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Energy savings potential of the high-rise office building stock. A case study of Belo Horizonte, Brazil.

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ABSTRACT

This study develops a framework to identify and analyse the energy savings potential of an existing building stock category. The methodology consists of six basic steps: (1) a method for obtaining reference buildings, (2) dynamic archetype model simulations, (3) an energy consumption baseline estimation, (4) energy retrofit measures selection and a cost optimal pathway analysis, (5) developing energy saving scenarios and (6) estimating building stock energy savings potential. In order to apply the proposed methodology, a case study took place in the city of Belo Horizonte, Minas Gerais, Brazil. Firstly, the city plan, the land use regulations and the building construction codes of Belo Horizonte were investigated in a temporal and spatial perspective. Secondly, a local city council database based on land tax information was used to study basic high-rise office building features. Thirdly, a field study was conducted based on the proposed building typology classification. The information gathered from the three inputs was used to obtain three reference buildings and describe their prevalent attributes. For each reference building, building archetype energy models were created and simulations were performed in EnergyPlus to assess their Energy Use Intensity (EUI). The BaseCase baseline of energy consumption was then estimated based on the simulated EUI of each archetype energy model. The results of the BaseCase baseline analysis emphasized the role of technical choices in reducing electric energy consumption, particularly the ones related to the HVAC system. They also showed that there are growing evidences that the high-rise office buildings are becoming more energetically intense. Furthermore, in order to assess the building stock energy savings potential, retrofit measures were selected based on their technical feasibility and suitability. A local sensitivity analysis was then used to prioritize the building retrofit measures and a sequential search optimization technique was applied in order to identify the cost optimal pathway for implementing the measures. Finally, three scenarios were developed based on the cost optimal pathway analysis results. The scenario projections were then estimated and compared to the BaseCase projection in order to assess the energy savings potential of the office building stock. The saving scenario results highlighted that there are significant opportunities for energy efficiency improvements in the existing high-rise office building stock of the city. Using current technologies, cost effective energy savings of up to 24% would be possible in the high-rise office building stock by 2036.

Regardless costs, by the year 2036, deeper retrofit packages could unlock savings up to 28%. Overall, the disaggregated scenario projections emphasized the significance of dealing with the existing high-rise office building stock but also highlighted that to shorten the current building stock consumption over the next 20 years the policy makers will have to pay close attention to the upcoming buildings.

Keywords:

Building stock modelling; reference buildings, building archetype models; building energy performance simulation; building stock retrofit and building stock energy savings potential.

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LIST OF ABBREVIATIONS

AGR - annual growth rate

AMDs - adapted morphological diagrams

ANN - artificial neural networks

CA - land utilization coefficient

CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior

CBCS - Brazilian Sustainable Construction Council

CBECS - Commercial Buildings Energy Consumption Survey

CEMIG- Compahia Energética de Minas Gerais

COP - coefficient of performance

DECM - Domestic Energy and Carbon Model

DOE – Department of Energy (USA)

EERE - Energy Efficiency and Renewable Energy

EPBD - European Directive on the Energy Performance of Buildings

EPRI - Electric Power Research Institute

ERPs -energy retrofit packages

EUI - energy use intensity

FEMP - Federal Energy Management Program

GHR -cooling degree-hours

HVAC -Heating, Ventilation and Air conditioning

IC - influence coefficient

IEA - International Energy Agency

IPTU - Imposto Predial e Territorial Urbano

ISO - International Organization for Standardization

LCC - life cycle cost

LPD - light power density

LSA - local sensitivity analysis

LUOS - Law of Use and Land Use of Belo Horizonte

NS - net savings

OM&R - Operation, Maintenance and Repair

PCC - partial correlation coefficients

PNNL - Northwest National Laboratory

PRCC - partial rank correlation coefficient

PROCEL - National Program for Electricity Conservation

PV – present value

R - perimeter distance requirement

RB – back perimeter distance requirement

RBs – reference buildings

RF – frontal perimeter distance requirement

RL – lateral perimeter distance requirement

RTQ-C - Technical Requirements of Quality for Energy Efficiency Level of Commercial, Public and Services Buildings

RTQ-R - Technical Requirements of Quality for Energy Efficiency Level of Residential Buildings

SA – sensitivity analysis

SHGC - glass solar heat gain coefficient

SMAPU/PBH - Secretaria Municipal Adjunta de Planejamento Urbano

SRC - standardised regression coefficients

SRRC - standardized rank regression coefficients

TO - building coverage ratio

TRY - test reference year

UA – uncertainty analysis

UHI - urban heat island

UK – United Kingdom

USA – United States of America

WWR - window to wall Ratio

ZEB - zero energy buildings

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1 INTRODUCTION

The urban intensification which took place in the last decades, has brought the application of many products and services that depend on energy, indicating a growing scenario of energy consumption, especially electricity (HABITAT, 2011). At a global scale, this rapid urban growth leads to the global environment and resource depletion which has emphasized the role of cities in climate change mitigation and in addressing sustainable development issues (HABITAT, 2011).

The building sector is among the largest consumers of energy worldwide. In countries such as US and UK approximately 40% of the energy consumption is attributed to the building sector (DOE, 2010; GOV.UK, 2012). In Brazil, currently over 45% of electric energy consumption is consumed in the building sector (MME, 2015).

During the last two decades, many governments, international organizations and researchers have been working to reduce building energy consumption. For instance, the Electric Power Research Institute (EPRI) estimates that building energy efficiency programs in US have the potential to realistically reduce the growth rate of electric energy consumption by 22% (EPRI, 2009). The International Energy Agency (IEA) has launched a set of ECBCS Annexes in order to promote energy efficiency of existing buildings, such as: Annex 50 – Prefabricated systems for low energy renovation of residential buildings and Annex 55 – Reliability of energy efficient building retrofitting (IEA, 2010, 2012). The European Directive on the Energy Performance of Buildings (EPBD), adopted in 2002, contains a number of requirements towards improving the energy performance of existing buildings and it is an example of legislation forcing the sector to become more energy efficient (EUROPEAN COMMISSION, [S.d.]). Voluntary rating schemes like LEED and BREEAM also play a role, enticing stakeholders to consider environmental aspects in constructions (LEE, 2012).

In Brazil, the first steps towards energy efficiency in buildings were undertaken in 2001 when the Energy Efficiency Law set up the basic rules for the National Policy on Energy Conservation. In 2009, the Technical Requirements of Quality for Energy Efficiency Level of Commercial, Public and Services Buildings (RTQ-C) were published, reinforcing governmental actions related to energy savings and creating conditions to start the Brazilian building labelling process (INMETRO, 2010).

Despite the growing evidence that much can be achieved addressing building energy savings, there are still many barriers to investments in building energy efficiency, especially regarding developing countries. According to Iwaro and Mwasha (2010) in developing countries the main obstacles are: economic/financial barriers, the lack of appropriate production technologies, behavioural and organizational constraints and information barriers. Economic/financial barriers are related to the higher up-front cost for equipment, the lack of access on financing and energy subsidies. The lack of appropriate production technologies deals with the reduced capability of producing energy-efficient and cost-effective products in line with energy regulations. Behavioural and organizational constraints are associated to the difficult on changing energy consumption patterns. At last but not least, the consumer lacks sufficient information (or expertise) to make decisions which would optimize their overall cost and energy savings.

In the search for overcoming these difficulties, especially concerning to the lack of information, this study aims to investigate building energy retrofit initiatives at an urban scale in an effort to address building stock energy savings potential. Building stock energy saving potential analyses are expected to become a key planning tool for municipalities, urban planners and architects in an attempt to understand and manage the energy demand of cities (REINHART; CEREZO DAVILA, 2016).

1.1 PROBLEM DESCRIPTION

How to access the energy performance and the energy savings potential of an existing building stock is the general problem addressed in this thesis. Both subjects are noted to be a challenge, especially in countries such as Brazil where the lack of building energy consumption benchmarks makes it hard to decide upon interventions in the building stock, as neither the existing nor the attainable energy performance are known.

A starting point for accessing building stock energy performance is the development of an energy consumption baseline which allows the identification of energy consumption patterns. Moreover, knowing consumption patterns permits finding opportunities for energy efficiency improvements. At the basis of this discussion, there are two subjects: the building stock energy modelling and the building stock energy retrofit.

The literature presents several techniques for building stock energy modelling and among them the bottom-up archetype technique is noted to be intensively used (BALLARINI; CORGNATI; CORRADO, 2014; HEEREN *et al.*, 2013; HEIPLE; SAILOR, 2008; MAURO *et al.*, 2015; YAMAGUCHI; SHIMODA; MIZUNO, 2007) due to its capabilities of estimating energy consumption without having to rely on historical data and evaluating the impact from different combination of technologies on energy consumption approaches (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009; ZHAO; MAGOULÈS, 2012). This technique sorts the building stock according to age, size, type, and similar criteria and utilizes these factors to define representative energy models. In doing so, this representative model is scaled up to the regional or national stock based on the representative weight of the modelled sample (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009).

In general, a bottom-up archetype technique requires several data sets including building geometry, construction attributes, system attributes and usage schedules. The information is then combined into a thermal model which goes under a simulation process, in many cases dynamic thermal simulation engines such as EnergyPlus, DOE2 and TRNYS (REINHART; CEREZO DAVILA, 2016). A literature review reveals that bottom-up archetype approaches have a limited link to urban context despite the knowledge that built urban patterns have long lasting impacts on the city energy consumption. The difficulties of considering inputs such as solar shading effects between buildings, surrounding building reflectance and local wind patterns among others rely on combining building massing models (which is the representation of the urban form) and building archetype models into a thermal model during the simulation process (ALLEGRINI *et al.*, 2015; REINHART; CEREZO DAVILA, 2016). In that sense, being aware of this gap, particularly when dealing with dense cities and high-rise buildings, is relevant especially for an accurate building stock energy savings potential evaluation.

Concerning the topic building stock energy retrofit, the basic step is to understand the term building retrofit and the concept of building energy performance. The term building retrofit, also called building refurbishment in the literature, describes a work required to upgrade an aged or deteriorated building (FLOURENTZOU; ROULET, 2002; MA *et al.*, 2012). According to the Brazilian NBR 15.575 (ABNT, 2013b), the term retrofit is used to describe the remodelling or upgrade of building systems through the inclusion of new technologies and concepts in order to increase property value and lifetime, to adapt to a new usage and to improve operational and energy efficiency. The basic principle behind building energy performance is to use less energy for operation, without impacting on the health and comfort of the occupants (MA *et al.*, 2012; REINHART; CEREZO DAVILA, 2016).

Existing building retrofits are noted to be a challenge due to the number of variables involved in the process. Many uncertainties such as the dynamic of the climate, building subsystem interactions and technologies, human behaviour, economic forces and government policies can affect the success of a retrofit project. From the perspective of the building stock, retrofits can be even more challenging, once all those questions are scaled up to the city (MA *et al.*, 2012; RAVETZ, 2008).

Currently, some studies are investigating building retrofit initiatives at an urban scale in an effort to address potential energy savings especially related to the commercial building stock (CHIDIAC, SE *et al.*, 2011; GRIEGO; KRARTI; HERNANDEZ-GUERRERO, 2015; HIGGINS *et al.*, 2014; HOOS *et al.*, 2016; MAURO *et al.*, 2015). It is noted that building stock retrofit measures usually rely on technical opportunities such as lighting systems and building mechanical system improvements. Moreover, they are frequently used to evaluate the effectiveness of current policies or to support further policies that target energy consumption and/or CO_2 emission reductions.

Regarding the Brazilian context, building stock retrofit studies are observed to be a hard work especially due to the lack of building energy consumption information or/and data access availability. Some recent projects are trying to overcome these difficulties. For instance, Borgstein and Lamberts (2014) proposed and tested a methodology for developing an energy performance benchmark model for buildings based on a voluntary data gathering initiative by the Brazilian Sustainable Construction Council (CBCS). Benchmarks were developed for the energy consumption of bank branches in Brazil. Silva, Almeida and Ghisi (2016) described a decision-making process that enables the improvement of the thermal and energy performance of residential buildings considering uncertainties in the operational input variables. Melo *et al.* (2014) investigated the applicability of artificial neural networks (ANNs) as a surrogate modelling technique to improve models accuracy for labelling proposes: an ANN was applied to model the building stock from Florianopolis.

Despite all efforts, a lack of building stock retrofit studies is noted in the Brazilian context. Starting from these considerations, this study aims to outline the steps necessary to identify and analyse energy efficiency improvement opportunities regarding the existing building stock.

1.2 PURPOSE

The central goal of this research is to develop a methodology for identifying and analysing the energy savings potential of an existing building stock category. A case study has taken place in Belo Horizonte, Minas Gerais, Brazil in order to identify the energy savings potential of the high-rise office building stock from the city.

The city of Belo Horizonte was chosen as the field study based on the socioeconomic importance of the city into the Brazilian context. The commercial building sector was selected for this study due to the representative weight of the sector in the overall electric energy consumption of the city, approximately 36% (PBH, [S.d.]). Office buildings, in particular high-rise buildings, were selected based on the understanding that high-rise commercial buildings are energetically intense (CBCS, 2015; GONÇALVES; BODE, 2015).

The scientific relevance of this research is the development of a novel methodology for obtaining reference buildings in their urban context without having to study specific buildings in depth or to access building construction databases. In that sense, it shows important applicability especially in underdeveloped countries.

The outlines of this research are based on:

- Developing a methodology for obtaining reference buildings and archetype energy models in order to estimate the energy use intensity baseline and to assess the energy consumption of an existing building stock category.
- Exploring the energy savings potential over time, through the simulation of building stock retrofit scenarios.
- Critically assessing the issues (barriers, driving factors, limitations) that have emerged from the methodology application;
- Providing guidelines to support further energy policies, targeting energy consumption reduction in the commercial building stock.

The overall structure of the thesis is illustrated in Figure 1. Based on this structure the contents of the following chapters are presented as follows.

Chapter 2 Background

Energy and Cities, Building Retrofit, Building Stock Modelling

Reference Buildings, Dynamic Energy Simulations

Sensitivity Analysis, Economic Analysis

Chapter 3 Methodology

General Method

Chapter 4 Belo Horizonte's Case Study
The energy consumption Baseline of high -rise office buildings

Applied Methodology

Results and Discussion

Conclusion and remarks

Chapter 5 Belo Horizonte's Case Study
The energy savings potential of high-rise office buildings

Applied Methodology

Results and Discussion

Conclusion and remarks

Chapter 6 Conclusion

Figure 1 – The thesis structure

Chapter two provides a background on building stock retrofits, building stock modelling, reference buildings, dynamic energy simulations and sensitivity and economic analyses focused on building energy performance.

Chapter three describes the general research methodology. The general methodology proposed here followed six steps: (1) a method for obtaining reference buildings, (2) dynamic archetype model simulations, (3) an energy consumption baseline estimation, (4) energy retrofit measures selection and a cost optimal pathway analysis, (5) developing energy saving scenarios and (6) estimating building stock energy savings potential.

Chapter four and five present the application of the general methodology in a case study. The case study took place in Belo Horizonte, Minas Gerais, Brazil. Chapter four develops the three first methodological steps in order to estimate the energy consumption baseline of the high-rise office building stock from Belo Horizonte. Chapter five develops the last three methodological steps with the purpose of assessing the energy savings potential of the office building stock from the city.

Finally, chapter six provides a summary of the work as well as research conclusions and future challenge discussions.

2 BACKGROUND

2.1 ENERGY AND CITIES

Cities are increasingly expanding their boundaries and population. At the beginning of the 20th century, less than 15% of the world's population lived in urban areas. Today, over 50% reside in urban areas and by 2100 estimations show that urban populations will represent 80% of the total world population (COHEN, 2006; SANTAMOURIS *et al.*, 2001). This rapid urbanization of the world is causing changes to the global energy use patterns and placing cities in the centre of the discussion concerning climate change mitigation and sustainable development achievement (HABITAT, 2011; STEEMERS, 2003).

In a response to this challenge, in the last two decades the concept of 'eco-cities' has gained increasing attention from researchers, urban planners, governmental and non-governmental organizations (JOSS; COWLEY; TOMOZEIU, 2013). In the literature, the discourse about 'eco-cities' is based on environmental quality and liveability in order to minimize waste and pollution, maximize energy efficiency in buildings, low-energy transportation, renewable energy generation and reduce ecological footprint (EAMES *et al.*, 2013; JOSS; COWLEY; TOMOZEIU, 2013; TSOLAKIS; ANTHOPOULOS, 2015).

Eco-cities initiatives have been proliferating across regions and continents. In terms of development, these initiatives could be categorized in a new development, urban expansion and urban retrofit (JOSS; COWLEY; TOMOZEIU, 2013). New developments found a propitious field in the context of rapidly urbanization such as China, where low carbon urban development has been promoted through low carbon pilot cities such Sino-Singapore Eco-City project in Tianjin and Dongtan Eco-City project in Shanghai among others (KHANNA; FRIDLEY; HONG, 2014; MIAO; LANG, 2015). Elsewhere, new development initiatives are underway. South Korea has developed an ideal prototype in New Songdo which is expected to produce a model to be export. In India for instance, the Ministry of Commerce and Industry plans four new eco-cities in the so-called Delhi-Mumbai Corridor, nevertheless in the United Arab Emirates the eco-city of Masdar was conceived to become an international hub for renewable energy research and development (JOSS; COWLEY; TOMOZEIU, 2013; TSOLAKIS; ANTHOPOULOS, 2015).

In contrast, countries within a long history of urbanization are noted to develop eco-city initiatives mainly centred upon existing urban areas through either urban expansion or urban retrofit. In many countries, particularly parts of Europe and US the challenge is to deal with building stock ageing and urban infrastructure. In this context, urban retrofits are observed to emerge as an essential path towards the sustainable agenda (DIXON *et al.*, 2014; DIXON; EAMES, 2013; JOSS; COWLEY; TOMOZEIU, 2013).

The term urban retrofit, although there is no overall agreement, has been used to address alteration of the fabric, form or systems in the built environment in order to improve energy, water and waste efficiencies. Understanding sustainable urban retrofit processes are complex, considering that cities are non-linear systems that interact in multiple scales (building, neighbourhood, city-region), domains (energy, water, resources use) and socio-technical ‘regimes’ (housing, non-domestic buildings, urban infrastructure). In this context, the critical challenge is to align the speed and direction of the multiples agents (public agencies, the private sector and users) towards the goals of sustainable development (DIXON; EAMES, 2013; EAMES *et al.*, 2013).

