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Renovation of Brazilian Buildings to Achieve Better Energy Efficiency and Indoor Environmental Quality



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## Renovation of Brazilian Buildings to Achieve Better Energy Efficiency and Indoor Environmental Quality

Master's Dissertation International Master in Sustainable Build Environment

Work supervised by

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#### Resumo

Ao longo dos anos as preocupações ambientais começaram a ganhar cada vez mais importância. Mundialmente, o setor da construção civil é um dos principais responsáveis pelo consumo de energia primária e emissão de dióxido de carbono (CO<sub>2</sub>). A sustentabilidade dos edifícios é hoje um vetor de progresso e mitigar o impacto da construção, dos materiais e dos equipamentos e sistemas em funcionamento com o foco no aproveitamento dos recursos e poupanças energéticas é um desafio que várias organizações internacionais procuram resolver. No Brasil, após a implementação, em 2010, do Regulamento Técnico da Qualidade para Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos – RTQC, considera-se que o próximo passo a ser dado em termos regulatórios seja analisar o padrão de consumo de energia das edificações. A reabilitação pode ser a chave para recuperar o setor da construção permitindo a otimização do desempenho energético de um edifício de modo a minimizar os consumos de energia da edificação e ao mesmo tempo ir de encontro às necessidades dos ocupantes. Assim, foi realizado um inquérito relacionado com o conforto dos trabalhadores de edifícios de escritórios localizados na cidade de Porto Alegre, estado do Rio Grande do Sul - Brasil, a fim de identificar os principais fatores de desconforto dos funcionários em seu local de trabalho, relacionados com o conforto térmico e acústico, iluminação, ventilação e qualidade do ar interior. O outro objetivo deste estudo foi criar um modelo virtual de edifício de escritórios, com características baseadas na revisão da literatura e nos resultados do inquérito, para realizar uma avaliação da demanda de energia. Diferentes soluções de reabilitação foram analisadas com o objetivo de identificar a mais adequada, com o melhor desempenho energético, para a renovação de edifícios de escritório. Os cenários com fachada com sistema ETICS, obtiveram os melhores e piores desempenho. A combinação com o pior desempenho foi a solução de reabilitação com sistema ETICS, vidro simples, sistemas de iluminação e HVAC conforme definido para o modelo base e sem adição de dispositivos de sombreamento. Enquanto as duas melhores soluções, ambas com bom desempenho energético total, também possuíam o sistema ETICS na sua composição, uma delas englobando vidro simples, sistemas de iluminação e HVAC (opção Best Practice) e sem nenhum sistema de sombreamento e a outra, contendo vidro duplo, sistemas de iluminação e HVAC (modelo base) e adição de sistema de sombreamento. Mediante os resultados obtidos neste estudo foi possível concluir que, por meio da aplicação de várias medidas de reabilitação, é viável tornar um edifício energeticamente mais eficiente, reduzindo as suas necessidades energéticas e melhorando a qualidade de vida dos ocupantes.

**Palavras-chave**: Eficiência Energética, Qualidade do Ambiente Interior, Conforto Térmico, Reabilitação, Bem-estar.

#### **Abstract**

Over the years, environmental concerns began to gain more and more importance. Worldwide, the construction sector is one of the main responsible for the consumption of primary energy and the emission of carbon dioxide  $(CO_2)$ . The sustainability of buildings is now a vector for progress and mitigating the impact of construction, materials, equipment and systems in operation with a focus on the use of resources and energy savings is a challenge that several international organizations seek to solve. In Brazil, after the implementation, in 2010, of the Technical Quality Regulation for Energy Efficiency of Commercial, Office and Public Buildings - RTQC, it is considered that the next step to be taken in regulatory terms is to analyze the pattern of energy consumption of buildings. Rehabilitation may be the key to recover the construction sector, allowing the optimization of the energy performance of a building to minimize the energy consumption and at the same time meet the needs of the occupants. Thus, a survey related to the comfort of workers at office buildings in the city of Porto Alegre, located in the state of Rio Grande do Sul - Brazil was carried out in order to identify the main causes of employees' discomfort at the workplace, related to thermal and acoustic comfort, lighting, ventilation and indoor air quality. The other objective of this study was to create a virtual model of an office building, with characteristics based on the literature review and the survey results, to carry out an energy demand assessment. Different renovation solutions were analyzed, aiming to identify the most adequate ones, with the best energy performance. The scenarios with façade with ETICS system obtained the best and worst performance. The combination with the worst performance was the renovation solution with ETICS system, simple glass, lighting systems and HVAC as defined for the base model and without the addition of shading devices. While the two best solutions, both with good total energy performance, also had the ETICS system in their composition, one of them encompassing simple glass, lighting systems and HVAC (Best Practice option) and without any shading system and the other, containing glass double, lighting and HVAC systems (base model) and addition of shading system. Based on the results obtained in this study, it was possible to conclude that, through the application of various renovation measures, it is feasible to make a building more energy-efficient, reducing its energy demand and improving the quality of life of the occupants.

**Keywords**: Energy efficiency, Indoor Environmental Quality, Thermal Comfort, Renovation, Well-Being.

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### **List of Abbreviations**

**ABNT** - Associação Brasileira de Normas Técnicas / Brazilian Association of Technical Standards

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

**BEN -** Balanço Energético Nacional / National Energy Balance

**CBCS** – Conselho Brasileiro de Construção Sustentável / Brazilian Council for Sustainable Construction

Cfa - Humid Subtropical Climate

CGIEE - Energy Efficiency Indicators and Levels Management Committee

CO<sub>2</sub> - Carbon Dioxide

CO - Carbon Monoxide

**COP** – Coefficient of Performance

**dB** - Decibels

**DOE** - North American Department of Energy

**EPE** - Empresa de Pesquisa Energética / Energy Research Company

**ETICS** - External Thermal Insulation Composite System

**GDP** - Gross Domestic Product

**GHG** - Greenhouse Gas

GtCO<sub>2</sub> - Gigatonne of Carbon Dioxide

**HVAC** - Heating, Ventilating and Air-Conditioning Systems

IAQ - Indoor Air Quality

**IEA** - International Energy Agency

**IEQ** - Indoor Environmental Quality

INMETRO - Instituto Nacional de Metrologia Normalização e Qualidade Industrial / National Institute of Metrology Standardization and Industrial Quality

**ISO** - International Organization for Standardization

**LBNL** - Lawrence Berkeley National Laboratory

**LEED** - Leadership in Energy and Environmental Design

**LED** - Light-Emitting Diodes

MIT - Massachusetts Institute of Technology

MME - Ministério de Minas e Energia / Ministry of Mines and Energy

Mt - Megaton

NO<sub>x</sub> - Nitrogen Oxides

O<sub>3</sub>- Ozone

PM - Particulate Matter

PV - Solar Photovoltaic Panel

**RHE** - Rotating Heat Exchangers

**RTQ-C** - Regulamento Técnico da Qualidade para o. Nível de Eficiência Energética de Edificações. Comerciais, de Serviços e Públicas / Technical Quality Regulation for Commercial, Office and Public Buildings

**SBS** - Sick Building Syndrome

**SDGs** - Sustainable Development Goals

**UN** - United Nations

**UNCED** - United Nations Conference on Environment and Development

**UNFCC** - United Nations Framework Convention on Climate Change

**USA -** United States of America

**VOCs** - Volatile Organic Compounds

**VRF** - Variable Refrigerant Flow

WHO - World Health Organization

WWR - Window to Wall Ratio

**WCED** - World Commission on Environment and Development

WGBC - World Green Building Council

#### 1. Introduction

### 1.1 Background

Throughout history, humankind has sought the way to perfection. The evolution of knowledge, such as science and technology, has allowed the society to understand how to transform energy and use it systematically, for the benefit of social welfare. The Industrial Revolution that started in the middle of the 1700s, and the major milestone of the energy use was originated in this period of the time, which redesigned not only lifestyles but also economic activity. The planet's population increased significantly reaching 1 billion by 1800 and then doubling again by 1926. By the beginning of the 21<sup>st</sup> century, it had grown up to 6 billion (Folk, 2018).

The population growth has affected the production and consumption of products and services, the use of resources (renewable and non-renewable), mobility, transport, health, education, information, thus creating new behavior patterns in society. Due to the current energy paradigm, namely the global dependence of fossil fuels when using coal as a power source for industry, from energy generation to manufacturing, the challenge of climate change and environmental issues related to different sectors emerged (Folk, 2018).

The construction industry is one of several energy-consuming sectors worldwide (International Energy Agency [IEA] & United Nations [UN], 2017). The building sector has significant impacts on the environment, wellbeing and economy. Within this sector, there are two main types of buildings: residential and non-residential (commercial and office buildings). Commercial buildings represent 23% of the European Union (EU) building stock, according to the European Commission Website (2019). The Commission also states that 1 in every 6 Citizens works in offices. A healthy and comfortable indoor environment is a basic premise in all buildings, bearing in mind that people spend 90% of their lives indoors (Attema, Fowell, Macko & Neilson, 2018). When considering office buildings, employees spend 2 080 hours in office spaces every year (Attema, Fowell, Macko & Neilson, 2018), making the indoor environmental quality (IEQ) a significant aspect for their health and wellbeing.

According to the National Energy Balance (BEN) (Empresa de Pesquisa Energética [EPE], 2019), the industrial, residential and commercial sectors accounted for approximately 80% of the consumed

electricity in Brazil in 2018. About 42.3% of electricity consumption comes from the building sector, and commercial buildings represent 16.9% of the total electricity consumption (EPE, 2019). In Brazil, the electricity matrix is predominantly hydraulic, around 66.6% (EPE, 2019). However, in recent years the country has faced a severe water crisis that resulted in the replacement of hydroelectric by thermoelectric generation. Brazil also uses more non-renewable energy in its internal energy supply, about 54.7% (EPE, 2018).

The construction sector has an important role in terms of energy demand and carbon dioxide (CO<sub>2</sub>) emissions, being one of the leading causes of the greenhouse effect. Therefore, energy savings and reduction of CO<sub>2</sub> emissions must be adequately addressed at the political level to mobilise the market for a low energy and greenhouse gas (GHG) society, which can bring significant benefits to the country, such as positive socio-environmental impacts.

This improvement can be achieved by adopting construction strategies that guarantee good indoor environmental quality, energy efficiency, and low CO<sub>2</sub> emission and is a way of minimising socio-environmental impacts and maximise the economic performance of buildings. Improving the energy performance of existing buildings is fundamental for reducing the emission of greenhouse gases as well as to mitigate climate changes (Giuli, Pos, & Carli, 2012). Besides that, the problems with indoor environmental quality at a building (thermal, acoustic, visual comfort and air quality) can be directly related to the comfort, health and productivity of the occupants (Giuli, Pos, & Carli, 2012).

To ensure a good indoor environment inside an office building where people feel good, perform well and minimise the risk of building related health problems, it is necessary to combine solutions that promote energy efficiency and contribute to a better indoor environmental quality. To guarantee the indoor environmental quality and a sustainable construction, the main comfort conditions as heating, cooling, lighting, indoor air quality (IAQ) and acoustic insulation must be considered. Projecting a future scenario, the National Energy Plan - 2030 (Ministério de Minas e Energia [MME] & EPE, 2007) predicts that with energy efficiency actions, the trend of increasing demand for energy consumption in Brazil may decrease if government policies in this sector continue. Regulations, studies and procedures to minimise this consumption have been elaborated, establishing parameters that describe the minimum efficiency of the buildings.

One of the reasons for the concern with the rationalisation of energy in buildings in Brazil began with the crisis in the electricity sector that occurred in 2001, which led the government to be also concerned with issues related to the rational end-use of electricity and its efficient use. Through Law No. 10.295 of December 19, 2001, the Energy Efficiency Indicators and Levels Management Committee (CGIEE) was established and regulated. In this law, it was accepted that "maximum levels of energy consumption, or minimum energy efficiency, should be created for energy-consuming equipment and devices manufactured or commercialised in the country, as well as for existing buildings". Among its main actions, is the development of the Technical Quality Regulation for Energy Efficiency of Commercial, Office and Public Buildings - RTQ-C (Instituto Nacional de Metrologia Normalização e Qualidade Industrial [INMETRO], 2010).

The labelling of commercial, office and public buildings must meet the requirements regarding the performance of the envelope, installed lighting system power and the efficiency of the air conditioning system. The classification is made for each requirement ranging from A (most efficient) to E (least efficient). Next, weights are assigned to the evaluated items: envelope (30%), lighting system (30%) and air conditioning system (40%) (INMETRO, 2010). The highest weight (70%) is given to the aspects related to the thermal balance of the building - the envelope and the air conditioning system - in the energy efficiency assessment of the building. The envelope has the primary function of controlling thermal gains to generate a thermal balance that provides fewer hours in which the air conditioning systems are used. Thus, the colours, materials and the composition and thickness of the construction components used influences the electricity consumption in a building and, therefore, must be considered in the project (Santana, 2006; Carvalho, Rovere & Gonc, 2010; Dornelles, 2008; Santos & Souza, 2012; Sozer, 2010; Sun, Giles & Lian, 2014).

Lamberts et al. (2014) states that a building is considered more energy efficient than another when it provides the same environmental conditions of comfort to its user, with lower energy consumption. The definition of consumption milestones can be made through the determination of similar primary characteristics, such as activities, volumetric energy supply groups, year of construction and then compared with secondary characteristics such as the use pattern of the building, the number of occupants, air conditioning, lighting, lighting controls, within the same activity analysed (Carlo, 2008).

According to Carlo (2008), energy demand is a function of variables that directly use energy, such as artificial lighting, appliances and air conditioning systems, and variables that interfere in these systems, such as building parts and how the system is used. In addition, the building contributes to energy consumption through thermal exchanges between the internal and external environments. For example, in hot climates the thermal gains are higher and, together with the internal gains, due to occupancy, equipment and lighting, they produce a thermal load that must be compensated by the air conditioning system in artificially conditioned buildings.

#### 1.2 Objectives of the Work

Based on the findings made previously and because there are no studies for the region under analysis that identify the main problems related to the indoor environmental quality in office buildings, the study aims to identify (with the help of an online survey) the main cause of employees' discomfort at the workplace, related to thermal, visual and acoustic comfort, ventilation and indoor air quality. The other objective of this study is to create a virtual model of an office building, with characteristics based on the literature review and with the answers from the survey, to carry out an energy demand assessment (using computer simulation). Different renovation solutions will be analysed and among those that will be simulated, the goal is to identify the most adequate, with the best energy performance (considering only the energy demand), of the building's renovation solution.

The city of Porto Alegre was chosen for the study as it has different and well-defined climates, summer is hot and humid, and winter is mild. Over the year, the weather is rainy and partly cloudy. Throughout the year, the temperature generally ranges from 10°C to 30°C and is rarely below 5°C or above 35°C (Instituto Nacional de Meteorologia [INMET], 2020), making a wide range of analyses, to cover the climate variability.

To achieve the defined objectives, it is necessary to understand the impact of an existing building in terms of the indoor environmental quality and the energy demand, in order to be able to propose different alternatives that can improve the final performance of the office building. Given the above, some points that deserve attention are highlighted, such as:

Need to identify the main indoor environmental quality problems in the existing office buildings.
 This was carried out through a survey to the occupants of several office buildings in Porto Alegre;

2) Characterize the most adequate renovation solutions for improving the energy efficiency of office buildings. The analysis was performed through dynamic simulation of a virtual reference building, determining the energy demand of the building considering different renovation solutions and packages (combination of solutions) for the envelope, lighting and HVAC systems.

#### 1.3 Structure of the Document

The present work is organized into five chapters. The first chapter presents an introduction to the proposed theme, addressing the contribution of the construction sector to the environment and people. Thus, the justifications were developed, and the objectives of the work were established. The structure of the document is also presented in the first chapter.

The second chapter presents the review of the bibliography, highlighting the generic concepts of sustainability, impact of energy consumption and emission of carbon dioxide (internationally and nationally) on the construction sector and finally, the characterization of the main factors that influence the health and well-being of people who occupy office buildings.

In the third chapter, the methodological procedure used in this research is presented in order to meet the proposed objectives. It begins with a description of the survey for identifying the universe of buildings to be studied, as well as the selection of the building characteristics for the definition of the virtual office building to be analysed.

The fourth chapter presents the research results. In section 4.1, the outcome of the research carried out in Porto Alegre are shown and in section 4.2, the results of the simulation are presented. At section 4.3, some good practices that can help to improve the indoor environmental quality at workplaces.

Finally, the research conclusions developed based on the results, and the bibliographic review are presented in chapter five. The limitations of the research and recommendations for future work are also listed in the last chapter.

#### 2. State of the Art

### 2.1 Sustainability General Concepts

Due to the increase in global warming, there is a need to discuss sustainability. These concepts are widely used when seeking to mitigate environmental degradation and guarantee economic and social growth. But still, there is a lack of knowledge regarding these concepts that need to be clarified. Since they have broad definitions, it can be easily interpreted according to the vision and knowledge of each individual.

In the last two centuries, the imbalance between the human being and the environment has been felt more strongly (Meadows et al., 1972). Along with the growing human, social and economic development that took place throughout the twentieth century, the environmental impact has grown, becoming a problem with global consequences. Based on this approach, in 1972 the first alert to the planet, prepared by the Massachusetts Institute of Technology (MIT), appeared in "Club of Rome" report (a group that came together to discuss a wide range of issues related to politics, international economics and, above all, the environment and sustainable development) (Meadows et al., 1972). This report has concluded that Earth would not support population growth much longer due to the pressure on natural and energy resources and consequently pollution, even considering cleaner technologies (Meadows et al., 1972).

In 1972 the United Nations (UN) held the first world conference about Man and the Environment (UN, 1972). In 1987 a report entitled "Our Common Future" prepared by World Commission on Environment and Development (WCED) under the UN released the universally adopted concept of sustainable development, defined as: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development is not a fixed state of harmony, but rather a process of change in which exploitation of resources, the direction of investments, the orientation of technological development and institutional changes are made consistent both with the needs of the present and with those of the future. (World Commission on Environment and Development [WCED] &UN, 1987).

The principles to guide countries in future sustainable growth were established in 1992, in Rio de Janeiro, at the United Nations Conference on Environment and Development (UNCED), popularly known as the Earth Summit. One of the main agreements signed during this conference was the Agenda 21 program that describes the first steps for countries to start sustainable development at both local and global levels.

All signatories of the 179 countries present in Rio-92 have pledged to meet the challenge of sustainable growth in its three dimensions of sustainability: social, economic and environmental.

