness (cm)**	**Conductance (W/m² C)**	**Resistance (m² C/W)**
Floors	26.36 (10 5/16”)	2.22[20] (0.39 Btu/hft²°F)	0.45 (2.56 hft²°F/Btu)
Ceramic tiles	0.79 (5/16”)		
Flooring mortar	2.06 (13/16”)		
Ribbed concrete slab	22.56 (8 7/8”)		
Dry wall ceiling	0.95 (3/8”)		
Walls			
Wall type A	124.15 (4’-5/8”)	1.114 (0.20 Btu/hft²°F)	0.898 (5.00 hft²°F/Btu)
Ceramic tiles	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete column	120 (3’-11”)		

[20] From (INMETRO, 2013)

Gypsum plaster	1.60 (5/8”)		
Wall type B	13.15 (5 1/8”)	2.457 (0.43 Btu/hft²°F)	0.407 (2.33 hft²°F/Btu)
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Ceramic perforated brick	9 (3 9/16”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type C	144.15 (4’-8 5/8”)	0.988 (0.17 Btu/hft²°F)	1.012 (5.88 hft²°F/Btu)
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete column	140 (4’-7”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type D	24.15 (9 ½”)	3.064 (0.54 Btu/hft²°F)	0.326 (1.85 hft²°F/Btu)
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete beam	20 (7 7/8”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type E	34.15 (13 7/16”)	2.607 (0.46 Btu/hft²°F)	0.383 (2.17 hft²°F/Btu)
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete column	30 (11 13/16”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type F	14.10 (5 9/16”)	2.404 (0.42 Btu/hft²°F)	0.416 (2.38 hft²°F/Btu)
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Ceramic perforated brick	9 (3 9/16”)		
Plaster mortar	1.60 (5/8”)		
Ceramic tile	0.95 (3/8”)		
Roof	38.77 (15 ¼”)	1.55[21] (0.27 Btu/hft²°F)	0.64 (3.70 hft²°F/Btu)
Corrugated fiber cement sheets	5.72 (2 ¼”)		
Wood structure	2.54 (1”)		
Air space	7 (2 ¾”)		
Ribbed concrete slab	22.56 (8 7/8”)		
Dry wall ceiling	0.95 (3/8”)		

Table 13 - Baseline exterior walls, floors and ceiling thermal properties.

[21] From (INMETRO, 2013)

When comparing U-values of each assembly shown in the table above (Table 13) it can be noticed that concrete columns and beams have elevated transmittance coefficients in comparison to regular wall assemblies, representing the “thermal bridges” mentioned in a previous chapter. The use of external insulation can contribute to reducing its impacts on the thermal performance of the envelope since it contributes to interrupt the thermal bridge.

The windows in a typical apartment are presented in Figure 40 and their properties in Table 14 below.

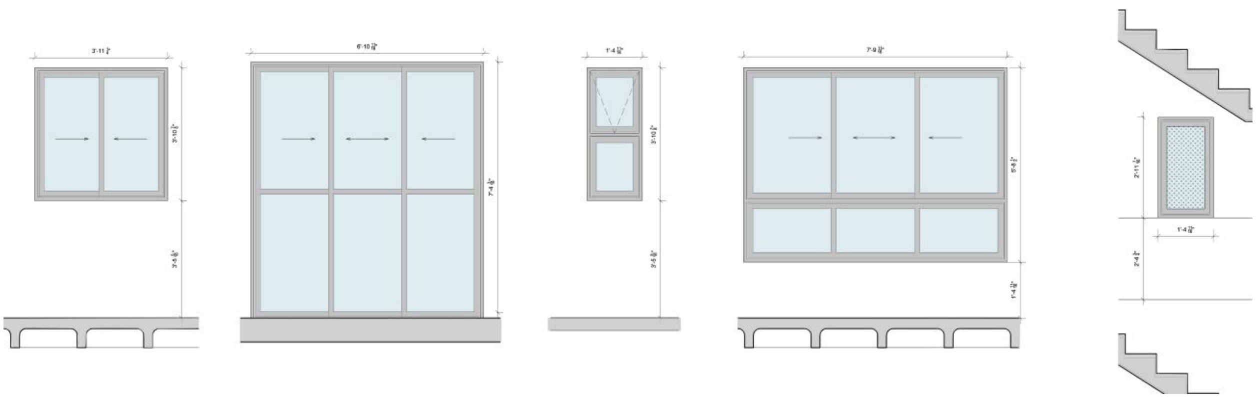

Figure 40 - Villa Benfica typical floor windows.

Window	Description	U-value (W/m²C)	Shading Coeff. (glass prop.)	Shading Coefficient (exterior elem.)
EA-01	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	1.0
EA-02	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	0.25
EA-03	Single Glazing, 3mm glass, clear glass	6.70 (1.18 Btu/hft²°F)	0.8	1.0
EA-04	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	1.0
EA-05	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	1.0

Table 14 - Baseline window properties.

As shown in the window properties table, EA-02 is the only one with a shading acting over the window. It is the door/window that gives access to the balcony and therefore is protected by the balcony above and walls surrounding it. The following diagram represents the shading mask over this window.

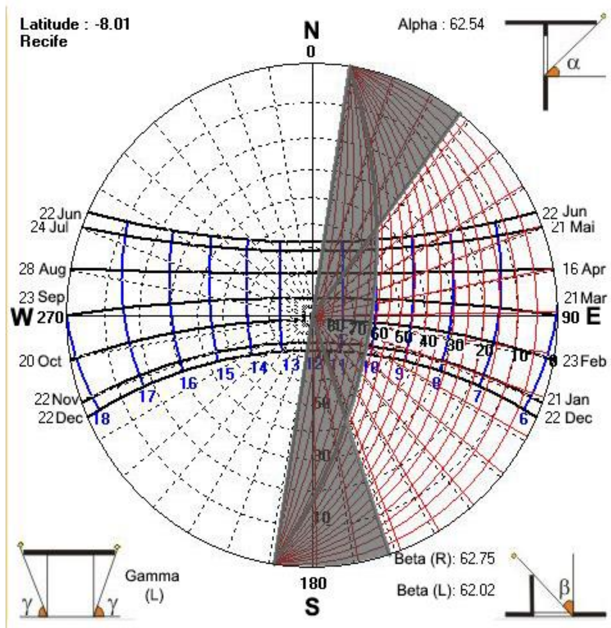

Figure 41 - EA-02 shading mask - Adapted from SolAr.

Although existent, the shading projected by the balcony as a small range, leaving unprotected during the initial hours of the day (from 6am to 10am).

6.3.4. OTTV Calculation Results

The table below shows the OTTV associated to each façade and contributions of each wall type. Qw indicates the total heat conduction through the walls, Qs indicates the total conduction through the glass, Qs indicates the solar radiation passing through the glass and contributing to the total heat gains.

DECEMBER 22nd					
Orientation	Wall Type	Qw	Qg	Qs	OTTV (W/m²)
East	A	64.97	2212.59	4057.99	16.28
	B	1479.28			
	C	32.69			
	D	1000.21			
	Total	2577.15			
North	A	24.45	1096.20	3795.79	16.34
	B	1336.84			
	D	786.03			
	E	281.36			
	F	69.07			
	Total	2497.74			
West	B	11843.06	237.99	9164.40	55.32
	D	4483.08			
	E	2032.97			
	F	598.84			
	Total	18957.96			
South	A	146.02	1096.20	21662.15	62.79
	B	2961.27			
	D	1756.34			
	E	623.25			
	F	152.99			
	Total	5639.87			

Table 15 - Baseline OTTV for December 22nd.

Apart from the west façade, heat gains from solar radiation in windows (Qs) is the most contributing element to the OTTV. This indicates the necessity of shading and improved window properties. The south façade presents the higher value related to windows, showing that a shading on this façade is important. In the west façade, the factor impacting the most relates to the wall types and properties, indicating the necessity of reducing the walls U-value. These results represent, therefore, the urgent need of shading elements over windows in the north façade, and improvement of U-values in walls facing west.

JUNE 22nd					
Orientation	Wall Type	Qw	Qg	Qs	OTTV (W/m²)
East	A	14.46	0	3498.27	7.49
	B	329.22			
	C	7.27			
	D	222.60			
	Total	573.55			
North	A	24.45	0	29711.84	76.80
	B	2701.44			
	D	1588.38			
	E	568.56			
	F	139.57			
	Total	5022.40			
West	B	8550.35	0	8326.10	42.94
	D	3236.66			
	E	1467.75			
	F	432.34			
	Total	13687.10			
South	A	14.67	0	3272.23	8.49
	B	297.52			
	D	176.46			
	E	62.62			
	F	15.37			
	Total	566.63			

Table 16 - Baseline OTTV for June 22nd.