In the context of urban retrofit, building stock retrofit is noted to play an important role in reducing energy consumption and associated greenhouse gas emissions of existing buildings. For instance, Carbon Trust report that existing non-domestic buildings can lead to 15% carbon reduction potential from cost-effective energy efficiency measures in UK (CARBON TRUST, 2009). Global Buildings Performance Network (GBPN) stated that is technically feasible to reduce 30% of world’s building consumption by 2050 through mainstream adoption of holistic policy measures that encourage the rapid uptake of deep energy efficient renovation and nearly zero energy new builds (GBPN, 2014).

In 2007, the International Energy Agency - IEA published a study on existing energy savings potential of commercial and residential US building sector (WAIDE; AMANN; HINGE, 2007). The study identifies four main end uses regarding the North American commercial building stock as shown in Table 1.

Among the considerations highlighted in this study, lighting and space conditioning are noted to have the biggest savings potential about 20% and 30% respectively. Moreover, the study indicates that envelope attributes (insulation, infiltration, solar heat gain coefficient, etc.) play an important role in optimizing lighting and cooling/heating once those attributes can impact on heat gaining and daylighting access.

Table 1 - Energy savings potential of the North American commercial building stock

End Use		% of Total Commercial Energy	Technology Options	Savings Potential
Space Conditioning	Walls	30%	• Improved Insulation	L
	Windows		• Spectrally specific glass	M
	Roofing		• Light-colored "cool" treatments • Upgraded roof insulation	M
	Space Heating		• Large buildings: efficient fans and pumps, systems to synergize heating, cooling and lighting • Small buildings: similar to residential options • Small-scale CHP	H
	Space Cooling		• Better compressors, high-efficiency modulating air handler fans • More precise refrigerant valves, variable speed blowers, improved coil designs, better motors • Advanced controls and integrated economizers for rooftop units • Improved O&M	M
	Ventilation		• Higher efficiency fans and filters, heat recovery	M
Lighting		20%	• Compact fluorescent and ceramic metal halide lamps • Scotopic, LED, "Super T8" fluorescent fixtures • Fully integrated daylighting controls • Hybrid solar lighting	H
Office Equipment		15%	• Both standby and active mode power reductions for computers • CPU management	H
Water Heating		5%	• "Point-of-use" systems • Commercial Heat Pump Water Heaters	M

Savings: L (Low) is <15% of end-use energy; M (Medium) is 15–25%; H (High) is >25%.

Source: Waide; Amann and Hinge (2007)

In a similar approach, the Pacific Northwest National Laboratory – PNNL (BELZER, 2009) elaborated a report regarding the existing commercial building energy savings potential based on six different retrofit studies in the US. And suggested that lighting has the greatest potential for energy savings followed by the air conditioning system; the improvement of lighting and air conditioning systems are usually associated with equipment modernization and its energy efficiency. Equipment such as elevators and pumps are associated to the building automation and energy management;

Ruparathna, Hewage and Sadiq (2016) written a critical review focused on energy efficiency regarding technical, organizational and behavioural changes in the existing commercial and institutional building stock. The critical review suggests that existing studies are predominantly focused on technical advancements and therefore there is a lack of comprehensive studies on building asset management (for example: building commissioning and energy metering) and behavioural improvements.

Regarding technical approaches, Ruparathna, Hewage and Sadiq (2016) identified that the most recurrent topics are related to: heating, ventilation and air conditioning (HVAC) systems, lighting systems and building envelope. In general, HVAC system energy saving approaches are based on upgrading the existing mechanical system to an energy efficient technology. However, they identified several studies that employ natural ventilation and mixed mode systems (natural ventilation/air conditioning) to improve the energy efficiency of the HVAC system. Concerning lighting system, the most common approaches rely on lamp upgrade, daylight integration and lighting control such as lighting sensor and automation. They also highlighted the challenge for automated lighting controls once they have a high initial cost and complicated commissioning process. In the case of the building envelope, saving approaches focus on wall/roof insulation and on improving window systems. They suggested that there has been an upward trend in innovative studies related to the building envelope. Among the studied topics they listed smart facades, new insulating paintings, high-performance windows and micro-generation through photovoltaic facade modules.

Some other studies focused on building stock retrofit are presented in Table 2. Similarly to the review presented by Ruparathna, Hewage and Sadiq (2016), it can be seen that there is a predominant focus on technical measures, particularly building envelope and systems (lighting and HVAC) in those studies. It is important to note that several retrofit selection criteria were found on those studies, but among them the use of sensitivity analysis was noted to play an important role in identifying key variables affecting energy performance and consequently the saving potential. Mauro *et al*. (2015) employed sensitivity analysis, specifically standardized rank regression coefficients (SRRCs), to identify proper retrofit actions of South Italy buildings from 1920 to 1970. Griego, Krarti and Hernandez-Gerrero (2015) performed sensitivity analysis to determine the impact of the labour rates for the capital construction costs and identify the effects of project life and discount rate on the Life Cycle Cost (LCC) of new and existing office buildings in Guanajuato, Mexico.

Table 2 – Examples of building stock retrofit studies

Authors	Information	Retrofit Measures	Results
Mauro *et al.* (2015)	**Focus on**: Office Building Stock. **Location:** Italy **Objective:** A new methodology for investigating the cost optimality of energy retrofitting a building category. **Measure Selection Criteria:** Category peculiarities, best practice, UA (Monte Carlo Analysis), SA (SRRCs)	**Envelope Measures:** Insulation of the external vertical walls; insulation of the roof; insulation of the floor; low-a plastering of the external vertical walls; low-a plastering of the roof; installation of double-glazed low-e windows with PVC frame; implementation of external shading of the windows; **System Measures:** efficient condensing boiler, heat pump, for heating generation;– efficient air-cooled chillers , water cooled-chillier, for cooling generation, Photovoltaic Panels (PV) **Use/Occupation Measures :**not mentioned	Envelope measures do not have strong influence on energy demand. Best savings in global costs were about 15% (Roof and wall absorptance, low-e window, shading, free night ventilation). Bigger savings were obtained in the presence of government incentives (Best combination HVAC substitution + PV+ low-e window incentives) about 72%.
Higgins *et al.* (2014)	**Focus on:** Office Building Stock **Location:** New South Wales, Australia **Objective:** Forecasting uptake of retrofit packages in office building stock under government incentive. **Measure Selection Criteria:** The packages are representative of options at different price points and they are considered typical retrofits suited to both landlord and tenants.	**Envelope Measures:** reflective paint on roof—low rise only, replace existing glazing with high performance glazing **System Measures :** Movement detector lights witches, LED exit lights, replacement blinds, T5 lighting, Solar HWS or Heat Pump, Chillers replacement, boiler plant upgrade, Chilled beams, Solar PV **Use/Occupation Measures:** Services tuning & rebalancing , update of O&M manuals, building users guide, Business Management System,	Results showed how a diffusion model can be used to evaluate the impacts of government policy to accelerate energy efficient retrofitting in office buildings.
Chidiac *et al.* (2011)	**Focus on**: Office Building Stock **Location:** Canada **Objective:** Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings **Measure Selection Criteria:** Not Mentioned	**Envelope Measures:** Infiltration rate, Improve wall U, Window U value **System Measures :** Lighting load, Convert HVAC : CAV to VAV, High efficient Boiler, Preheat and Economizer, Dayligthing **Use/Occupation Measures :** not mentioned	Reductions in electrical consumption and increases in natural gas consumption were over predicted. The estimated combined reduction in electrical consumption for this Energy Retrofit Measures (ERM) set (heat recovery, daylighting, boiler efficiency economizer/preheat upgrade and lighting load reduction) was approximately 29 and 31% over all cities modelled. For natural gas the changes in consumption were 28%, 34% and -5% for Edmonton, Ottawa and Vancouver respectively.

Hoos *et al*. (2016)	**Focus on:** Institutional building stock **Location:** Luxembourg **Objective:** Energy consumption of non-retrofitted institutional building stock in Luxembourg and the potential for a cost-efficient retrofit. **Measure Selection Criteria:** derived from European retrofit projects (retrofit measures and cost).	**Envelope Measures:** For buildings with a normal consumption, only constructional changes of the building envelope are considered for retrofit, e.g. the insulation of the envelope, the ceiling and new windows. **System Measures:** A renewal of the heating system was only considered for the retrofit of buildings with a high consumption and results in higher retrofit costs. **Use/Occupation Measures :** not mentioned	A certain amount of sample buildings was analyzed and then separated into three groups of low, normal and high end-energy use. Buildings with a low consumption showed an end-energy use between 90 and 130 kWh/(m^2a), while buildings with a high consumption showed values between 150 and 190 kWh/(m^2a). It was more cost efficient to retrofit the class of buildings with a high consumption, since the costs per one kWh saving were between 0.04 and 0.08 Euro /kWh. Retrofitting the class of "normal" energy use was more expensive with values between 0.07 and 0.19 Euro /kWh (considering an amortization time of 25 years and no interest rate).
Danielle Griego, Moncef Krartia Abel Hernandez-Guerrero (2015)	**Focus on:** New and Existing Office Buildings **Location:** Mexico **Objective:** Energy efficiency optimization of new and existing office buildings in Guanajuato, Mexico **Measure Selection Criteria:** The sequential search optimization technique was used to define the most cost-effective energy efficiency packages for both new construction and retrofit of office buildings. A sensitivity analysis was performed to determine the impact of the labour rates on the capital construction costs.	**Envelope Measures:** Assembly Roof U-value (insulation above deck), Assembly Wall U-value (mass wall), Maximum WWR, Window U-value, Window SHGC **System Measures :** LPD building, Split system AC (COP) **Use/Occupation Measures :** not mentioned	Energy efficiency measures were investigated for both existing and new construction office buildings. The results from the optimization analysis indicated that the most cost-effective potential for energy conservation in both new and existing offices was achieved by reducing office equipment loads and introducing more efficient lighting technology and controls. Over 49% annual energy savings can be achieved cost-effectively for both retrofit and new construction commercial office buildings. For the new office building it was indicated that single pane low-transmissive glazing at 30% WWR was the optimum fenestration configuration. Moreover, it was found that the low-transmissive glazing was more cost effective than high efficiency HVAC equipment to reduce cooling energy consumption for the new construction case. Another finding was the negative impact on cooling energy consumption when adding exterior wall and roof insulation in both new and existing office buildings.

Source: Author's own elaboration

Regarding the Brazilian context, retrofit studies were encouraged from 1980's on by the implementation of the National Program for Electricity Conservation (PROCEL) in which the objective was to promote the efficient use of electricity. Among the first initiatives regarding buildings, in 1996 the PROCEL promoted the development and application of a methodology for assessing building energy performance of commercial and public buildings. The initiative named *Projeto 6 cidades* chose two commercial or public buildings in six Brazilian cities in order to assess the energy saving potential and then implement retrofit measures. The FIESC and Eletrosul buildings in Santa Catarina were among those buildings studied. In the study, Eletrosul building presented a saving potential of 25% in lighting and air conditioning whereas the FIESC building presented a saving potential of 35% in lighting (PEDRINI; WESTPHAL; LAMBERTS, 2002). Eletrosul building was noted to have those measures implemented and the monitored results indicated energy savings of approximately 23% (SERAFIN, 2010).

In the Brazilian context, a lack of building stock retrofit studies is observed regardless of all efforts to promote retrofit studies. In a recent study, Didone, Wagner and Pereira (2014) developed a method for evaluating the potential of transforming Brazilian office buildings into Zero Energy Buildings (ZEB) in two different climates (Fortaleza and Florianópolis). The method was divided into three steps: the evaluation of the prototype case (reference building), the development of an optimal case (low energy building) according to the Brazilian energy efficiency labelling system and the determination of ZEB case. The ZEB case was obtained by the application of solar energy technologies (BIPV) in the building. The results showed that the number of photovoltaic modules necessary to obtain ZEB is bigger in Florianopolis due to the higher energy consumption, especially cooling. Moreover, they suggested that the application of the Brazilian energy efficiency regulation for buildings allowed a reduction of almost 50% in the final energy consumption. Giglio *et al.* (2014) studied the use of solar heating systems for water in Londrina. A case study was undertaken with 200 low-income families. The objective was to assess the energy saving potential for heating water. The research strategy involved a cluster analysis designed to improve the understanding of what energy savers and other influencing factors exist. Five clusters were created and the results suggested that only two clusters demonstrated good electric energy savings, representing 47% of families.

2.2 BUILDING STOCK ENERGY MODELLING

Building stock energy modelling is the basis of any quantitative energy building stock performance assessment method, and can be considered the process of determining the amount of energy use of a given building stock based on relevant information collected (WANG; YAN; XIAO, 2012).

In the literature, there are two different approaches related to building stock energy modelling: top-down and bottom-up (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009). Top down modelling works at an aggregated level, commonly investigates historical data collections of energy consumption and its relation to available aggregated data such as gross domestic product and market prices to provide a picture of the existing stock. Bottom-up modelling works at a disaggregated level by using data of representative buildings and extrapolating the results to represent the large scale (regions, cities or nations) (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009).

Top-down models are considered as an useful tool for estimating energy supply requirements at a regional and national scale. However, top-down models are noted to have no inherent capability to detail current and future technological options as they have no explicit representation of the energy consumption by end-users, which compromises the identification of key areas for energy consumption improvements (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009). Sailor and Lu (2004), Balaras *et al.* (2007), Summerfield, Lowe and Oreszczyn (2010) and Sandberg, Sartori and Brattebo (2014) are typical examples of top-down approaches.

Sailor and Lu (2004) developed a standardized approach for estimating seasonally and spatially detailed diurnal profiles of anthropogenic heating for cities in the US based upon a population density formulation. Balaras *et al.* (2007) presented a methodology to determine the priorities for energy conservation measures in Hellenic residential buildings to reduce the environmental impact from CO_2 emissions. Primary data used was based on the available information from the results of the 1990 ce2nsus and the construction activities after 1990. Summerfield, Lowe and Oreszczyn (2014) developed two models to identify the trajectory of total delivered energy to UK households and provide benchmarks for the UK domestic sector. Both models use multiple linear regressions to fit consumption data since 1970 derived from public database available in the United Kingdom. Sandberg, Sartori and Brattebo (2014) presented a segmented dynamic dwelling stock model for understanding the nature of the long-term development in stocks, their turn-over and need for maintenance based on the population size, number of people per dwelling, the dwelling stock demand and construction. A case study took place in Norway and the results showed that detached houses constructed between 1945 and 2011 would dominate the renovation activity in the coming decades and suggested that the renovation rates commonly assumed in roadmaps and action plans in Europe do not seem to be realistic.

Bottom-up models are divided in two main categories: statistical and engineering models, although is not unusual to find hybrid models that mix characteristics of both methods (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009; ZHAO; MAGOULÈS, 2012).

Statistical methods are data-driven approaches that use monitored data from buildings to produce models capable of predicting building sector behaviour (COAKLEY; RAFTERY; KEANE, 2014; SALTELLI *et al.*, 2008). The literature lists several statistical and machine learning techniques that can be used in the context of building energy such as regression models and artificial neural networks (ANNs) (CHOUDHARY, 2012; MELO *et al.*, 2014; TIAN; CHOUDHARY, 2012). These approaches relate a set of influential input parameters to metered outputs through an algorithm (COAKLEY; RAFTERY; KEANE, 2014; SWAN; UGURSAL, 2009). The benefits of these techniques are the capability of determining typical end-use energy consumption. However, since statistical approaches rely on historical consumption data, they have limited capability to predict changes in building technologies and human behaviour (AYDINALP-KOKSAL; UGURSAL, 2008; KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009).

Engineering methods rely on knowledge from building physics to calculate the energy consumption. Engineering models are considered “law-driven” or “first principle” models, where a set of physical rules (for instance on heat and mass transfer) are applied in order to predict the behaviour of a given system with specific properties and conditions (COAKLEY; RAFTERY; KEANE, 2014; SALTELLI *et al.*, 2008). Benefits related to engineering models are the capabilities of estimating energy consumption without having to rely on historical data and of evaluating the impact of different combination of technologies on energy consumption. Drawbacks of this method are the need of detailed input information and the assumption of occupant behaviour which can significantly impact energy consumption (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009; ZHAO; MAGOULÈS, 2012).

The literature presents several engineering techniques for building stock energy modelling: distribution, sample and archetypes (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009; WANG; YAN; XIAO, 2012). Distribution techniques utilize distributions of appliance ownership and use with common appliance ratings to calculate the energy consumption of each end-use (HOWARD *et al.*, 2012). Sample techniques refer to the use of real sample data as the input information for the model. If the sample is representative of the regional or national stock, the stock energy consumption can be estimated by applying appropriate weightings to the results (ASCIONE *et al.*, 2013; SCHAEFER; GHISI, 2016). The archetype technique is noted to be intensively used (BALLARINI; CORGNATI; CORRADO, 2014; CAPUTO; COSTA; FERRARI, 2013; FONSECA; SCHLUETER, 2015; FOLIENTE; SEO, 2012; HEEREN *et al.*, 2013; HEIPLE; SAILOR, 2008; MAURO *et al.*, 2015; YAMAGUCHI; SHIMODA; MIZUNO, 2007). This technique sorts the building stock according to age, size, type, and similar criteria and utilizes these factors to define reference building energy models. The energy consumption estimated for the reference building is scaled up to the regional or national stock based on the representative weight of the modelled sample (KAVGIC *et al.*, 2010; SWAN; UGURSAL, 2009). Typical applications of bottom up models are shown in Table 3.