At Rio + 10, the term sustainable development reaffirms the quest to improve the quality of life for all the world's inhabitants without increasing the use of natural resources beyond the Earth capacity. Although sustainable development may require different actions in each region of the world, efforts to build a sustainable way of life include the integration of actions in three main areas, previously mentioned in Rio-92 but with a more elaborate description (UN, 2002):

- Growth and Economic Equity Global economic systems, now interconnected, require an
  integrated approach to promote responsible long-term growth while ensuring that no nation or
  community is left behind.
- Conservation of Natural Resources and the Environment To conserve the environmental heritage
  and natural resources for the future, economically viable solutions must be created to reduce the
  consumption of resources, prevent pollution and to preserve natural habitats.
- Social Development All over the world, people need jobs, food, education, energy, health services, water and sanitation. While discussing these needs, a global community must also ensure that a rich array of cultural and social diversity and labour rights are respected and that all members of society can participate in determining their futures.

In June 2012, with the Rio + 20 Conference on Sustainable Development, where Governments decided to develop global Sustainable Development Goals (SDGs), building on the Millennium Development Goals but also including issues such as natural resources management, sustainable consumption and production, effective institutions, good governance, the rule of law and peaceful societies.

In 2015, at the 70<sup>th</sup> UN General Assembly on 25 September 2015, world leaders adopted a new global sustainable development framework, the 2030 Agenda for Sustainable Development, which represents a commitment to eradicate poverty and achieve sustainable development worldwide, by 2030 (European Commission, 2016), having at its core the SDGs. Seventeen SDGs (Table 1) and their 169 associated targets are universally applicable and interlinked.

Table 1 - 17 UN Sustainable development goals for 2030 agenda (Adapted from European Commission, 2016).

Goal	Objective	Goal	Objective
1 % 	End of poverty in all its forms everywhere	<u>∭</u> 5 <del>=</del>	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3	Ensure healthy lives and promote well- being for all at all ages	4==	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5 mm.	Achieve gender equality and empower all women and girls	g mann	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable and modern energy for all	81222	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9100000	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	10 mmin (=>	Reduce inequality within and among countries
ald:	Make cities and human settlements inclusive, safe, resilient and sustainable	©	Ensure sustainable consumption and production patterns
13211	Take urgent action to combat climate change and its impacts*	14 flavor	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
151	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	16 MOLARINA METI	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17 ===== &	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development		

<sup>\*</sup> Acknowledging that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change.

In the same year, the Paris Climate Agreement (COP21), the Addis Ababa Action Agenda, as an essential part of the 2030 Agenda, and the Sendai Framework for Disaster Risk Reduction were also adopted (European Commission, 2016).

The current concept of sustainable development was mentioned in conferences such as COP-25, which took place in Madrid in 2019. The sustainable development concept still focuses the same three pillars, re-emphasizing the urgent need to address the significant gap between the aggregate effect of Parties' mitigation efforts in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels (United Nations Framework Convention on Climate Change [UNFCCC], 2019). As this approach has been developed, the concepts of sustainability and sustainable development continue to evolve. The following sections address energy performance and CO<sub>2</sub> emissions in the world and their direct link with sustainability in civil construction.

#### 2.2 Energy Performance and CO<sub>2</sub> Emission Relevance at Global Level

The twentieth century was characterised by significant technological advances and social developments that were supported by oil exploration, with an increased request for all fuels (IEA, 2019). Led by natural gas comprising 46%, oil 15%, and coal 9%, in total fossil fuels accounted for 70% of the demand growth. They outweighed the 24% increase from renewables in primary energy demand (IEA, 2019). Figure 1 shows that the global total primary energy demand (energy production plus energy imports, minus energy exports) grew by 2.3% in 2018 (IEA, 2019).

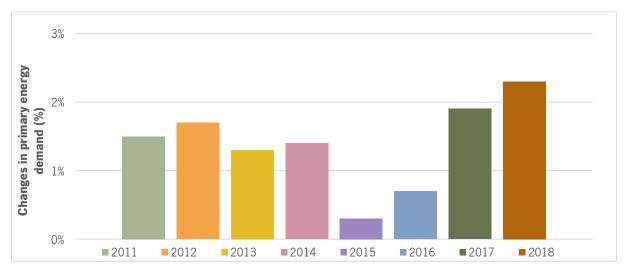


Figure 1 – Changes in global primary energy demand in the world, 2011-2018 (Adapted from IEA, 2019).

When related to final demand (refers to final consumption by the different end-use sectors and also includes non-energy use), also increased in 2018, by 2.2% (IEA, 2019). It is possible to verify, in Figure 2, that the highest growth was in gas (5.7%) and electricity (4.1%). The gas demand growth was driven by its use in industry and buildings for heating and cooling (IEA, 2019).

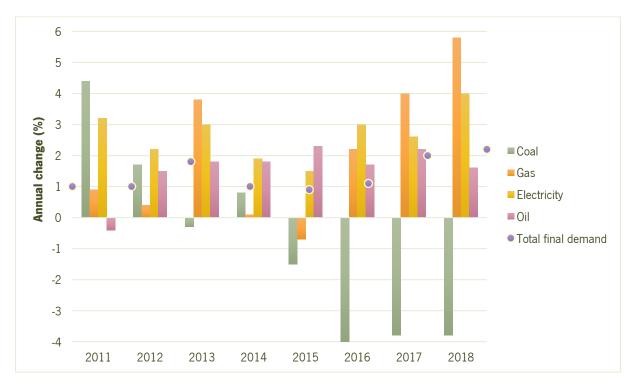


Figure 2 – Change in global final demand, by fuel, 2011-2018 (IEA, 2019).

The high energy demand is one of the main problems that modern society is facing. This is due, mainly, to the increased quality of life and comfort standards, leading to the use of not always energy-efficient products and equipment (air conditioning systems, appliances, among others).

In Europe, average daily temperatures in 2018 were 1.8°C above average. In North America, the temperatures in April, May, July and August were more than 2°C above average. While summer months were hotter than average, there were periods of the year when weather conditions were either close to or below historical averages (IEA, 2019). These exceptional weather events, as seen in temperature anomalies in many parts of the world, have motivated an additional energy demand.

Regarding the policies and energy-efficient measures from the European Commission, it is stated that: At present, buildings account for 40% of total energy consumption in the Union. The sector is expanding, which is bound to increase its energy consumption. Therefore, the reduction of energy consumption and

the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions (European Union, 2018).

Electricity, generated mainly by coal and natural gas, has increased by more than 19% since 2010. This has become one of the most important sources due to the increasing use of energy and global emissions (IEA & UN, 2019). In 2018, a major exchange between coal and gas, driven by the economy and politics, contributed to reducing the carbon intensity of general energy use. With this transition to less carbon-intensive natural gas, 95 Megatons (Mt) of CO<sub>2</sub> emissions were avoided and almost 60 Mt of coal demand decreased (IEA, 2019).

Despite the reduction of the carbon intensity of global energy use,  $CO_2$  emissions rose 1.7% in 2018 and hit a new record (IEA, 2019). As cities are responsible for over 70% of the emissions, an urban challenge is coming from several dimensions such as urban infrastructure, transport, buildings, and waste that can change the impact of  $CO_2$  emissions on the environment (IEA & UN, 2017).

Decarbonising the buildings and construction sector is critical to achieving the Paris Agreement commitment and the United Nations Sustainable Developments Goals. Building construction and operations accounted for the largest share of both global final energy use (36%) and energy-related CO<sub>2</sub> emissions (39%) in 2018 (Figure 3) (IEA & UN, 2019). Energy is a key factor in global efforts to achieve sustainable development (Vera & Langlois, 2007), and buildings can be essential to achieving this goal (Rey et al., 2007).

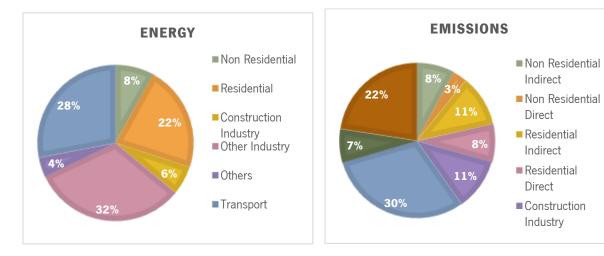


Figure 3 – Global share of buildings and construction final energy and emissions in 2018 (Adapted from IEA & UN, 2019).

From the aspects that influence global buildings sector energy use, those that have contributed most to the growth in the energy demand since 2010 are floor area, population and building occupancy. Improvements in building envelopes (e.g. higher insulation level and better windows) and in the performance of building energy systems (e.g. heating, cooling and ventilation) and appliances (e.g. stove) have helped to offset energy demand growth (Figure 4).

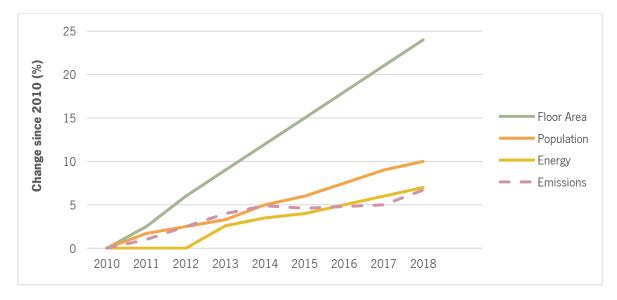


Figure 4 – Changes in floor area, population, building sector energy use and energy related emissions globally, 2010-2018 (Adapted from IEA & UN, 2019).

The increase in floor area and the demand for electricity, which is still mainly generated by fossil fuels, also results in the growth of CO<sub>2</sub> emissions. In 2018, global emissions from the building sector grew for the second consecutive year, increasing 2% compared to 2017, to 9.7 Gigatonne of carbon dioxide (GtCO<sub>2</sub>) (IEA & UN, 2019). From 2010 to 2018, changes in building sector energy consumption, per unit of floor area, show that the most significant reductions were in global average space heating (-20%) and lighting (-17%) (IEA & UN, 2019). Light-emitting diodes (LEDs) continue to be important in decreasing energy consumption for lighting. As the floor area increases and the energy use for space heating reduces indicating that building envelope has improved (IEA & UN, 2019).

Nevertheless, higher investments in efficiency and passive design strategies are needed to limit demand, reduce energy intensity and decrease the CO<sub>2</sub> emissions (IEA & UN, 2019). Among the ways to lower greenhouse gas emissions are the reduction of deforestation and protection of natural areas, the use of renewable energy sources, the use of biofuels, investing in reducing energy consumption and improving energy efficiency, reuse and recycling materials, investing in low carbon technologies.

### 2.3 Energy Consumption in Brazil

The Brazilian electricity matrix is one of the cleanest in the world, it has predominantly renewable origin, with emphasis on the hydropower that accounts for 66.6% of the domestic supply, as shown in Figure 5 (EPE, 2019). Renewable sources account for 83.3% of the domestic supply of electricity, which is the result of the sum of the amounts referring to domestic production plus imports, which are mainly of renewable origin (EPE, 2019).

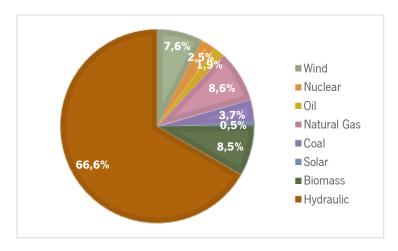


Figure 5 – Domestic electricity supply by source (Adapted from EPE, 2019).

In Brazil, the industrial, residential and commercial sectors accounted for more than 80% of the electricity spent in the country in 2018 (EPE, 2019) as shown in Figure 6. According to the National Energy Plan 2030 (Brasil, 2007), the energy consumption of buildings is projected to grow by 3.7% by the year 2030. It is understood, therefore, that the factors that influence the electricity consumption in buildings will play a key role in setting goals for the constructions field.

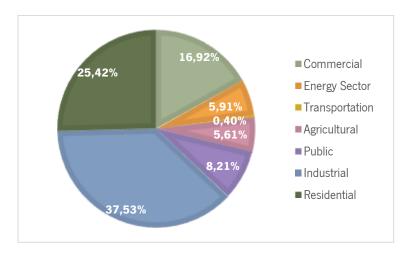


Figure 6 – Electricity consumption share by sector in Brazil (Adapted from EPE, 2019).

Energy consumption in buildings in Brazil has grown rapidly, due in part to the increase in the comfort standards inside the buildings. Recent peaks in energy consumption alongside with high construction rates, highlight the urgency in energy efficiency increase since the constructions and systems now being installed will be consuming energy over the next few decades. In Brazil, the data available on energy consumption in buildings shows that for residential, commercial and public buildings air conditioning is the largest energy-consuming system (EPE, 2019) as shown in Figure 7.

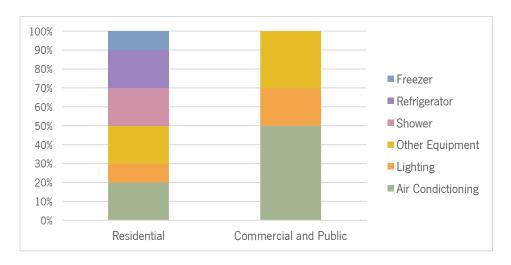


Figure 7 – Electricity consumption share by sector in Brazil (Adapted from EPE, 2019).

Available data indicates how crucial it is to make clean and renewable sources of energy accessible and to use more widely passive and low-energy designs in building construction. The implementation of energy efficiency strategies in buildings not only decrease peak energy consumption but also minimise overall energy use and its impact on the environment (Kneifel, 2010; Nikolaou et al., 2015).

Projecting a future scenario, National Energy Plan 2030 (MME & EPE 2007) predicts that, with energy efficiency actions, the trend of increasing demand for energy consumption in Brazil tends to stabilise. The National Energy Efficiency Plan 2030 (MME & EPE, 2011) estimates a potential for energy consumption reduction of approximately 30% with the implementation of energy efficiency actions in the lighting, and air conditioning systems and architectural intervention in the building sector. The following sections address how the indoor environmental quality and the energy performance of office buildings in Brazil, and related energy consumption and CO<sub>2</sub> emissions.

#### 2.4 Indoor Environmental Quality

Ensuring the comfort of the occupants is the main requirement for the indoor environment of a building. The lack of comfort conditions can be caused by several factors, like: temperatures, airspeed, high or low relative humidity, odour presence, insufficient or excessive lighting levels, unacceptable noise levels, the concentration of pollutants, microorganisms or dust suspended in the air and others. According to Loder and Zaplatosch (2018):

"Spending regular time in safe, natural areas is associated with a variety of benefits, including physical health, mental health, cognitive function, social-emotional function and additional personal benefits".

Thermal and acoustic comfort, lighting and indoor air quality are the parameters that must be considered when assessing the IEQ. Several factors, including building location and geometry, materials used, air conditioning and ventilation systems, occupation and activities, impacts on the indoor environmental quality (Silva, 2009).

#### 2.4.1 Thermal Comfort

For occupants to produce to their full capability, their workspace needs to be thermally comfortable. However, thermal comfort is based on the thermal adaptation of individual occupants which is correlated to factors such as geographic location and climate, time of year, gender, race, and age (Quang, Hea, Knibbs, Dear, & Morawska, 2014). Ensuring a thermal environment that satisfies all occupants is a difficult task since individual comfort preferences vary greatly depending on their particular acclimatisation to the local environment, on quantifiable physiological conditions (air temperature, humidity, airspeed, etc.), and non-quantifiable factors, personal variants, such as habits, mental state, education, metabolism, clothing, etc..

The human being has a thermoregulatory mechanism that allows the body to remain at a temperature, practically constant, around 36.5°C to 37.0°C, creating a thermal balance between man and the environment (Silva, 2009). Occupants' discomfort arises whenever the thermal balance between the human body and the environment is not stable, that is when there are differences between body and building temperature. According to the American Society of Heating, Refrigerating and Air-Conditioning

Engineers - ASHRAE 55: 2017 Standard, an individual is in thermal comfort when he has neither feeling hot nor cold (ASHRAE, 2017).

ASHRAE 55: 2017 suggest that, in naturally ventilated buildings, without heating and cooling systems, an environment can be said to achieve "reasonable comfort" when at least 80% of its occupants are thermally comfortable, for that the indoor comfort temperature (the operative temperature) will change according to the outside temperature, as shown on Figure 8 (ASHRAE, 2017).

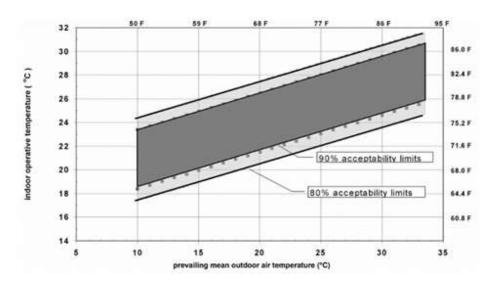


Figure 8 – Acceptable operative temperature, t₀, ranges for naturally conditioned spaces (ASHRAE 55:2017).

For Rupp & Ghisi (2019), in the humid Brazilian subtropical climate, this broader range of adaptive temperature variation can be used to assess thermal comfort in office buildings with central air conditioning or during the operation of the air conditioning system in buildings with hybrid ventilation. Users have adapted to variations in internal temperature according to external temperatures (according to the theory of adaptive thermal comfort), mainly due to the adjustment of clothing, during the use of natural ventilation in buildings with hybrid ventilation. Therefore, the adaptive model can be used to assess thermal comfort in office buildings with hybrid ventilation during the operation of natural ventilation (the 90% range of acceptability showed results closer to the thermal acceptability of users).

Some aspects influence thermal comfort in buildings, such as the thermal resistance of the elements of the building envelope, thermal inertia, the solar factor of the glazing and characteristics of the shading system. Indoor temperatures are influenced by a few factors, including the building design, building orientation, occupation density, ventilation strategies, building structure (Bluyssen, 2009). Thermal comfort can be controlled via so-called heating, ventilating and air-conditioning systems (HVAC). Heating

can be provided through convection, conduction, radiation and air-conditioning systems (Bluyssen, 2009). Regulation of relative humidity can be provided through (de)humidification systems via an air conditioning system or locally. In addition, one can adjust one's clothing and type of activities (Bluyssen, 2009).