During the winter the temperature difference, when considering mean values, is equal to the interior temperature, reducing a significant amount of heat gains especially associated with conduction contributions from windows (zero in the table). The difference, when compared to the summer months (December 22nd) is that the sun's path occurs over the north façade instead of the south. This façade's contribution is higher during this month, along with the west façade, always receiving the highest insolation values. In this month, the windows in the north façade have a significant contribution to the OTTV, indicating the necessity of shading elements, and the wall's properties are driving the gains in the west façade, reinforcing the need for insulation.

6.3.5. Simulation Model Results

The simulation of the baseline building confirms the necessity of improving the building's efficiency to overcome the excessive use of artificial cooling. Figure 42 (left) shows how the energy is being used in this typical building. In the same context, the simulation also indicates the necessity of addressing to the building envelope for reducing the contributions to cooling loads, as shown in Figure 42 (right).

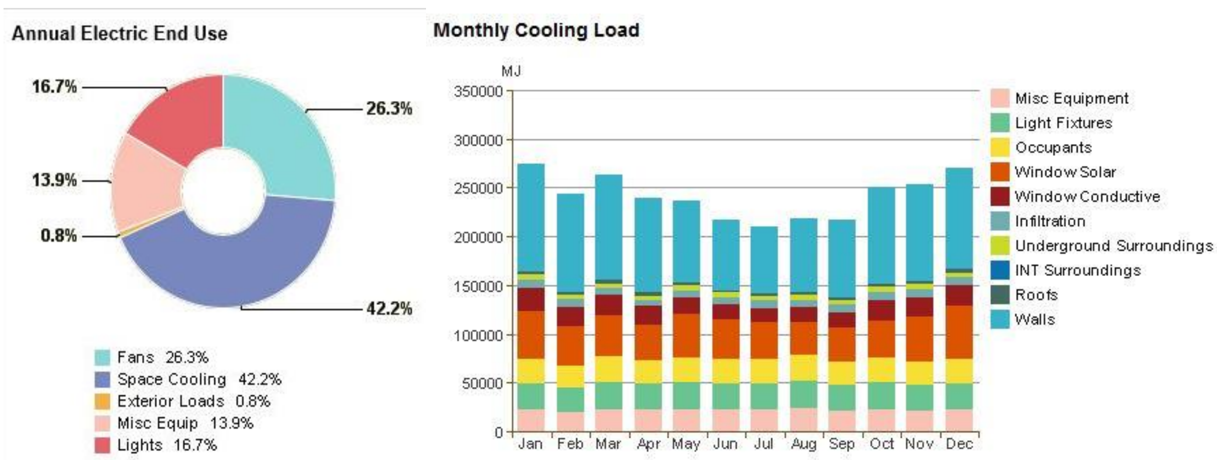

Figure 42 – Distribution of electricity use (left) and amount of monthly cooling loads (right) in the baseline building – From Green Building Studio.

As shown in Figure 42 left, the HVAC system is responsible for almost 69% of the total electric use in the building, having a significant impact. The second figure shows cooling loads associated to exterior elements (walls, roofs, interior surfaces, underground surfaces, infiltration, window conductive and window solar), and cooling loads associated with internal loads (occupants, light fixtures, and miscellaneous equipment). As seen, walls are the elements with the highest contribution to the loads, with window solar (radiation through the glass) as the second element. Therefore, actions targeting reduction in cooling loads must involve changing the building envelope. Internal loads associated with lighting fixtures and equipment can be reduced with the use of efficient equipment.

Over the year, the peak consumptions occur during the summer months (Dec-Mar), as shown in Figure 43 below, and reduced during the winter months (Jul-Sep).

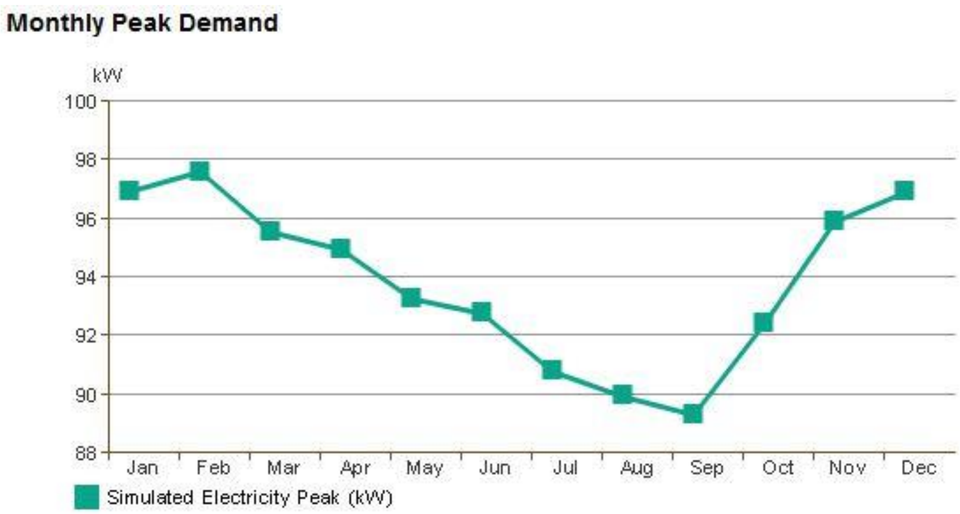

Figure 43 - Baseline monthly peak demand - From Green Building Studio.

The total Energy Use Intensity represents a measurement of energy use by floor area. In the baseline building, the EUI associated is 185 kWh/m²/year (17.20 kWh/sf/year) for electricity use, and 257 MJ/m²/year (22.64 kBtu/sf/year) for fuel use, adding to a total of 921 MJ/m²/year (81.13 kBtu/sf/year). The fuel use is 100% associated with the domestic hot water heating system, and as previously mentioned, the software used in the simulation does not have an option of an electric shower. Therefore, the fuel calculated would be associated with electricity use as well. Since this parameter is constant in all simulations, it does not affect the comparison values and does not invalidate the results.

Based on the baseline's OTTV calculation results associated with the simulation results and strategies associated with a climate responsive architecture, the following cases are presented:

- Case 1: Including shading over south and north openings, and modifying window properties of east and west windows, to address gains from transparent surfaces;
- Case 2: Applying a ventilated façade over the entire building, to address gains from opaque surfaces;
- Case 3: Applying strategies to improve capturing and ventilation rate inside the apartments, to take advantage of a natural resource.

6.4. Retrofitting Case 1: Transparent Elements

A study for evaluating impacts of the application of advanced glazing and overhangs in residential buildings in Tehran, Iran (Ebrahimpour & Maerefat, 2010), presents valuable information for one of the strategies adopted in this research. The authors studied the effects of four types of glazing (single pane, double pane, single low-e pane and double low-e pane), several dimensions and positions of overhangs and side fins, and the combination of both strategies, in all model façade's orientations (north, south, east, and west). Although Tehran has different sun path and solar incidence characteristics in comparison to Recife, strategies can be applied adapting to suit the best orientation.

In windows placed in the south elevation, two solutions brought around 50% efficiency to the building: the use of single pane glazing with overhangs with 3m in width and 1m in depth, and use of single or double low-e pane glazed window, without overhangs. In Tehran, the south façade receives sun year-round, with a high incidence angle during summers and a low incidence angle during winters. In the case of Recife, the south façade receives most of the sun during summers, with a high angle of incidence as well. Therefore, these results may be applicable to this study's situation, in relation to the summer. Since this solution will be to retrofit an existing building, the cheapest solution (adding overhangs only), that aggregates the same positive impacts, was adopted in both the south and north façade. In Recife during the winter, the sun travels along the north façade with almost the same intensity as its path along the south façade in the summer.

For the windows located in the East and West elevations of the Tehran building, the research showed that the most significant contribution to the efficiency occurred with the use of double pane low-e glazing windows, which are also used in this retrofit case.

For proper sizing and determination of shading elements, the software SOL-AR 6.2 was used. This software was developed by the Federal University of Santa Catarina (UFSC), from an association between the Department of Civil Engineering (ECV) and the Laboratory for Energy Efficiency in Buildings (LabEEE). The software provides the solar chart for any latitude and facilitates the process of dimensioning shading devices by providing the shadow mask when each angle is specified by the user. After determining the angles in plan, section, and view, the software generates the mask as a result.

Figure 44 show the shading mask of windows located on the south elevation. The angles alpha, beta, and gamma determine the dimensions of the shading elements in section, plan, and elevation, respectively.