Table 3 - Summary of typical applications of bottom up energy models

Authors	Case study	Objective	Bottom up technique	Number of archetypes	Type of simulation	Building Input	Urban inputs	Validation
Yamaguchi; Shimoda and Mizuno (2007)	Osaka, Japan	City level energy management	Archetypes	612	Dynamic	Building systems ; Equipment; local energy generation and distribution systems	no	no
Heiple and Sailor (2008)	Houston US	Estimating total energy consumption in the building sector	Archetypes	30	Dynamic (eQUEST, DOE)	Not mentioned	no	Yes. Comparison between aggregated annual EUI and metered data from existing buildings
Heeren *et al.* (2013)	Zurich	Environmental impact assessment and target control	Archetypes	13	Dynamic (algorithms)	Building geometry; Envelope features; Building systems	no	no
Foliente and Seo (2012)	New South Wales, Australia	Methodology to develop scenarios to reduce CO_2 emission and energy use in office building stock in the State of New South Wales	Archetypes	324	Dynamic (eQUEST, DOE)	Building geometry; Envelope features; Building systems; Equipment; Occupancy	no	Yes. Comparison against metered data
Mauro *et al.* (2015)	South Italy	Identifying cost-optimal retrofit packages for office buildings built in South Italy during 1920–1970	Archetypes	1	Dynamic (energyplus; matlab, slabe)	Building geometry; Envelope features	no	no
Melo *et al.* (2014)	Florianopolis, Brazil	Investigating the use of artificial neural networks to estimate the energy consumption of commercial buildings	Archetypes	16	Dynamic	Envelope features	no	no
Ballarini; Corgnati and Corrado (2014)	Italy	Identifying energy savings and CO_2 reduction	Archetypes	18	Steady state	Building geometry; Envelope features	no	no
Caputo; Costa and Ferrari (2013)	Italy	Estimating Energy consumption at the city level	Archetypes	56	Dynamic (Energyplus)	Building geometry; Envelope features	no	Yes. Comparison with the *Sistema Informativo Regionale Energia Ambiente* database
Fonseca and Schlueter (2015)	Switzerland	Characterization of spatiotemporal building energy consumption patterns in neighbourhoods and districts	Archetypes + statistic	172	Dynamic (algorithms)	Envelope features; Building systems	no	Yes. Comparison against metered data.

Howard *et al.* (2012)	New York, U.S	Estimating annual building energy consumption by block area	Distribution	-	Dynamic (algorithms)	Not mentioned	-	Yes. Comparison against the total consumption data (agreement +/-20%)
Ascione *et al.* (2013)	Italy	Mapping urban energy	Sample	-	Steady-state	Building geometry; Building systems	yes, shading effect	Yes. Comparison with energy bills
Mata; Sasic Kalagasidis; and Johnsson (2014)	France, Germany, Spain and UK	Methodology by which national building stock may be aggregated through archetype buildings	Archetypes + statistic	99 France, 122 Germany, 120 Spain, 252 UK	Dynamic (algorithms)	Building geometry, Envelope features	no	Yes. Comparison between the estimated results and national/international benchmarks.
Schaefer and Ghisi (2016)	Brazil	Development of a method for obtaining reference buildings for low-income housing stock in Florianopolis	Sample	2	Dynamic (Energyplus)	Building geometry	no	no
Chidiac *et al.* (2011)	Canada	Comparison of the effectiveness of single and multiple energy retrofit measures	Archetypes	3	Dynamic (EnergyPlus)	Envelope features; Building systems, occupancy	no	Yes. Comparison against the final delivered energy use intensity of the government office spaces in Canada.
Griffith *et al.*(2008)	USA	Methodology for modelling building energy performance across the commercial sector	Archetypes	4,820	Dynamic (EnergyPlus)	Building geometry, Envelope features, Building systems; Equipment, occupancy.	no	Yes. Comparison against 2003 CBECS survey results.

Source: Author's own elaboration

Concerning bottom up archetype modelling examples listed in Table 3, Yamaguchi; Shimoda and Mizuno (2007) suggested a district clustering modelling approach to evaluate the options involved in a variety of energy management concepts such as advancement in technologies, local energy generation and CO_2 emission factor. The bottom-up structure of the model took into account the performance of energy consuming appliances/equipment, building systems, and local energy generation and distribution systems. A case study was carried out in Osaka city, Japan, in order to investigate energy policy initiatives targeting energy savings. The work suggested that the improvement in insulation performance, introduction of advanced outdoor air intake control, and introduction of inverter into HVAC systems accounted for an amount of CO_2 emission reduction that was comparable to those due to advancement in lightings, office equipment, and heat source machines.

Heiple and Sailor (2008) presented a methodology for estimating hourly and seasonal energy consumption profiles of the building sector at spatial scales down to the individual parcel. The method combined annual building energy simulations for prototypical buildings and a geospatial data framework (GIS) to estimate electric energy and gas consumption. A case study took place in Houston, U.S.

Heeren *et al*. (2013) proposed a framework for a building stock modelling based on the investigation of life cycle energy and total environmental impact. The building stock was clustered in 13 archetypes described by construction period, building technological systems, construction components and form factor. The case study took place in Zurich in order to evaluate the effectiveness of retrofit measures and their dynamics on the building stock regarding CO_2 emission. The results suggested that there would be a potential to reduce greenhouse gas emission in 85% by 2050.

Ballarini, Corgnati and Corrado (2014) developed a procedure to create residential reference buildings according to the European Project *TABULA* and to investigate sets of retrofit measures on the reference buildings. Geometrical data, construction features, the characteristics of the space heating systems and the domestic hot water systems were the basis to describe 18 archetype energy models. The performed study showed there was an enormous energy saving potential even with basic energy retrofit actions for this sector in Europe.

Mauro *et al.* (2015) developed a methodology to detect the retrofit package that represents the cost-optimal solution for a given building category and to evaluate the effectiveness of current financial incentives directed to these retrofit measures. A representative building sample of

South Italy office buildings from 1920 to 1970 was used to evaluate potential variations in energy performance. Characteristics related to geometry, envelope and operational systems were the basis to describe the reference building energy model. The results suggested that the cost-optimal retrofit package was represented by the installation of condensing gas boiler, water-cooled chiller and full-roof photovoltaic systems.

Griffith *et al.* (2008) developed a bottom up methodology to model building energy performance across the entire U.S commercial building sector. The process obtained reference buildings from the 2003 Commercial Buildings Energy Consumption Survey (CBECS) public database. EnergyPlus models were created to represent those buildings. The input parameters used to detail the energy models were: the architectural program (climate, internal gains, ventilation requirements, operating schedules, and comfort tolerances), form (the geometry of the building and its elements), fabric (the materials used to construct the building - insulation levels, glazing systems, and thermal mass) and all the energy-consuming equipment that was part of the building (HVAC equipment as well as lighting systems, controls, etc.). Their effort resulted in an extensive number of models (4,820 archetypes) used to further examine the potential of different technology scenarios for the commercial building stock.

A close investigation of the works presented in Table 3 also indicates that bottom up archetype models require a combination of several data sets including building geometry, envelope features, building systems, occupancy and usage. The number of variables in the process and their interaction are defined by the energy quantification method used and its complexity. Usually those methods are classified as dynamic methods and steady-state methods. Dynamic methods usually adopt detailed simulation tools such as EnergyPlus and are capable of capturing building dynamics such as thermal interactions of the envelope and systems, while steady-state methods ignore or simplify building dynamics by correlation factors (WANG; YAN; XIAO, 2012).

Furthermore, it is important to note that among the data sets used to describe bottom-up archetype energy models in Table 3 it is not usual to find urban context inputs such as solar shading effect between buildings, local wind patterns, etc (ALLEGRINI *et al.*, 2015; REINHART; CEREZO DAVILA, 2016). In general, the difficulties of addressing urban context inputs in a dynamic thermal simulation rely on combining building massing models which are the representation of the urban context and building archetype models into a thermal model (REINHART; CEREZO DAVILA, 2016). In practice, studies that tackle this topic usually are required to mix capabilities of existing tools such as GIS (ASCIONE *et al.*, 2013; FONSECA; SCHLUETER, 2015), computer fluid dynamic (CFD) models (GRACIK *et al.*, 2015) and urban thermal simulation engines (ex. SUNTOOL, CITYSIM, etc.) (ROBINSON *et al.*, 2007, 2009). Within this complex context, the majority of bottom up archetype modelling approaches, specially related to dynamic simulations, ignore the urban context inputs.

The interaction between urban contexts and buildings is an area of ongoing research. Recent studies have explored the connection between geometry of urban canyons and energy consumption (STRØMANN-ANDERSEN; SATTRUP, 2011), the influence of the Urban Heat Island (UHI) on the cooling and heating demand of buildings (GRACIK *et al.*, 2015; SANTAMOURIS *et al.*, 2015) and the effect of building shape and urban density on ventilation (SANAIEIAN *et al.*, 2014) and solar access (RATTI; RAYDAN; STEEMERS, 2003; OKEIL, 2010; PISELLO *et al.*, 2012, 2014). For instance, Pisello *et al.* (2012) proposed a method of assessing mutual building shading effect and evaluating the potential magnitude of this effect on building energy performance prediction. The finds showed that a building can mutually influence the energy dynamic of other buildings. Regarding the climatological context, the study revealed that not considering the building shading effect could lead to energy performance inaccuracies up to 42% in summer and up to 22% in winter. Stromann-Andersen and Satrup (2011) presented a detailed analysis of the solar radiation and daylight distribution in a range of urban canyons in order to address different urban densities and to demonstrate these distribution effects on the total energy use in the city of Copenhagen. The results showed that the geometry of urban canyons had an impact on total energy consumption in the range of up to 30% for office buildings and over 19% for housing.

Collectively, these studies outline that to consider the impact of the urban context on building stock energy consumption, particularly in dense cities, can become relevant especially for an accurate building stock energy saving potential evaluation.

2.3 OBTAINING REFERENCE BUILDINGS

Several studies listed previously show that the building stock can be studied thorough archetype models. In general, archetype models are built based on a reference building concept. According to the European Energy Performance of Buildings Directive (EPBD), reference buildings refer to "*buildings characterized by and representative of their functionality and geographic location, including indoor and outdoor climate* *condition"*(EPBD, 2010). Moreover, it is interesting to note that there is no uniform agreement related to the level of detail and accuracy to be considered for reference buildings (CORGNATI *et al.*, 2013). For instance, Dascalaki *et al.* (2011)*,* used reference buildings to sort out the Hellenic residential building stock and assess their energy performance. At first, reference buildings were derived from existing building typologies present in the building sector sorted by building age, size and climate zone. Moreover, complementary information regarding building geometry and systems were incorporated. Similarly, Griffith *et al.* (2008) in their study to model building energy performance across de US commercial sector recommended, firstly, sorting the data collected into three categories: building activity, location and size. Furthermore, they suggested including information of building form, material, systems and operation.

Defining properly a reference building relies on the amount of information and source reliability. Usually a common approach is to extract data from an official database at a regional or national level. However, if there are no data available it is not unusual to rely on experts' assumption. The EPBD recommend sorting the buildings data by age, location and type. Additionally, EPBD suggests characterizing Reference Buildings (RBs) through four main areas of investigation: form, envelope, system and operation. The form refers to building type, size and general geometry. The envelope refers to construction technologies and material used to describe thermophysical properties. Systems concern the heating/cooling systems, lighting systems and etc. Operations consist of operational parameters affecting the building use. Additionally, EPBD recommends performing dynamic energy simulations in order to assess energy performance (EPBD, 2010).

The EPBD pointed out as input documentation for the establishment of RBs, the work carried out within the TABULA Project (BALLARINI; CORGNATI; CORRADO, 2014) which identifies three methodologies to classify RBs:

- *''Example Building''* - the method is used when no statistical data are available, and therefore it relies on the basis of experts' assumption and studies. Information from different sources but all based on experts' experience are combined to provide a building that is likely to represent a group of buildings, within a selected location and age.
- *''Real Building''* – the method identifies the RBs through the statistical analysis of a large building sample. The RB is a real existing building with average characteristics

of a typical building stock category. The reference building shows characteristics similar to the mean geometrical and construction features found on the statistical sample.

- *"Theoretical Building"* – similarly this method identifies the RBs through the statistical analysis of a large building sample. This method processes statistical data in order to define RBs from the most common features found in a building stock category.

Figure 2 illustrates the general method for obtaining reference buildings described by the TABULA Project.

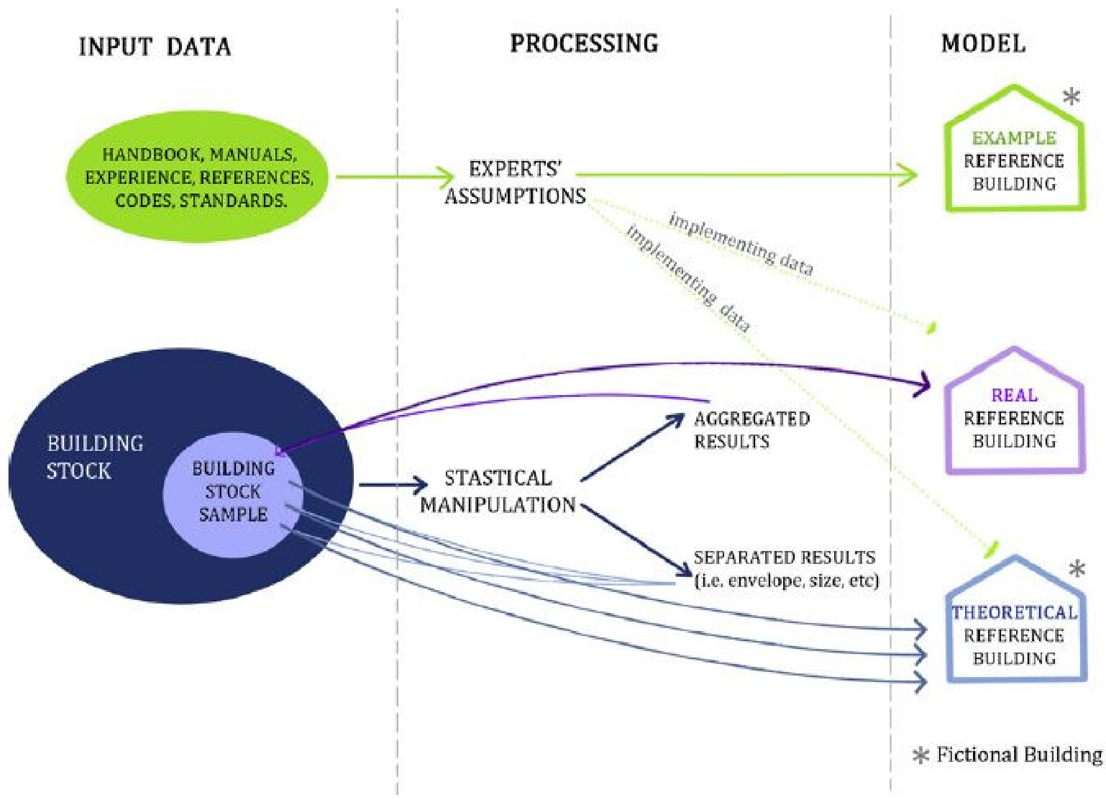

Figure 2 – General method for obtaining reference buildings
Source: Corgnati et al. (2013)

Currently, several governments are promoting the creation of reference building databases (ex. TABULA, ASIEPI, etc), in order to support large scale thermal performance studies (CORGNATI *et al.*, 2013). Nevertheless, in Brazil, no reference building database is available. In the last years, few countrywide studies have been carried out in this area. Santana (2006) studied the influence of construction parameters on energy consumption in Florianopolis by means of dynamic simulation. For obtaining reference buildings, a field survey with 35 office buildings was carried out in order to collect building construction and occupation information. Carlo (2008) collected data related to the envelope such as window-to-wall ratios, glazing types, solar protection, etc, from 1.103 Brazilian commercial and institutional buildings in the cities of Recife, Salvador, Belo Horizonte, São Paulo and Florianópolis. Data were collected through photographic surveys. The prevalent features found in the field survey were the basis to create energy archetype models used to evaluate current energy use efficiency of non-residential building envelopes. Schaefer and Ghisi (2016) developed a method for obtaining reference buildings for low-income housing stock in Florianópolis. Field surveys were performed in order to build a database on geometrical features of houses. Hierarchical and non-hierarchical cluster analysis techniques were applied in combination in order to obtain reference buildings. The reference building was taken as the nearest house to the mean of its cluster. The 120 housing units sample database obtained from the survey resulted into two reference buildings.

2.4 DYNAMIC SIMULATION FOR ENERGY CALCULATION

Dynamic simulations have been accepted as an important tool for analysing building energy performance. In general a typical dynamic simulation approach requires input that feeds a simulation engine (detailed mathematical models) in order to obtain key building performance indicators (CRAWLEY *et al.*, 2008; WANG; YAN; XIAO, 2012). A general data flow and some typical inputs and simulation engine structure are presented in Figure 3.

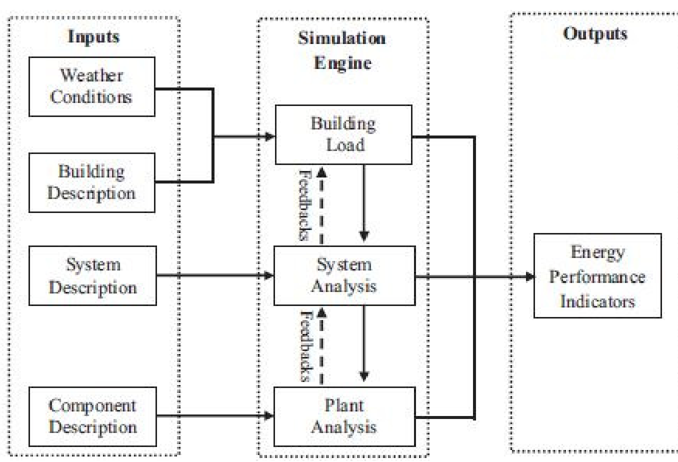

Figure 3 – General data flow of a dynamic simulation

Source: Wang; Yan and Xiao (2012)

Building energy simulation tools started in the 70's, but only from the 90's on, with the popularization of personal computers and improvement of processors and memory capacity, they became accessible to companies and research groups engaged in the development of interfaces for those programs (MENDES *et al.*, 2005).

Over the last 50 years several energy performance simulation programs have been developed worldwide (ex. EnergyPlus, TRNSYS, DOE-2, BLAST, COMIS, ESP, COMBINE, etc). The core tools in the building energy field are observed to be whole-building energy simulation programs. Among those programs, EnergyPlus is observed to be extensively tested and widely used over the years (CRAWLEY *et al.*, 2008).

2.4.1 ENERGYPLUS

EnergyPlus is a modular simulation engine which the structured code is based on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus has three basic components: a simulation manager, a heat and mass balance simulation module, and a building system simulation module. The simulation manager controls the entire simulation process. Detailed information of the overall structure interactions can be found in EnergyPlus Engineering Reference Documentation (DOE, 2015). The overall program structure is shown in Figure 4.