Regarding the influence that uncomfortable temperatures can cause in the employees' performance, it is known that if the indoor temperature is hot or cold will have different consequences. Workers efficiency can be reduced by up to 6% when offices are very hot and up to 4% when they are very cold (IEA & UN, 2017). Besides that, when indoor environments are too warm, there are evidence of increases in Sick Building Syndrome (SBS) symptoms, bad mood, increasing heart rate, respiratory symptoms, and feelings of fatigue (Bluyssen, 2009). Cold and dry environments have been found to facilitate the spread of the influenza virus because low humidity levels permit virus particles to stay in the air longer and humid environments are conducive to mould and fungal growth (Bluyssen, 2009).

The frequency and severity of heat events are rising significantly due to global climate change, making control of thermal parameters in buildings a critical public health issue (Bluyssen, 2009). In the construction sector, some aspects that influence thermal comfort, such as envelope thermal resistance, glazing solar factor and shading devices have the potential to mitigate heat exposure or exacerbate it. For example, in places with a cold climate, the façade of buildings should be well isolated to reduce heat loss to the outside.

The windows should be oriented to the north (in Southern Hemisphere) to, in the winter, take advantage of the solar radiation for indoor heating (Figure 9) (Moita, 2010). Changing the post-construction structure is considered inefficient and can become expensive. The building design and physical adaptation to achieve thermal comfort must be considered at the design stage (Jazizadeh, Ghahramani, Becerik-Gerber, Kichkaylo, & Orosz, 2014).

The diagram, in Figure 9, shows how the sun is lower in winter, while it is much higher in summer (Dornelles, 2008). During the day, the low winter sun can shine through the windows to allow thermal energy to be absorbed into the building's thermal mass (Dornelles, 2008). In order to reduce heat losses, in cold climates, it is recommended that the glass panes are doubled (double glazing) or even tripled (Sozer, 2010). An insulated window covering, or thick shade can also be used to help insulate the windows and help keep the heat in the building after the sun settles (Sozer, 2010).

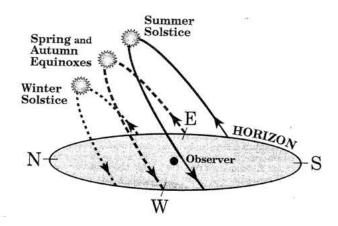


Figure 9 – Influence of the solar orientation for the positioning of the building (Retrieved from Google images, 2020).

In the summer, as temperatures rise, a passive solar building uses its thermal mass to help keep the building cool (Dornelles, 2008). The summer sun's path aides in this process by travelling high in the summer sky (Dornelles, 2008). Thus an overhang or another type of external shading system is needed to shade or cover the window, in the summer, so that the rays are blocked before entering the building when it is desired to have the building cooler than the outside temperature (Sozer, 2010).

#### 2.4.2 Visual Comfort - Lighting Quality

Lighting has always been intuitively linked to well-being and health. The bright environments are considered more comfortable and healthier than dark ones (Santos, 2002). Lighting in spaces consists of two sources: daylight and artificial light. The quality of light in an indoor space is determined by the light source (natural and/or artificial), the distribution of the light in the space and how light is perceived (Santos, 2002).

Visual comfort is a condition of the lighting needs inside buildings. To ensure visual comfort is necessary to avoid excessive light and shadow differences (as they can disturb the visual performance of the occupants), correctly locate glazing and artificial light sources (to avoid glare). The amount of light provided must be adequate for visual tasks (Santos, 2002). Visual comfort at work has an impact on comfort after work as well. Some studies have looked at the impact of visual comfort on sleep quality at home after work. These studies have documented differences in impacts by gender, age, and seasons on the overall discomfort levels and effects on health. Several visual comfort criteria such as view type,

view quality and social density have an impact on the physical and psychological health of the occupants (Al horr et al., 2016).

Natural lighting is essential in buildings and offers several advantages: free and renewable energy source, have the amount of sunlight available and vary throughout the day and year. However, care must be taken regarding natural lighting so that it does not cause discomfort in those who will enjoy it and for doing this, it is necessary to avoid chaining and overheating the compartments. A solution to these drawbacks is the use of movable shading systems to protect inhabitants from unwanted solar radiation (Silva, 2009).

Comfortable light needs controllability and healthy light (day-night) and does not cause blinding through lighting systems or direct sunlight, or glare (e.g. from computer screens). Positioning and intensity of lighting systems, surface area treatment, solar screens and solar reflecting glazing are means to achieve this (Bluyssen, 2009). Open-plan offices have adverse effects on visual comfort which leads to a negative impact on occupant well-being. The geometry of windows, photometry of surfaces, amount of glazing etc., all have an impact on the illumination levels in a work area (Al horr et al., 2016).

Daylight exposure and access to windows at work have been linked to improved mood, reduced sleepiness, lower blood pressure and increased physical activity. In contrast, the lack of natural light has been associated with physiological, sleep, and depressive symptoms (Bluyssen, 2009). Preference for windows and therapeutic impact of natural views is well established in the literature (Al horr et al., 2016). The brightness influences occupant comfort by affecting their ability to perform certain types of tasks such as reading, writing and more (Bluyssen, 2009).

Office workers exposed to artificial and natural lighting conditions reported experiencing less glare and less sleepiness earlier in the day under natural light compared to when they were under artificial light (Bluyssen, 2009). Another beneficial aspect of natural light is related to circadian rhythms that are linked to the progress of the day and the night. A serotonin rule or "internal clock" of the human being works as a coordinator of all functions with a determined rhythm coinciding with a 24-hour cycle. In this way, sleep cycles are determined (Martins, 2010). However, to influence basic cognitive processes like attention, working memory and executive functions and learning and memory can be impaired when the sleep-wake cycle is disrupted (Martins, 2010).

Light flickering distracts people and can lead to physical complaints such as headaches (Bluyssen, 2009). Reflection, blinding, too little light and poor colouring of light can lead to the tiredness of the eye or adaptation problems, decreased alertness and poor concentration (Bluyssen, 2009).

The availability and quality of daylight can be improved by increasing (Baker & Steemers, 2002):

- The openings size, making new ones or redistributing them;
- The windows transmittance, by reducing the obstruction due to frames or replacing the existing glazing with one with higher transmittances;
- The externally reflected component, treating nearby external surfaces with high-reflectance finishes:
- The internally reflected component, using internal room surfaces with high-reflectance finishes;
- The penetration of light, using special elements such as light shelves or prismatic glazing.

Good lighting requires equal attention to the quantity and quality of lighting. Although enough lighting is required on the task level, in many cases visibility depends on the way the light is distributed, the characteristics and colour of the light source and surfaces, together with the level of brightness of the system. The recommended values, from the International (Organization for Standardization [ISO] 8995:2002), are considered to represent a reasonable balance, considering the requirements for safe, healthy and efficient work performance.

Natural light, complemented by artificial light, should provide a comfortable and luminous interior environment suitable for carrying out different visual tasks that take place inside the compartments. With automatic or manual dimming or intensifying of light, appropriate integration of artificial light and daylight can be achieved (Bluyssen, 2009).

#### 2.4.3 Acoustic Quality

Acoustic comfort, like thermal comfort, is a subjective concept, primarily depending on the occupants, the materials used in the design of the building and the outdoor noise. Sometimes, a building can respect the regulatory requirements, however the occupants, due to their habits, their sensitivity, and other factors such as difficulty opening windows, due to the high sound levels coming from outdoors, can make the workers uncomfortable (Bluyssen, 2009). There is a direct relationship between acoustic comfort and occupant productivity in commercial buildings (Al horr et al., 2016). With the growth in open-plan

offices, issues of acoustic comfort and privacy have been identified as significant issues impacting on occupant productivity (Al horr et al., 2016).

Acoustic quality is considered a form of environmental pollution and the presence of background noise can be disruptive and interfere with an individual's ability to communicate and perceive speech clearly at a normal speaking volume. Also, acoustic discomfort has a great influence on man and on his ability to concentrate, even becoming a strong motivator for action (Bluyssen, 2009).

Noise has unpleasant effects, both physiologically and psychologically, on the population. Workers, at office buildings, are susceptible to distractions from the noise while working. Noise exposure can increase accidents and impair employee performance and productivity, especially during difficult and complex tasks. Thus, good office acoustics is essential to the performance, productivity, health and well-being of the occupants (Bluyssen, 2009).

Acoustic problems emanate from airborne sounds, outdoor noise, noise from adjacent spaces, office equipment and from nearby facilities. Acoustic problems in offices could be divided into two major categories: annoyance from various noises and lack of communication privacy. The level, the spectrum, and the variation with time of the noise may influence the level of disturbance (Al horr et al., 2016). Noise from other people talking, telephones ringing, and other irregular sounds may create more annoyance and disturbance compared to the more continuous regular sounds (Al horr et al., 2016). To ensure that noise in a space is being controlled, some strategies can be used, such as the introduction of absorption materials, which decrease the sound pressure level and suppress echoes, in addition to reducing the reverberation time produced and also the volume (Bluyssen, 2009).

Several factors must be analysed to reduce noise inside buildings, such as the location and orientation of the building; the presence of textures in the surroundings, for example, vegetation; use of high mass walls; the use of double glazing with different glass thicknesses and high noise reduction rates; the use of acoustic absorbent materials (Silva, 2009). The reduction of noise entering a space can also be established by closing sound leaks, preventing or reducing contact sound transmission, and applying active (noise) control.

Sound insulation of the surface areas of the space is a material characteristic and determines the sound transfer between spaces. Absorbing materials can be categorized on the base of their absorption mechanism (Bluyssen, 2009):

- Porous materials: these are materials with an open structure. Larger pores (porosity) result in more of the wave remaining in the material. Examples of porous materials are glass fibre, soft polyurethane foam, or polyester and polyether-based (open-structure) material. These materials absorb mainly high-frequency sounds;
- Resonating panels: these are thin panels constructed on a layer of air (usually filled with mineral wool) before a hard wall. The panels absorb mainly low tones and can be compared to a mass-spring system. The system starts to resonate with its resonance frequency, and the sound is transferred to heat (and is, therefore, being absorbed). The result is a high absorbance with the resonance frequency. The frequency band at which absorption takes place can be increased by introducing mineral wool;
- Resonators and perforated panels: these panels make use of one of the oldest forms of sound absorption, using the resonance principle of Helmholz. An enclosed empty volume with air, connected via a small channel to the outside (comparable to the mass-spring system), resonates with a given frequency and energy will be absorbed through friction losses (damping) in or near the channel. This damping can be increased by introducing porous material behind the hole, which broadens the frequency area absorbed but lowers the absorption peak.

Green building guidelines have started including acoustic comfort as one of the criteria, but the overall priority for this is low. Leadership in Energy and Environmental Design (LEED), has included acoustic credits as an option. Still, a lot more need to be done to make it a mandatory element of sustainable construction orientation (Schiavon & Altomonte, 2014).

#### 2.4.4 Indoor Air Quality

As people spend most of their time indoors today, the air must be pleasant and fresh so as not to impact people's health and well-being negatively. There are two main groups of pollutants, chemical and biological. Among the chemical pollutants, one can distinguish gases and vapours (inorganic and organic) and particulate matter. The biological pollutants consist of microbiological (dust) particles floating in the air that originate from viruses, bacteria, protozoa, mould, mites, insects, birds, mammals and pollen. Moulds can form aerosols through their spores (Bluyssen, 2009).

Common chemical indoor pollutants that pose risks to human health include nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), ozone (O<sub>3</sub>), particulate matter (PM), and volatile organic compounds (VOCs) such as formaldehyde, limonene, and benzene. In offices, schools, and residential buildings, these pollutants may come from printers, pest and rodents, cleaning supplies, personal care products, paint, pollen, and fungal spores (Bluyssen, 2009).

Radiological hazards such as radon, a gas that naturally emanates from soil and rock and can enter buildings through cracks and fissures in the foundation, are carcinogens. The verification of this gas is not carried out so often in buildings since it has no smell or colour, there is no way to notice its presence without undergoing specific tests. Radon is considered the second leading cause of lung cancer behind smoking (Bluyssen, 2009).

The pollutants sources that directly or indirectly emit substances to indoor air are:

- Outdoor sources (e.g. traffic and industry);
- Occupant-related activities and products (e.g. tobacco smoke; equipment: laser printers and other office equipment; consumer products: cleaning, hygiene, and personal care products);
- Building materials and furnishings: insulation, plywood, paint, furniture (particleboard), floor and wall coverings, etc.;
- Ventilation system components (e.g. filters, ducts, humidifiers).

Volatile organic compounds are a class of chemicals that are commonly associated with IAQ issues. Volatile Organic Compounds are chemicals with a high vapour pressure that emit gas into the air and can come from building materials, consumer products, paints, personal care products, furniture, and many other products (Bluyssen, 2009). Exposure to indoor air pollutants has been repeatedly linked to asthma, allergies, bronchitis, and chronic obstructive pulmonary disease.

The exposure to indoor air pollutants is influenced by indoor environmental parameters such as ventilation rate, air velocity, temperature, relative humidity, the activities taking place in the indoor environment resulting in introduction or removal of the same or other pollutants, and the time (age of product) and duration of the exposure (Bluyssen, 2009).

From HVAC system, the indoor air pollutants can be emitted by different sources (Bluyssen, 2009):

 Air filters: both new and used filters pollute the air. Due to their constituent material, new filters emit VOCs;

- Air ducts: oil residuals are the dominant source of pollution in new ducts. Depending upon the
  machinery used in the manufacturing process, new spiral wound ducts, flexible ducts and other
  components of the ductwork might contain small amounts of processing oil residuals. Growth of
  microorganisms, dust and debris accumulated in the ducts during the construction at the worksite
  (mostly inorganic substances) and organic dust accumulated during the operation period in the
  ducts can be sources of pollution as well;
- Air humidifiers: micro-organisms are the primary source of air pollution if the air humidifier is not
  used in a manufacturer-recommended way and/or if it is not maintained correctly. Desalination
  and demineralisation devices and agents can also contribute to pollution of the passing air;
- Rotating heat exchangers (RHEs): in general, are not pollutant sources in themselves, except
  when the wheels are dirty. RHEs may transport contaminants from the supply to the exhaust in
  three ways: through air caught by the wheel; by leakage between wheel and gasket; and by
  adsorption/desorption on the surface area of the wheel;
- Cooling and heating coils: without condensed or stagnating water in the pans are components
  that make a small contribution to overall perceived air pollution. On the other hand, cooling coils
  with condensed water in the pans are microbiological reservoirs and amplification sites that may
  be a major source of pollution in the inlet air.

Results from office building studies in the United States have shown that fungal concentrations in floor or chair dust lead to eye irritation, asthma and upper respiratory symptoms (Chao et al., 2003). Research has also established that fungal concentrations can lead to lower job satisfaction. Based on the research on SBS buildings must be designed to reduce the exposure to indoor chemicals, and there should be continuous monitoring of indoor air.

As defined by the World Health Organization (WHO) in 1984, SBS refers to the nonspecific set of health effects associated with time spent in a building (Wang et al., 2008). Uncomfortable temperature and humidity, chemical and biological pollution and physical conditions are some of the factors identified as a root cause of SBS (Simonson, Salonvaara, & Ojanen, 2002). SBS leads to an increase in self-reported illness absences and reduced productivity in offices. To minimize exposure to chemicals in indoor environments, it is important that buildings continuously monitor indoor air as well as control water pipes to prevent leakage (Redd, 2002).

Research indicates that SBS symptoms are 30–200 percent more frequent in mechanically ventilated buildings (Al horr et al., 2016). SBS leads to an increase in self-reported illness absences and reduced productivity in offices (Al horr et al., 2016). To guarantee air quality, it is necessary to manage pollutants and control their source. In addition, there are three other ways to control exposure, directly or indirectly: ventilation, air cleaning and activity control (for example, designated smoking areas in a non-smoking building) (Bluyssen, 2009).

#### 2.4.5 Ventilation

The ventilation of a building makes it possible to guarantee the indoor air quality and, in some cases, to reduce energy consumption (for example, night ventilation during the summer, in conjunction with thermal inertia) (Bluyssen, 2009). The need to guarantee an adequate indoor air quality obliges to resort to a process to introduce or remove air from a space, to evacuate the indoor air and replace it with fresh outdoor air.

Ventilation systems can be divided into natural, mechanical and hybrid. Natural ventilation should be controlled using openings, installed on purpose. Infiltration of air, which may occur through gaps such as small cracks in the structure and around poorly sealed components such as windows and pipework, is not a proper way to ensure natural ventilation since the airflow rate through this leakage cannot be controlled. Natural ventilation can occur in four ways (Figure 10) (Mansouri, Allard, & Musy, 2003):

- a) Single side ventilation: consists of an opening in a unique façade, causing a bidirectional flow, in which the cooler air enters through the lower part and the warmer air exits through the upper part of the opening;
- b) Crossflow ventilation: occurs when air enters a space, through one or more openings, on a façade, and exits through one or more openings on the opposite façade. This type of ventilation is recommended for large spaces since the airflow runs through the entire area from the inlet to the outlet;
- c) Stack ventilation: originates in the temperature difference between the indoor and outdoor air of the building. When the indoor temperature is higher than the outdoor temperature, the coldest external air enters the building through the lowest openings and the warmest indoor air exits through the higher openings;

d) Top-down ventilation: the force of the winds promotes the movement of air through the environment.

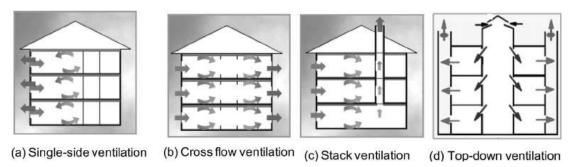


Figure 10 – Types of ventilation: Single-side ventilation (a), Crossflow ventilation (b), Stack ventilation (c), Top down ventilation (d) (Mansouri, Allard, & Musy, 2003).

The natural ventilation is generally well appreciated by building's occupants, who understand and control it easily, the energy for moving the air is free, and the system does not break down. However, it cannot be used in noisy or polluted areas and it is efficient mainly when having openings on both sides of the space. Another negative point is that the airflow rate varies with the meteorological conditions, and adequate control is needed to ensure the ventilation requirements (Mansouri, Allard, & Musy, 2003).

The mechanical ventilation system is often used where natural ventilation cannot fulfil the requirements, either because of poor outdoor conditions (noise, pollution and climate) or in locations that cannot be naturally ventilated (Mansouri, Allard, & Musy, 2003). This system allows ventilation of deep spaces with low ceilings and rooms that are not accessible to natural airflow.

Mechanical ventilation is often not well accepted by occupants, who lack control over it (Bluyssen, 2009). Also, the installation of this system can be considered expensive and can be noisy. If mechanically ventilated, the mechanical system of a building is designed to bring in and filter outdoor air and deliver it to the occupied area.