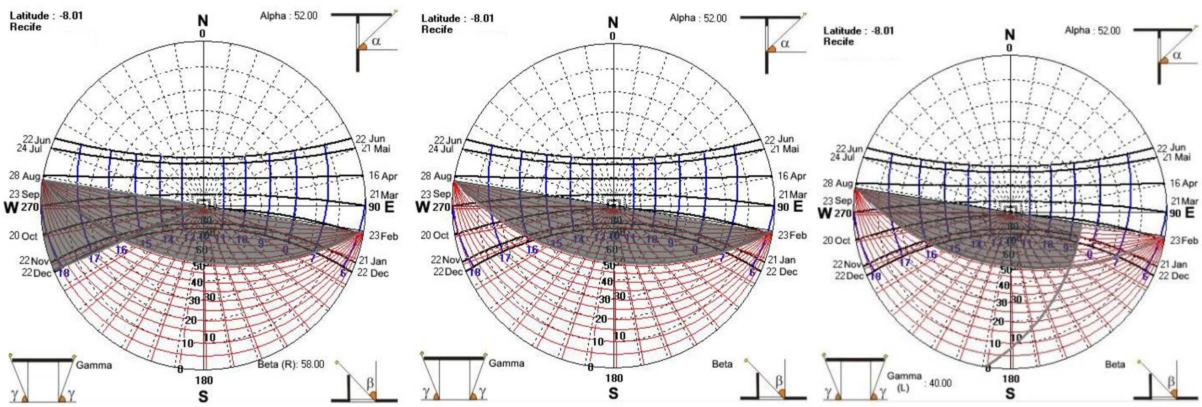

Figure 44 - Shading mask for window1, 2&3, and 4, in sequence, for the South elevation.

The objective of this shading strategy in the south elevation is to protect the window from solar radiation between 9am and 3pm, moments when the solar intensity is elevated. In window one, a vertical element was inserted since the window is too close to the end of the wall (right), and the shading would not be effective considering just the use of a horizontal overhang. The continuous overhang proposed over all windows provides an “infinite” effect of the shading on the left side of window one, on both sides of windows two and three, and on the right side of window four. In all situations, at 3pm during summer, the windows are completely shaded, providing a shading coefficient equivalent to 0,25 (Lamberts, 1997).

The same strategies mentioned above are used in the north elevation, as shown in the shading masks below (Figure 45). The only difference is the angle “alpha” of 52° instead of 55°, increasing the depth of the overhang. This change is necessary to adapt to the sun’s lower position in the north façade during the winter.

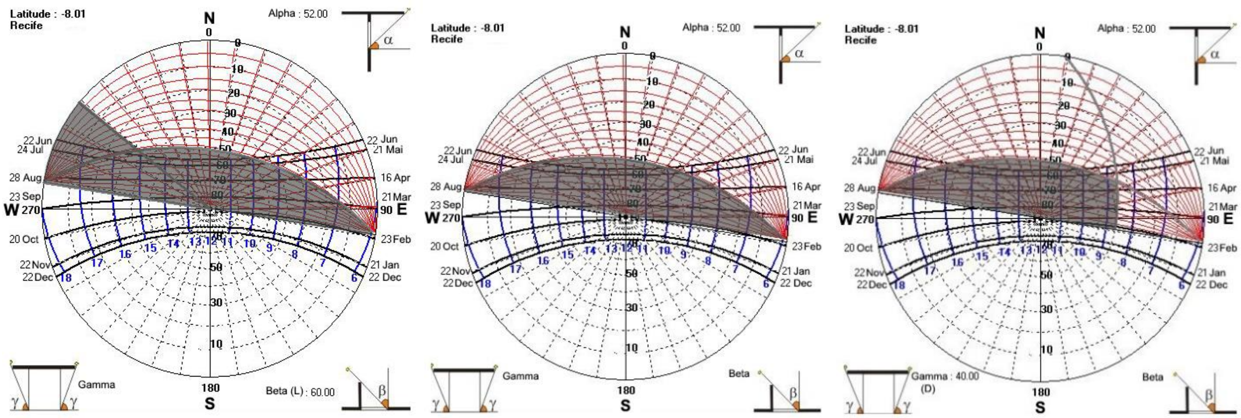

Figure 45 - Shading mask for windows 1, 2&3, and 4 for the North elevation.

Figure 46 below shows sizing and how the new element is inserted in the facade of the residential tower. These overhangs can be integrated into the building's façade as new elements to contribute to the building's aesthetics. The overhangs can be designed in countless ways, aggregating a unique element to the façade.

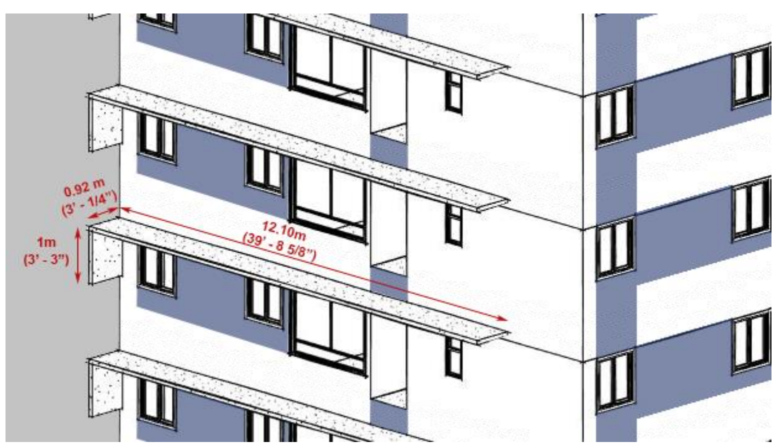

Figure 46 - Shading element applied to the Baseline Building's façade.

In relation to the windows properties, as previously mentioned, only the east and west oriented windows were altered, considering double pane low emission glazing. The glazed doors in the balconies were not changed since the balcony already provides shading effect over the window. The values used in the simulation and OTTV calculation are the following:

Window	Description	U-value (W/m²C)	Shading Coeff. (glass prop.)	Shading Coefficient (external elem.)
EA-01 N&S	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	0.25
EA-01 E	Low-E double glazing, aluminum frame	2.21 (0.39 Btu/hft²°F)	0.65	1.0
EA-02	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	0.25
EA-03	Low-E double glazing, aluminum frame	2.21 (0.39 Btu/hft²°F)	0.65	1.0
EA-04	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	0.25
EA-05	Single Glazing, 3mm glass, clear glass, aluminum frame	6.70 (1.18 Btu/hft²°F)	0.8	1.0

Table 17 - Retrofit Case 1 window's properties.

6.4.1. OTTV Calculation Results

The OTTV table was developed based on the baseline, with the information regarding windows changed, to reflect the new solution, following the information presented in the previous table.

DECEMBER 22nd					
Orientation	Wall Type	Qw	Qg	Qs	OTTV (W/m²)
East	A	64.97	1659.69	4057.99	15.26
	B	1479.28			
	C	32.69			
	D	1000.21			
	Total	2577.15			
North	A	24.45	1096.20	948.95	10.05
	B	1336.84			
	D	786.03			
	E	281.36			
	F	69.07			
	Total	2497.74			
West	B	11843.06	78.50	7914.71	52.57
	D	4483.08			
	E	2032.97			
	F	598.84			

	Total	18957.96			
South	A	146.02	1096.20	5415.54	26.87
	B	2961.27			
	D	1756.34			
	E	623.25			
	F	152.99			
	Total	5639.87			

Table 18 - Retrofit Case 1 OTTV for December 22nd.

The use of solar shading proved to be very effective, reducing significantly the heat gains from windows (both conductive and through radiation). The elevated value in the west façade is indicative of the necessity to reduce heat gains through opaque surfaces.

JUNE 22nd					
Orientation	Wall Type	Qw	Qg	Qs	OTTV (W/m²)
East	A	14.46	0	3498.27	7.49
	B	329.22			
	C	7.27			
	D	222.60			
	Total	573.55			
North	A	24.45	0	7427.96	27.53
	B	2701.44			
	D	1588.38			
	E	568.56			
	F	139.57			
	Total	5022.40			
West	B	8550.35	0	7190.73	40.73
	D	3236.66			
	E	1467.75			
	F	432.34			
	Total	13687.10			
South	A	14.67	0	818.06	3.06
	B	297.52			
	D	176.46			
	E	62.62			
	F	15.37			
	Total	566.63			

Table 19 - Retrofit Case 1 OTTV for June 22nd.

In the winter months, the calculation shows the same relationship, but with the highest reductions associated with the south facing windows.

6.4.2. Simulation Model Results

The annual electric use composition and the cooling loads result from the simulation of this study case are shown in Figure 47 below.