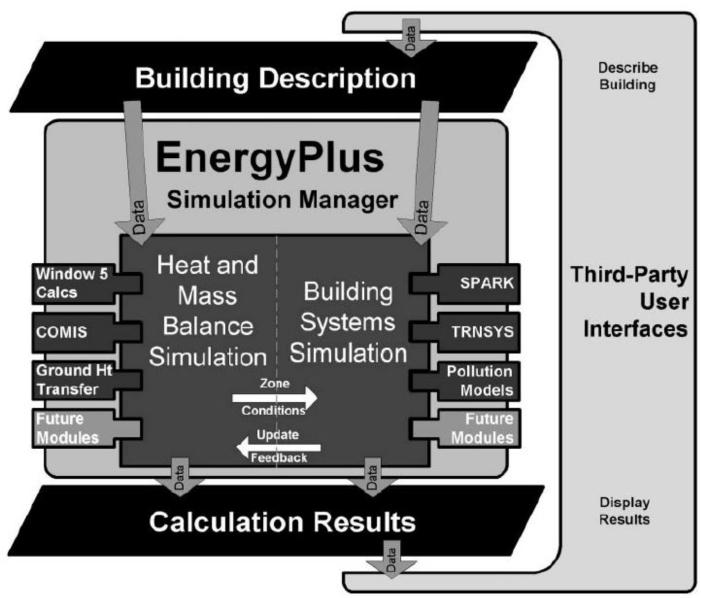

Figure 4 – Overall EnergyPlus structure
Source: Crawley et al. (2000)

Loads calculated by a heat balance engine at a user-specified time step are passed to the building systems simulation module at the same time step. The EnergyPlus building system simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response. This integrated solution is noted to provide more accurate space temperature prediction (CRAWLEY *et al.*, 2000).

The basis for the zone and air system integration is to formulate energy and moisture balances for the zone air and solve the resulting ordinary differential equations. According to the EnergyPlus Engineering Reference Documentation (DOE, 2015) the formulation of the solution scheme starts with a heat balance on the zone air, where the sum of zone loads and air system output is equal to the change in energy stored in the zone as shown in Equation 1.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{Nsl} \dot{Q}_i + \sum_{i=1}^{Nsurfaces} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{Nzones} \dot{m}_i C_P (T_{zi} - T_z) + \dot{m}_{\inf} C_P (T_\infty - T_z) + \dot{m}_{sys} C_P (T_{\sup} - T_z) \tag{1}$$

Where:

$C_z \frac{dT}{dt}$	energy stored in zone air [1]
$\sum_{i=1}^{Nsl} \dot{Q}_i$	sum of the convective internal loads
$\sum_{i=1}^{Nsurfaces} h_i A_i (T_{si} - T_z)$	convective heat transfer from the zone surfaces [2]
$\sum_{i=1}^{Nzones} \dot{m}_i C_P (T_{zi} - T_z)$ -	heat transfer due to interzone air mixing[3]
$\dot{m}_{\inf} C_P (T_\infty - T_z)$ -	heat transfer due to infiltration of outside air[4]
$\dot{m}_{sys} C_P (T_{\sup} - T_z)$	air systems output[5]

An air system output equation assumes that the zone supply air mass flow rate is exactly equal to the sum of the air flow rates leaving the zone through the system return air plenum and being exhausted directly from the zone. Both air streams exit the zone at the zone mean air temperature.

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[1] $C_z = \rho_{air} C_p C_T$, where ρ_{air} zone air density, C_p zone air specific heat, C_T sensible heat capacity multiplier.

[2] h_i Internal convection coefficient, A_i Surface area, T_{si} Surface temperature, T_z zone air temperature.

[3] $\dot{m}$ air mass, C_p zone air specific heat, T_{zi} Interzone air temperature, T_z zone air temperature.

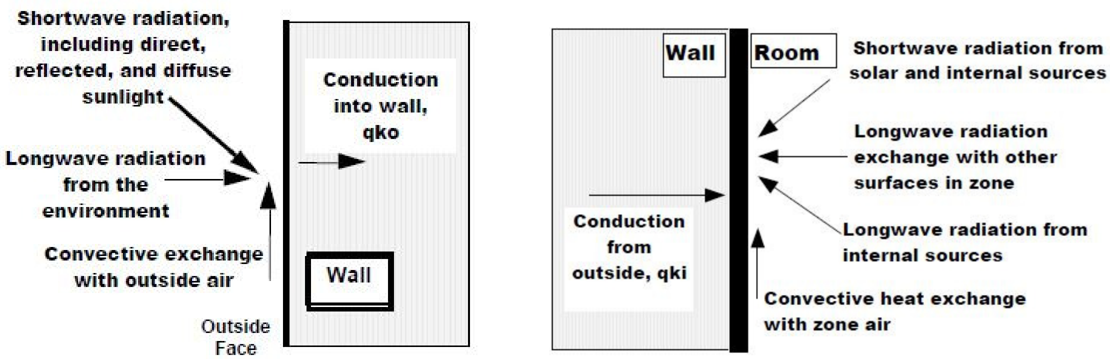
[4] $\dot{m}$ air mass, C_p zone air specific heat, T_∞ Outside temperature, T_z zone air temperature.

[5] $\dot{m}$ air mass, C_p zone air specific heat,T_{sup} supply air temperature, T_z zone air temperature.

Based on the EnergyPlus Engineering Reference Documentation (DOE, 2015) a summary of the surface heat balance processes as well as the glazing heat balance calculation is presented as follows.

2.4.1.1 Surface heat balance processes

Figure 5 presents the external and internal components involved in the surface heat balance.



(a) (b)

Figure 5 – Outside heat balance control volume diagram (a) and Inside heat balance control volume diagram (b) according to EnergyPlus documentation

Source: EnergyPlus Engineering Reference Documentation (DOE, 2015)

The heat balance on the outside face is shown in Equation 2:

$$q''_{\alpha sol} + q''_{LWR} + q''_{CONV} - q''_{ko} = 0 \quad \textbf{(2)}$$

Where:

$q''_{\alpha sol}$ =Absorbed direct and diffuse solar (short wavelength) radiation heat flux;

q''_{LWR} = Net long wavelength (thermal) radiation flux exchange with the air and surroundings.

q''_{CONV} = Convective flux exchange with outside air.

q''_{ko} = Conduction heat flux into the wall,

The heat balance on the inside face is presented in Equation 3 as follows:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \quad \textbf{(3)}$$

Where:

q''_{LWX}= Net longwave radiant exchange flux between zone surfaces.;

q''_{SW}= Net short wave radiation flux to surface from lights,

q''_{LWS}= Longwave radiation flux from equipment in zone.

q''_{ki} = Conduction flux through the wall

q''_{sol}= Transmitted solar radiation flux absorbed at surface;

q''_{conv} = Convective heat flux to zone air.

2.4.1.1.1 Convective flux exchange with outside air (q''_{CONV})

Heat transfer from surface convection is modelled using the classical formulation as shown in Equation 4:

$$Q_c = h_{c,ext} A(T_{surf} - T_{air})$$

(4)

Where: Q_c = rate of exterior convective heat transfer, $h_{c,ext}$ = exterior convection coefficient, A = surface area, T_{surf} = surface temperature, T_{air} = outdoor air temperature.

EnergyPlus therefore offers a possibility of selecting different methods for determining values for $h_{c,ext}$.: Adaptive, TARP, MoWitt, DOE-2, SimpleCombined. The default method is DOE-2. The exterior surface convection coefficient for very smooth surfaces is calculated as:

$$h_{c,glass} = \sqrt{h_n^2 + [aV_z^b]^2}$$

(5)

Where h_n = Natural convective heat transfer coefficient, V_z = local wind speed calculated at the height above ground of the surface; a and b are constants given in Table 4:

Table 4 – a and b constants

Wind Direction	**a** $(W/m^2k(m/s)^b$	**b**
Windward	3.26	0.89
Leeward	3.55	0.617

Source: Booten; Kruis and Christensen (2012)

For (ΔT < 0.0 and an upward facing surface) or (ΔT > 0.0 and a downward facing surface) an enhanced convection correlation is used as presented in Equation 6:

$$h_n = \frac{9.482\ |\Delta T|^{1/3}}{7.283 - |\cos \emptyset|}$$

(6)

For (ΔT > 0.0 and an upward facing surface) or (ΔT < 0.0 and a downward facing surface) a reduced convection correlation is used as shown in Equation 7:

$$h_n = \frac{1.810\ |\Delta T|^{1/3}}{1.382 + |\cos \emptyset|}$$

(7)

Where $\emptyset$ is the surface tilt angle.

For less smooth surfaces, the convection coefficient is modified according to the Equation 8:

$$h_c = h_n + R_f(h_{c,glass} - h_n)$$

(8)

Where R_f is a multiplier given in Table 5.

Table 5 - Surface Roughness Multipliers

Roughness Index	R_f	Material Examples
Very rough	2.17	stucco
Rough	1.67	Brick
Medium rough	1.52	Concrete
Medium Smooth	1.13	Clear pine
Smooth	1.11	Smooth plaster
Very smooth	1	glass

Source: Walton (1981)

2.4.1.1.2 Convective heat flux to zone air (q''_{conv})

The convective heat flux is calculated as follows:

$$Q_c = h_i A(T_{si} - T_z)$$

(9)

Where: h_i Internal convection coefficient, A_i Surface area, T_{si} Surface temperature, T_z zone air temperature.

There are different modelling options available in EnergyPlus for inside convection coefficients, h_i .: Adaptive, TARP, Simple Natural (SimN), Ceiling Diffuser (CeiD) and Trombe Wall. The default method is TARP and it is calculated as:

For no temperature difference or a vertical surface the following correlation is used as presented in Equation 10:

$$h_i = 1.31|\Delta T|^{1/3}$$

(10)

For (ΔT < 0.0 and an upward facing surface) or (ΔT > 0.0 and a downward facing surface) an enhanced convection correlation is used following Equation 6. For (ΔT > 0.0 and an upward facing surface) or (ΔT < 0.0 and a downward facing surface) a reduced convection correlation is used following Equation 7.

2.4.1.1.3 Conduction through the walls

There are different conduction transfer function solution options available in EnergyPlus: Conduction Transfer Function (CTF); Detailed Conduction Finite Difference (CondFD); Conduction Finite Difference Simplified (CondFDS); Combined Heat and Moisture Transfer (HAMT) e Effective Moisture Penetration Depth (EMPD). The default method is CTF and it is shown in Equations 11 and 12 as follows:

For the inside heat flux q''_{ki}

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_o T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta}$$

(11)

For the outside heat flux q''_{ko}

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta}$$

(12)

Where X_j= Outside CTF coefficient, j= 0,1,...nz.; Y_j= Cross CTF coefficient,j= 0,1,...nz.; Z_j = Inside CTF coefficient, j= 0,1,...nz.; Φ_j = Flux CTF coefficient, j = 1,2,...nq.; T_i = Inside face temperature; T_o= Outside face temperature;

The basic method used in EnergyPlus for CTF calculations is known as the state space method and is detailed in the Engineering Reference Documentation (DOE, 2015).

2.4.1.2 Glazing heat balance calculation

The window glass face temperatures are determined by solving the heat balance equations on each face for every time step. As an example, for a window with one glass layer there are 2 N faces and therefore 2N equations to solve. The Figure 6, shows the variables used in the glazing heat balance equations for a window with one glass layer.

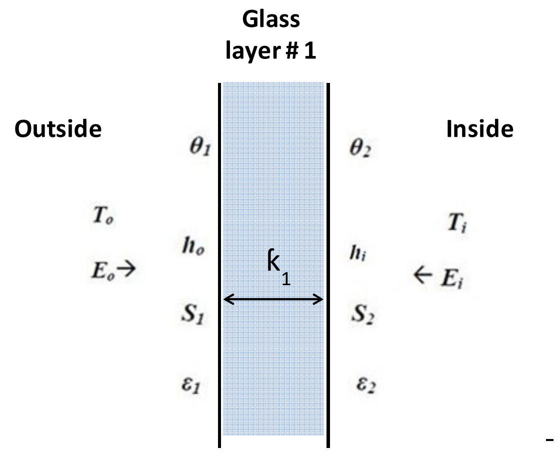


Figure 6 - Glazing system with one glass layer showing the variables used in heat balance equations.

Source: EnergyPlus Engineering Reference Documentation (DOE, 2015)

In deriving the heat balance equations, the following assumptions are made: the glass layers are thin enough that heat storage in the glass can be neglected and therefore there are no heat capacity terms in the equations; the heat flow is perpendicular to the glass faces and is one dimensional; the glass layers are opaque to infrared radiation, the glass faces are isothermal; the short wave radiation absorbed in a glass layer can be apportioned equally to the two faces of the layer. In doing so, the Equations 13 and 14 for one glass layer are presented as follows:

$$E_0\varepsilon_1 - \varepsilon_1\sigma\theta_1^4 + k_1(\theta_2 - \theta_1) + h_0(T_0 - \theta_1) + S_1 = 0$$

(13)

$$E_i\varepsilon_2 - \varepsilon_2\sigma\theta_2^4 + k_1(\theta_1 - \theta_2) + h_i(T_i - \theta_2) + S_2 = 0$$

(14)

Where

E_0 , E_i	Exterior, interior long-wave radiation incident on window
ε_i	Emissivity of face i
k_i	Conductance of glass layer i
T_0 , T_i	Outdoor and indoor air temperatures
σ	Stefan-Boltzmann constant
θ_i	Temperature of face i
S_i	Radiation (short-wave, and long-wave from zone internal sources) absorbed by face i
h_0 , h_i	Outside and room-side convection coefficient

The equations for double glazing (N=2) and for N=3 and N=4 are analogous. Information regarding edge-of-glass effect, window frame and shading device systems and their effect on the window heat balance calculation are detailed in the Engineering Reference Documentation (DOE, 2015).

2.5 SENSITIVITY ANALYSIS IN BUILDING ENERGY ANALYSIS

Sensitivity analysis is a valuable tool for energy simulation models in building energy analysis and therefore it has been widely used to explore the performance of different energy saving measures in buildings. The aim of a sensitivity analysis is to observe the system response to input parameter modifications (LAM; WAN; YANG, 2008).

According to Tian (2013), the typical steps for implementing sensitivity analysis in building performance analysis are: (1) to determine input variations; (2) to create building energy models; (3) to run energy models; (4) to collect simulation results; (5) to run sensitivity analysis and to present sensitivity analysis results.

Concerning input variations, it is noted that they are mainly dependent on the research purpose. For instance, to assess the energy performance in a new building using different design options the possible ranges for the design variables should be analysed. To investigate energy use variations in an existing building, the variations should be focused on finding out the key variables affecting energy use.

Regarding the second step, building energy models are created with different input combinations. Programs such as EnergyPlus, ESP-r, TRNSYS and DOE-2 have been used in sensitivity analysis to create and simulate those models.

In the subject of running energy models, most of sensitivity analysis methods involve a large number of simulation runs which are usually the most time-consuming process in the sensitivity analysis. It is not uncommon the use of parallel computing method to speed up the simulation.

The forth step (to collect simulation results) is very straightforward and usually involves a lot of data, which can demand, in some cases, the use of script language to automate the process. Finally, the last step is to run sensitivity analysis based on the inputs and outputs obtained from earlier steps and present the results from the sensitivity analysis.

In the domain of building energy analysis, sensitivity analysis can be divided into local and global approaches. Local sensitivity analysis belongs to the class of the one-factor-at-a-time methods whereas global sensitivity analysis is interested in the influences of uncertain inputs over the whole input space (TIAN, 2013).

In general, local sensitivity analysis is calculated when one input factor is changed and all other factors are fixed. Low computational cost, implementation and interpretation simplicity are some advantages of this method, which explains its intense use in the field of building energy analysis (CHENG; STEEMERS, 2011; LAM; WAN; YANG, 2008; RASOULI *et al.*, 2013). However, this method has some drawbacks. It is noted that it explores only a reduced space of input factors around a base case and interactions among changed input factors cannot be considered (TIAN, 2013).

Cheng and Steemer (2011), Lam, Wan and Yang (2008) and Rasouli *et al*. (2013) show typical examples of the use of local sensitivity analysis in building energy analysis. Cheng and Steemer (2011) presented a methodology for developing, evaluating an applying the Domestic Energy and Carbon Model (DECM) for predicting the energy consumptions and carbon dioxide emissions of the existing English housing stock. They applied local sensitivity analysis to exam the effects of various building fabric and service system parameters on the modelled average carbon emissions per dwelling. The findings were the basis to develop a set of predicted charts that provides rapid estimations of energy efficient measures on dwelling energy consumptions and carbon emissions taking into account the potential rebound effect. Lam, Wan and Yang (2008) investigated the electric energy use characteristics of 10 existing air-conditioned office buildings in subtropical Hong Kong. Energy simulations were carried out by the DOE-2 program. Parametric and local sensitivity analysis were performed in order to assess the significance and impact of input design parameters on energy conservation measures. Results suggested that indoor design condition, electric lighting and chillers COP could offer great electric energy savings potential, in the order of 14%, 5.2% and 11%, respectively. Rasouli *et al*. (2013) used local sensitivity analysis to evaluate the uncertainty impact of building and HVAC system parameters on the energy savings potential and economics of energy recovery ventilators for an office building located in Chicago. Simulations were performed by the TRNSYS program. Results suggested that the most significant impact on total HVAC system energy performance was caused by the ventilation rate.

Generally, global sensitivity analysis methods explore uncertain input factors over the whole input space, based on the consideration that a handful of data points thrown into that space is effective, in the sense of being informative and robust (SALTELLI *et al.*, 2008). Global sensitivity analysis includes regression methods, screening-based, variance-based and meta-modelling approaches. Regression methods are the most widely used method for global sensitivity analysis in building energy analysis (DE WILDE; TIAN, 2009; HOPFE; HENSEN, 2011; HYGH *et al.*, 2012; TIAN; CHOUDHARY, 2012; TIAN; DE WILDE, 2011) because they are considered fast to compute and easy to understand. Many indicators can perform sensitivity analysis usually after the use of the Monte Carlo method, such as SRC (Standardised Regression Coefficients), PCC (Partial Correlation Coefficients), SRRC (standardized rank regression coefficient) and PRCC (partial rank correlation coefficient). SRC and PCC are only suitable for linear models and the rank transformation (SRRC and PCC) can be used for non-linear but monotonic functions among inputs and outputs (TIAN, 2013).