Combining natural and mechanical driving forces offers opportunities for improving the indoor environment and reducing energy demand when combined, it's called hybrid ventilation. Investing in advanced ventilation systems, combining with natural ventilation, can further mitigate energy costs, environmental and health impacts (Bluyssen, 2009).

Healthy offices have low concentrations of CO<sub>2</sub>, VOCs and other pollutants, as well as high ventilation rates. Also, have a wide variety of plant species inside and out as well as views of nature from workspaces. It needs to be taken into consideration the fact that by implementing plants not only the air quality will be improved, but also contribute to the biophilia, which promotes the human connection with nature being positive for the overall productivity and comfort of people (Bluyssen, 2009).

In buildings with lower ventilation rates, air quality is often reported as stuffy and unpleasant (Bluyssen, 2009). Not only does this make the indoor environment uncomfortable to work in, but the increased pollutants can cause health problems (Bluyssen, 2009). Poorly ventilated spaces promote symptoms such as headache, fatigue, shortness of breath, sinus congestion, cough, sneezing, eye, nose, throat, and skin irritation, dizziness, and nausea (the SBS) (Mansouri, Allard, & Musy, 2003).

## 2.5 Energy Performance and Environmental Quality of Office Buildings

Although buildings, in general, have contributed to the increase in energy demand in recent decades, they also have a strong potential for greater rationalisation of this consumption. The construction, operation and use of buildings represent an important part of the energy demand in Brazil and represent a high potential for energy savings (Conselho Brasileiro de Construção Sustentável [CBCS], 2015).

The construction industry, in general, has undergone significant changes regarding construction techniques and materials such as excessive waste production, environmental degradation and air pollution, contributing to global warming (IEA & UN, 2019). Consequently, governments give this sector notable importance when considering sustainable development targets. Non-residential buildings are responsible for 8% of the global final energy demand and 11% of the CO<sub>2</sub> emissions (IEA & UN, 2017).

According to the World Green Building Council (WGBC), eight actions can transform an office into a healthier space: indoor air quality and ventilation; thermal comfort; noise and acoustics; biophilia; daylight and lighting; interior layout; look and feel; and location and access to amenities (World Green Building Council [WGBC], 2016). The first three aspects have a significant influence on the employee's productivity. When controlling the air pollutants, such as volatile organic compounds and the amount of

carbon dioxide, it is possible to have an increase of 101% on cognitive activities (WGBC, 2016). Controlling the acoustics can avoid 66% of distraction at offices (WGBC, 2016).

The basic principle of improving a building's energy efficiency is to use less energy for heating, cooling and lighting, without affecting the health and comfort of its occupants (Kolokotsa; Nikolaou & Stravrakakis, 2011). Brugnera (2018) states that investing in energy efficiency must be a premise linked to the architectural design process, which can guarantee buildings with lower energy consumption, emissions and cost throughout their life cycle. It is, therefore, necessary to invest in "unconsumed energy", which is not restricted to a building, but a neighbourhood, a city, a country.

The demand in São Paulo and Rio de Janeiro for high standard buildings has been growing. The buildings follow architectural standards linked to the international style, with fully glazed façades, open-plan offices, with wider spaces, flexible layouts, artificial lighting systems and undisturbed air to maintain the internal environmental conditions constant (Dalziel, 2003). As a result, currently, about 50% of the energy consumption of these buildings is due to the air conditioning system (CBCS, 2015).

According to Brugnera (2018), one of the most recent studies on the comparative analysis of different construction solutions for the façade of office buildings, taking into consideration environmental, energy and cost performance, it is possible to observe that the glass façade is less suitable in all orientations since it is the one that leads to the highest energy consumption, and environmental impacts, besides being the most expensive of all. The same applies to the scenarios with the largest openings (Window to Wall ratio Percentage [WWR] of 80%), especially when there are no shading devices.

The use of external shading systems is an important strategy for buildings in Brazil, as they block direct solar radiation before it can penetrate through the windows (Carvalho et al., 2010, Santos & Souza, 2012). Carvalho et al. (2010) found that solar radiation is the main source of heat gains in the fully glazed building at the city of Rio de Janeiro, Brazil. To try to reduce the demand of electricity in the fully glazed building, external solar protections were implemented, resulting in a reduction in the use of air conditioning of 6.35% and a reduction in the total demand of electricity of 3.93% (Carvalho et al. 2010). As the building had few floors, the introduction of trees in the surrounding area was analyzed. The results indicated a reduction in the total demand of electric energy of 1.85% (Carvalho et al. 2010).

The percentage of openings on the façade is considered the variable with the most significant impact on the envelope demand indicator, according to the classification of the Technical Quality Regulation for Commercial, Office and Public Buildings - RTQ-C (INMETRO, 2010). In tests carried out for office buildings in the city of Florianópolis - Brazil, the higher the percentage of opening, the lower the level of envelope efficiency tends to be (Fossati & Lamberts, 2010). The increase in the percentage of openings on the façade reached a variation of 41.6% of the total energy demand in tests carried out in office buildings located in Florianópolis (Santana & Ghisi, 2007).

Santana (2006), using simulation, found that, for office buildings in Florianópolis, there was up to 12% energy savings using solar shading devices and that every 10° increase in the vertical angle of the shading system, electricity demand was reduced by 1.8%, especially due to air conditioning system use reduction. However, Fossati and Lamberts (2010) observed that this is a strategy little explored in office buildings in Brazil. Carlo (2005), in a survey made for an evaluation of energy efficiency with a building sample, in five Brazilian cities, verified that 80% of large office buildings did not have horizontal brises, and almost none of the buildings had vertical brises.

With the increase in the relevance given to concerns with environmental issues, natural ventilation proves to be an interesting alternative to reduce the electricity demand in buildings and, consequently, the environmental impact generated by the use of air conditioning systems (Vera & Langlois, 2007). The use of hybrid ventilation systems allows the buildings to benefit from natural ventilation, and, when it is not possible to obtain comfort due to extreme temperature conditions outdoors, the building will operate with the artificial system, ensuring thermal comfort conditions for users (Zhai, Johnson & Krarti, 2011). A study analysing the energy consumption in several buildings in the city of Belo Horizonte - Brazil, found that buildings with hybrid air conditioning consume about 40% less electricity than edifices with central air conditioning (Veloso, Souza & Koury, 2015).

In residential buildings, occupants are responsible for controlling energy costs and with this, they have a motivation to maintain the balance between energy use and their comfort preferences. However, at office buildings, workers are not involved and aware of the consequences of their behavior to energy consumption (Jazizadeh et al., 2012).

There is a lack of studies that focus on the indoor environmental quality of office buildings in Brazil and how it affects the occupants' well-being and productivity. Thus, studies to identify good solutions to decrease energy demand, improving the general energy performance, are necessary. Users should be involved in the decision making, as the decisions are essential to improve their health, well-being and comfort during the working hours.

### 3. Methodology

This chapter describes the research carried out, including the survey developed to understand the indoor environmental quality of office buildings at the city of Porto Alegre-Brazil and the methodology used to estimate the energy demand of the case study building. For the simulation of the energy performance, the DesignBuilder program was used. The description of the renovation solutions for the façade is also presented here.

This study was carried out to identify the best renovation solutions regarding the energy performance of a case study representative of the office building in Porto Alegre. This section presents the entire process, from data collection to the definition of the building's geometric, construction solutions and use characteristics. First, a survey was developed to find out the characteristics (and problems) of the existing office buildings in Porto Alegre. Then the questionnaire developed by the author was administered and the results, combined with the literature review, helped to create the simulation model for the case study.

# 3.1 Porto Alegre City Analysis and Climate

Porto Alegre is the capital of Rio Grande do Sul, located in the south of Brazil, as showed in Figure 11. It is around 497 km<sup>2</sup> and the population is estimated in 1,447,344.00. According to Google Environmental Insights Explorer (Google, 2018), based on 2018 data, Porto Alegre has 400,000.00 buildings and 24% of the area are non-residential buildings (including offices, retail, warehouses, commercial and mixed-use buildings). The buildings are responsible for 43% of the emissions of greenhouse gas of the buildings, around 225,000.00 ton of CO<sub>2</sub> per year (Google, 2018).

The climate of Porto Alegre is classified, according to Köppen-Geiger classification (Köppen, 1936), as humid subtropical climate (Cfa), having as its remarkable characteristic the high variability of temperature. The presence of Lake Guaíba's vast body of water contributes to increasing atmospheric humidity rates and changing local climatic conditions. Precipitation occurs mainly in the form of rain, which is well distributed throughout the year, with the annual average remaining around 1425 millimetres (mm). According to data from the National Institute of Meteorology (INMET), the lowest recorded temperature in Porto Alegre was  $-0.2^{\circ}$ C in July 1993 and the highest reached  $40.6^{\circ}$ C in February 2014 (Instituto

Nacional de Meteorologia, 2020). The average maximum and minimum temperature are presented in Figures 12 and 13. The precipitation average in Porto Alegre between 1985-2015 is shown in Figure 14.



Figure 11- Map of Brazil: Location of Porto Alegre (Retrieve from Google images, 2020).

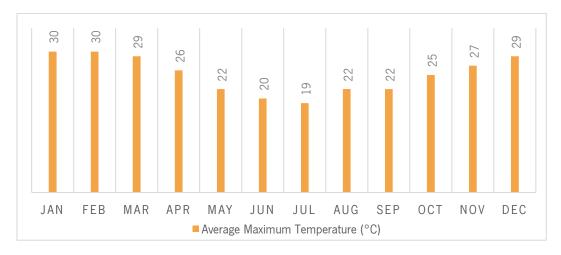


Figure 12 – Average maximum temperature in Porto Alegre during 1985-2015 (°C) (Adapted from My Forecast, 2020).

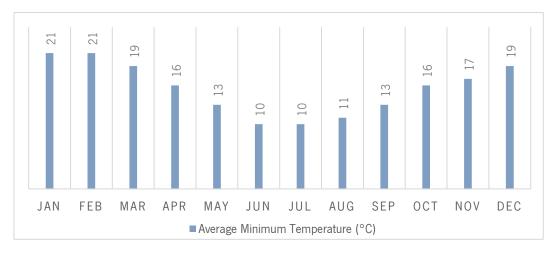


Figure 13 – Average minimum temperature in Porto Alegre during 1985-2015 (°C) (Adapted from My Forecast, 2020).

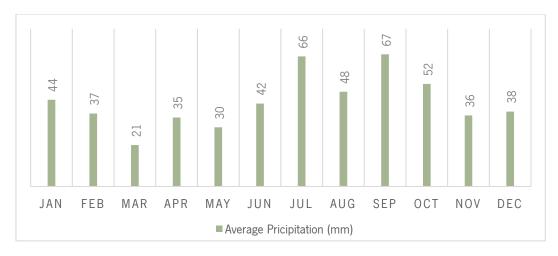


Figure 14 – Average Precipitation in Porto Alegre during 1985-2015 (mm) (Adapted from My Forecast, 2020).

According to Solarimetric Atlas of Brazil (Tiba, 2000), most of the Brazilian territory is located relatively close to the Equator line, so that it does not have significant variations in the solar duration of the day (Tiba, 2000). However, most of the Brazilian population and the country's socio-economic activities are concentrated in regions farther from Ecuador. In Porto Alegre, the southernmost Brazilian capital, the solar length of the day varies from 10 hours and 13 minutes to 13 hours and 47 minutes, approximately.

## 3.2 Questionnaire Application

A questionnaire about indoor environmental quality in offices in Porto Alegre was prepared to evaluate the occupants' main complaints. A set of questions related to potential comfort problems and their effects on occupants' satisfaction during working hours was developed.

The questionnaire (Annex I) was prepared in Portuguese since the survey was conducted in a Brazilian city, and it was available online to facilitate the analysis and to obtain the answers more quickly. The survey was conducted with people who worked in office buildings in Porto Alegre, Brazil. Based on this research, the responses were analysed, considering several factors, including thermal, acoustic and visual comfort, in addition to the indoor air quality.

The evaluation of any perception of comfort, resulting from human sensations and depending on several factors (physical, physiological and psychological), where a strong subjective component intervenes, being difficult to stipulate with precision. However, there is a comfort scale which consists of seven levels of discomfort, ranging between very comfortable, neutral and very uncomfortable. Acoustic comfort, as well as thermal comfort, are linked to cultural habits and practices, is subjective. Still, an assessment of the indoor environmental quality of buildings can be carried out, based on measurable physical criteria as a way of predicting whether the occupants are comfortable.

The main goals of survey applications to enquire people is to understand the main aspects of a healthy office building. The questionnaire was prepared, based on models suggested in international standards (ASHRAE 55:2017, EN 15251: 2007, ISO 7730: 2005). Questions were elaborated to identify the occupants' satisfaction level regarding thermal, acoustic and luminous comfort and indoor air quality. The questionnaire, Annex I, was divided into six sections with questions regarding the physical workspace:

- 1° Section: general questions about age, gender, city; location inside the building (ground floor, intermediate floor or last floor); building characteristics; elements close to the workspace (windows, air conditioning, etc.); characteristics that influence productivity (multiple-choice the 3 main should be defined) and what generates more discomfort to the worker.
- 2° Section: regarding the luminous comfort, if the amount of lighting was not enough or was excessive and if there was a need for natural light.
- 3° Section: acoustic comfort, what is the noise level at the workspace, how much noise affect performance and communication with people around.
- 4° Section: thermal comfort, how people feel and would like to feel when working and if thermal comfort contributes to performance at work.
- 5° Section: quality of the environment took into consideration issues such as the development of symptoms related to employee health and time spent using the computer.

- 6° Session: air quality, multiple choice questions were made to characterize the air quality in the work environment and if there were plants near the workstation.
- 7° Section: the last section, inquires globally, how employees felt at their workplace on a scale ranging from very uncomfortable to very comfortable.

The questionnaire was prepared using the Google tool, called Google Form, and applied virtually to several professionals in different areas of study. Of a total of 103 professionals who responded, only 80 responses were considered for the analysis of the results, due to criteria such as: working in Porto Alegre and inside an office building. The survey also helped to understand the main characteristics, related to the features and type of façade, for example, of office buildings in Porto Alegre. This data was used in the next phase, building performance simulation, for the definition of the case study building characteristics.

#### 3.3 Energy simulation tool

Computer simulation tools used in buildings analysis allows the calculation of the building envelope heat gains, predicting the thermo-energetic performance, providing diagnoses and indicating improvement points, being important to improve the buildings energy efficiency (Hong; Chou; Bong, 2000). DesignBuilder was specifically developed around the simulation capabilities of EnergyPlus, which is one of the most known energy simulation software tools.

EnergyPlus is a fully integrated building, envelope, HVAC, water, and renewable sources simulation program, allowing for the simulation of heating, cooling, ventilation and artificial lighting systems. It was created by the Lawrence Berkeley National Laboratory (LBNL), at the initiative of the North American Department of Energy (DOE) from two other software (BLAST - "Building Loads Analysis and System Thermodynamics" and DOE) and is fully integrated into DesignBuilder, taking advantage of the quality of its interface. This program is based on the geometric and physical characteristics of the building and the different integrated systems to calculate the heating and cooling needs that guarantee the occupants' comfort and to evaluate the building's energy performance. The reliability of its results and the wide variety of output data make Energy Plus one of the most used building simulation software worldwide (Streicher, 2005).

DesignBuilder offers a 3D building modelling platform for easy and quick manipulation, having available realistic elements that provide visual and immediate details such as wall thicknesses, windows, slabs, implementation of window glazing and frames and allows the visualisation of areas and volumes. The default settings allow to quickly assign to the given models and characteristics of buildings, activities and occupations, HVAC and lighting systems.

#### 3.3.1 Building Model Definition

To identify the best solution for renovation, focusing on the thermal behavior of office buildings, it will first be necessary to define a base model from which some changes will be made, to analyze the effect of the variation of certain aspects in the overall performance of the building. To create the model, it is necessary to define the general geometry of the building, the characteristics of the different construction elements (walls, floors, windows), the conditions of the exterior and interior environment, the type of ventilation and aspects related to the artificial lighting of the interior space.

A literature review allowed to identify what were the characteristics in buildings studied in research that dealt with their energy performance in Brazil (Santana, 2006; Westphal, 2007; Benedetto, 2008; Figueiredo, 2007; Carlo, 2005; Bessa, 2010; Marcondes, 2010; Andreis, 2014; Duarte, 2014; Umakoshi, 2014; Brugnera, 2018). A study by Brugnera (2018) presented results of interviews conducted with professionals in the field of energy efficiency consulting for office buildings in São Paulo. In addition, Brugnera (2018) analysed, through the Buildings database, 142 buildings, located in São Paulo, in areas with a high concentration of commercial buildings.

Through these sources, information regarding the following characteristics was collected: format of the standard floor, conditioned area by floor, ceiling height, number of floors, window to wall ratio¹ (WWR), constructive characteristics of the façade, ceiling and pavement, internal loads, type of air conditioning system, and the number of simulated thermal zones. In Table 2, it is possible to identify the characteristics of the buildings, collected in previous studies, that were the base to create a hypothetical model representative of the office buildings in Brazil. The format of the reference floor, conditioned area by floor, ceiling height, number of floors, construction characteristics of the virtual office building will be used

<sup>&</sup>lt;sup>1</sup> WWR - represents the percentage of glazed area on the façade.

according to the work done by Brugnera (2018). In the following subsections, the geometry, materials, building use characteristics, HVAC system are presented in detail.

Table 2 – Building characteristics in Brazil (Adapted from Brugnera, 2018).

Dellalia a Observants vistina	Reference (average values)					
<b>Building Characteristics</b>	Literature overview	Interview	<b>Buildings Database</b>			
Format of the Reference Floor Plan	Square (30m x 30m; 35m x 35m); Rectangular (26mx15m; 40m x 60m). Both with core.	Variable	Variable			
Area of the Reference Floor Plan (m²)	950 m²	Conditioned area between 3,000m <sup>2</sup> and 50,000m <sup>2</sup> (building as a whole)	924 m²			
Ceiling height (m)	2.90m	2.50m to 3m (useful); 3.70m to 4.20m (total - technical galleries between 0.80m and 1.00m)	2.80m			
Number of Floors	10	Data not available	17			
Window to Wall Ratio (%)	30 - 100	50 - 80	Data not available			
Type of Façade	Traditional masonry and Curtain Walls	Curtain Walls	Variable			
Type of Glass	Colorless, Reflective, Double	Low solar factor glass	Data not available			
Internal Heat Gains	Lighting: 12W/m <sup>2</sup> People: 8m <sup>2</sup> /person; 117W Equipment: 16.2 W/m <sup>2</sup>	Data not available	Data not available			
HVAC	Type: Split; Central; Control temperature: 25°C (cool); 18°C (heat)	Type: VRF (unitary system); Control temperature from 20°C to 24°C	Type: Central			
Finishing Floor Materials	Raised Floor with Carpet	Data not available	Raised Floor with Metalic Structure			
Finishing Ceiling Materials	Plasterboard Ceiling	Data not available	Modular Ceiling			
<b>Number of Thermal Zones</b>	5 (4 + core <sup>1</sup> )	Not Applicable	Not Applicable			

<sup>&</sup>lt;sup>1</sup> Core - zone located in the center of the building, a nucleus, usually used in an office building, where the stairs, elevators, bathrooms and pantries are located.