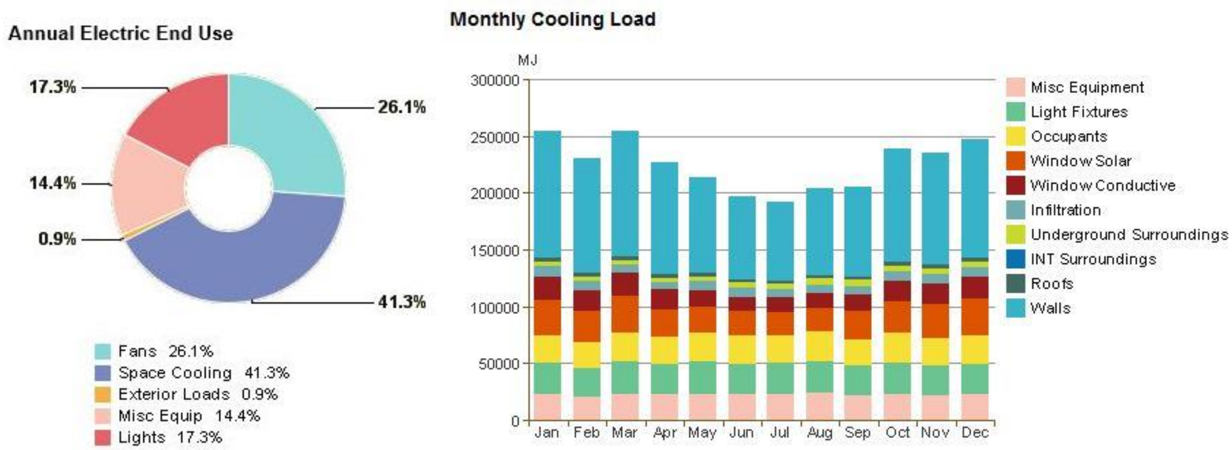

Figure 47 - Distribution of electricity use (left) and amount of monthly cooling loads (right) in the Retrofit Case 1 – From Green Building Studio.

The electricity associated to space cooling reduced from 42.2% in the baseline building to 41.3% in this study case. When analyzing the monthly cooling loads, the loads in general reduced, in particular, the contributions of window solar and conductive, reducing around 33% each when compared to their contributions in the baseline building.

The monthly peak demand also presented a reduction in comparison to the baseline building, of approximately 4 kW, as shown in figure 48.

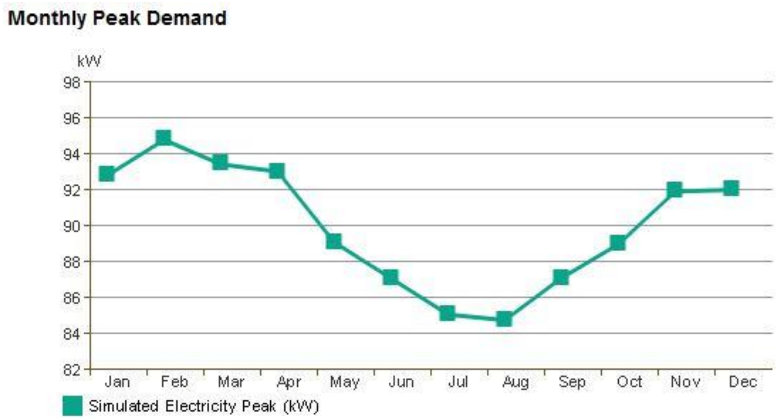

Figure 48 – Retrofit Case 1 monthly peak demand - From Green Building Studio.

The total Energy Use Intensity associated with this Case is 179 kWh/m²/year (16.63 kWh/sf/year) for electricity use, and 257 MJ/m²/year (22.64 kBtu/sf/year) for fuel use, adding to a total of 900 MJ/m²/year (79.27 kBtu/sf/year). These numbers represent an improvement of 3.2% in the electricity use and an improvement of 2.3% in the total consumption, compared to the baseline building. These results represent a small number when compared to higher improvements calculated in the OTTV tables.

6.4.3. Payback period calculations

For the shading elements, simple materials were considered due to their reduced prices. The calculations are based on reinforced concrete, manufactured at the construction site. These materials are commonly used in general constructions and do not require a special workforce. They are also resistant to exterior conditions and do not require maintenance.

PRICE COMPOSITION – SHADING ELEMENTS			
Ready mixed concrete, 11MPa, supplied and poured	R$ 340.40 /m^3[22] ($ 103.15[23] /m^3)	46.8 m^3	R$ 15,930.72 ($4,827.49)
Reinforcing steel CA-60, cut, folded and placed	R$ 7.55 /kg[4] ($ 2.29 /kg)	3,744 kg	R$ 28,267.20 ($ 8,565.82)
Form work	R$ 83,36 /m^2[4] ($ 25.26 /m^2)	104 m^2	R$ 8,669.44 ($ 2,627.10)
Total			R$ 52,867.36 ($ 16,020.41)

Table 20 - Price composition for the Retrofit Case 1 overhangs.

For the double pane low-e windows, an average price of R$ 275.78 ($ 83.57) per square meter retrieved from an online software with a database for material prices, supply, and installation (CYPE, 2015). The total price for windows in the east and west façade is, therefore, R$ 34,425.89 ($ 10,432). The total investment in this retrofit option is R$ 87,293.25 ($ 26,452.5).

The payback period calculated for this option is 8.65 years, as follow:

$$Ni\ (years) = \frac{R\$\ 87{,}293.25}{\left(362{,}880\,\frac{kWh}{year} - 350{,}723.52\ kWh/year\right)\ x\ R\$0.83} = \frac{R\$\ 87{,}293.25}{R\$\ 10{,}089.88/year} = 8.65\ years$$

[22] Based on the ENLURB table: prices for construction services and materials establish by the city hall as city baseline

[23] Conversion rate: $1 = R$3.30

6.5. Retrofitting Case 2: Opaque Elements

As mentioned, a ventilated facade is a good solution for hot climates such as Recife's, since it improves the thermal characteristic of the wall, increases the speed during a construction process (in case of a new construction), guarantees security in the connections of pieces (preventing from falling off), prevents pathological manifestations, and presents a good aesthetic.

In this system, most part of the radiant heat is reflected, the remaining heat promoting a "chimney effect" throughout the air layer.

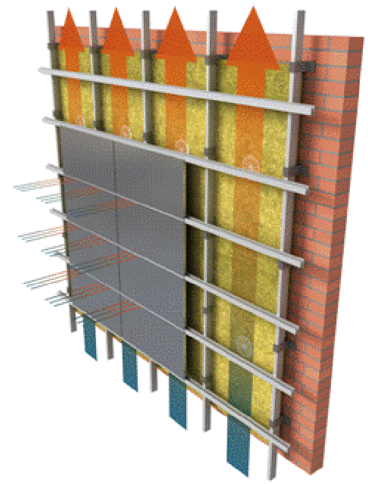

Figure 49 - Ventilate Facade composition.

Figure 49 shows the layer's configuration on a ventilated façade system: a finish material, a secondary structure, air space, insulation and an existing backup wall. The table below provides the final composition of each wall after adding the ventilated system, as well as their associated thermal characteristics.

Building construction materials specifications			
Material	**Thickness (cm)**	**Conductance (W/m² C)**	**Resistance (m² C/W)**
Floors	26.36 (10 5/16")	2.22[24] (0.39 Btu/hft²°F)	0.45 (2.56 hft²°F/Btu)
Ceramic tiles	0.79 (5/16")		
Flooring mortar	2.06 (13/16")		
Ribbed concrete slab	22.56 (8 7/8")		
Dry wall ceiling	0.95 (3/8")		
Walls			
Wall type A+	143.69 (4'-8 1/4")	0.229 (0.04 Btu/hft²°F)	4.363 (25 hft²°F/Btu)
Ceramics slabs	1.30 (1/2")		
Air layer	15.24 (6")		
Rigid fiberglass insulation	3.00 (1 3/16")		
Ceramic tiles	0.95 (3/8")		
Plaster mortar	1.60 (5/8")		
Concrete column	120 (3'-11")		

[24] From (INMETRO, 2013)