The works of Hygh *et al.* (2012) and de Wilde and Tian (2009) are typical examples of SRC and SRRC indicator use, respectively. Hygh *et al.* (2012) presented a modelling approach to quantify building energy performance in early design stages. They explored the energy performance of office buildings in four USA cities by using SRC sensitivity indicator. The results suggested that standardized regression coefficients can serve as an effective decision support tool in order to obtain the influences of design parameters on building energy use. De Wilde and Tian (2009) used SRRC as a sensitivity indicator to identify the key factors for uncertainty in the overheating and energy use prediction from an office building in UK. The time horizons of the study were 2020, 2050 and 2080. Regarding predicted heating energy, the results showed that the dominant input factors were infiltration, lighting gain and equipment gain. Regarding cooling energy and overheating, by 2020 and 2050, the main factors would be lighting gain and equipment gain, however, by 2080, climate prediction would become the dominant factor.

2.6 ECONOMIC EVALUATION OF ENERGY RETROFIT MEASURES

The challenge to successfully reduce the energy consumption in the building sector over the next decades is to find effective strategies for retrofitting existing buildings (PNNL, 2011). In recent years, a considerable amount of researches have been investigating the technical and economic energy saving potential of existing building retrofit measures (CHIDIAC, *et al.*, 2011; MENASSA, 2011; KUMBAROĞLU; MADLENER, 2012; HILLEBRAND *et al.*, 2014; GRIEGO; KRARTI; HERNANDEZ-GUERRERO, 2015; MAURO *et al.*, 2015).

Generally, most of the economic analysis relies on classical mathematical methods such as the payback, the rate of return on investment, the cost-benefit ratio, the rate of return and the net present value, all used to make decisions on capital projects. The work of Chidiac *et al.* *(*2011) is a typical example of this approach. Chidiac *et al.* *(*2011) proposed a methodology that combines energy calculation models with an economic analysis in order to determine the feasibility and cost effectiveness of implementing energy retrofit measures in office buildings in three Canadian cities - Ottawa, Edmonton and Vancouver. A total of 12 energy retrofit measures related to lighting, insulation and HVAC systems among others were simulated. Present value analysis and payback period were used to evaluate the cost effectiveness of the retrofit measures. Results suggested that retrofitting the lighting fixtures was more cost effective in Edmonton and Ottawa than in Vancouver, retrofitting the boiler system was more effective for larger buildings and for buildings located in colder climates, the payback period for upgrading the roofing insulation was influenced by the size of the building and the climate region and exterior wall insulation upgrades were not cost effective once payback period exceeded 100 years.

Another example of this classical approach is the work of Griego, Krarti and Hernandez-Guerrero (2015). The authors developed a methodology to evaluate various combinations of energy efficiency measures to estimate an optimum set of recommendations for existing ones and new office buildings in Guanajuato, Mexico. Life-cycle cost (LCC) analysis together with the sequential search optimization technique illustrated in Figure 7 were used to define the most cost-effective energy efficiency packages for both new construction and retrofit of office buildings.

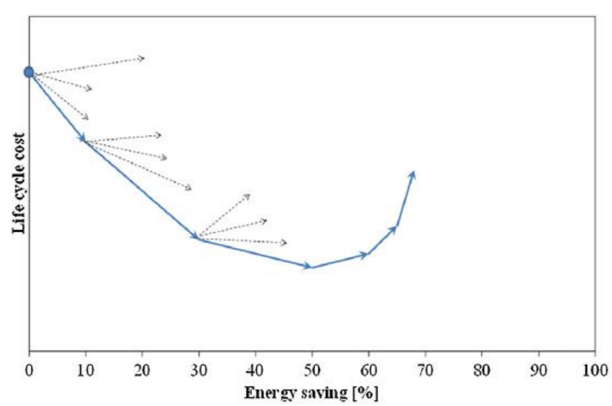


Figure 7 - Sequential search optimization methodology to find optimal solution

Source: Griego; Krarti and Hernandez-Guerrero (2015)

At first, the energy efficiency measures were individually considered for the energy baseline with a specific life cycle cost. The most cost-effective measure was chosen based on the steepest slope consisting of the LCC to energy savings ratio. The selected optimal measure was then removed from the parameter search space for future evaluation and then the remaining measures were simulated to find the next optimal option. This process was repeated until the optimal solution was reached.

The study results indicated that in both new and existing offices the most cost-effective potential for energy conservation was achieved by reducing office equipment loads and adding efficient lighting technology and controls. The study also indicated that over 49% annual energy savings could be achieved cost-effectively for both retrofit and new construction commercial office buildings.

Besides the use of the classical mathematic methods, discussions of uncertainty and dynamic economic modelling can be added to the context of building retrofit economic analysis as shown in the works of Menassa (2011), Kumbaroğlu and Madlener (2012) and Hillebrand *et al* (2014). Menassa (2011) presented a quantitative approach to determining the value of the investment in sustainable retrofits for existing buildings by taking into account different uncertainties associated with the life cycle costs and a framework for single or multi-phase investment evaluation. Kumbaroğlu and Madlener (2012) developed a techno-economic methodology for evaluating energy retrofit of buildings by introducing a sequential real options investment appraisal methodology to evaluate the value of waiting under uncertainty. Hillebrand *et al* (2014) proposed a methodology to evaluate the energy efficiency potential of office buildings by taking into consideration the uncertainty of future energy prices and the possibility of delaying an investment.

Among the economic analysis based on those classical methods, LCC analysis is noted to be particularly suitable for evaluating building retrofit measures alternatives (FULLER; PETERSEN, 1996; GLUCH; BAUMANN, 2004). LCC is a technique which enables comparative cost assessments to be made over a specific period of time; taking into account relevant economic factors both in terms of initial costs and future operational costs (ISO 15686-5, 2008).

In the last years, several standards and guidance documents have been working on harmonizing the existing life-cycle costing techniques. Among them it's worth mentioning:

- ISO 15686-5 Building and construction assets - Service-life planning - Part 5: Life-cycle costing (ISO 15686-5, 2008);
- VDI 2067 - Part 1 : Economic efficiency of building installations: Fundamentals and economic calculation (VDI 2067 - 1, 2000);
- Handbook 135, Life-Cycle Costing Manual for the Federal Energy Management Program, Energy Efficiency and Renewable Energy (EERE) Information Centre (FULLER; PETERSEN, 1996).

In general, the LCC method evaluates the costs of owing, operating, maintaining and eventually disposing building system(s) over a given study period with all costs discounted to reflect the time-value of money. Typical steps related to LCC methods are: (1) setting the study period, (2) estimating investment-related costs and operation costs as well as their times of occurrence, (3) discounting future costs to present value and (4) computing LCC.

The study period for an LCC analysis is the time over which the costs and benefits related to a capital investment decision are of interest to the decision maker. ISO 15686-5 suggests that the LCC analysis study period should be chosen within the range of 20 to 40 years (ISO 15686-5, 2008). The Federal Energy Management Program (FEMP) of the U.S Department of Energy suggests that the LCC study period should not exceed 25 years (FULLER; PETERSEN, 1996). Moreover, people tend to not invest in measures from which they cannot benefit themselves in their own lifetime, and therefore long timeframes are not attractive. Additionally, long term predictions are difficult and very uncertain and going beyond 40 years prediction makes it even more unreliable in terms of cost forecasts.

There are numerous costs associated with acquiring, operating, maintaining and disposing of building systems. Generally, they are distinguished between investment-related and operational costs. Acquisition costs, residual values (resale, savage or disposal costs) and capital replacement costs are usually understood as investment-related costs whereas operating, maintaining and repairing costs are operational costs.

LCC analysis also requires that all system-related costs be identified by time of occurrence. System-related costs occurring at different points in time must be discounted to their present values in order to be combined into an LCC analysis. In this process, additional understanding on discount rate and inflation is required. The discount rate used to discount future cash flow to present value is based on the investor's money time-value. From a government perspective, this parameter will be based on the long term interest rate, whereas in the private sector the investors will rather use the minimum acceptable rate of return for investments of equivalent risk and duration (FULLER; PETERSEN, 1996; VRIJDERS; DELEM, 2010).

Regarding adjusting for inflation, there are two different approaches: constant or current cash. Estimate future costs and savings in constant cash means use “real” discount rate that excludes the inflation rate. In contrast, to estimate future costs and savings in current cash means use discount rate with a “nominal” discount rate that includes the inflation rate. Both types of calculation result in identical present-value life-cycle costs.

Equations 15 and 16 show the constant and current cash flows approaches to support a same decision.

- Constant cash and real discount rate

$$PV = F_t \, . \left[\frac{1+e}{1+d}\right]^t$$

(15)

Where, PV = present-value, F_t = cash amount, e = real escalation rate, d = real discount rate, t= number of years.

- Current cash and nominal discount rate

$$PV = F_t \, . \left[\frac{1+E}{1+D}\right]^t$$

(16)

Where, PV = present-value, F_t = cash amount, E = nominal escalation rate, D = nominal discount rate, t= number of years.

The real discount rate (d) can be derived from the nominal discount rate (D), if the rate inflation (I) is known as shown in the Equation 17.

$$d = \frac{(1+D)}{(1+I)} - 1$$

(17)

Similarly, the real escalation rate (e) can be derived from the nominal price escalation (E), if the rate inflation (I) is known as presented in the Equation 18.

$$e = \frac{(1+E)}{(1+I)} - 1$$

(18)

Regarding the LCC calculation, the general formula requires the identification of each cost by year and amount. To calculate LCC, firstly each cost to be incurred during the study period should be computed. Secondly these present values should be summed. A general formula for building-related projects can be stated as follows:

$$LCC = I + Repl - Res + E + W + OM\&R \tag{19}$$

Where:

LCC = Total LCC in present-value of a given alternative, I = Present-value investment costs, Repl = Present-value capital replacement costs, Res = Present-value residual value less disposal costs, E = Present-value energy costs, W= Present-value water costs and OM&R = Present-value non-fuel operating, maintenance and repair costs.

In general, the LCC calculation by itself has little value. However, it becomes valuable when used to compare design alternatives which can perform the same function in order to identify which alternative is more cost effective. The alternative with the lowest LCC is the preferred alternative.

3 METHODOLOGY

This chapter describes the general methodology developed to identify and analyse the energy savings potential from an existing building stock category. The general methodology is presented in Figure 8. In the flowchart, six main steps are identified: (1) a method for obtaining reference buildings, (2) dynamic archetype model simulations, (3) an energy consumption baseline estimation, (4) energy retrofit measures selection and a cost optimal pathway analysis, (5) developing energy saving scenarios and (6) estimating building stock energy savings potential.

Regarding the method for obtaining reference buildings, the land use regulations/building codes, the land tax database and the field study represent the three inputs. The land use regulations and building codes investigation identify the influences of those instruments on the building typologies over time. The land tax database describes basic features of the building stock such as usage, age, location and area. The field survey identifies prevalent building characteristics. From the combination of these three inputs, representative building typologies from an existing building stock category are identified.

Concerning the dynamic archetype simulation, information gathered from the representative building typologies, the technical literature and normative standards are used to characterize the archetype energy models. Furthermore, simulations are performed in EnergyPlus to assess Energy Use Intensity (EUI) of each archetype energy model. The energy consumption baseline of the existing building stock is then estimated taking into account the simulated EUI, the growth rate of the existing building stock as well as the building stock area. The baseline estimated is then named BaseCase Baseline.

Regarding the fourth step, the process of selecting Energy Retrofit Packages (ERPs) is done by first identifying potential retrofit measures based on technical feasibility and suitability, then prioritizing those measures applying a sensitivity analysis (SA) and finally applying a sequential search optimization technique in order to identify the cost optimal pathway for implementing the measures. Furthermore three scenarios are developed based on the cost optimal pathway analysis results. The scenario projections are then estimated and compared to the BaseCase projection in order to assess the energy savings potential of the existing building stock category.

The following topics describe relevant information related to each methodological step regarding the existing office building stock.

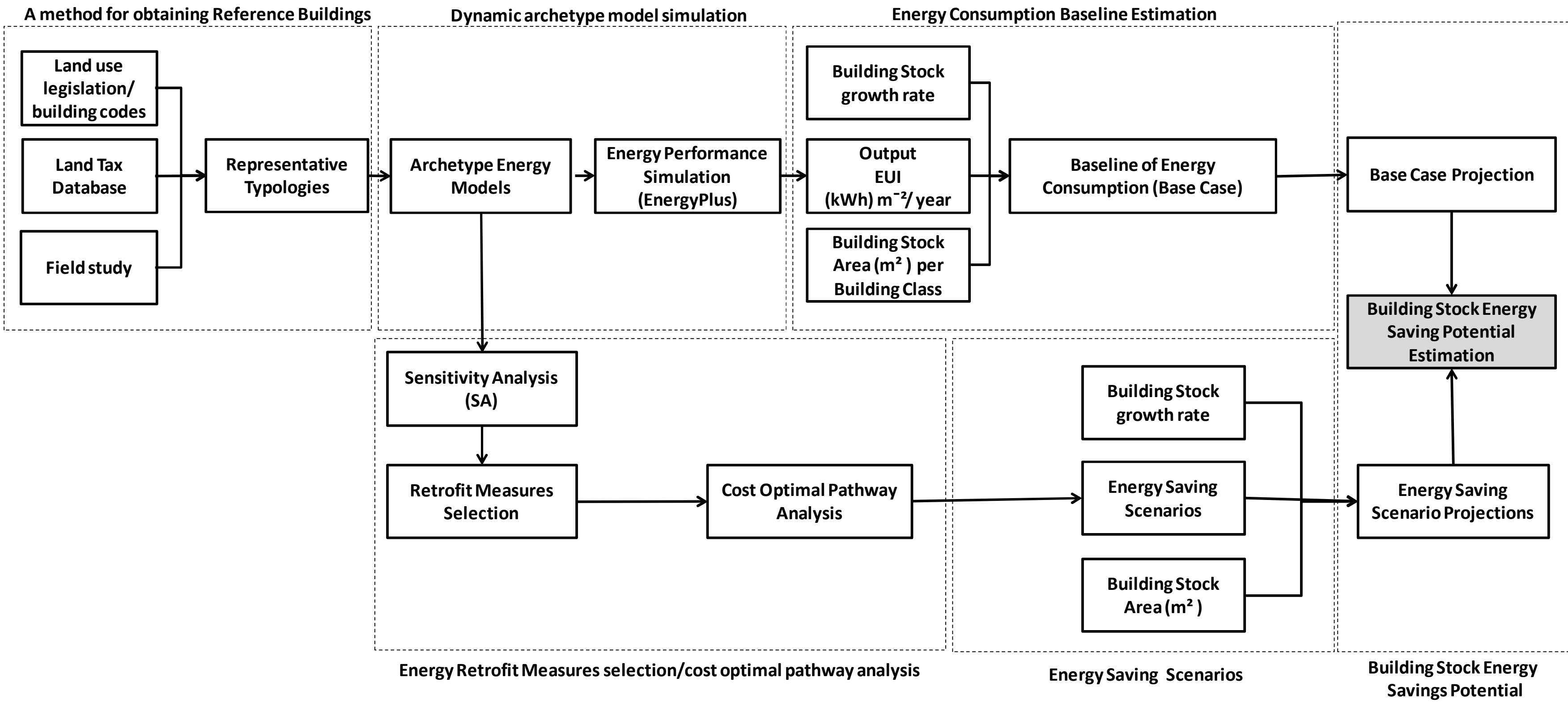


Figure 8 – The general methodological flowchart

Source: Author's own elaboration

3.1 A METHOD FOR OBTAINING REFERENCE BUILDINGS

Information gathered from the three inputs (the land use legislation/building code investigation, the land tax database and the field survey) were the basis to obtain reference buildings.

3.1.1 LAND USE LEGISLATION AND BUILDING CODES INVESTIGATION

Land use regulations and building codes are instruments which monitor the city development over time. In general, those instruments outline specific dimensions such as physical forms, social and economic criteria. Understanding the impact of physical form criteria on the built environment is the main goal of this investigation once those physical form criteria tend to be prescriptive, providing a set of definite instructions, rather than providing general guidance or advice. For instance, it is not unusual finding sets of standards for: building disposition (lot size, frontage, and setback requirements), building configuration (frontage type, building height), building function (uses for each zone), urban quarter configuration, street patterns and so on.

Different regulations for the built environment occur throughout a city history. An investigative approach started by examining land use regulations and building construction codes in a temporal and spatial perspective.

3.1.2 LAND TAX DATABASE

Information found on the land tax database is noted to be capable of describing building stock characteristics. Among the land tax information selected to characterize the office building stock were: building age, building use, location, building area and land tax index.

The building age allowed situating the building in a historical perspective, helping on the identification of the land use legislation, the building codes and architectural style influences. The building use permitted to differentiate the building stock area by residential and non-residential uses. Among non-residential uses it was also possible to identify commercial buildings and in specific office buildings. The location helped to map the building across the city. Building area permitted to estimate the buildings height through an investigation of the relationship among plot area, building total area and land use legislation rules. Moreover, the building area combined with the building age allowed quantifying the building stock size and growth rate. Regarding the land tax index, the number of indexes associated with a same address suggested whether the internal building concept tend to be a cellular building or an open office building. Additionally, it also suggested if the building was a multi-owner building or a single owned building.

3.1.3 FIELD SURVEY

The field survey followed two basic steps: (1) Adapted Morphological Diagram analysis and (2) *in loco* visits.

3.1.3.1 Adapted Morphological Diagram (AMD)

The methodology used to organize the urban and building data collected during the field survey was based on the "Morphological Box" developed by BAKER, FANCHIOTTI and STEEMER. (2013) and adapted by AMORIM (2014). The "Morphological Box" is an instrument for morphological analysis of existing buildings from the environmental point of view. In this research, the "Morphological Box" was used to develop Adapted Morphological Diagrams (AMDs) and to cluster similar characteristics of a building sample impacting on the thermal comfort and energy efficiency.

The elaborated AMD was categorized in levels, parameters and subcategories as shown in Table 6. The levels were divided in urban and building levels. For each level the morphological parameters were listed and for each parameter a set of subcategories were described. The full description for each subcategory is presented in Appendix A.

Table 6 – Adapted Morphological Diagram (AMD) levels, parameters and subcategories.

Level	Parameters		Subcategories					
Urban	**A**	Street width	A1	A2	A3			
	B	Sky view	B1	B2	B3	B4		
Building	**C**	Facade Reflectance	C1	C2	C3	C4	C5	C6
	D	Roof Reflectance	D1	D2	D3			
	E	Glazing colour	E1	E2	E3	E4		
	F	Roof Characteristics	F1	F2	F3			
	G	Solar orientation						
	H	Number of floors						
	I	Building shape	I1	I2	I3	I4	I5	
	J	Ground floor characteristics	J1	J2	J3	J4		
	L	Window to wall ratio	L1	L2	L3	L4	L5	
	M	Window - facade distribution	M1	M2	M3			
	N	Daylight control	N1	N2	N3	N4		
	O	Environmental conditioning strategy	O1	O2	O3	O4		

Source: Author's own elaboration

The urban parameters analysed were: street width and sky view. Both parameters are related to the solar radiation access and consequently thermal performance. Moreover, the sky view angles from front, back and lateral facades represent the surrounding buildings height, as illustrated by the subcategories in Figure 9.