### 3.3.1.1 Geometry and Materials

The case study defined is a virtual building, with similar characteristics of the study by Brugnera (2018) and combined with the results from the survey. The case study building (Figure 15) has a rectangular shape, a total area of  $800m^2$  ( $20m \times 40m$ ), a core (unconditioned area) of  $300m^2$  ( $10m \times 30m$ ) and a ceiling height of 2.70m (3.75m in total – adding the area of the suspended ceiling and raised floor). In the unconditioned area are located the elevators, bathrooms and stairs.

The distance between the façade and the core is 5m – the region of influence of the solar radiation on the internal environment to define a thermal zone (ASHRAE, 2013). Only the offices' area is thermally conditioned, and the façade is mixed – traditional masonry wall, with windows, WWR of 50%. The building largest façades are north and south oriented.

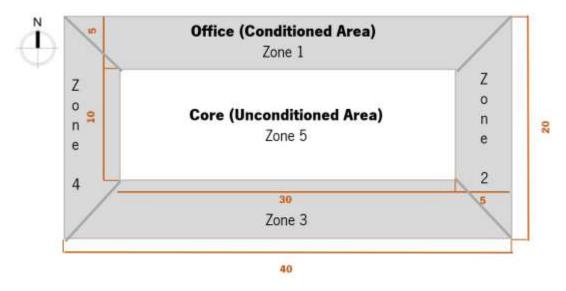


Figure 15 – Case study building reference floor plan and thermal zones (Adapted from Brugnera, 2018).

This model (Figure 15) was divided into five thermal zones (four for the offices and one for the core), according to the procedure indicated by the ASHRAE 90.1 standard (ASHRAE, 2013). Virtual walls create the division between the office areas (fictitious surfaces of air spaces), configured using only air resistance. For the evaluation of the building's energy demand, only one floor was simulated, representative of an intermediate floor, according to the answers of the survey (85% of people replied as being the working office floor, Section 4, Figure 17).

This simulated floor (with adiabatic floor and ceiling) works as a building module, which represents the thermal behavior of the other intermediate floors. The case study building has traditional façade, consisting of a single masonry wall (hollow brick wall) taking into consideration the answers from the survey, presented at Figure 18, section 4.1. For the virtual office building to be analyzed, the WWR will be considered as 50% taking into consideration the answers from the survey conducted and the data from the study of Brugnera (2018), that found that the most common office building types in Brazil has a window to wall ratio of 55% to 80%. In this case, for the largest façade the size of the window is  $1.50 \times 3.00 \times$ 

The floor is raised with carpet floor finishing, this detail is in accordance with the studies by Figueiredo (2007) and Bessa (2010). The concrete slab has a suspended ceiling with an air gap, technical space for ducts and installations, the ceiling finishing is plaster. The internal walls belonging to the central core are drywall and the external walls are masonry. Table 3 presents the construction details regarding all of the materials of the floor, ceiling, internal and external walls.

Table 3 – Thermal property of the virtual office building elements (The author, 2020).

Construction component	Materials	Thickness (m)	λ** (W/(m.K))	ρ** (kg/m³)	c** (KJ/(kg.K))	U-value* (W/(m².K))
F1	Concrete slab	0.150	1.750	2200	1.00	
Floor	Air gap	0.100	0.300	1000	1.00	
(internal)	Carpet	0.050	0.100	270	1.40	
	Concrete slab	0.150	1.750	2200	1.00	0.89
Ceiling	Air gap	0.750	0.300	1000	1.00	
(internal	Gypsum plasterboard	0.015	0.350	875	0.84	
lasta and a	Gypsum plasterboard	0.015	0.350	875	0.84	
Internal	Air gap	0.050	0.300	1000	1.00	2.30
walls	Gypsum plasterboard	0.015	0.350	875	0.84	
External	Plastering mortar	0.025	1.150	2000	1.00	
	Masonry block	0.140	0.900	1600	0.92	2.71
walls	Plastering mortar	0.025	1.150	2000	1.00	

<sup>\*</sup> Thermal transmittance coefficient (U-value) based on DesignBuilder data.

<sup>\*\*</sup> Density (ρ), conductivity (λ) and specific heat (c ) were taken from NBR 15220-2: Thermal Performance of Buildings - Part 3: Brazilian bioclimatic zoning and construction guidelines for single-family housing of social interest (ABNT, 2005b).

## 3.3.1.2 Definition of Building Usage Characteristics

The thermal load density includes heat gains from people, equipment and artificial lighting. The building model has an air-conditioned area, referring to the offices and a non-air-conditioned area, belonging to the service areas, stairs, elevators, etc. (Brugnera, 2018). Such loads are considered only for the office area (air-conditioned area), being fixed data in the simulation, as the building use directly influences them. The hourly occupancy pattern is from Monday to Friday, from 8 am to 7 pm (Table 4).

## 3.3.1.3 HVAC System

The air conditioning system selected for the study is a VRF (variable refrigerant flow), for heating and cooling, which is a central system of direct expansion with several evaporator units (Coefficient of Performance, COP, of 3.11) (Brugnera, 2018). The system uses at least one compressor with variable capacity or one that can distribute refrigerant gas through a network of pipes, and devices capable of controlling the individual temperature of each thermal zone. The air conditioning system was simulated, with a controlled temperature of 18°C and 24°C, respectively (Brugnera, 2018). Table 4 summarizes the general parameters used in the simulation of the building model selected for this study.

Table 4 – General parameters for the simulation of the case study building - base model (Adapted from Brugnera, 2018).

	General Parameters of the Simulation					
	Reference Floor Plan (m²)	20 m x 40 m (10 x 30 core) = 800 m <sup>2</sup>				
	Ceiling Height (m)	2.70m (useful); 3.75 m (total)				
Dimensions	Conditioned area (m <sup>2</sup> )	500m <sup>2</sup>				
	Window to Wall ratio (%)	50%				
	Floor analyzed	1 reference floor plan				
	Туре	VRF Split Fan coil system				
IIVAC Custom	COP	3.11 RTQ-C (INMETRO, 2013); ASHRAE 90.1 (2013)				
	Setpoint	24°C (cooling); 18°C (heating)				
HVAC System	Use pattern	Monday to Friday, from 8 am to 7 pm				
	Capacity	≥40 kW and < 70 kW				
	Classification	Multi-split VRF				
<b>Artificial Lighting</b>	Type (on-off)***	Power Density = 9.7 W / m <sup>2</sup> - RTQ-C (INMETRO, 2013)				
Nº People / m²	8m² / person; (117 W)					
Equipment****	16.2 W/m², NBR 16401-					
	1(2008)					
Occupancy (h)	Monday to Friday, from 8					
	am to 7 pm					

Table 4 – General parameters for the simulation of the case study building - base model (Adapted from Brugnera, 2018) (Conc.).

	General Para	ameters of the Simulation
		Raised floor with carpet finishing (15cm concrete slab + 10cm gap + 5cm carpet)
	Floor	Roughness of the carpet: Smooth  Thermal Resistance of the carpet (m <sup>2</sup> .K/W) 0.367
	11001	Thermal Absorbance of the carpet 0.90
		Solar Absorbance of the carpet 0.75
		Visual Absorbance of the carpet 0.75
	Ceiling	Slab + Air gap + Suspended Ceiling (concrete slab 15cm + air gap 75cm + 1.5cm plasterboard)
	Internal Wall	Drywall (plasterboard 1.5 cm + air 5 cm + plasterboard 1.5 cm)
Materials		Roughness: Smooth
	Internal Wall Partion	Thermal Resistance (m <sup>2</sup> .K/W) 0.18
	between zones	Thermal Absorbance 0.75
	between zones	Solar Absorbance 0.75
		Visual Absorbance 0.52
	External Wall	Masonry (mortar 2.5cm + mansonary block 20cm + mortar 2.5cm)
		Single glass, laminate Low Emissive - Low-e (8mm) with
	Windows	aluminium window frame
	***************************************	Tvis* 0.72%
		U-value** = $5.67W/m^2$

<sup>\*</sup> Tvis - Transmittance to solar radiation in the visible spectrum (normal incidence)

Low-Emissive Solar Control Glass (Low-e) (Ref. Neutral 70 clear - GUARDIAN, 2010).

### 3.4 Building Simulation

Fourteen simulations were performed, considering as fixed parameters: geometry, construction solution for the floor, ceiling, internal walls, window to wall ratio (50%), internal gains, control temperature (setpoint) for cooling and heating, in addition to the occupation period. As variable parameters, façade types, type of glass (single and double), existence (or not) of a shading device and lighting and HVAC system as best practice (best theoretical option for the parameters according to DesignBuilder).

<sup>\*\*</sup> U-value - thermal transmittance coefficient

<sup>\*\*\*</sup> On-off lighting system, activated during the occupation period without considering the use of natural lighting (not dimmable, efficient) RTQ-C (INMETRO, 2013).

<sup>\*\*\*\*</sup> NBR 16401 (ABNT, 2008); ASHRAE Fundamentals (ASHRAE, 2009)

<sup>\*\*\*\*\*</sup> The equipment load density refers to a computer and monitor, a printer and fax, for each workstation (1 workstation/person) NBR 16401-1(ABNT, 2008).

### 3.4.1 Energy Renovation Solutions

This section is intended for the definition of energy renovation measures in the case study. Although the office building under study is virtual, the goal is to verify and minimize its energy demand by applying the 3 types of different renovation measures listed in the following sections. These three alternatives will compose a matrix of 14 options of possible solutions, shown in table 8, foreseeing a better thermal behavior for the virtual building under analysis.

#### 3.4.1.1 Reinforcement of Thermal Insulation - Exterior Walls

The application of thermal insulation on the exterior walls is one of the ways to reduce the energy consumption of the building and at the same time improve the thermal comfort conditions, reducing the heat exchanges between the interior and exterior, minimising the heating and/or cooling needs and reducing the risks of condensation. What determines the performance level of a thermal insulation system is its thermal transmittance coefficient (U-value).

The higher the U-value, the less insulating capacity the element will have. In other words, the lower the U-value, resulting from the increase in the thickness of thermal insulation, corresponds to greater initial investment and lower energy consumption during the building's operation phase. There are three possible options for the application of thermal insulation reinforcement, characterised by the relative position of the insulation to be applied, namely:

- Thermal insulation from the inside;
- Thermal insulation from the outside;
- Thermal insulation in the air cavity (limited to the case of double pane walls).

For this case study, it was decided to reinforce the thermal insulation from the outside, not only because it is easy to apply but also because it will not affect on the operation of the office and the working hours of the employees. Therefore, within this type of reinforcement, the solution consisting of composite thermal insulation systems from the outside, known as External Thermal Insulation Composite System (ETICS), was considered. In this way, the constructive characteristics of the exterior walls were changed to carry out the analysis of this renovation measure. Table 5 shows the type of construction of the walls after the renovation.

Table 5 – Exterior wall materials for ETICS (The author, 2020).

Exterior wall materials	Thickness (m)	λ* (W/m.K)	R ** (m².K/W)	Density (kg/m²)
Gypsum mortar	0.02	0.84	0.039	1200
Masonry block	0.14	0.90	0.15	1600
Air gap	0.04	-	0.18	-
Masonry block	0.14	0.90	0.15	1600
Plastering mortar	0.025	1.15	0.027	2000
EPS - Expanded Polystyrene	Х	0.04	-	15
Plastering mortar	0.008	0.35	0.023	950
Glass fiber	0.002	0.04	0.050	12
Gypsum mortar	0.02	0.84	0.039	1200

<sup>\*</sup> Conductivity (λ)

The impact of the renovation solutions, through the increase of the thermal insulation level, was assessed considering four different situations, each one corresponding to a different thermal insulation thickness. Table 6 shows the different thicknesses of expanded polystyrene (EPS) used in the simulation and the values of the thermal resistance R ( $m^2$ .K/W) and thermal transmission coefficient U-Value (W/ $m^2$ .K) of the refurbished wall.

Table 6 – Proposed renovation solutions for the façade – opaque part (The Author, 2020).

Simulation option	EW-04*	EW-06	EW-08	EW-10
EPS thickness (m)	0.04	0.06	0.08	0.10
Total thickness (m)	0.43	0.45	0.47	0.49
Total thermal resistance - R (m <sup>2</sup> .K/ W)	1.803	2.303	2.803	3.303
Thermal transmission coefficient – U-Value (W/ m <sup>2</sup> .K)	0.555	0.434	0.357	0.303

<sup>\*</sup> EW - External Wall + Thermal insulation, EPS, thickness (m)

### 3.4.1.2 Solar control

Among the many different reasons for controlling the amount of sunlight that is allowed in a building, the excess of solar gain is considered the main one, and that, predominantly in hot and sunny climates, can result in high cooling energy consumption. In addition, too much sunlight can lead to the use of curtains, resulting in a more extensive use of artificial lights, increasing the energy consumption of the building.

<sup>\*\*</sup> Thermal resistance (R)

In almost all climates, the control and diffusion of natural lighting improve daylight. This solar control can be carried out through shading devices that, when well designed, reduce heat gain peaks and the need for cooling in the environment. These devices can also improve the user's comfort and the best quality of daylight inside the buildings, leading to greater satisfaction and productivity in the offices. Figure 16 shows the horizontal shading used in the project, optimized for the ideal orientation for Brazil.

A simplified protection geometry was created, modelled using the "Louvres tools" from DesignBuilder, it was considered a group of 3 blades each window, the distance from the window is 0.3m, the blade depth is 1.5m, the angle between the blade is  $15^{\circ}$  and the material is steel with a thickness of 0.002m. For aesthetical standardization the same shading system characteristics were used in all the façades.

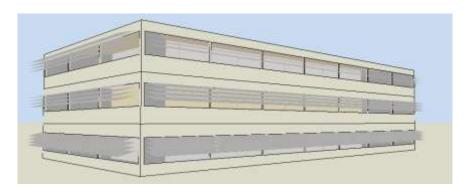


Figure 16 – Illustration of the horizontal shading devices (The author, 2020).

# 3.4.1.3 Double Glass

The solar factor indicates the fraction of solar energy that effectively passes through the glazing and is transmitted to the interior of the building the lower the solar factor of the glass, the smaller the amount of energy transmitted through it (Martins, 2010). Glasses with low solar factor provide good protection against radiation, being ideal for use in glazing with direct sunlight and without sun protection (Martins, 2010). In renovation situations it is possible to intervene by replacing a single glass with a double glass, in order to improve its performance. In this case study, it was selected only a different type of glazing with lower solar transmittance radiation and lower thermal transmittance to verify the impact that it has on the building thermal behavior. Double Laminate with Low Solar Factor (Ref. Neutral Gray - GUARDIAN) = external glass 6mm + air 12mm + internal glass 6mm. Thickness = 24mm, Tvis = 0.40%, U = 2.53 W/m² and the window frame was considered the same as the previous one with aluminum frame.

### 3.4.1.4 Best Practice

DesignBuilder offers the "Best practice" option for certain parameters, such as lighting, glazing, HVAC system, among others, which consists of considering the best theoretical option for the parameters in question. Therefore, two models were simulated, one for each intervention proposed for the façade, but with changes in the parameters related to lighting and HVAC system, for the "best practice" option, shown in Table 7, to increase the energy efficiency of the building and analyse its impact on energy consumption.

Table 7 - Comparison of characteristics for lighting and HVAC systems by DesignBuilder software and base model building (The Author, 2020).

Best Practice Options by DesignBuilder			Base Model		
Lighting	Power Density (W/m²)	7.5	Lighting	Power Density (W/m²)	9.7
System	Radiation Fraction	0.42	System	Radiation Fraction	0.72
	Visible Fraction	1.80		Visible Fraction	1.80
HVAC	Central heating using	Natural gas	HVAC	VRF Split Fan coil system	Electricity
System	water radiator	ivatural gas	System	VIVI Split I all Coll System	Liectricity

With the three alternatives selected above, it was possible to set up a matrix with 14 different simulations, to subsequently assess the best and worst performance related to the energy performance of the virtual office building for the city of Porto Alegre. Table 8 shows all 14 simulated solutions and their characteristics that were developed in this case study.

Table 8 - Matrix of the characteristics (variables) of the 14 simulated solutions (The Author, 2020).

SOLUTION	EXTERNAL WALL	GLAZING TYPE	LIGHTING SYSTEM	HVAC System	SHADING DEVICE
1 (Base Model)	Masonry + Mortar (e= 25 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	None
2	Masonry + Mortar (e= 25 cm)	Double Glass Laminate (e =24mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	None
3	Masonry + Mortar (e= 25 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	Horizontal Steel Blades (North, South, West and East Façades)

Table 8 - Matrix of the characteristics (variables) of the 14 simulated solutions (The Author, 2020) (Cont.)

SOLUTION	EXTERNAL WALL	GLAZING TYPE	LIGHTING SYSTEM	HVAC SYSTEM	SHADING DEVICE
4	Masonry + Mortar (e= 25 cm)	Double Glass Laminate (e =24mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	Horizontal Steel Blades (North, South, West and East Façades)
5	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 40 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	None
6	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 42 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	None
7	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 44 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m²	VRF Split Fan coil system	None
8	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 46 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	None

Table 8 - Matrix of the characteristics (variables) of the 14 simulated solutions (The Author, 2020) (Conc.)