Gypsum plaster	1.60 (5/8”)		
Wall type B+	32.69 (1’ -13/16”)	0.505 (0.09 Btu/hft²°F)	1.98 (11.11 hft²°F/Btu)
Ceramics slabs	1.30 (1/2")		
Air layer	15.24 (6”)		
Rigid fiberglass insulation	3.00 (1 3/16”)		
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Ceramic perforated brick	9 (3 9/16”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type C+	163.69 (5’- 4 1/4”)	0.203 (0.03 Btu/hft²°F)	4.918 (33.33 hft²°F/Btu)
Ceramics slabs	1.30 (1/2")		
Air layer	15.24 (6”)		
Rigid fiberglass insulation	3.00 (1 3/16”)		
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete column	140 (4’-7”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type D+	43.69 (17 3/16”)	0.631 (0.11 Btu/hft²°F)	1.584 (9.09 hft²°F/Btu)
Ceramics slabs	1.30 (1/2")		
Air layer	15.24 (6”)		
Rigid fiberglass insulation	3.00 (1 3/16”)		
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete beam	20 (7 7/8”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type E+	53.69 (1’-9 1/16”)	0.537 (0.09 Btu/hft²°F)	1.861 (11.11 hft²°F/Btu)
Ceramics slabs	1.30 (1/2")		
Air layer	15.24 (6”)		
Rigid fiberglass insulation	3.00 (1 3/16”)		
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Concrete column	30 (11 13/16”)		
Gypsum plaster	1.60 (5/8”)		
Wall Type F+	33.64 (1’- 1 3/16”)	0.49 (0.08 Btu/hft²°F)	2.022 (12.50 hft²°F/Btu)
Ceramics slabs	1.30 (1/2")		
Air layer	15.24 (6”)		

Rigid fiberglass insulation	3.00 (1 3/16”)		
Ceramic tile	0.95 (3/8”)		
Plaster mortar	1.60 (5/8”)		
Ceramic perforated brick	9 (3 9/16”)		
Plaster mortar	1.60 (5/8”)		
Ceramic tile	0.95 (3/8”)		
Roof	38.77 (15 ¼”)	1.55[25] (0.27 Btu/hft²°F)	0.64 (3.70 hft²°F/Btu)
Corrugated fiber cement sheets	5.72 (2 ¼”)		
Wood structure	2.54 (1”)		
Air space	7 (2 ¾”)		
Ribbed concrete slab	22.56 (8 7/8”)		
Dry wall ceiling	0.95 (3/8”)		

Table 21 - Retrofit Case 2 exterior walls, floors and ceiling thermal properties.

6.5.1. OTTV Calculation Results

The OTTV table was developed based on the baseline with information regarding wall’s thermal properties changed to reflect the new solution.

DECEMBER 22nd					
Orientation	Wall Type	Qw	Qg	Qs	OTTV (W/m²)
East	A	13.37	2212.59	4057.99	12.51
	B	304.07			
	C	6.73			
	D	206.04			
	Total	530.21			
North	A	5.03	1096.20	3795.79	11.95
	B	274.79			
	D	161.92			
	E	57.98			
	F	14.21			
	Total	513.93			

[25] From (INMETRO, 2013)

West	B	2434.41	237.99	9164.40	25.95
	D	923.49			
	E	418.94			
	F	123.21			
	Total	3900.06			
South	A	30.05	1096.20	21662.15	52.89
	B	608.71			
	D	361.80			
	E	128.44			
	F	31.48			
	Total	1160.46			

Table 22 - Retrofit Case 2 OTTV for December 22nd.

Altering wall's composition and thermal property values reduced significantly the heat transmission associated to opaque elements. The larger impact occurs in the west façade, where the area of opaque elements is larger and the insolation values are higher.

JUNE 22nd					
Orientation	Wall Type	Qw	Qg	Qs	OTTV (W/m²)
East	A	11.65	0	3498.27	6.67
	B	67.67			
	C	1.50			
	D	45.85			
	Total	126.68			
North	A	19.71	0	29711.84	68.02
	B	555.30			
	D	327.20			
	E	117.17			
	F	28.72			
	Total	1048.09			
West	B	1757.57	0	8326.10	21.73
	D	666.74			
	E	302.47			
	F	88.95			
	Total	2815.73			
South	A	11.83	0	3272.23	7.51
	B	61.16			
	D	36.35			
	E	12.90			
	F	3.16			
	Total	125.40			

Table 23 - Retrofit Case 2 OTTV for June 22nd.

In the winter months, the higher contribution occurs in the north façade. In these months, the insolation is higher in this same façade, justifying the contribution of the windows through solar radiation.

6.5.2. Simulation Model Results

The annual electric use composition and the cooling loads results from the simulation of this study case are shown in Figure 50 below.

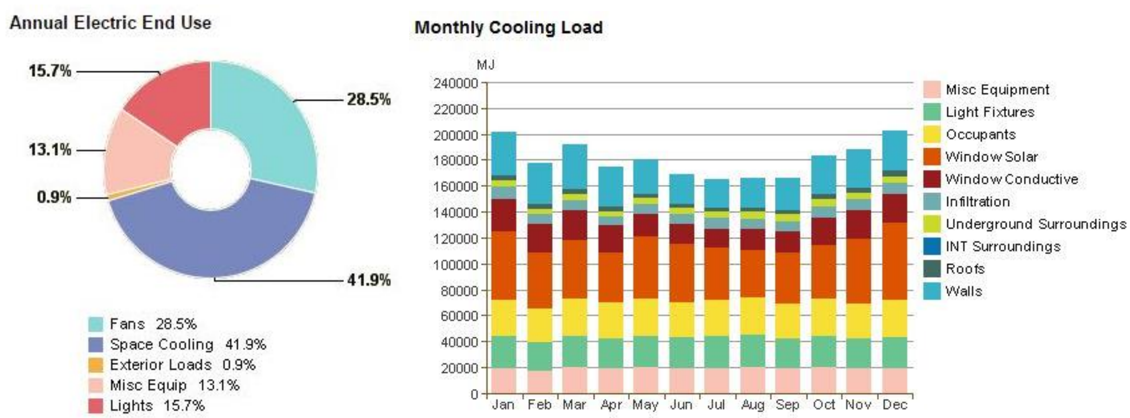

Figure 50 - Retrofit Case 1 monthly peak demand - From Green Building Studio.

The electricity associated to space cooling reduced from 42.2% in the baseline building to 41.9% in this study case. When analyzing the monthly cooling loads, the loads reduced significantly, in particular, the contributions from walls, of around 73%.

The monthly peak demand also presented a reduction in comparison to the baseline building, of approximately 8 kW, as shown in Figure 51.

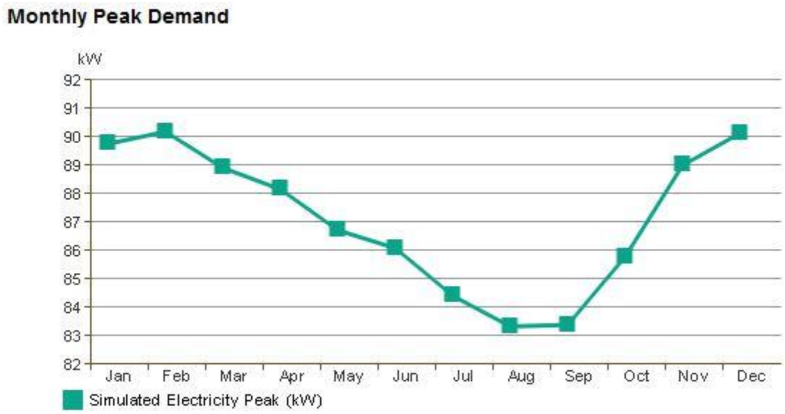

Figure 51 - Retrofit Case 2 monthly peak demand - From Green Building Studio.

The total Energy Use Intensity associated is 170 kWh/m²/year (15.80 kWh/sf/year) for electricity use, and 257 MJ/m²/year (22.64 kBtu/sf/year) for fuel use, adding to a total of 871 MJ/m²/year (76.72 kBtu/sf/year). These numbers represent an improvement of 8.82% in the electricity use and an improvement of 5.74% in the total consumption, compared to the baseline building. These results represent a good improvement when compared to the reductions calculated in the OTTV tables.

6.5.3. Payback period calculations

According to researches on manufacturing and construction websites, as well as magazines (Rocha, 2011), the average price for a ventilated façade system is R$ 350 /m² ($106.06 /m²) including material and installation price. The total price for the ventilated façade case is, therefore, R$ 1,295,000 ($392,424.24).

The payback will happen in 52.8 years, as follow:

$$Ni\ (years) = \frac{R\$\ 1{,}295{,}000}{\left(362{,}880\frac{kWh}{year} - 333{,}376.92\frac{kWh}{year}\right)\ x\ R\$0.83} = \frac{R\$\ 1{,}295{,}000}{R\$\ 24{,}487.56/year} = 52.8\ years$$

6.6. Retrofitting Case 3: Natural Ventilation

The first step in defining how to apply strategies that improve natural ventilation conditions involve evaluating the existing conditions associated with the baseline. The following figure represents the prevailing winds and their interaction with the existing building.

Figure 52 - Winds incidence in a typical floor on the baseline building representing summer conditions(left) and winter conditions (right).