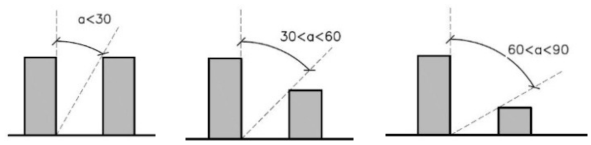


Figure 9 - Building sky view subcategories from the AMDs

Source: Author's own elaboration

Facade reflectance, roof reflectance and roof characteristics are building envelope parameters related to the heat gain and consequently thermal performance. The parameters window to wall ratio and glazing colour are noted to affect heat gain as well as visible lighting transmittance and therefore impact on thermal and lighting performance.

The building shape and window/facade distribution parameters determine patterns of internal daylighting distribution and natural ventilation feasibility, especially cross ventilation. Daylight control systems influence the amount of lighting and natural ventilation inside a building space and therefore affect thermal and daylighting performance. In general, external shading systems work on diminishing facade heat gain, whereas internal daylight controls such as curtains/venetian work on controlling the brightness.

The environmental conditioning parameter represents the cooling strategy adopted by the buildings. Air conditioning systems are observed to have great impact on building energy consumption, especially high-rise office buildings (GONÇALVES; UMAKOSHI, 2015).

3.1.3.2 In Loco visits

In loco visits were conducted to collect data on artificial lighting and air conditioning from office building spaces. The data were obtained by means of semi-structured questionnaires answered in the presence of the researcher and a walk-through audit of the office rooms. The questionnaire used is presented in Table 7 and it gives technical and operational information about the lighting and the HVAC systems.

Table 7 - *In loco* Survey Questionnaire regarding office buildings

In Loco Survey	
Room Area	
Tenant or Owner?	
Lighting System	
Select the Lamp Type and describe the Rated Power	
Incandescent	
Fluorescent	
Led	
Others	
Select the Lighting System Characteristics	
ON/OFF	
Multiple Lighting Circuits	
Dimmer	
Others	
Select/describe the Lighting Routine	
Operating hours	
Turned ON only if necessary	
Others	
Select the Daylighting Control	
Blinds/Venetians	
Shading devices	
Others	
HVAC System	
Select the HVAC Type	
Window Air System	
Split System	
Central Air Conditioner	
Natural Ventilation Only	
Others	
Describe the HVAC System Characteristics	
Btus/h	
COP	
Select/Describe the HVAC Routine	
Operating hours	
Turned ON only if necessary	
Others	

Source: Author's own elaboration

3.2 DYNAMIC ARCHETYPE MODEL SIMULATION

The information gathered from the three inputs was used to describe reference building prevalent attributes. For each reference building, a building archetype energy model was created. In this study, building archetype energy models demand more information than those used to describe the reference building and therefore it was necessary to get information on technical literature and normative standards such as ASHRAE 90.1 (ASHRAE, 2010) and CIBSE (CIBSE, 2004) to fill out the gaps.

Table 8 presents the key attributes that are necessary to characterize building archetype energy models.

Table 8 - Key attributes of the office building archetype energy models

Building physics and building envelope
Floor plan
Floor plan dimension (m^2)
Building shape
Number of floors
Solar orientation
Surrounding built environment
Window to Wall Ratio - WWR (Front/Back Facade)
Window to Wall Ratio-WWR (Lateral Facade)
Glass colour
Glass thickness
Glass Solar Heat Gain Coefficient (SHGC)
External wall U - (W/m².K)
Internal wall U - (W/m².K)
Roof U - (W/m².K)
Wall Absorptance
Roof Absorptance
Building systems and building operational routines
Lighting level required (lux)
Light power density -LPD (W/ m²)
Office devices density (W/ m²)
Air conditioning type
Air conditioning coefficient of performance-COP, (w/w)
Cooling Setpoint (^{o}C)
Area Conditioned (%)
Outdoor Air flow rate per person (L/s.person)
Space heating (yes/no)
Population (floor area per person)
Operational day time (hours)
Lighting schedule (operating hours/year)
Office devices schedule (operating hours/year)
Air conditioning schedule (hours)

Source: Author's own elaboration

The tool selected to evaluate energy performance was EnergyPlus 8.1, developed by the US Department of Energy (DOE, 2015). This tool was selected based on the fact that the program enables whole-building performance simulation and has been extensively tested (CRAWLEY *et al.*, 2000, 2008; HENNINGER; WITTE; CRAWLEY, 2004) and widely used over the years. In this methodology the simulations were performed for the duration of one whole year (8760 hours).

The energy performance indicator used to equalize the way that energy use is compared between energy models is the Energy Use Intensity (EUI), expressed as a function of kilowatt-hours per square meter per year [kWh / m²/ year].

In order to reference different building solar orientations, four sets of simulations were performed for each energy model considering the city plan grid. The EUI results from the simulations were presented in terms of mean values obtained by dividing the sum of observed values by the number of simulations.

3.2.1.1 Validation

In general, the accuracy of building performance predictions depends on two key factors: input data accuracy and the tool ability of predicting real building performance when given faultless input data. The accuracy of the input data is usually constrained by the level of detail incorporated into the model, the accuracy to which the building physical, systems and routine attributes are known, user's expertise and the available time. The tool ability of predicting real building performance is related to the tool capability of predicting building performance for a specific type of building in a particular climate (JUDKOFF *et al.*, 2013). In the context of this study, the input data accuracy was driven by the field survey whereas the tool ability of predicting performance was determined by the use of the software EnergyPlus, which is known to be widely tested and used to predict building performance.

Validation is commonly recognised as necessary to a gradual improvement in the quality of energy models. In the validation process the model results can be compared with monitored data sets or with other similar studies (AHMAD, 1998; JUDKOFF *et al.*, 2013). Comparative studies involve a direct comparison of the results obtained from two studies using similar inputs. The comparative study is a useful technique as it does not require data from real buildings. Differently, empirical validation requires the comparison between the energy model outcomes and measured data sets obtained usually from real buildings instrumentation or energy bills (HEO; CHOUDHARY; AUGENBROE, 2012; JUDKOFF *et al.*, 2013). In the context of this study, the validation can occur based on the archetype EUI results or based on the overall building category baseline consumption results. The choice for one or other is noted to be linked to data availability which is in general one of the most important challenges faced by the researchers in this field.

3.3 ENERGY CONSUMPTION BASELINE ESTIMATION

A baseline of energy consumption was estimated considering the EUI of each building archetype energy model, the office building stock growth rate as well as the building stock area. Information to compute the stock growth rate and the building stock area was found in the land tax database. The Annual Growth Rate (AGR) calculation of the office building stock is determined by the following equation:

$$AGR = \left(\frac{EV}{BV}\right)^{\frac{1}{n}} - 1$$

(20)

Where: AGR = annual growth rate; EV = amount of area from the current year; BV = amount of area from the previous year and n = Number of periods (years)

The estimated baseline was then named BaseCase Baseline.

3.4 ENERGY RETROFIT MEASURES SELECTION AND A COST OPTIMAL PATHWAY ANALYSIS

An understanding of the BaseCase baseline energy consumption reveals opportunities for energy performance improvements at an urban scale. Additionally, it provides a starting point for considering retrofit measure options that are relevant for each building archetype energy model.

Firstly, potential retrofit measures options were selected based on their technical feasibility and suitability. Secondly, a local sensitivity analysis was applied to prioritize retrofit measures. Thirdly, a sequential search optimization technique was applied in order to identify the cost optimal pathway for implementing the measures.

3.4.1 LOCAL SENSITIVITY ANALYSIS

The local sensitivity analysis was chosen in this work to identify the impact of input parameters related to retrofit measures on the building stock energy savings potential. The local sensitivity analysis method used is presented in Figure 10 as follows:

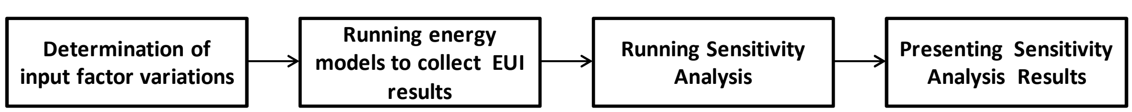


Figure 10 – Local sensitivity analysis flowchart
Source: Author's own elaboration

For each archetype energy model, the first step was to determine input factor variations. The present study focuses on input factors which were promising energy retrofit interventions. The input perturbation value represents the retrofit measure intervention. Secondly, a simulation was performed for each input factor in order to obtain the EUI result perturbation. Thirdly, the sensitivity analysis was performed. As a measure of the sensitivity, an Influence Coefficient (IC) was calculated following the Equation 21:

$$IC = \frac{\Delta OP}{OP_{BC}} \Big/ \frac{\Delta IP}{IP_{BC}} \tag{21}$$

Where ΔOP and ΔIP are changes in output and input respectively, whereas OP_{BC} e IP_{BC} are BaseCase values of output and input respectively.

The IC results allowed ranking the input factors in order of importance. The sign of the IC indicates whether the output increases (positive coefficient) or decreases (negative coefficient) as the corresponding input factor increases. Input factors affecting the EUI are believed to have a significant influence on the building energy saving potential.

3.4.2 COST OPTIMAL PATHWAY ANALYSIS

Local sensitivity analysis results were the starting point to select potential retrofit measures. The selected measures went through an optimization procedure in order to generate a cost-optimal pathway for implementation. The optimization procedure employs a sequential search methodology. The sequential search method has been widely used to find optimal solution regarding energy system designs (CHRISTENSEN *et al.*, 2005; CHRISTENSEN, CRAIG; BARKER; HOROWITZ, 2004; GRIEGO; KRARTI; HERNANDEZ-GUERRERO, 2015; HOROWITZ *et al.*, 2008; IHM; KRARTI, 2012).

The basic sequential search method is shown in Figure 11 and evaluates efficient measures combinations in order to determine the most cost-effective solution at each sequential point along a pathway. All options are simulated one by one in the presence of an initial base case. Energy savings and energy-related costs of each option are computed and the most cost-effective (steepest slope) option is chosen as the optimal point for the iteration. The chosen option is then removed from future evaluations by the search. Remaining efficiency measures are simulated in the presence of this new optimal point and the iterative process repeats (HOROWITZ *et al.*, 2008).

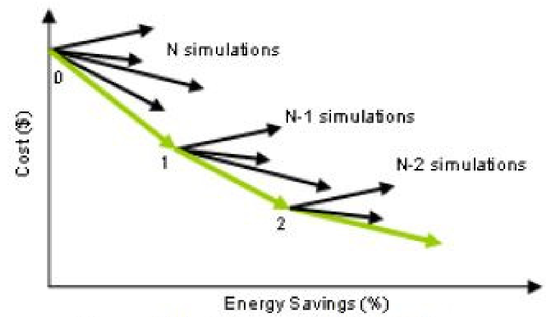


Figure 11 – Basic sequential search process

Source: Horowitz et al. (2008)

The sequential search approach also can provide apart from the optimal solution a set of options that achieves other desired energy use savings. In this study Figure 12 illustrates a schematic cost optimal pathway. As shown in Figure 12, at the end of the optimization process, a cost optimal pathway for implementation of all selected measures was designed. The designed cost optimal pathway provides a sequence of retrofit measures combination where each point differs from one measure to its predecessor. For instance, in Figure 12 the numbers 1, 2, 3 and 4 mean the number of measures combined into an Energy Retrofit Package (ERP). Number 1 means individual measure, number 2 means two combined measures and so on.

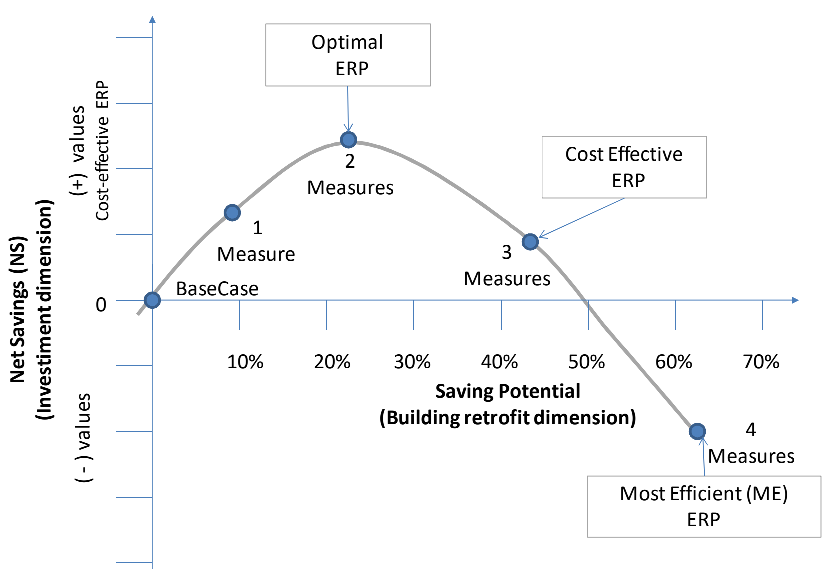


Figure 12 – Schematic cost optimal pathway

Source: Author's own elaboration

In this study the economic method used to evaluate the ERP cost effectiveness was the Net Savings (NS) which is consistent with the Life Cycle Cost (LCC) method but easier to interpret. NS directly states the cost effectiveness of a design alternative relative to an identified base case (a positive NS value means that an ERP is cost effective).

In the scheme presented in Figure 12, ERPs with positive NS values are considered cost effective. The Optimal ERP point means the ERP with maximum NS value whereas the Cost Effective ERP point indicates the most efficient and cost effective ERP. The Most Efficient ERP point means the ERP with the greatest energy saving potential regardless of cost effectiveness.

3.4.2.1 Energy Retrofit Packages saving potential evaluation

The energy Saving Potential (SP) of each Energy Retrofit Package (ERP) was calculated as follows:

$$SP = \left(\frac{EUI_{ERP}}{EUI_{BC}} - 1\right) . 100$$

(22)

Where, EUI_{BC} is the Energy Use Intensity of a base case, EUI_{ERP} is the Energy Use Intensity of an energy retrofit package alternative.

3.4.2.2 Economic Evaluation

Life-Cycle Cost (LCC) and Net Savings (NS) are the economic methods used to evaluate the ERP cost effectiveness. LCC is the total cost of owning, operating, maintaining and eventually disposing of the building or building systems over a given period of study with all costs adjusted (discounted) to reflect the time-value of money. NS is a supplementary measure of economic performance, consistent with LCC analysis that calculates in present-value the net amount that a project alternative is expected to save over the study period. Considered as a relative measure of economic performance, the NS is computed for a project alternative relative to an identified base case (FULLER; PETERSEN, 1996).

3.4.2.2.1 Life-Cycle Cost (LCC)

In this study, the general formula for computing LCC for building-related projects can be stated as follows (FULLER; PETERSEN, 1996):

$$LCC = I + Repl - Res + E + OM\&R$$

(23)

Where:

LCC = Total LCC in present-value of a given alternative, I = Present-value investment costs, Repl = Present-value capital replacement costs, Res = Present-value residual value less disposal costs, E = Present-value energy costs, and OM&R = Present-value non-fuel operating, maintenance and repair costs.

3.4.2.2.2 Net Savings (NS)

The Net Savings for an ERP alternative, relative to the base case can be calculated by subtracting the LCC of the alternative from the LCC of the base case as follows:

$$NS = LCC_{BASE\ CASE} - LCC_{ALTERNATIVE} \tag{24}$$

NS formula for building related projects can also be calculated as follows:

$$NS_{ERP:BASE\ CASE} = [\Delta E + \Delta OM\&R] - [\Delta I + \Delta Repl - \Delta Res] \tag{25}$$

Where

$NS_{ERP:BASE\ CASE}$ = Net savings which means operation-related savings minus additional investment costs for a retrofit alternative relative to the base case.

$\Delta E = (E_{BASE\ CASE} - E_{ERP})$ Savings in energy costs attributable to the alternative.

$\Delta OM\&R = (OM\&R_{BASE\ CASE} - OM\&R_{ERP})$ Savings in OM&R costs attributable to the alternative.

$\Delta I = (I_{ERP} - I_{BASE\ CASE})$ Additional initial investment cost required for the alternative relative to the base case.

$\Delta Repl = (Repl_{ERP} - Repl_{BASE\ CASE})$ Additional capital replacement costs.

$\Delta Res = (Res_{ERP} - Res_{BASE\ CASE})$ Additional residual value.

All amounts are in Present Value (PV).

The ERP alternative was considered to be cost effective relative to the base case if the NS was greater than zero.

3.5 DEVELOPING ENERGY SAVING SCENARIOS AND ESTIMATING BUILDING ENERGY SAVINGS POTENTIAL

The cost optimal pathway analysis was the basis to develop three energy saving scenarios regarding the existing building stock.

- Scenario 01 – Optimal Solution.

  The scenario represents the savings that would result if all related office building stock adopted the Optimal ERP solution.

- Scenario 02 – Cost Effective Solution.

  The scenario represents the savings that would result if all related office building stock adopted the Cost Effective ERP solution.

- Scenario 03 – Most efficient Solution.

  The scenario represents the savings that would result if all related office building stock adopted the Most Efficient ERP solution, regardless of cost.

In this study, the EUI from the solutions do not replaced the BaseCase EUI instantaneously, but rather was phased in over 20 years using a replacement rate of 5% a year. The saving scenarios were then projected considering the changes in the EUI of each building archetype energy model over the years as well as the related office building stock growth rate.

All scenario projections were estimated and compared to the BaseCase projection in order to assess the energy savings potential of the office building stock. The BaseCase projection is a frozen efficiency scenario that represented the electric energy consumption if no retrofit measures were implemented.

The difference between the BaseCase and the saving scenario forecasts were considered to be the existing building stock savings potential.

4 THE ENERGY CONSUMPTION BASELINE OF EXISTING HIGH-RISE OFFICE BUILDINGS: A CASE STUDY OF BELO HORIZONTE.

4.1 BELO HORIZONTE'S CASE STUDY METHODOLOGY

Figure 13 shows the first three methodological steps applied in Belo Horizonte case study. The three steps were the basis to develop the energy intensity baseline of the existing high-rise office building stock in the city.