SOLUTION	EXTERNAL WALL	GLAZING TYPE	LIGHTING SYSTEM	HVAC SYSTEM	SHADING DEVICE
9	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 46 cm)	Double Glass Laminate (e =24mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	Horizontal Steel Blades (North, South, West and East Façades)
10	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 46 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	Horizontal Steel Blades (North, South, West and East Façades)
11	Gypsum mortar + Masonry block + Air gap + Masonry block + Plastering mortar + EPS + Plastering mortar + Glass fiber + Gypsum mortar (e= 46 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 7.5 W / m²	Central heating using water radiator	None
12	Masonry + Mortar (e= 25 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 7.5 W / m <sup>2</sup>	Central heating using water radiator	None
13	Masonry + Mortar (e= 25 cm)	Single Glass Laminate Low Emissive (e =8mm) + aluminium window frame	Power Density = 9.7 W / m <sup>2</sup>	VRF Split Fan coil system	Horizontal Steel Blades (North and South Façades)
14	Masonry + Mortar (e= 25 cm)	Double Glass Laminate (e =24mm) + aluminium window frame	Power Density = 9.7 W/ m <sup>2</sup>	VRF Split Fan coil system	Horizontal Steel Blades (North and South Façades)

Renovation of Brazilian Office Buildings to Achieve Better Energy Efficiency and Indoor Environmental Quality

4. **Results** 

This section presents the results of the survey carried out (section 4.1), the analysis of the energy

performance of the studied renovation scenarios using DesignBuilder (section 4.2) and the suggestions

of good practice (section 4.3), based on the following structure:

• Presentation of the results of the survey carried out;

Presentation of the energy performance of the 14 renovation scenarios evaluated, considering

the energy demand, analysing the influence of the façade type and of each varied parameter

(glass type, shading device, lighting and HVAC system) in energy performance;

Presentation of good practices that can help make the environment of the office building more

sustainable.

4.1 **Analysis and Discussion of the Survey Results** 

The survey was carried out through an online platform and sent to the workers of several office buildings

in Porto Alegre. The results obtained were collected from 7 October 2019 to 25 October 2019.

During the period in which the people were responding to the questionnaire, Brazil was in the spring.

According to "My Forecast" weather website (Forecast, 2020), in Porto Alegre, the average climate

conditions in October, when the survey was applied, were:

Maximum temperature: 24.4°C;

Minimum temperature: 16.1°C;

Mean air temperature: 20.6°C;

• Precipitation: 52.3mm;

Relative humidity: 78%;

Wind velocity: 14.8 km/h (4.1 m/s).

The first part of the questionnaire is informative. Figure 17 shows where most of the people work inside

the office building. The majority, 85%, works on an intermediate floor. It is also possible to verify, in Figure

18, that most of the façades are masonry walls and windows, 46%. This information was used to define

the base model building characteristics for the simulation in Chapter 3.

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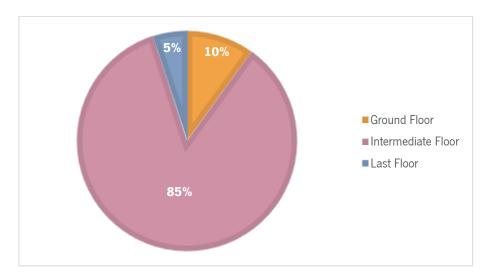


Figure 17 – Location floor of the workplace inside the office buildings in Porto Alegre (The author, 2020).

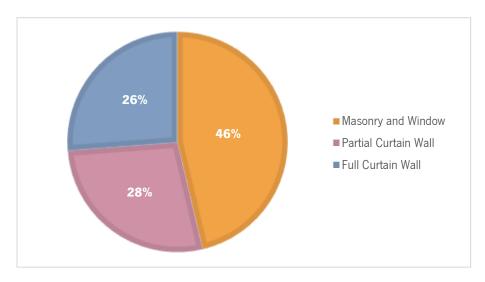


Figure 18 – Main characteristics of the façade of the office buildings in Porto Alegre, according to the survey (The Author, 2020).

## 4.1.1 Demographic Characterization of the Survey

From the 103 answers obtained, 49.5% of the workers were men and 50.5% women. The majority (81%) of the persons who answered this survey were between 19 and 35 years old (Figure 19). Only 90.3% (93 persons) of the respondents works in Porto Alegre and, and 86% of them works in office buildings, totalizing 80 responses considered for the analysis of comfort-related problems in office buildings.

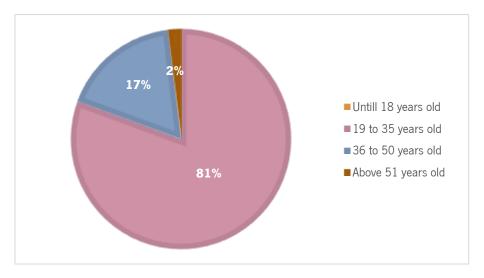


Figure 19 – Age of the employees, that answer the survey, in Porto Alegre (The author, 2020).

The next part of the questionnaire aims to diagnose the general working environment conditions for the user. The intention is to identify how the user perceives, in his daily routine, important aspects, from the general comfort of the room to the use of natural light, of air conditioning systems and his satisfaction with the window, the position he occupies, exterior view and perception internal air quality.

## 4.1.2 Indoor Air Quality

The information obtained serves as a parameter for the human perception of indoor air quality and helps in the identification and characterization of any problems in the air quality. In a multiple-choice question, the respondents were asked to identify the perception of the air quality, 35% of them characterised the air as clean. For most of the workers, the air was considered as dusty, stale, smelly and stuffy and just 10% considerate the air as fresh (Figure 20).

No flow, muffled and dusty air are indicative of deficiencies in air change rate. Odors present all the time are probably associated with the building structure, furniture and even the cladding. Occasional odors may be due to occupant activity, air conditioning or external factors. Therefore, a more specific assessment is needed to define the cause of the problem.

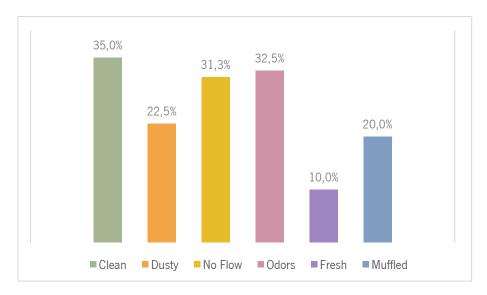


Figure 20 – Indoor air quality characteristics in office buildings, according to survey conducted in Porto Alegre (The author, 2020).

The answers to the question related to the health symptoms developed after starting the work journey at the office showed that the symptoms that the occupants manifested are:

- headache (65%);
- sinusitis (20%);
- sneeze or runny nose (47.5%);
- dry eyes (40%) and tearing eyes (22.5%);
- throat problems (36.3%); and
- breathing problems, such as asthma and bronchitis (11.3%).

The types of symptoms possibly related to air quality (rhinitis or asthma for example) and their time of onset are useful situations in the characterization of problematic situations. According to Associação Brasileira de Normas Técnicas (ABNT NBR: 16401-3, 2008), the percentage of satisfied with the air quality must be above 80% of the verified sample and any symptom (mentioned above) in more than 20% of the occupants requires an assessment of the environment.

#### 4.1.3 Thermal Comfort

From the analysis of the answers of the survey, carried out at the beginning of the spring (with outdoor average air temperatures between 16°C and 25°C), regarding the thermal environment, it can be concluded that, in general, 63.7% of the workers were uncomfortable. The ISO 7730 (2005) standard considers that a space presents conditions of thermal comfort when no more than 10% of its occupants

feel uncomfortable. Some of the respondents referred to being cold (41.1%) and 22.5% as being hot, in their workplace, and just 36.3% feel neutral (Figure 21).

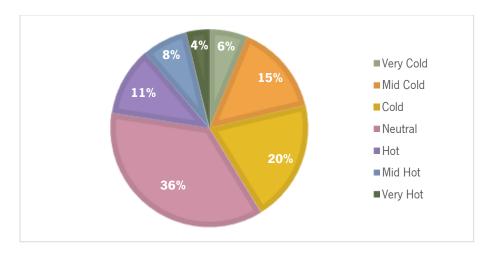


Figure 21 – Classification of thermal comfort conditions in the workplace, according to survey conducted in Porto Alegre (The author, 2020).

When we are in a hot environment, the body uses energy to cool itself. The most common is through sweat, which cools the skin and helps the body to maintain the proper temperature. It turns out that after 26°C, this energy spent to maintain body temperature starts to be higher. Thus, the drop in performance and the increase in errors ends up being a consequence, since part of the energy that should be going to the brain, is being used to produce sweat and keep our bodies cool. The opposite, keeping the environment cool reduces the humidity of the air, this can also cause discomfort in the body.

When asked how they would like the work environment to be, 67.5% choose it to be neutral. Also, 85% said that thermal comfort favours productivity at the workplace. Thermal neutrality is a condition necessary, but not sufficient for a person to be in thermal comfort, as people may be in thermal neutrality and be subjected to local thermal discomfort (e.g. subjected to significant asymmetry radiation, to localized airflow, or be affected by a cooled or heated floor), and therefore, not be in thermal comfort.. In Brazil, NR17 (2018) determines that the temperature of the work environment where intellectual activities are carried out, such as laboratories, offices, development rooms, project analysis, have a temperature between 20°C and 23°C, with a relative humidity of not less than 40%.

# 4.1.4 Lighting Quality

According to ABNT NBR 5413 (1992), the illuminance for offices varies between 750-1500 Lux. These values established by the standard are minimum averages for artificial lighting indoors. Calculations are required to determine the appropriate illuminance. In this research, only the perception of the occupants was used. The results show that 68.7% of the workers consider the environment bright (Figure 22).

In general, the occupants (62.5%) do not miss natural light. For 20% of the workers, the illumination level in the work area is neutral (adequate). Almost half, 46.3%, of the persons who answered the survey, work in office buildings with a mixed façade (masonry and glazed, 50% window to wall ratio) and report to be close to the windows, meaning that they have easy access to daylight.

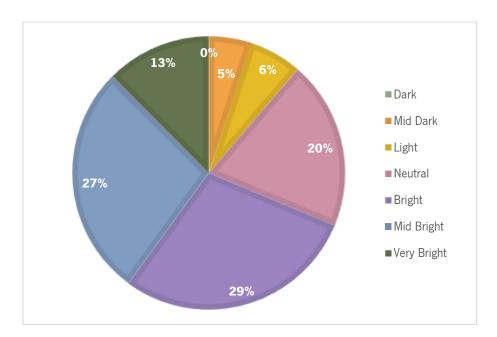


Figure 22 – Classification of lighting quality in the workplace, according to survey conducted in Porto Alegre (The author, 2020).

# 4.1.5 Acoustic Quality

The maximum noise levels for offices, according to ABNT NBR 10152 (1987), 45-65 dB(A). Levels higher than this are considered uncomfortable. As no measurements were made in this work, it is not possible to evaluate according to the standard. Thus, the human perception parameter was used to assess the

acoustic comfort of the office under analysis. Most respondents complained about the noise (Figures 23, 24 and 25):

- Approximately 55% of people that answered the survey said that the noise is loud and 15% are neutral about the noise at their workspace;
- 58.8% said that they sometimes have the communication affected by the noise;
- approximately 53.8% think that sometimes the noise affects their productivity;
- 35% said that the noise always affects their productivity; and
- 11.3% always feel affected by the noise at their workplace.

The discomfort caused by the noise reflects the need for good sound insulation between workstations, such as the use of panels, and between indoor environments such as a meeting room and equipment (such as walls and ceiling well insulated). As in this research, it was not possible to identify whether the external noise interfered in the results, good insulation of façades is desirable so that the environmental noise does not affect the internal environments of the offices, disturbing the workers.

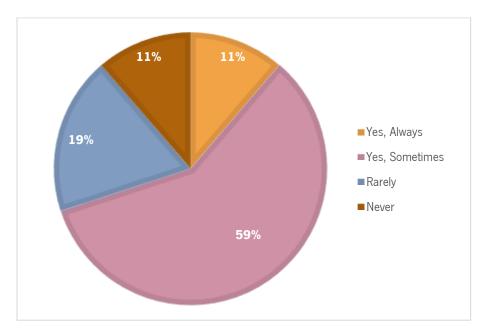


Figure 23 – How often noise in the workplace affects communication in office buildings, according to survey conducted in Porto Alegre (The Author, 2020).

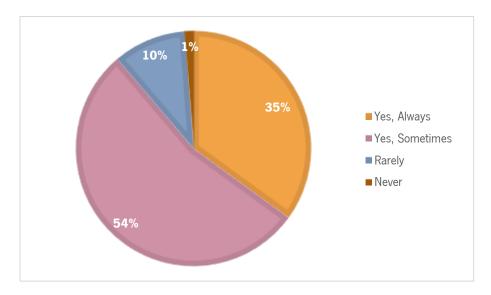


Figure 24 – How often the performance at work is affected by acoustic problem in office buildings, according to survey conducted in Porto Alegre (The Author, 2020).

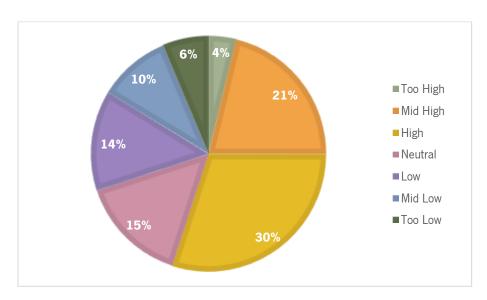


Figure 25 – Classification of level noise at the workplace, according to survey conducted in Porto Alegre (The Author, 2020).

## 4.1.6 General Findings

The relationship between the discomfort level related to air quality, thermal, acoustic and lighting environment is found in the final question of the questionnaire. From the respondents, 68.7% are, in general, comfortable at their workplace, 31.3% are dissatisfied with the indoor environmental quality at their workplace. For 51.2% of the respondents, the more uncomfortable office place is next to the air-conditioning system and 92.5% of the occupants would like to have some type of plants inside the

office building. The three main factors which influence productivity according to the survey are:  $1^{st}$  noise,  $2^{nd}$  temperature and  $3^{nd}$  ventilation (Figure 26).

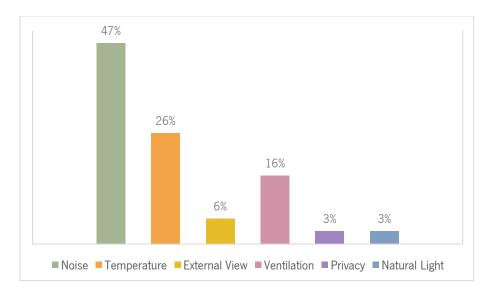


Figure 26 – Main indoor environmental quality factors which influence the work performance in office buildings, according to survey conducted in Porto Alegre (The Author, 2020).

It was also verified that 78.8% of the persons work full time in front of the computer (Figure 27), this percentage can be related to 58.8% of the stress when talking about the indoor environmental quality and 18.8% of the people that started to use glasses after the work in the office building.

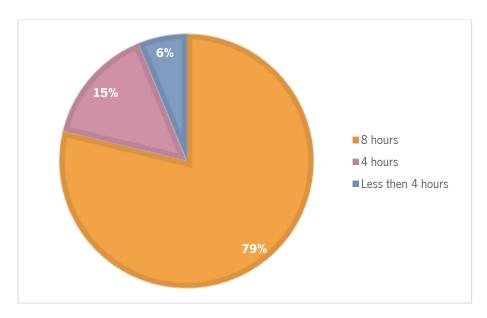


Figure 27 – How often is the computer used in the workplace, according to survey conducted in Porto Alegre (The Author, 2020).

An important aspect is to keep your eyes well lubricated when working at the computer. In addition, taking breaks to allow the relaxation of the eye muscles to stretch the back and relieve tension in the shoulders and neck is extremely important for the health and productivity of the workers.

After this first analysis of the results of the survey, it was possible to notice that the main problems are related to the building's acoustics (which can be internal and external) and thermal comfort. With this last aspect in mind, some of the proposed renovation solutions aimed at reducing the impact of discomfort on the general satisfaction of the worker.

### 4.2 Analysis and Discussion of the Energy Demand Simulation Results

Through the dynamic simulation performed, using DesignBuilder, the energy demand diagnosis of the building under study is presented below. With the building model adequately defined at chapter 3, it is possible to obtain the respective energy performance, according to its characteristics and surroundings, and to identify the main energy uses. For this case study, annual energy simulations were carried out, focusing the diagnosis on global, heating and cooling demand. The geometry, construction solution for the floor, ceiling, internal walls, window to wall ratio (50%), internal gains, control temperature (setpoint) for cooling and heating, in addition to the occupation period were considered as fixed parameters.

### 4.2.1 Case Study Base Model Analysis

The first analysis performed, using DesignBuilder, was the analysis of the case study office building in is current state, focusing mainly on energy demand for the reference floor plan. The simulation was performed for a year, considering the base model characteristics from the methodology section 3, Table 4. The main energy uses (heating, cooling, lighting and office equipment's) for the virtual building and its total energy demand were analysed to understand the energy performance and after to compare to the other renovation solutions. Table 9 presents the values of the global annual energy demand of the case study building in its current state.

Table 9 – Global energy demand for the reference floor plan for the base model characteristics (The Author, 2020).

Solution	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)
1	258,655.40	182.30

Table 10 presents the energy demand for the different purposes of energy use, namely cooling and heating needs and other uses which is total energy consumed by lighting and electric office equipment (computers, faxes and printers).

Table 10 – Energy demand for the main energy uses at the reference floor plan for the base model characteristics (The Author, 2020).

Solution	Energy Uses (at the reference floor plan)	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)	Variation of Energy Demand (%)
	Heating	1,481.00	1.00	1%
	Cooling	151,677.90	106.90	59%
1	Others (lighting and office equipment's)	105,496.60	74.40	41%
	Global	258,655.40	182.30	100%

According to Table 10, 59% of the building's energy demand relate to cooling needs, and only about 1% to heating needs. The remaining 41% are due to other purposes, namely lighting and office equipment (computers, faxes and printers).

Through dynamic simulation, it is possible to obtain the total energy corresponding to the thermal gains of the building, the internal gains, namely due to the lighting, equipment, occupation and the solar gains through the windows. In Figure 28, it is possible to observe the influence of each of these aspects on the annual energy balance of the base model simulated in DesignBuilder. The thermal gains of the building are mostly due to solar gains, followed by the gains due to computer and other equipment operation.

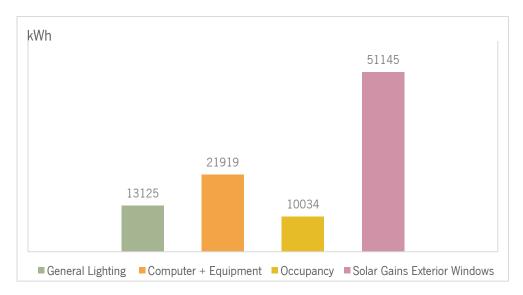


Figure 28 – Annual internal and solar thermal gains (kWh) for the reference floor plan (The Author, 2020).