As shown in Figure 52, during summer conditions, all apartments are receiving winds in directions and intensity that contribute to cross ventilation inside the spaces. The apartments configuration allows the airflow to enter from the living room and bedrooms and exit through the kitchen, contributing to the air quality in those spaces but requiring open doors to allow a complete path between the positive and negative pressure zones. The apartment located in the northwest corner presents the worst condition in comparison to the rest. The Wind incidence angle hitting the north facade is close to 90 degrees (in relation to a perpendicular axis from the window), reducing the velocity and frequency of winds entering through these windows. Buoyancy effects are most likely to happen in this apartment, especially considering the combination of sun radiation in the west and north facade, contributing to insing interior temperatures. At nights when door are frequently closed for privacy necessities, the ventilation shifts to a single sided solutions since each room has a single opening to the exterior.

During the winter, wind velocity is higher and the direction has larger frequencies when compared to summer conditions. In similarity to the situation on the north facade during summer, the wind direction hitting the building's east facade have a high incidence angle, creating a negative pressure zone along that facade. The ventilation in the southeast apartment can occur from the kitchen and into the other spaces around 38.5% of the time. The apartment located in the northwest corner is receiving winds at low speeds and frequencies, indicating that buoyancy effects are most likely to occurs.

Based on this analysis, the strategies used in the final proposition are wing walls, integrating with vertical shading elements proposed in the retrofitting case 1, and different types of window openings to improve wind-driven air flows and to promote entrances and exits facilitating the buoyancy effect.

Figure 53 - Typical floor plan with the addition of wing walls.

Figure 53 represents the impacts on wind-driven ventilation with the use of wing walls in the baseline building. These elements, indicated in boxes “A”, are generating a larger area of positive pressure and directing the airflow to the adjacent window. The wing walls presented in these boxes are the vertical shading elements dimensioned in retrofitting case 1, representing an integration between one strategy and another. The box “B” indicates the use of a wing wall as well, but using a transparent material. The east façade, as well as the northeast and southeast corners, have valuable views to the river. The use of an opaque vertical element adjacent to the window would partially block a valuable view.

To improve stack effect ventilation, the bedroom and living room windows were modified as shown in figure 54. In buoyancy patterns, the airflow will be stronger the larger the vertical separations between inlets and outlets are, and the larger the difference between indoor and outdoor temperatures (Allocca, Chen, & Glicksman, 2003).

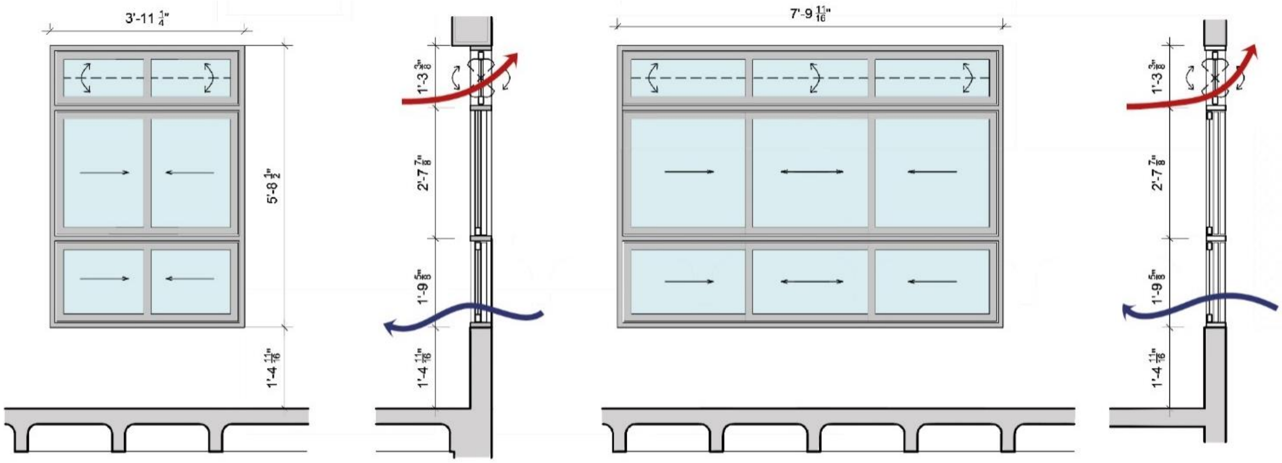

Figure 54 - New windows proposed for Retrofit Case 3.

As shown in the figure above, the bedroom window (left) is elongated to reach the same height as the living room window, and two separated parts were added. At the top, a pivoting window along a horizontal axis is included, to allow warm air to exit and to allow this part to be left open even during rainy moments. At the bottom, sliding windows were added to allow maximum ventilation entry. Using the same logic, the living room window was subdivided into the same three parts.

Dividing the windows into different sections generates a versatility of options, where each part can be combined to provide maximum efficiency depending on the situation. The impact of the user in these alternatives is important since he will need to manually adjust each section. Adding extra window area can also impact negatively on the final thermal transfer value since it is adding transparent areas that are vulnerable to solar incidence, but improvements in ventilation overcome the added heat gain. The following figure represents the impact of improving natural ventilation in the overall comfort sensation. As shown, increasing natural ventilation in interior spaces can contribute to around 60% of improvement to comfort sensations.

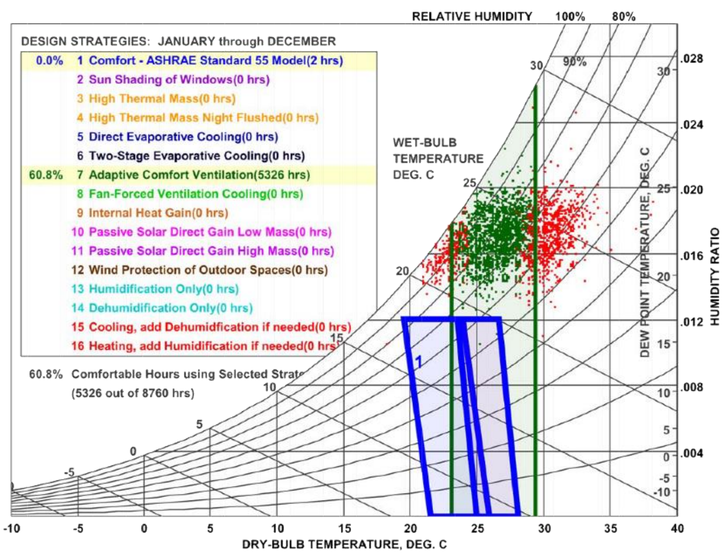

Figure 55 - Recife's psychometric chart representing contribution of natural ventilation.

A negative effect of modifying these windows is the price increase of the product. The new subdivisions imply in extra aluminum profiles, using more material. Analyzing the overall benefits of applying these strategies, the positive aspects overcome the negative, and the price invested in larger windows is paid back with the decrease in electricity use.

7. Results

Each retrofit case presented a contribution toward reducing the electricity consumption of the building. One option approached transparent surfaces, the other addressed to opaque surfaces and the third contributed with both options by improving the natural ventilation. Figure 56 bellow represents the differences obtained between the cases and the baseline in terms of Overall Thermal Transfer Value and provides what would be the combination of all strategies into one single option.

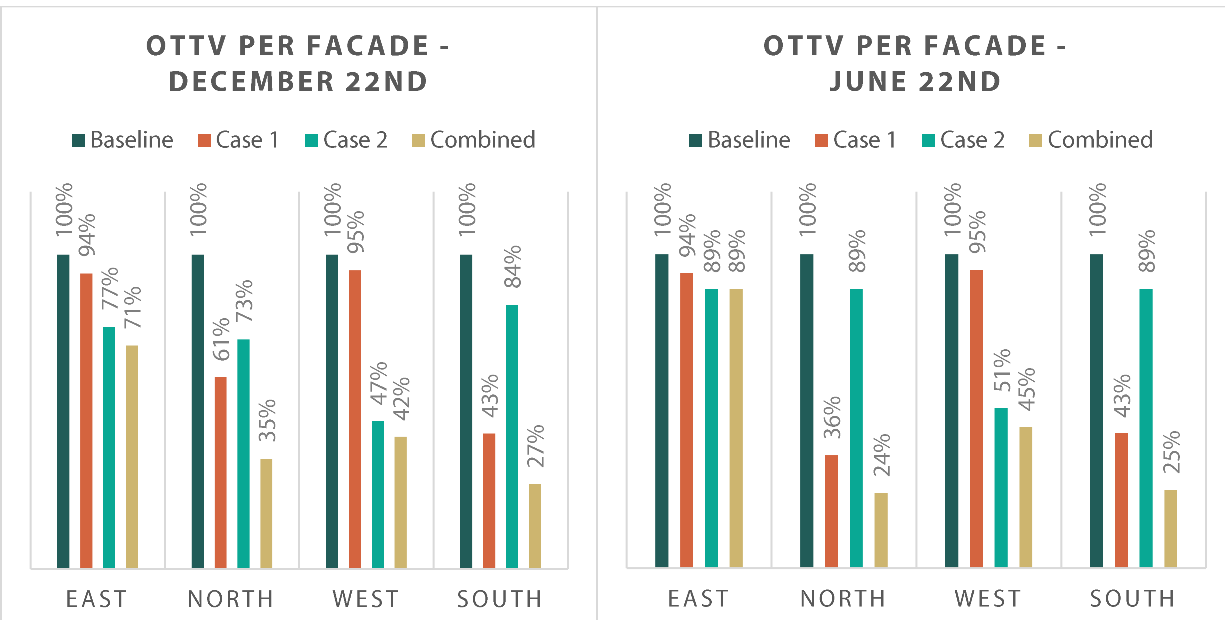

Figure 56 - OTTV results comparison for December and June.