Regarding the method for obtaining reference buildings, firstly the city plan, the land use regulations and the building construction codes of Belo Horizonte were investigated in a temporal and spatial perspective with a focus on their effect on the high-rise commercial building typology. The influence of the land use legislation on the building typologies of the city was the starting point to propose a building typology classification. Secondly, a local city council database (SMAPU/PBH, [S.d.]) developed by the *Secretaria Municipal Adjunta de Planejamento Urbano* (SMAPU/PBH) and based on land tax information was then used to study basic high-rise office building features. Thirdly, a field study was conducted based on the building typology classification which had been found. The information gathered from these three inputs was used to describe prevalent attributes from three reference building typologies. For each of this, building archetype energy models were created and simulations were performed in EnergyPlus to assess EUI.

Finally, the baseline of energy consumption was estimated considering the EUI simulated for each archetype energy model and the growth rate area of the existing high-rise office building stock indicated over the years by the SMAPU/PBH database.

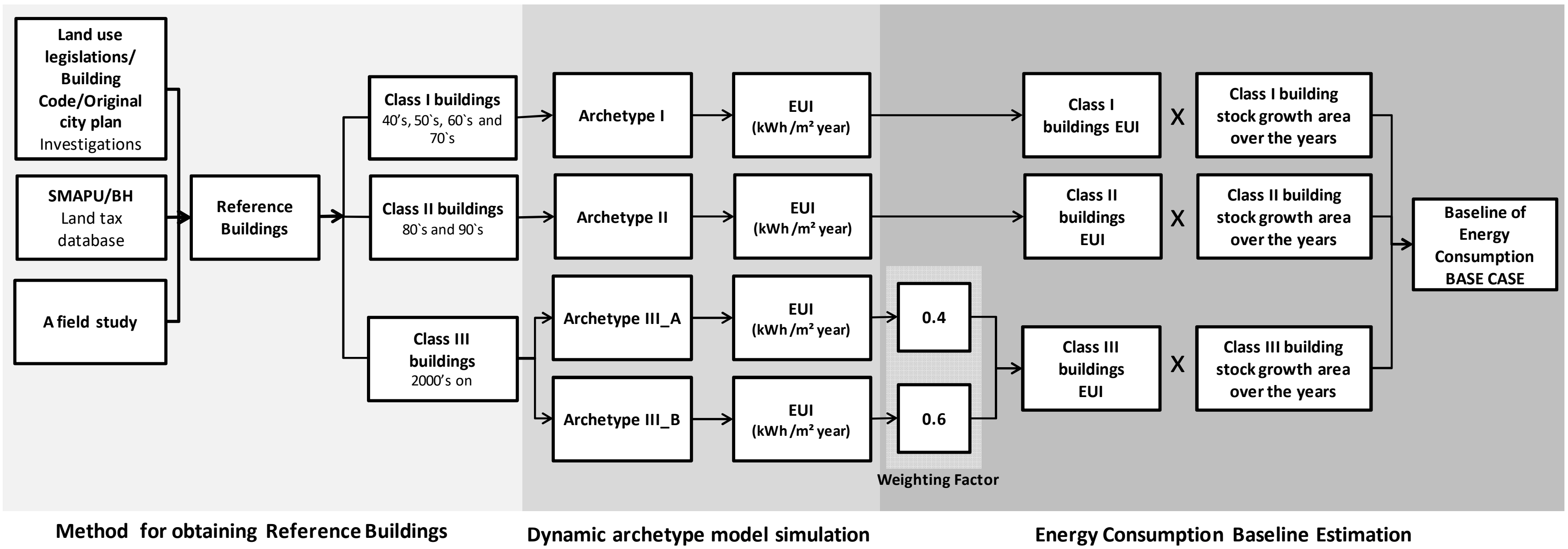


Figure 13 – Method for estimating the energy consumption baseline of Belo Horizonte's high-rise office buildings

Source: Author's own elaboration

4.1.1 BELO HORIZONTE'S CASE STUDY: THE METHOD FOR OBTAINING REFERENCE BUILDINGS

4.1.1.1 Land Use legislation Investigation

Different regulations for built environment have occurred throughout Belo Horizonte's history. An investigative approach started by examining the land use regulations and the building construction codes available on the city council website at the web address https://leismunicipais.com.br. Nine different regulatory contexts for high-rise commercial buildings were addressed together with their building typological outcomes. In the context of the city, three building typological categories were then identified and named *Class I, Class II* and *Class III*. Class I buildings are related to high-rise office buildings from the 40's, 50`s, 60`s and 70`s decades, Class II buildings are related to high-rise office buildings from the 80`s and 90`s and Class III buildings are related to high-rise office buildings from 2000's on.

4.1.1.2 SMAPU/PBH database

The SMAPU/PBH database reports information for the building sector based on land taxing - *Imposto Predial e Territorial Urbano* (IPTU). The data were available from 1889 until 2011. Among the SMAPU/PBH information selected to characterize the office building stock were: building use, building age, location (address), building area, height and land tax index. The information was organized following the steps and filters presented in Figure 14.

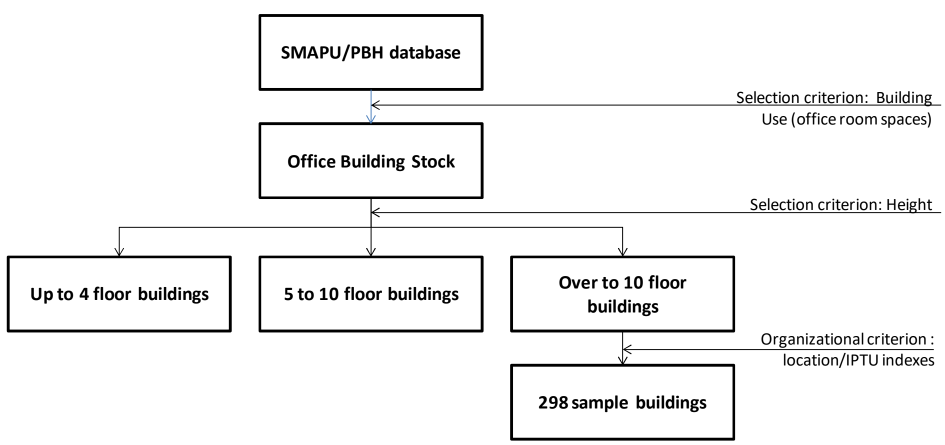


Figure 14 – SMAPU/BH database Flowchart

Source: Author's own elaboration

The filters used were: building use, height, location and IPTU index. The building use filter permitted to select commercial spaces and among commercial spaces it was also possible to separate office room spaces. The height characteristic of the buildings which hold the office room spaces was provided by the height filter. Three height categories were defined for office buildings: small (up to 4 floors), medium (from 5 to 10 floors) and high-rise buildings (over 10 floors). The location combined with the IPTU index was used to gather information related to a specific building. In other words, all IPTU indexes linked to a same address were considered to be part of the same specific building. This step was used to select buildings to the field survey.

In the Brazilian context, the area values presented in the so called IPTU correspond to the sum of the gross room area (included external perimeter wall thickness and internal partition measured to their centre line) and the common area shared. Moreover, IPTU areas from a specific office building are computed separately for office rooms and parking spaces. In the context of this case study, only office room areas were computed.

The SMAPU/PBH database analysis identified 298 high-rise office buildings to the field survey. A list of the sample buildings is presented in Appendix B.

4.1.1.3 Field Survey

The field survey followed two basic steps: Adapted Morphological Diagram analysis and *in loco* visits. However, in this case study, a third step was added as shown in Figure 15. This step regards internal distribution evaluation used to define the internal space distribution of the archetype energy models used during the simulations.

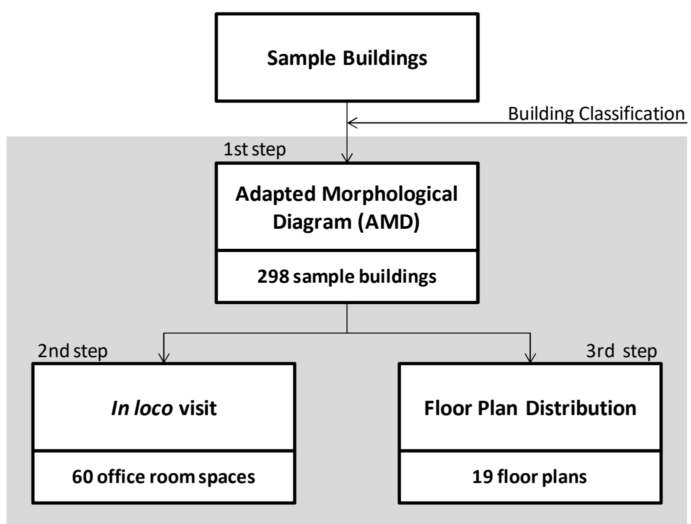


Figure 15 – Field Survey structure

Source: Author's own elaboration

The field study was carried out taking into account the building classification proposed. Firstly, the address reported on the SMAPU/PBH database was the starting point for localizing the buildings in the urban fabric by using Google Earth®. Images of the buildings and their urban context were captured through the Street View feature and then analysed using the AMDs. The potential of the street view tool to collect information from buildings and urban parameters is shown in Figure 16. A total of 298 high-rise buildings were analysed using AMDs.

Figure 16 - Example of images collected during the AMDs analysis.

Source: Google Earth throughout Street View

The information gathered from the AMDs was computed and the results expressed as a function of frequency of occurrence and in some cases mean values as shown in Table 9.

Table 9 – Building attributes summary according to the AMDs

		Class I/II and III buildings
Street Width		Based on frequency of occurrence
Sky View		Based on mean values
Facade Reflectance		Based on frequency of occurrence
Roof Reflectance		Based on frequency of occurrence
Glazing colour		Based on frequency of occurrence
Roof Characteristics		Based on frequency of occurrence
Solar Orientation		Based on frequency of occurrence
Number of Floors		Based on mean values
Building Shape		Based on frequency of occurrence
Ground floor characteristic		Based on frequency of occurrence
Window wall ratio	**Front**	Based on mean values
	Left	Based on mean values
	Right	Based on mean values
	Back	Based on mean values
Window-facade distribution		Based on frequency of occurrence
Daylighting control		Based on frequency of occurrence
Environmental conditioning strategy		Based on frequency of occurrence

Source: Author's own elaboration

Regarding the second step, *in loco* visits gathered information on artificial lighting and air conditioning. The data were collected by means of questionnaires answered in the presence of the researcher as well as a walk-through audit of the office rooms. Technical information was collected and confirmed with suppliers. Operational schedules of both systems were gathered together with occupant behaviour data. A total of 60 work spaces in 12 buildings were visited. Those selected buildings were part of the most representative office building typology found in the city (Class II buildings). The questionnaires were examined and the results expressed as a function of frequency of occurrence.

Regarding the third step, floor plans were analysed in terms of internal distribution. The information was categorized into vertical distribution (stairs and elevators), horizontal distribution, technical support areas and workspaces. Collected information regarding the internal distribution is presented in Appendix C. A total of 19 floor plans were studied and the results expressed as a function of mean values.

4.1.2 BELO HORIZONTE'S CASE STUDY: DYNAMIC ARCHETYPE MODEL SIMULATION

The information gathered from the earlier steps was used to describe prevalent attributes of three reference buildings: Class I, Class II and Class III buildings. For each of these, building archetype energy models were created. The archetype energy model from the Class I buildings were named Archetype I, the archetype energy model from the Class II buildings were named Archetype II. However, to better characterize Class III buildings it was necessary to create two archetype energy models: Archetype III_A (cellular office buildings) and Archetype III_B (open office buildings). Data source of the models came from the previous step and also from the technical literature and normative standards as shown in Tables 10 and 11.

Table 10 - Key attributes of the archetype model envelope and physics

Building physics and building envelope	
	Data source
Floor plan concept	SMAPU/PBH database
Floor plan dimension (m^2)	Assumption based on SMAPU/PBH Database and Original Plot subdivision
Building shape	Field survey (AMD)
Number of floors	Field survey (AMD)
Solar Orientation	Field survey (AMD)
Surrounding built environment	Field survey (AMD)
WWR (Front/Back Facade)	Field survey (AMD)
WWR (Lateral Facade)	Field survey (AMD)
Glass color	Field survey (AMD)
Glass thickness	NBR 6123 (ABNT, 1988), NBR 7199 (ABNT, 1989)
Glass Solar Heat Gain Coefficient (SHGC)	Technical Catalogue (CB3E; ABIVIDRO, 2015)
External wall U - (W/m².K)	Assumption/ NBR15520-2 (ABNT, 2005)
Internal wall U - (W/m².K)	Assumption/ NBR15520-2 (ABNT, 2005)
Roof U - (W/m².K)	Assumption/ NBR15520-2 (ABNT, 2005)
Wall Absorptance	Thermal Proprieties Catalogue (INMETRO, 2013)/field study
Roof Absorptance	Thermal Proprieties Catalogue (INMETRO, 2013)/field study

Source: Author's own elaboration

Table 11 - Key attributes of the archetype model systems and routines

Building systems and building routines	
	Data source
Lighting level required (lux)	ISO/CIE 8995-1 (ABNT, 2013a)
Light power density -LPD (W/ m²)	RTQ-C (INMETRO, 2014) , CIBSE Guide F(CIBSE, 2004)
Office devices density (W/ m²)	CIBSE Guide F (CIBSE, 2004)
Air conditioning type	Field Survey
Air conditioning coefficient of performance - COP, (w/w)	Technical Catalogue ("Hitachi Air Conditioning", [S.d.], "Tabelas de consumo/eficiência energética - Condicionadores de Janela (Window Air Conditioning - Coefficient of Performance)", 2016)
Cooling Setpoint (^{o}C)	NBR 16401 (ABNT, 2008)
Area Conditioned (%)	Field Survey
Outdoor Air flow rate per person (L/s.person)	NBR 16401(ABNT, 2008)
Space heating (yes/no)	Field Survey
Population (floor area per person)	NBR 9077 (ABNT, 2001)
Operational day time (hours)	Field Survey
Lighting schedule (operating hours/year)	ASHRAE 90.1(ASHRAE, 2010)/ CIBSE Guide F (CIBSE, 2004)
Office devices schedule (operating hours/year)	ASHRAE 90.1(ASHRAE, 2010)/ CIBSE Guide F(CIBSE, 2004)
Air conditioning schedule (hours)	ASHRAE 90.1(ASHRAE, 2010)/ CIBSE Guide F(CIBSE, 2004)

Source: Author's own elaboration

The developable volume of each building archetype energy model took into account the city original plot subdivisions as well as land use parameters.

Regarding wall and roof, the system assumptions were driven by traditional Brazilian construction patterns and the transmittance was calculated based on NBR15520-2 methodology considering the wall and roof systems presented in Figure 17 as follows:

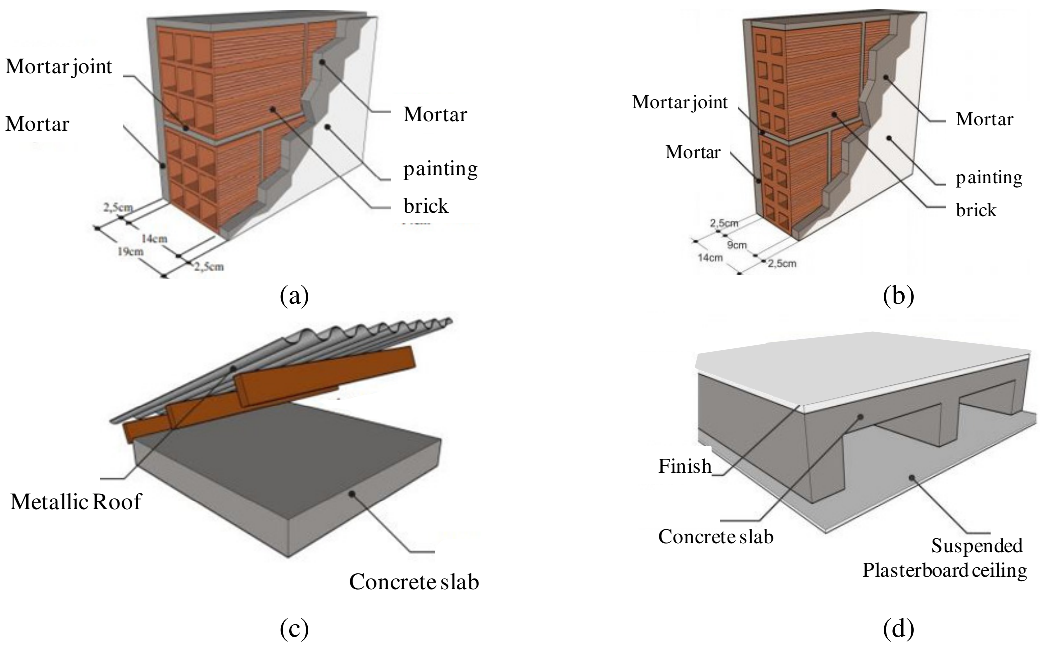


Figure 17 – External Wall (a), internal wall (b), multi-plane roof (c), concrete slab roof (d)

Source: based on the Thermal Proprieties Catalogue (LABEEE, 2014)

The Lighting Power Density (LPD) adopted took into account the lighting systems found in the field survey as well as the data from lighting suppliers (NOVAES, 2016). The LPD value was set based on the correlation between the predominant artificial lighting system found and the lighting system efficiency classification suggested by Technical Regulation for the Quality Level of Energy Efficiency in Commercial, Service and Public Buildings - RTQ-C (INMETRO, 2010) as shown in Tables 12 and 13.

Table 12 – Lighting system used to establish RTQ-C classification.

Equipment	**A**	**B**	**C**	**D**
Luminary	Reflector and louver	Reflector only	No reflector	No reflector
Lamp	28W/2900lm	32W/2700lm	32W/2700lm	40W/2600lm
Ballast	Electronic (loss of 6W)	Electronic (loss of 6W)	Electromagnetic (loss of 12.5W)	Electromagnetic (loss of 15W)
Rated power (Watts)	62.0	70.0	76.5	95.0
Luminous Efficacy	93.55	77.14	70.59	54.74

Source: Based on Ramos and Lamberts (2010)

Table 13 – LPD (W/m²) by activity according to RTQ-C

Activity	LPD Level A	LPD Level B	LPD Level C	LPD Level D
Hall/horizontal distribution	7.10	8.52	9.94	11.36
Cellular Offices	11.90	14.28	16.66	19.04
Open Offices	10.50	12.60	14.70	16.80

Source: Based on RTQ-C (INMETRO, 2012)

The same process was then used to define the window air conditioning coefficient of performance (COP). The value was set by comparing the air conditioning systems found in the field survey with the energy efficiency classes values from the Brazilian Labelling Program ("Tabelas de consumo/eficiência energética - Condicionadores de Janela (Window Air Conditioning - Coefficient of Performance)", 2016). Table 14 presents the COP values of window air conditionings according to the Brazilian Labelling Program.