The high internal and solar gains make the building's air conditioning system operate fundamentally to cool the space. As the building has high solar gains and several ways (internal and external) can be adopted to improve energy performance, it was decided to analyse three of them, taking into consideration only external options. Those three ways will be addressed in the sequence of this chapter and will be used to make a comparison from the base model data:

- 1) Adding thermal insulation to the façade;
- 2) Changing the glazing type at the façade;
- 3) Adding a shading system at the façade.

The internal gains due to the office equipment (computers, faxes and printers) are also high. Thus it is necessary to improve the thermal performance of this kind of equipment (not subject of analysis in this study). As the lighting system used is already efficient, the heat gains due to lighting are lower. Nevertheless, as the lighting system operation is not optimized taking into account the daylight availability in the building it will also be possible to reduce the energy consumption for lighting. This is also not the subject of this study. As the aim of the study is characterize the most adequate renovation solutions for improving the energy performance of office building in Porto Alegre, Brazil. A set of renovation solutions were defined considering only external improvements.

# 4.2.2 Building Performance with the Implementation of the Proposed Renovation Solutions

The 14 proposed renovation scenarios are shown in chapter 3, Table 8. For this case study, it was decided to reinforce the thermal insulation from the outside, not only because it is easy to apply but also because it does not disturb the working environment (since the building under analysis is an office). Therefore, characterization of the building's performance with this type of reinforcement was considered the solution consisting of composite thermal insulation systems from the outside, known as "ETICS" (see chapter 3 section 3.4.1.1).

It was given consideration to adding shading devices from the outside (details in chapter 3 section 3.4.1.2) and also the replacement of single glazing with double glass, with better efficiency (details in chapter 3 section 3.4.1.3), in order to improve the energy performance of the building. Also, the tool called "best practice" of the software DesignBuilder, was used to compose the renovation solutions. This tool was used only for lighting and HVAC systems (as seen in chapter 3 section 3.4.1.4).

# 4.2.2.1 Solutions for the Renovation of the Façade – ETICS System Analysis

After the renovation intervention using the ETICS system, with different thicknesses in the thermal insulation material (EPS), it is possible to analyse the results of the analysis of the behavior and the energy performance of the building shown in Table 11.

Table 11 – Energy demand for the main energy uses at the reference floor plan for ETICS envelope system characteristics considering different thicknesses of insulation (The Author, 2020).

Solution	Insulation Thickness (EPS)	Heating Demand (kWh/m².year)	Cooling Demand (kWh/m².year)	Total Energy Demand (kWh/m².year)
5	EW-04	0.90	118.20	193.40
6	EW-06	0.90	118.90	194.10
7	EW-08	0.90	119.40	194.60
8	EW-10	0.90	119.80	195.20

In Table 11 it is also possible to observe that the improvement of the thermal insulation level in the renovation of the exterior walls leads to negative trends regarding the heating and cooling demand. The energy demand for cooling have a small increase. The energy demand variation are shown in Table 12

indicating the variation of the total energy demand used for cooling and heating and total energy demand (which includes lighting and office equipment's) the building before and after the intervention.

Table 12 – Variation of energy demand for heating and cooling and the total energy demand at the reference floor plan comparing the base model with ETICS envelope system characteristics and the different thickness of insulation (The Author, 2020).

Solution	Insulation Thickness (EPS)	Heating + Cooling Demand (kWh/m².year)	Variation of Heating and Cooling Demand (%)	Total Energy Demand (kWh/m².year)	Variation of Total Energy Demand (%)
1	None	107.90	-	182.30	-
5	EW-04	119.00	10%	193.40	6%
6	EW-06	119.70	11%	194.10	6%
7	EW-08	120.30	11%	194.60	7%
8	EW-10	120.80	12%	195.20	7%

As seen in the values presented in Table 12, the implementation of thermal insulation in the exterior walls resulted in an increase of up to 12% in the heating and cooling demand, corresponding to an increase of about 7% in the global energy demand, mostly due to the cooling demand increase. In this particular case, the heating needs are not significant enough to outweigh the cooling needs, and thus, transmission losses through the envelope do not have an overall beneficial effect on the yearly energy consumption. Excessive building insulation may prevent the heat loss through the walls (anti-insulation effect), and thus generate the need for energy intensive active systems to remove this thermal load. As it is an office building, the behavior of the occupants and the equipment (which generates heat) can become the main factors in building energy efficiency.

The anti-insulation behavior is observed in locations with average yearly temperatures in the range of 13 °C to 21 °C (Friess; Rakhshan & Davis, 2016). The present study is aligned with this result, as for Porto Alegre location and temperature. Additional results from Guan (2010) found that in all eight capital cities of Australia, increasing wall insulation results in higher cooling load and higher total energy consumption for the office building under study. All the eight capital cities of Australia exhibit moderate climate with low heating requirements and moderate to high cooling needs.

The results of the current study also agree with Pan et al. (2012) that identified that for zones in Guangzhou, increasing the wall insulation thickness does not decrease the total energy demand of the office building under study. These findings again match the results of the current study which has predominately cooling needs with low heating demands which cannot outweigh the increase in cooling energy demands due to heat-trapping for the increased perimeter insulation thickness. This same effect was observed by Chvatal & Corvacho (2009), who studied buildings in Portugal and affirm that in office buildings with high internal loads, it is not recommended to use high thermal insulation levels, which would cause the "trapping" of the heat inside the buildings. Thus, increasing the insulation level can restrict the loss of heat stored inside, causing a consequent increase in the consumption of the air conditioning system for cooling.

### 4.2.2.2 Solutions for the Renovation of the Façade - Shading System Device

In order to obtain the maximum benefits from the sun's rays in winter, letting them pass through the gap, or in the summer season, to intersect them, a fixed horizontal shading system (mentioned in chapter 3) was integrated outside of the windows at the virtual building. Two analyses were carried out, single and double glazing with the addition of shading device in windows at the façade and their impact on the virtual building. The results are shown in Figure 29 and it is possible to see the only parameter which varies is the solar gains, the addition of a shading device decreases solar gains by 41,330 kWh (80%).

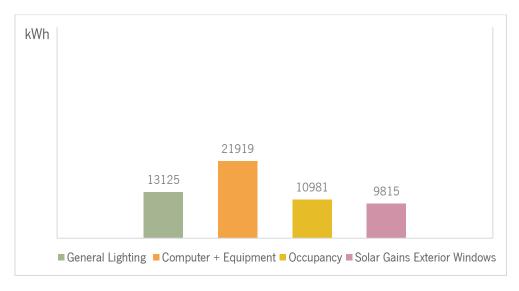


Figure 29 – Annual internal and solar thermal gains (kWh) for the reference floor plan after adding an external shading system at the windows of the façade (The Author, 2020).

Information regarding equipment lighting and occupation are exactly the same as nothing has been changed that would affect these parameters, show in Table 13 below.

Table 13 – Energy demand for the main energy uses at the reference floor plan after adding an external shading system to the windows of the façade (The Author, 2020).

Solution	Energy Uses (at the reference floor plan)	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)	Variation of Energy Demand (%)
3	Heating	1,483.30	1.10	1%
	Cooling	107,580.60	75.80	50%
	Others (lighting and office equipment's)	105,496.60	74.40	49%
	Global	214,560.50	151.20	100%

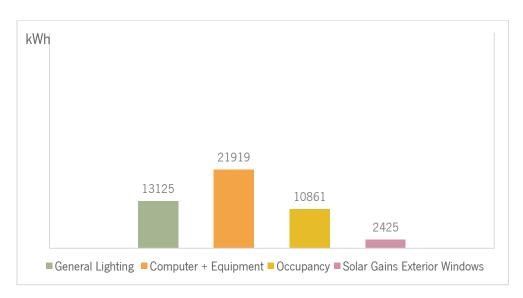


Figure 30 – Annual internal and solar thermal gains (kWh) for the reference floor plan after adding double glazing and external shading system at the windows of the façade (The Author, 2020).

An analysis, with windows with double glazing and the shading device, was also used, which showed an even more significant decrease in solar gains (Figure 30) although the global energy demand is very similar to the single glazing with shading devices (Table 14).

Table 14 – Energy demand for the main energy uses at the reference floor plan after adding double glazing and external shading system at the windows of the façade (The Author, 2020).

Solution	Energy Uses (at the reference floor plan)	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)	Variation of Energy Demand (%)
	Heating	1,223.00	0.90	1%
	Cooling	103,748.40	73.10	49%
4	Others (lighting and office equipment's)	105,496.60	74.40	50%
	Global	210,470.00	148.40	100%

Considering the same window size and the same shading device, changing only the type of glass from simple to double, we found that the solar gains decreased by 80% when treated with single glass and up to 95% when changed to double glass (Table 15).

Table 15 - Variation of total solar gains at the reference floor plan comparing the use of single/double glazing when adding shading device system at the windows of the façade (The Author, 2020).

Solution	Solar Gains (kWh)	Variation of Solar Gains (%)
1	51,145.00	-
3	9,815.00	-80%
4	2,425.00	-95%

The results of the current study agree with the study of Brugnera (2018), which states that using a shading device always generates energy savings, regardless of climate, WWR and type of glass. In Curitiba and São Paulo, the combination of colourless glass, large openings (80%) and use of the shading device generate savings of 30.6% and 26.3%, respectively. Manaus' climate presents different results, with a maximum saving of 13.5% when adding shading devices. In climates with high temperatures throughout the year, the existence of the shading device has lower impact on thermal performance. This was also verified in the study by Carvalho, La Rovere and Gonçalves (2010), who reached 6.4% of reduction in the energy consumption of air conditioning using a shading device on all the façades of a building.

Also, a study conducted in Belo Horizonte, Brazil, showed that office buildings that have some type of shading protection consume, on average, 40% less energy than buildings without shading protection on the façades (Veloso, Souza, & Kourya, 2015). Chvatal & Corvacho (2009) also assert the importance of

using a shading device to control heat gains from solar radiation. Thus, a shading device prevents solar radiation from directly impacting the glass, making the building gain less heat. This can also be seen in Table 15, as the scenarios with a shading device have reduced consumption compared to the other scenarios.

## 4.2.2.3 Solutions for the Renovation of the Façade - Glazing Analysis

As the main objective of this simulation is to evaluate the impact of the chosen window frame and glass in the thermal performance of the building (and not in what concerns the illuminance) a constant artificial lighting regime was adopted for this simulation throughout the building's occupancy time. Thus, it is possible to analyze the influence of the thermal insulation characteristics of the windows and its effect on the thermal gains. To improve the energy performance of the virtual building, it was considered to replace the existing glazing at the façade from single glass laminate low emissive (e =8mm, U =  $5.67W/m^2$ , Tvis = 0.72%) by double glass laminate (e =24mm, U =  $2.53 W/m^2$ , Tvis = 0.40%) keeping the aluminium window frame, as shown in Table 16.

Table 16 – Energy demand for the main energy uses at the reference floor plan after adding double glazing at the windows of the façade (The Author, 2020).

Solution	Energy Uses (at the reference floor plan)	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)	Variation of Energy Demand (%)
2	Heating	1,232.50	0.90	1%
	Cooling	131,879.10	93.00	55%
	Others (lighting and office equipment's)	105,496.60	74.40	44%
	Global	238,608.30	168.20	100%

Table 16 shows that replacing the glazing type from single glass to double shows the cooling needs decrease from 59% to 55% comparing to Table 10 (section 4.2.1) and the energy demand for the lighting and office equipment's increase 3%. As the cooling demand decreases 4% and the other energy uses increases 3% the variation in total energy demand is basically the same, comparing to the single glazing.

The total energy due to the thermal gains for the simulation of the renovation solution corresponding to double glazing is represented in Figure 31. It is possible to see the decrease of the solar gains, in

38,861.00 kWh (75%), what is 4 times less related to the glazing window at the façade when comparing to the single glazing at the base model.

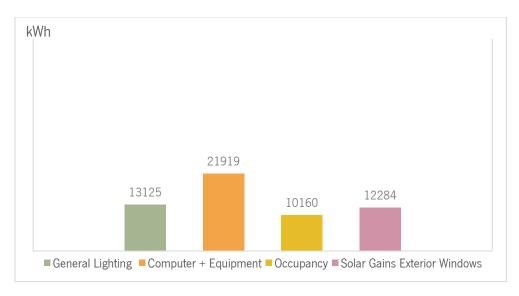


Figure 31– Annual internal and solar thermal gains (kWh) for the reference floor plan after adding double glazing at the windows of the façade (The Author, 2020).

As seen in the values presented in Table 17, it is possible to conclude that the use of double glazing can decrease 8% in global energy demand and turns into an effective solution for the building thermal behavior.

Table 17 - Variation of energy demand for heating and cooling and the total energy demand at the reference floor plan for the base model characteristics, comparing the single and double glazing (The Author, 2020).

Solution	Heating + Cooling Demand (kWh/m².year)	Variation of Heating and Cooling Demand (%)	Total Energy Demand (kWh/m².year)	Variation of Total Energy Demand (%)
1	107.90	1 20/	182.30	00/
2	93.80	-13%	168.20	-8%

Brugnera (2018) verified, in the city of Manaus, the influence of changing the type of single glazing (colorless) to double and found that it has a greater impact on smaller windows (WWR of 30%), with a maximum savings of 10.8%. This is because in Manaus, as the temperature are very high, the higher the WWR, the greater the heat gains through the windows, so the change in the type of glass has a reduced

impact on energy consumption in larger windows. Also, for Curitiba and São Paulo, when there are large windows (WWR of 80%), changing the type of glass from colorless to reflective can generate savings of up to 23.4% (Curitiba) or 21.4% (São Paulo) (Brugnera, 2018).

# 4.2.3 Defined Solution Packages of Renovation Solutions Analysis

After the individual analysis carried out for each renovation measure studied, the analysis of different combinations of renovation measures done to assess the impact of their simultaneous application.

Therefore, two solutions were considered for the building envelope, one being the base model and the other the ETICS system with 0.1000m thick (to assess the worst hypothesis related to thermal insulation, since it had the worst energy performance). In addition, to evaluate the heating and cooling energy demand of the building, the best practice options for lighting and the HVAC system, different types of glass (single and double) and also shading system were considered. The analysis is divided into six simulations, from solution 9 to 14 (description mentioned in charpter 3, Table 8) shown below at Table 18.

Table 18 – Energy demand for the main energy uses at the reference floor plan for 6 different solutions (The Author, 2020).

Solution	Energy Uses (at the reference floor plan)	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)	Variation of Energy Demand (%)
	Heating	963.80	0.70	0%
	Cooling	104,733.00	73.80	52%
9	Others (lighting and office equipments)	97,524.20	68.70	48%
	Global	203,220.00	143.20	100%
	Heating	1,265.40	0.90	1%
10	Cooling	108,927.80	76.80	52%
	Others (lighting and office equipments)	97,524.20	68.70	47%
	Global	207,717.40	146.40	100%

Table 18 – Energy demand for the main energy uses at the reference floor plan for 6 different solutions (The Author, 2020) (Conc.).

Solution	Energy Uses (at the reference floor plan)	Total Energy Demand (kWh/year)	Energy Demand by Total Construction Area (kWh/m². year)	Variation of Energy Demand (%)
	Heating	1,771.80	1.30	1%
	Cooling	113,628.30	80.10	57%
11	Others (lighting and office equipment)	83,607.20	58.90	42%
	Global	199,007.20	140.30	100%
	Heating	2,148.70	1.50	1%
	Cooling	115,853.80	81.70	56%
12	Others (lighting and office equipment)	90,074.80	63.50	43%
	Global	208,077.30	146.70	100%
	Heating	1,492.40	1.00	1%
	Cooling	126,363.60	89.10	54%
13	Others (lighting and office equipment)	105,496.60	74.40	45%
	Global	233,352.60	164.50	100%
	Heating	1,233.20	0.90	1%
14	Cooling	115,899.50	81.70	52%
	Others (lighting and office equipment)	105,496.60	74.40	47%
	Global	222,629.30	156.90	100%

The comparison of energy demand is shown in Table 18 indicating the variation of the total energy and the other energy uses for the situation of the building after renovation. The solutions 9 and 14 represents the ones which has the biggest decrease (7%) in energy demand for cooling when comparing to the solution one. When the analysis is made, taking into account all the proposed solutions, and focused only on the heating and cooling demands, it is possible to analyze better the variations in Table 19.

As shown in the values presented in Table 19, it is possible to conclude that the application of several renovation measures becomes more effective than the use of only one measure, and, in the case of combinations, reductions of up to about 23% can be achieved (solution 11). Level of heating and cooling demand, resulting in a decrease in the building's energy demand around 31% (solution 4 and 9). Solutions 5, 6, 7 and 8 were the ones that the ETICS system was applied without changing any characteristics of

the base model, and presented the worst results, reaching an increase of up to 7% in the total energy demand.

Table 19 – Variation of energy demand for heating and cooling and the total energy demand at the reference floor plan for the base model characteristics (solution 1) comparing to the other 13 different renovation solution (The Author, 2020).

Solution	Heating + Cooling Demand (kWh/m².year)	Variation of Heating and Cooling Demand (%)	Total Energy Demand (kWh/m².year)	Variation of Total Energy Demand (%)
1	107.90	-	182.30	-
2	93.80	-13%	168.20	-8%
3	76.90	-29%	151.20	-17%
4	74.00	-31%	148.40	-19%
5	119.00	10%	193.40	6%
6	119.70	11%	194.10	6%
7	120.20	11%	194.60	7%
8	120.80	12%	195.20	7%
9	74.50	-31%	143.20	-21%
10	77.70	-28%	146.40	-20%
11	81.30	-25%	140.30	-23%
12	83.20	-23%	146.70	-20%
13	90.10	-16%	164.50	-10%
14	82.60	-23%	156.90	-14%

To complement the analysis of Table 19, it was created the Figure 32 and it is possible to observe that all solutions, except the 4 solutions (5,6,7 and 8) of the ETICS system with single glazing, are more efficient solutions when talking about energy performance, comparing to the base model building. The ETICS system can cause anti-insulation effect, requiring more energy for cooling in the office space. However, when the system is combined with other renovation measures such as different type of glazing and the presence of shading devices, the entire building can experience a significant reduction in energy demand between 21 and 23% (soluiton 9 and 11).