In all cases, the North, West and South orientations presented the lowest values of thermal transfer, with the North orientation presenting higher improvements during winter and the South during summer. This result is compatible with the sun's positioning through the year. The East orientation demonstrated the lowest improvement in comparison to the rest since the sun's incidence occurs only in the mornings and with lower intensities. The combination of all strategies can reduce heat gains up to 76%, such as presented in the North orientation in June.

The following figure (Figure 57) represents cooling loads associated with the building's external envelope, both opaque and transparent surfaces.

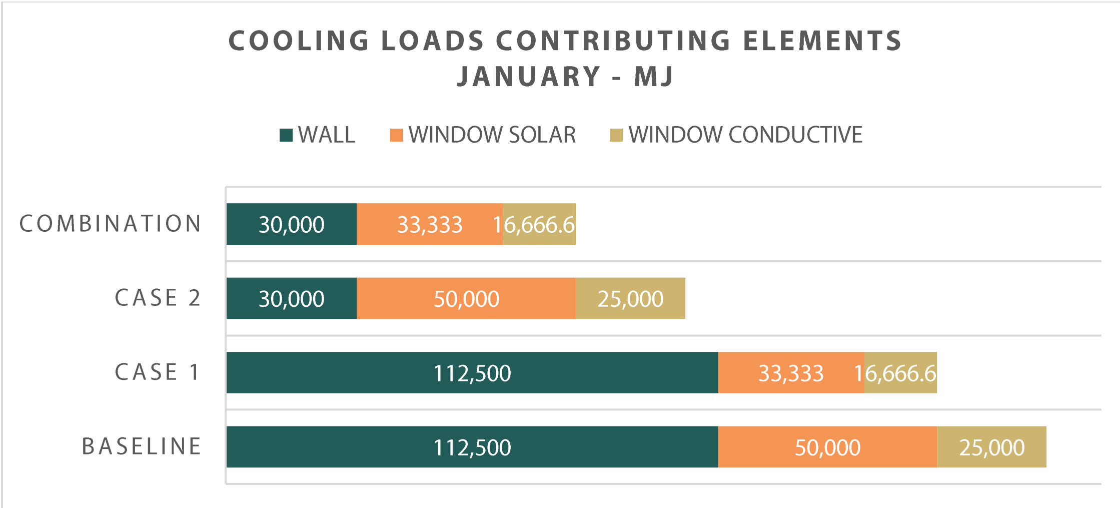

Figure 57 - Comparison of cooling loads and contributing elements.

In Case 1, the window solar and conductive contribution reduced, as expected. When comparing to the reduction in Thermal Transfer Value, the simulation presented a larger reduction than the mean results obtained in the calculations. The OTTV resulted in a mean improvement of 26.75% while the simulations improved around 33%. In Case 2, the reductions in wall contributions are significantly high both in the simulation and in the Thermal Transfer Values.

The following figure (Figure 58) represents the comparison in total energy use of all cases as well as the combination into a final one.

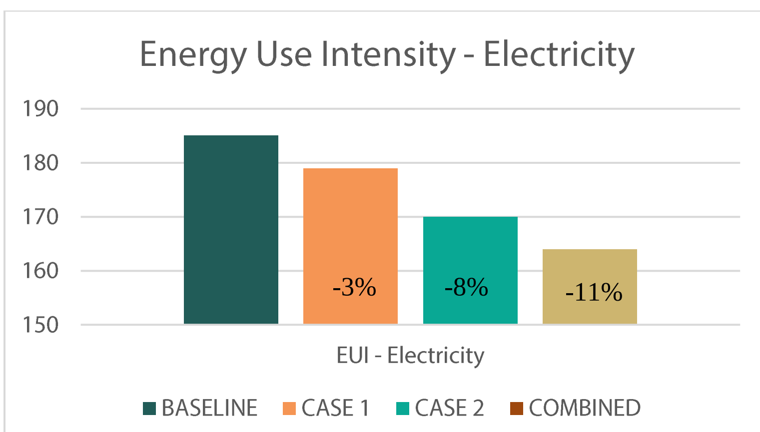

Figure 58 - Comparison results of total EUI.

When comparing Case 1 and Case 2 with the baseline, the total energy use reduces with each situation in 3% and 8% in sequence, as shown in Figure 59. The combined option represents

11% of improvement in the energy use. When comparing with the OTTV results, the simulated total reductions are lower than expected, but still represent significant improvements. These reductions when associated to the value paid in electricity, reflects in the data below (Table 24).

Building's annual electricity bill			
Baseline	**Case 1**	**Case 2**	**Combined**
R$ 362,800.00 [$ 109,939.40]	R$ 350,723.52 [$ 106,279.85]	R$ 333,376.92 [$ 101,023.31]	R$ 321,300.44 [$ 97,363.77]

Table 24 - Cases energy cost per year.

As shown, when associating values to the total annual building energy use, the combined situation can provide savings of R$ 31,767.25 ($ 12,575.63) per year. Although significant, these values need to be associated with the total investment cost in each retrofit case, to provide an idea on the viability of the solution. The following table (Table 25) represents a comparison of cases in terms of payback periods.

Retrofit payback period		
Case 1	**Case 2**	**Combined**
8.65 years	52.8 years	55.35 years

Table 25 - Payback period comparison.

As shown, the addition of an overhang and modifying window properties appears as the only viable option when considering payback period. In general, families live in the same location between ten to fifteen years, and therefore the investment in a ventilated façade or a combination of both strategies would go beyond the timeframe where the initial investor would get the financial payback. Case 2 and the combined strategy require an investment from governments or other public entities to be able to validate the modifications.

Case 3 does not have quantifiable measurements since natural ventilation presents many variables that are not measured by OTTV calculations nor simulation using Revit 2016. This case presents qualitative results. As shown in the psychometric chart, natural ventilation can provide 60% of hours of comfort in a year, and when associated with the other cases, improves significantly their performances. The inclusion of natural ventilation strategies decreases up to 25% the building’s electricity consumption.

8. Conclusions

The results exemplify that not all building retrofit strategies are applicable when only considering the owner's investment or a single building element, such as the building envelope. When analyzing payback calculations for the proposed cases, the radical option of changing the entire building's façade proved to be a too expensive investment. Although these elements alone might not generate enough savings to overcome the investment cost, when associated with other retrofit strategies such as the use of efficient household equipment and air conditioning systems, integrated daylight and artificial lighting systems, and uses of alternate sources of energy such as solar heating, have the potential to generate a larger positive impact. The contributions of 11% in savings from the building envelope might go up to 40% when the entire building is considered as a system. Integrating these basic strategies at the beginning of the design process is also fundamental, since it has the potential to provide the same or even more benefits, with a lower or no extra investment cost.

When analyzing the improvement at the city level, an 11% reduction due to envelope changes in one single building multiplied by the number of similar typologies distributed in all Brazilian urban centers, can generate a significant number of savings, benefiting both the user and the city itself. Each efficiency improvement in energy removes a cost that the city and its residents no longer have to pay (WRI, 2016). According to the World Resources Institute, every $1 invested in efficiency measures saves $2 in new power plants and electricity distribution (WRI, 2016). Local governments must play a significant role in reshaping the cities, interrupting the idea of "business as usual" that has been leading to decades of inefficiencies, and placing the building sector in the path to meet the envisioned sustainability goals. Governments and decision maker must take action in implementing building efficiency codes and standards, establishing efficiency improvement targets, provide incentives and finance as well as engage building owners, managers, and occupants to contribute towards a sustainable development.

The research showed, therefore, that there are available solutions to be applied in existing building that reduce their energy demand and improve interior thermal comfort, but not all changes can be performed by the building owner itself. There is the need of a collaboration between local governments to facilitate these retrofits, transforming them into viable and replicable strategies.