When comparing the base model façade with double glazing ( $168 \text{ kWh/m}^2$ .year) and the base model with double or single glazing plus the shading at the larger façades ( $156 \text{ and } 164 \text{ kWh/m}^2$ .year) there is no significant difference. Thus, the shading system is shown as not very useful when not applied to the entire construction. However, a shading system in all the façade can be quite efficient, both for a combination of single and double glazing, reducing up to 19% the total energy demand (solution 3 and 4).

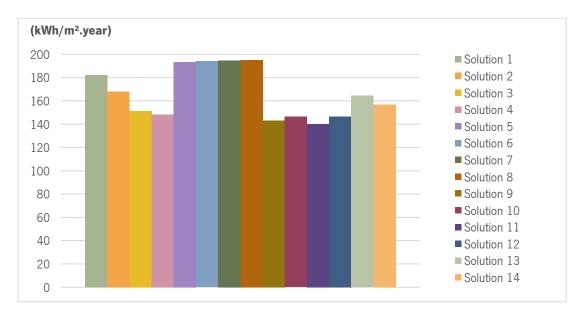


Figure 32– Total energy demand at the reference floor plan for the base model characteristics (solution 1) comparing to the other 13 different renovation solution (The Author, 2020).

However, despite the combination of renovation measures showing beneficial results for the energy performance of buildings, these may not be the most economical and justified measures, so it is necessary to carry out an economic analysis of the studied solutions.

# 4.3 Suggestion of Good Practices to Integrate with Previous Proposals

Concerning the implementation of good practice rules in buildings renovation to improve their energy performance, there are essentially two responsible entities: the designer and the user, taking into account the objective of reducing the building energy demand.

The designer must define the intervention proposal, considering the requirements of the regulations in force, the use of efficient solutions for the envelope and construction elements, combined with efficient systems. The designer's first objective should be to improve the thermal insulation of the building's envelope, in order to reduce the thermal exchanges with the outdoor environment. Then, it is necessary to define the strategies for better natural lighting and ventilation use, always taking into account the solar shading devices, preferably placed from the outside.

From the users' perspective, in addition to monitoring the building, they must adopt appropriate behaviors concerning energy savings. Among the many guidelines contained in manuals for energy efficiency, the following should be highlighted (Macedo, 2013):

- Adjust the use of mechanical systems according to the building's air conditioning needs;
- Prefer natural ventilation to mechanical ventilation;
- Prefer natural lighting to artificial lighting;
- Do not leave lighting systems turned on in spaces that are not occupied;
- Do not leave electrical equipment in standby mode;
- Use equipment and artificial lighting with a high energy rating;
- Place insulation tapes under doors and caulk the window slits;
- Properly control the shading systems to increase or decrease the incidence of solar radiation,
   depending on the season;
- Place plants in some areas of the building, in order to improve air quality.

Good sound masking systems can mitigate or eliminate other acoustic problems post-occupancy. Open plan environments with daylighting could be productive workspaces as long as the acoustic design is not ignored. Besides that, materials have a crucial role to play on building performance and their selection requires special attention. Materials used in a building affect thermal performance, indoor pollution, visual comfort and acoustical comfort. Architects and designers can select materials that do not produce irritating odors or VOCs.

One essential measure to be implemented in order to improve energy efficiency is related to artificial lighting, which should be seen as complementary to natural lighting. A study conducted by Santos, Batista, Pozza & Rossi (2015), shows that fluorescent lamps used in offices must be replaced by more efficient ones and the right choice is the adoption of LED lamps. This type of lamp, although more expensive, has energy efficiency, being 80% more efficient than incandescent lamps and with a lifespan between 25,000 and 40,000 hours, 5 times longer than a compact fluorescent lamp, in addition to not generating reactive energy, releasing little heat and not containing mercury (Santos, Batista, Pozza & Rossi, 2015).

Another measure to be applied is the introduction of extraction systems in the bathrooms, in order to extract odors and renew the air, to avoid condensation and concentration of pollutants. Thus, together

with the natural ventilation processes in the building, the renovation of 40% to 60% of the indoor air per hour must be ensured, in order to make it cooler and more pleasant. The improvement in air quality obtained by reducing the pollution load by 2–2.5 times was similar to that obtained by increasing the outdoor air supply rate by 3 times (Wargocki at al., 2002).

Browning, Ryan and Clancy (2014), found that a third (33%) of all respondents in the global study say that office design would affect their decision to work for a company. The same study shows that 47% of the offices don't have natural light, 58% don't have plants, 11% don't have windows (Browning, Ryan & Clancy, 2014).

Research has shown that natural elements such as plants and flowers are at the top of the list for the desired element in workspaces, second only to natural lighting (WGBC, 2016). The analysis showed that the perception of well-being could increase by up to 15% when people work in environments that incorporate natural elements, enabling a connection with nature, in relation to those who have no contact with nature in their workplace (WGBC, 2016). These results are aligned with the research carried out in this work that showed earlier in section 4.1.6), that most workers (92.5%) would like to have some kind of natural element (such as plants) in their workplace. Other strategies, such as providing control to the occupants and providing them training and raising their awareness, has an impact on the overall satisfaction of the occupant of the building.

# 5. Conclusion

The high energy demand of the construction sector shows the need and interest in studying the issues of energy renovation in buildings. This dissertation focused on the study of energy renovation measures aimed at improving the energy performance of office buildings in Porto Alegre - Rio Grande do Sul, Brazil. These measures focused on increasing thermal insulation levels, the performance of the windows glass and the use of shading devices on the building's façade.

Initially, a bibliographic review was carried out that allowed deepening the knowledge about the energy renovation of office buildings in Brazil and on issues that contribute to improving their energy behavior. Subsequently, a survey was carried out using the Google Form tool. The online questionnaire was delivered to office workers in Porto Alegre. Workers were able to identify the main items related to thermal, acoustic, visual comfort, in addition to assessing the indoor air quality and relating it to well-being and productivity issues. Finally, the thermo-energetic simulation with DesignBuilder software, allowed assessing the energy performance for different office building renovation solutions.

For this analysis, three types of renovation measures were considered, namely the application of thermal insulation on the exterior walls (with application of ETICS), the replacement of the windows' glass and the installation of shading systems, establishing for each measure different thicknesses and types of material. Some variables remained the same, for example: geometry, constructive solution for floors, internal wall, window-to-wall ratio (50%), internal gains, control temperature (set-point) for cooling and heating, in addition to occupation period.

With the results of the questionnaire was possible to conclude:

- The three main factors which influence productivity according to the survey are: 1st noise, 2nd temperature and 3rd ventilation;
- Only 10% of the respondents consider fresh air, and perception of odors a comfort problem, which can be related to the high number of people who have: headaches (65%) and sinusitis (20%); sneezing or runny nose (47.5%); dry eyes (40%) and watery eyes (22.5%); throat problems (36.3%) and breathing problems, such as asthma, bronchitis (11.3%);
- Regarding thermal comfort, 85% answered that there is an influence on productivity in the workplace, and only 36% are satisfied with their workplace;

- For 56% of workers, workplace lighting is medium or very bright;
- Regarding acoustic comfort, 35% answered that noise always affects their productivity and 11.3%
   always feel affected by noise in the workplace;
- 92.5% of the occupants would like to have some type of plant inside the office building;
- 78.8% of people work full time in front of the computer.
- Based on the literature, the indoor environmental quality reflects on the health, comfort and productivity of the occupants of the building. The main reason for the lack of awareness for these topics is due to the fact that the effects of indoor air pollution are mostly chronic and long term and most are not directly and immediately life-threatening. However, there is a growing concern about people's dissatisfaction with the air quality in their workplaces.

From the results obtained from each simulation, the following is concluded:

- Current building's energy diagnosis shows that its energy demand is relatively high, with a value
  of around 182 kWh/m².year, corresponding to about 60% heating and cooling needs and the
  remaining 40% to other uses, such as lighting and equipment;
- The renovation of the opaque façade by applying thermal insulation leads to an increase in the energy demand. It is concluded that the increase in the cooling needs makes the solution ineffective for the city of Porto Alegre, because of the anti-insulation effect. However, if the combination of renovation measures is chosen, it can become more energy efficient;
- Regarding the type of glass chosen, a renovation based only on the glazing type does not produce significant reductions in energy demand. However, opting for double glazing with shading devices on the entire façade may prove to be more effective;
- Concerning the use of shading devices, there are no significant decreases in energy consumption
  when the system is applied only to the larger façades. It is concluded that all the envelope must
  be considered to significantly reduce energy consumption;

Intervening only in the façade, opaque part, it is not possible to reduce the energy demand of the building to the maximum. For this to be achieved, it is necessary to combine sustainable practices with the use of efficient lighting and equipment. Then, it is necessary to evaluate the different combinations of renovation solutions for the envelope (opaque and glazed part of the façade and shading systems) to choose the best alternative. Then, it is necessary to select the use of efficient systems and equipment, in order to reduce the energy demand of the office.

Designers must take into account a range of factors such as sick building syndrome, thermal, visual and acoustic comfort. Literature suggests that green building designs don't automatically guarantee that the building designed will be comfortable and ensure occupant well-being. More specific and in-depth considerations on occupant well-being are required along with the impact on building energy efficiency and sustainability. Just designing a potentially comfortable building is not enough. One also needs to monitor building and occupant performance during its operation phase.

Although the study was done for a virtual office building, it should be noted that the results presented correspond to a specific building, and should not be considered as a generality, since each case is a different case study, and the renovation of buildings must be studied rigorously for each of them. Thus, it can be concluded that, if the best intervention solutions are applied to the building, it may have a great potential for energy savings, contributing significantly to sustainable development.

#### **5.1 Limitations of the Work**

Among the options used in this research, is presented the point of view of the energy performance analysis, which in this study does not consider the use of natural lighting or the use of efficient (dimmable) systems, and the total energy consumption of the building was used. In this sense, the impact of natural lighting, to optimize electricity use and taking advantage of daylight, avoiding, for example, glare and / or overheating near the openings was not considered. For shading, only one system size, with one type of material and the same orientation was used.

The same solar orientation was maintained for all applicable parameters, with the largest façades facing north-south. In addition, the same geometry (rectangular), with a large central area destined to the nucleus, as identified in the data collection and respect for this type of modification applied in Brazil was used. As densities of people, construction solutions and materials for the floor, ceiling, internal walls, WWR (50%), temperature control (setpoint) for heating and cooling, were fixed data. It was considered only two types of glazing (single and double).

Likewise, user behavior can influence the energy consumption of the edition and it is still difficult to be included in these simulations, what limits to work with the maximum of these fixed variables, to identify

how the design parameters influence the energy performance of the building. Finally, in relation to the questionnaire applied to workers, the external noise in the questionnaire in the item related to acoustic comfort was not considered.

#### **5.2 Recommendations for Future Work**

This dissertation aimed to explore solutions for the renovation of office buildings in Porto Alegre (with a focus on energy performance) and to analyse the comfort and well-being of workers at their office buildings. This process, of well-being and productivity research, is still not explored in the construction industry in the city of Porto Alegre, but, in the long term, it is believed that it will be an integral part of project design since there is a big impact on people and environment, it is recommended for future work:

- a) Work with other geometries and types of buildings, other than just free-standing offices, in order to identify how improvements in energy performance could be reflected better environmental performance;
- b) Evaluate other types of façades, covered with vegetation and other materials (such as the use of photovoltaic panels, for example);
- c) Including in the analysis the use of natural lighting (through integration with artificial lighting, through a dimmable system) would be interesting in the sense of understand how much this portion influences the total energy consumption of this type of building, in addition to the insertion of analyzes of the quality of interior lighting, which can assist in the detection glare cases, for example, which can generate spaces with better visual comfort for users;
- d) Using passive strategies, such as natural ventilation which can be carried out by means of hybrid ventilation systems (combination of natural ventilation and use of artificial thermal conditioning systems), can help both in reducing energy consumption and improving comfort thermal inside this type of building;
- e) To study the economic aspect, in order to generate recommendations regarding the type of façade and its characteristics, more adequate for each southern region of the country;
- f) Include in the LCA analysis the impacts arising from the façade maintenance phase, in which cleaning, replacement and repair services are performed directly related to the durability of the materials;

- g) Carrying out more studies on the subject, in order to highlight the importance of the well-being of the building's occupants;
- h) Exploration of other performance analysis and modeling programs, such as BIM;
- i) Carrying out studies with the objective of reaching a zero energy balance building;
- j) Including in the analysis, solar painels as an alternative improving the economical and environmental impact of renovation.

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# Annex I

The main objective of the questionnaire was to assess thermal, acoustic, and luminous comfort and air quality in the work environment, identifying their influence on the environment and productivity. The research was conducted in Portuguese since the study was directed to the city of Porto Alegre in Brazil. With a total of 23 questions, the questionnaire was divided into sessions: Generic questions, luminous, acoustic and thermal comfort, work environment and air quality and final globally question about how the workers feel inside their offices.

# Conforto no Ambiente de Trabalho

\*Obrigatório

Este questionário tem como principal objetivo avaliar o conforto térmico, acústico, luminoso e a qualidade do ar no seu ambiente de trabalho, identificando posteriormente, a influência destes sobre o meio ambiente. A pesquisa será realizada apenas em edifícios comerciais/de serviço em Porto Alegre-RS. A sua participação, anonima, é fundamental para o desenvolvimento deste estudo. Por favor, responda objetivamente e com franqueza às questões a seguir.

Sex	to: *
0	Feminino
0	Masculino
0	Prefiro não dizer
Ida	de: *
0	Até 18 anos
0	19 à 35 anos
0	36 à 50 anos
0	Acima de 51 anos
Voc	cë trabalha em Porto Alegre? *
0	Sim
0	Não

Onde	vocë trabalha: *
O E	m casa
O e	difício comercial (esta alternativa é apenas para prédios comerciais de escritório, xoluindo qualquer outra modalidade como indústria, shoppings ou hospitais por xemplo)
0 0	oworking
0 0	utra:
Locali	zação do seu local de trabalho: *
O T	érreo
OA	ndar intermediário
00	obertura
O Alvens	ria e Janelias Pele de Vidro Pele de Vidro
No se próxir	u local de trabalho localize, em um raio a 2 metros, quais elementos estão nos: *
	anelas
_ A	r condicionado
□ B	anheiro
_ E	quipamentos eletrônicos (impressoras, elevador, etc.)
_	arede interna do edifício (não faz divisa com o ambiente externo)
_ P	arede externa do edifício (faz divisa com o ambiente externo)
	utra:

Qui	al é o luga	ar que vo	cê se sent	te descon	fortável	trabalhan	do: *		
	Perto de	janelas (de	evido a entr	rada de ar)					
	Com a lu	z do sol dir	reta						
	Próximo	ao ar cond	icionado						
	Outra:								
Quais		ipais fatore	Visibilidade		Luz	idade no tri Decoração Mobiliário		Luz natural	Presença de elemento verdes ni decoraçã (Flores,
	77a=0V				-	-			Plantas etc.)
1*	0	0	0	0	0	0	0	0	0
2*	0	0	0	0	0	0	0	0	0
3*	0	0	0	0	0	0	0	0	0
resp	ponda ås	seguinte	s questõe	990			al de traba		
			0 1	2	3 4	5	6		
р	ouco ilum	inada	0 0	0	0 0	0	O Mui	to ilumi	nada
	:ê sente f	falta da ilu	uminação	natural: *					
Voc									
Voc	Sim								

Qual o nivel d	e ruído e	existent	e na su	a mesa	de trat	alho: (s	endo 3	neutro). *
	0	1	2	3	4	5	6	
Muito alto	0	0	0	0	0	0	0	Muito baixo
Você conside	ra que o	ruido a	trapalh	a o seu	desem	penho	no trab	alho: *
Sim, semp	re.							
Sim, as ve	zes.							
Raramente	atrapalh	a.						
Não atrapa	alha.							
A sua comuni  Sim, semp  Sim, as ve	re. zes.		essoas	ao redo	or é afe	tada pe	elo ruido	0; *
Raramente	. ereragram							
Raramente	alha. apenas questões	r:						alho, responda neutro). *
Raramente Não atrape Considerando as seguintes o	alha. apenas questões	r:						

	0	1	2	3	4	5	6	
Muito Frio	0	0	0	0	0	0	0	Muito Quente
Como o confo	rto tërr	nico co	ntribui	para o	seu rer	ndimen	to no tra	abalho: *
O Favorece								
O Atrapalha								
O Neutro								
		eçou a	trabalh	ar nest	e local,	você ji	aprese	entou algum
Desde que voi desses proble		eçou a	trabalh	ar nest	e local,	você ji	aprese	entou algum
	mas: *				e local,	você ji	aprese	entou algum
Sim, respire	mas: * atórios (a	asma, br	onquite	, etc)	e local,	você ji	à aprese	entou algum
Sim, respire Sim, sinusi Sim, uso de	mas: * atórios (a te	asma, br	onquite	, etc)	e local,	você ji	à aprese	entou algum
Sim, respire Sim, sinusi Sim, uso de Sim, hábito	mas: * atórios (a te é óculos de fuma	asma, br	onquite	, etc)	e local,	você ji	à aprese	entou algum
Sim, respire Sim, sinusi Sim, uso de Sim, hábito Sim, stress	mas: * atórios (d te e óculos de fuma	asma, br	onquite	, etc)	e local,	você ji	à aprese	entou algum
Sim, respire Sim, sinusi Sim, uso de	mas: * atórios (a te	asma, br	onquite	, etc)	e local,	você ji	à aprese	entou algum
Sim, respire Sim, sinusi Sim, uso de Sim, hábito	mas: * atórios (d te e óculos de fuma	asma, br	onquite	, etc)	e local,	você ji	à aprese	entou algum
desses proble  Sim, respire Sim, sinusi Sim, uso de Sim, hábito Sim, stress Não, nenhu Outra:	mas: * atórios (d te e óculos de fuma	ou lente	onquite	etc)				
desses proble  Sim, respire Sim, sinusi Sim, uso de Sim, hábito Sim, stress Não, nenhu Outra:	mas: * atórios (a te e óculos de fuma m.	ou lente	onquite	etc)				
Sim, respire Sim, sinusi Sim, uso de Sim, hábito Sim, stress Não, nenhu Outra:  Quantas horas	mas: * atórios (a te e óculos de fuma m.	ou lente or você u	onquite	etc)				

Para finalizar								
Considerando as ques você se sente: (sendo				obre o	amb	iente	de tra	balho, no geral
	0	1	2	3	4	5	6	
Muito desconfortável	0	0	0	0	0	0	0	Muito confortável