Future work involving the context of this research might investigate the application of the same retrofit elements in a typical mid-rise residential building in a different location. Applying in a city with similar climate characteristics but a worse energy mix, dependable of non-renewable sources. The improvements might be higher is this new context.

Another opportunity could involve investigating the effects of using efficient household equipment to lower energy consumption associated to plug loads. As shown in section 3.4 (Energy Consumption), refrigerators represent the highest use of electricity in a household in Brazil's Northeast region, representing another target for efficiency measures.

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10. Appendix A

ENERGY CONSUMPTION PER SECTOR - 2013					
Location	**Total consumption (TWh)**	**Industrial (%)**	**Residential (%)**	**Services (%)**	**Other (%)**
Portugal	46.2	34.4	27.9	34.6	3.1
Colombia	50.9	30.5	40.9	23.9	4.7
Czech Rep.	56.7	40.0	25.8	24.5	9.7
Chile	61.5	56.4	16.0	13.2	14.4
Finland	80.8	47.3	27.5	22.1	3.1
Norway	108.8	40.3	34.2	22.9	2.6
Argentina	125.2	40.4	30.8	23.7	5.1
Sweden	127.3	42.5	30.5	24.2	2.8
New York (US)	143.2	9.5	35.4	53.1	2.0
Illinois (US)	143.5	31.5	32.7	35.4	0.4
Quebec (CAN)	167.6	39.6	37.5	21.8	1.1
South Africa	197.1	59.5	19.7	14.3	6.5
Mexico	233.8	62.7	22.6	9.6	5.1
Spain	240.3	30.2	31.2	33.4	5.2
California (US)	259.5	18.1	34.7	46.9	0.3
Italy	296.7	40.6	23.4	30.4	5.6
United K.	317.6	30.8	36.1	30.6	2.5
Texas (US)	365.1	25.9	37.6	36.5	0.0
France	434.1	26.3	36.5	32.1	5.1
South Korea	481.4	52.1	13.3	31.7	2.9
Brazil	498.4	42.1	23.6	24.0	10.3
Germany	525.8	43.0	26.1	28.6	2.3
Russia	740.3	45.7	17.9	21.9	14.5
India	868.7	44.1	22.0	8.8	25.1
Japan	922.7	29.9	31.1	36.1	2.9
China	4,128.1	67.7	15.1	5.9	11.3

Source: (Arnau, 2015)

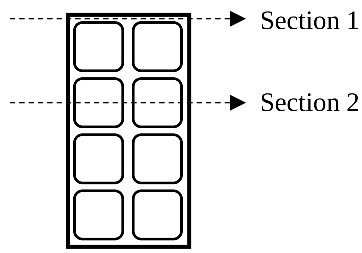
11. Appendix B

December 22nd													
	06am	**07am**	**08am**	**09am**	**10am**	**11am**	**12pm**	**1pm**	**2pm**	**3pm**	**4pm**	**5pm**	**6pm**
S	59	220	301	331	336	332	327	332	336	331	301	220	59
SE	124	492	661	665	571	420	251	89	63	58	48	33	10
E	121	495	663	645	509	302	68	68	63	58	48	33	10
NE	53	228	304	279	158	68	68	68	63	58	48	33	10
N	10	33	48	58	63	68	68	68	63	58	48	33	10
NW	10	33	48	58	63	68	68	68	185	279	304	228	53
W	10	33	48	58	63	68	68	302	509	645	663	495	121
SW	10	33	48	58	63	89	251	420	571	665	661	492	124
H	30	214	484	730	930	1062	1103	1062	930	730	484	214	30
Total					971		531			1092	1070		
March / September 22nd													
S	0	30	48	55	63	68	65	68	63	55	48	30	0
SE	16	342	473	439	322	154	65	68	63	55	48	30	0
E	22	490	705	689	547	326	65	68	63	55	48	30	0
NE	16	368	552	567	488	347	164	68	63	55	48	30	0
N	0	49	104	146	181	204	205	204	488	146	104	49	0
NW	0	30	48	55	63	68	164	347	488	567	552	368	16
W	0	30	48	55	63	68	65	326	547	689	705	490	22
SW	0	30	48	55	63	68	65	154	322	439	473	342	16
H	0	185	466	739	954	1091	1129	1091	954	739	466	185	0
Total					854		400			945	905		
June 21st													
S	-	23	43	50	58	60	63	60	58	50	43	23	-
SE	-	130	201	143	58	60	63	60	58	50	43	23	-
E	-	316	573	586	477	285	63	60	58	50	43	23	-
NE	-	329	634	714	682	568	421	250	89	50	43	23	-
N	-	163	349	454	521	553	569	553	521	454	349	163	-
NW	-	23	43	50	89	250	421	568	682	714	634	329	-
W	-	23	43	50	58	60	63	285	477	586	573	316	-
SW	-	23	43	50	58	60	63	60	58	143	201	130	-
H	-	105	351	587	773	904	946	904	773	587	531	105	-
Total					1114		758			1140	1008		

Latitude 8° South. Solar Radiation over vertical and horizontal surfaces in W/m². (Frota & Schiffer, 2001)

12. Appendix C

Perforated ceramic block Resistance calculation



Section 1:

$A1 = 0.0019m^2$

$R1 = \frac{0.10}{0.90} = 0.1111$

Section 2:

$A2 = 0.04x0.19 = 0.0076m^2$

$R2 = \frac{0.015}{0.90} + 0.16 + \frac{0.01}{0.90} + 0.16 + \frac{0.015}{0.90} = 0.3644$

$Rblock = \frac{4xA1 + 4A2}{\frac{5xA1}{R1} + \frac{4xA2}{R2}} = 0.236$

Wall type B Resistance calculation

Section a (ceramic + plaster + mortar + plaster):

$Aa = 0.01x0.19 + 0.01x0.2 = 0.0039m^2$

$Ra = \frac{0.01}{1.30} + \frac{0.015}{1.15} + \frac{0.09}{1.15} + \frac{0.015}{1.15} = 0.112$

Section b (ceramic + plaster + block + plaster):

$Ab = 0.19x0.19 = 0.0361m^2$

$Rb = \frac{0.010}{1.30} + \frac{0.015}{1.15} + 0.236 + \frac{0.015}{1.15} = 0.2697$

$Rwall = \frac{0.0039 + 0.0361}{\frac{0.0039}{0.112} + \frac{0.0361}{0.2697}} + 0.13 + 0.04 = 0.407$

Wall type A Resistance calculation

Only section (ceramic tile + plaster + concrete + gypsum plaster):

$$R = \frac{0.01}{1.30} + \frac{0.015}{1.15} + \frac{1.20}{1.75} + \frac{0.015}{0.70} = 0.728$$

$$Rt = \frac{1}{\frac{1}{0.728}} + 0.13 + 0.04 = 0.8978$$

Wall type C Resistance calculation

Only section (ceramic tile + plaster + concrete + gypsum plaster):

$$R = \frac{0.01}{1.30} + \frac{0.015}{1.15} + \frac{1.40}{1.75} + \frac{0.015}{0.70} = 0.84213$$

$$Rt = \frac{1}{\frac{1}{0.84213}} + 0.13 + 0.04 = 1.0121$$

Wall type D Resistance calculation

Only section (ceramic tile + plaster + concrete + gypsum plaster):

$$R = \frac{0.01}{1.30} + \frac{0.015}{1.15} + \frac{0.20}{1.75} + \frac{0.015}{0.70} = 0.1564$$

$$Rt = \frac{1}{\frac{1}{0.1564}} + 0.13 + 0.04 = 0.3264$$

Wall type E Resistance calculation

Only section (ceramic tile + plaster + concrete + gypsum plaster):

$$R = 0.00769 + 0.01304 + 0.1714 + 0.0214 = 0.21353$$

$$Rt = \frac{1}{\frac{1}{0.21353}} + 0.13 + 0.04 = 0.3835$$

Wall type F Resistance calculation

Section a:

$$Aa = 0.01x0.19 + 0.01x0.2 = 0.0039m^2$$

$$Ra = \frac{0.01}{1.30} + \frac{0.015}{1.15} + \frac{0.09}{1.15} + \frac{0.015}{1.15} + \frac{0.01}{1.30} = 0.11976$$

Section b (ceramic + plaster + block + plaster):

$$Ab = 0.19x0.19 = 0.0361m^2$$

$$Rb = \frac{0.010}{1.30} + \frac{0.015}{1.15} + 0.236 + \frac{0.015}{1.15} + \frac{0.010}{1.30} = 0.27746$$

$$Rwall = \frac{0.0039 + 0.0361}{\frac{0.0039}{0.11976} + \frac{0.0361}{0.27746}} + 0.13 + 0.04 = 0.416$$

13. Appendix D