Table 14 – COP values – Window Air conditioning according to the Brazilian Labelling Program

	Coefficient of performance (W/W)			
Classes	Category 1 <=9.000 Btu/h	Category 2 between 9.001 and 13.999 Btu/h	Category 3 between 13.999 and 20.000 Btu/h	Category 4 between >=20.000 Btu/h
A	>= 2.93	>= 3.03	>= 2.88	>= 2.82
B	>= 2.84	>= 2.94	>= 2.71	>= 2.65
C	>= 2.76	>= 2.86	>= 2.59	>= 2.48

Source: Based on the Brazilian Labelling Program -Window Air Conditioning - Coefficient of Performance (2016)

Regarding the central air conditioning system, the COP value was set based on the Hitachi Air Conditioning catalogue under the name *Chiller Parafuso a Ar série SAZ* ("Hitachi Air Conditioning", [S.d.]) and referenced on the air condensed chiller/faincoil system found in the field survey.

4.1.2.1 Energy performance simulation procedure

The tool selected to evaluate energy performance was EnergyPlus V.8.1, developed by the U.S Department of Energy (DOE, 2015). Simulations were performed for the duration of one whole year (8760 hours) using the TRY (Test Reference Year) climate file of Belo Horizonte (LABEEE, [S.d.]). According to Köppen-Geiger, Belo Horizonte's climate is classified as Cwa which means a humid subtropical climate with dry winter and hot summer (ALVAREZ *et al.*, 2013).

Simulations were carried out considering specifically the office tower. Descriptions of the thermal interactions were analysed taking into consideration the tower subdivision and the floor subdivision. The tower was divided into bottom floor, intermediate floor and roof floor as illustrated in Figure 18. To estimate the floor plan EUI only the office rooms and the horizontal distribution were considered. No vertical transportation consumption was considered to compute the floor plan EUI and consequently the office tower EUI.

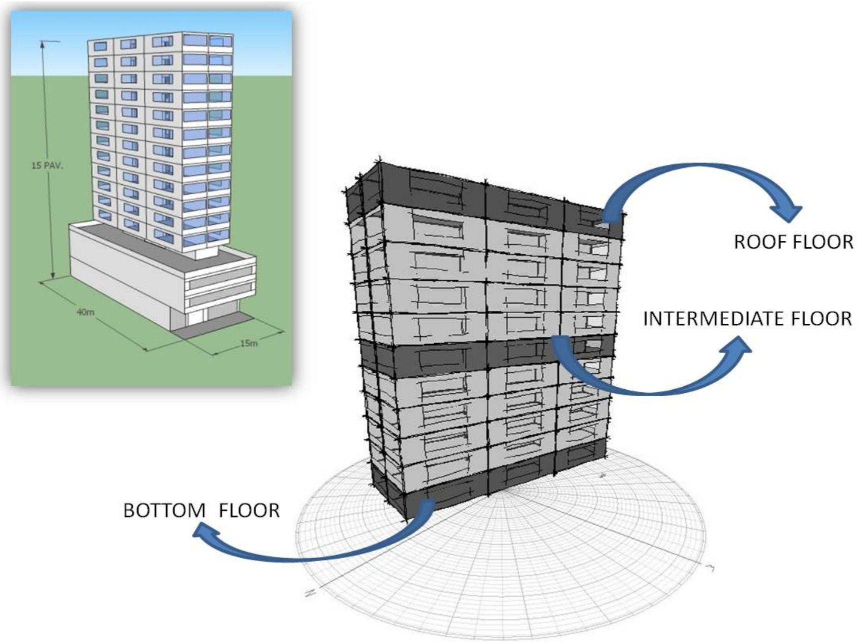


Figure 18 – Office tower subdivisions: roof floor, intermediate floor and bottom floor

Source: Author's own elaboration

The floor zone subdivision followed prevalent internal characteristics of each reference building. Zones were numbered according to their position on the floor as shown in Figure 19. Each position has the same correspondence on the bottom, intermediate and roof floor.

The floor EUI was the sum of each room EUI and horizontal distribution EUI. The archetype EUI in a given orientation was presented in terms of weighted arithmetic mean where the bottom and roof floor weight contribution were equal to 1(one) and the intermediate floor weight contribution was equal to the number of remaining floors from the related office tower.

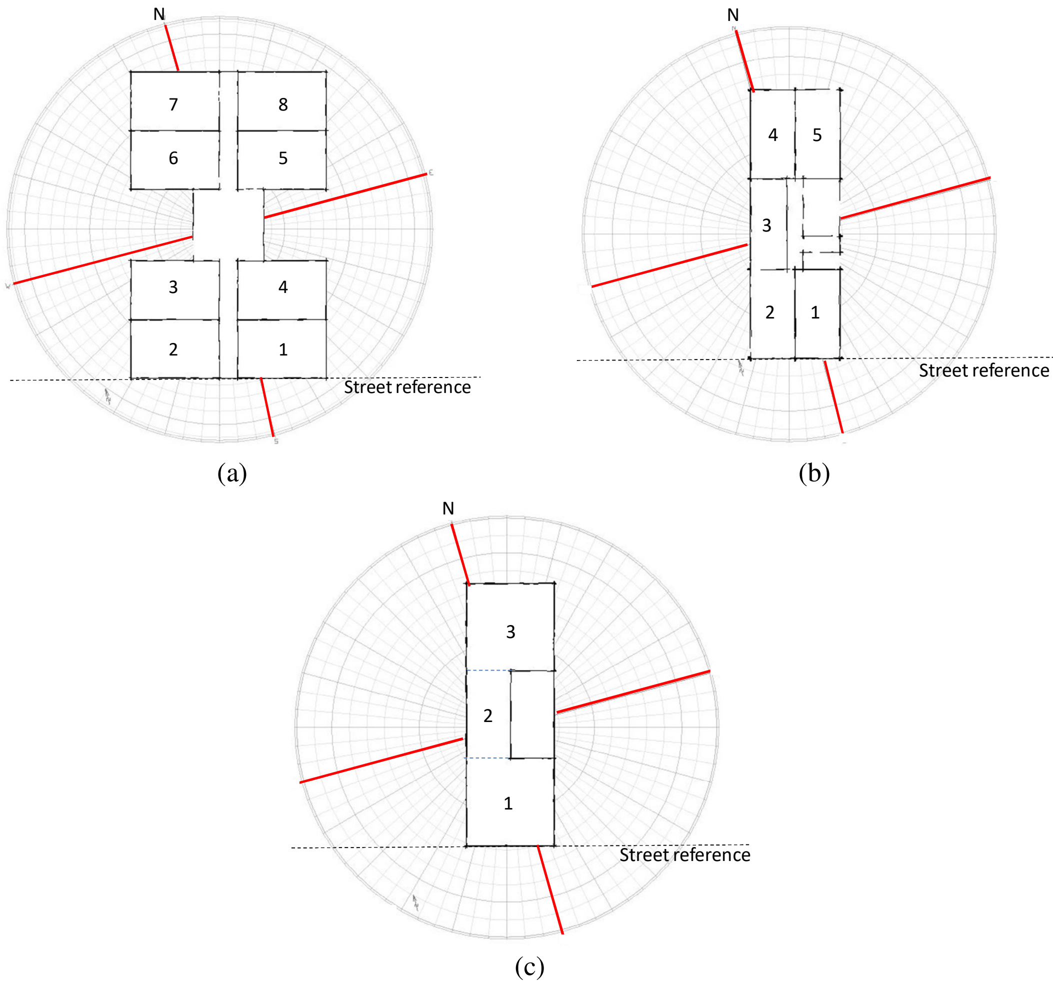
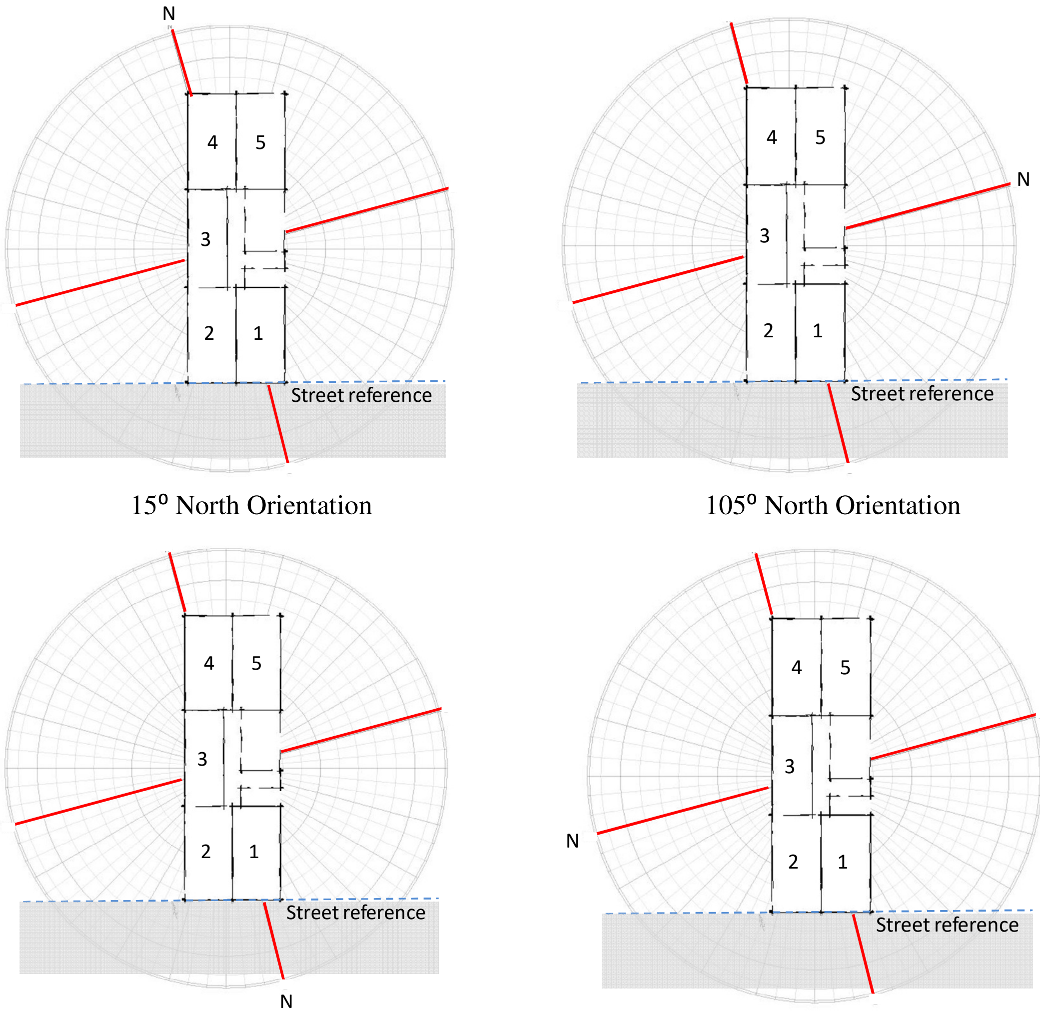


Figure 19 - Floor zone subdivision: (a) Archetype I, (b) Archetype II and III_A (c) Archetype III_B

Source: Author's own elaboration

Four sets of simulations were run for each building archetype energy model considering 15°, 105°, 195°, and 285° North orientations. These values were based on the original city plan grid. During the simulation process, the surround urban context rotated with the building as shown in Figure 20. Images of the building orientation used during the simulation for all building archetype energy models are presented in Appendix D.

The EUI final results from each building archetype energy model were presented in terms of mean values obtained by dividing the sum of observed values by the number of simulations.



15° North Orientation | 105° North Orientation

195° North Orientation | 285° North Orientation

Figure 20 – Example of Archetype II orientations regarding the simulations.

Source: Author's own elaboration

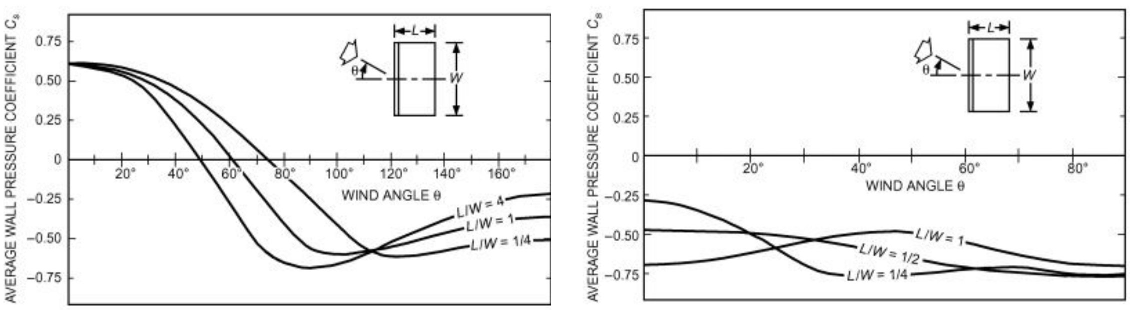
In the context of this case study, mixed mode systems (natural ventilation/air conditioning) are an important characteristic of Archetypes I, II and III_A. The multi-zone Airflow Network model was used to simulate natural ventilation. The wind pressure coefficients were calculated by the EnergyPlus software. In EnergyPlus the wind pressure is determined by Bernoulli's equation, assuming no height change or pressure losses (DOE, 2015):

$$p_w = C_p \ \rho \ \frac{{V_{ref}}^2}{2}$$

(26)

Where: p_w= Wind surface pressure relative to static pressure in undisturbed flow [Pa]; ρ = Air density [kg/m^3]; V_{ref} = Reference wind speed at local height [m/s]; C_p = Wind surface pressure coefficient [dimensionless].

C_p it is a function of location on the building envelope and wind direction. For walls and roofs, the wind pressure coefficients are provided by 2001 ASHRAE Fundamentals Handbook (ASHRAE, 2001) based on the original work performed by Akins; Peterka and Cermak (1979). "Surface Averaged Wall Pressure Coefficients for Tall Buildings" and "Surface Averaged Roof Pressure Coefficients for Tall Buildings" are presented in Figure 21. For a given incident angle and building aspect ratio, the program uses linear interpolation to calculate the corresponding wind pressure coefficient C_p .



(a) (b)

Figure 21 - Surface Averaged Wall Pressure Coefficients for Tall Buildings and Surface Averaged Roof Pressure Coefficients for Tall Buildings.

Source: Akins; Peterka and Cermak (1979)

In Archetypes I, II and III_A, the windows were set to be operable and the control strategy adopted was based on temperature, which means that, windows were opened whenever the zone temperature would be higher than outside temperature and the zone temperature would be higher than the ventilation setpoint temperature defined in this work as 20^{0}C, assumption based on the RTQ-R (INMETRO, 2012). The air mass flow coefficients, exponents and discharge coefficient of openings used are shown in Table 15.

Table 15 - Parameters for natural ventilation simulation

Component description	Windows (Metal window , Pivot)	Doors (Interior wood pivot door)
Air mass flow coefficient when opening is closed (kg/s.m)	0.00041	0.00204
Air mass flow exponent when opening is closed (dimensionless)	0.66	0.59
Discharge coefficient for opening factor 2 (dimensionless)	0.6	0.65

Source: Based on Liddament (1986)

In order to control the mixed mode system, hourly control schedules of air-conditioning and natural ventilation were created considering the thermal comfort. The method to assess thermal comfort was the Adaptive Standard ASHRAE 55 (ASHRAE, 2004) set to 90% acceptability limit. Acceptable operative temperature ranges for naturally conditioned spaces is presented in Figure 22.

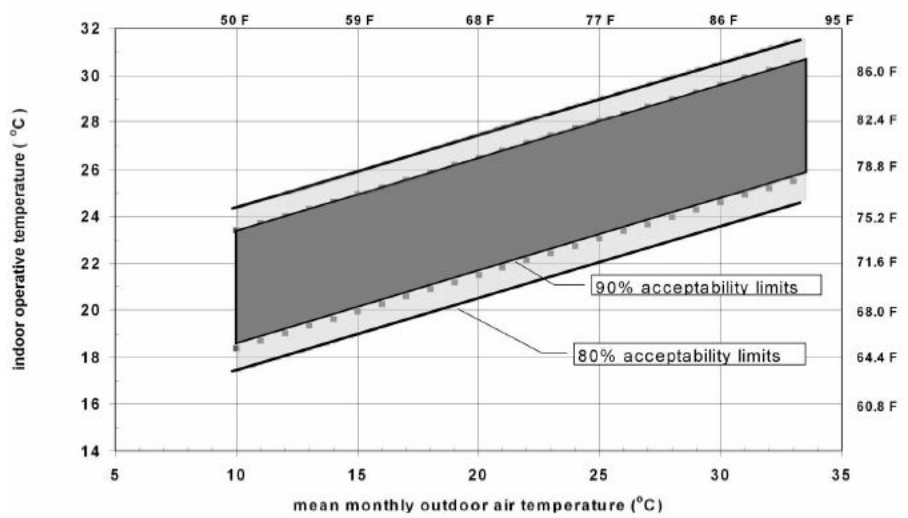


Figure 22 – Acceptable operative temperature range for naturally conditioned spaces

Source: ASHRAE Standard 55 (2004)

For each hour, if the value for the control schedule of natural ventilation is set to one (1), natural ventilation would be allowed with no use of air-conditioning; if the value is set to zero (0) then the use of air conditioning would be necessary, without natural ventilation. The control schedule of air conditioning is the opposite of the control schedule of natural ventilation, which means that whenever natural ventilation is allowed, the use of air-conditioning is not-allowed and vice versa.

4.1.2.2 Validation

In the context of this study, there was no available metered data regarding the office building stock energy consumption and thus empirical validation was not possible. Regarding similar studies, the study conducted by the Brazilian Sustainable Construction Council (CBCS) and named *Benchmarking de escritórios corporativos* (CBCS, 2015) was used to establish a comparison between the archetype energy model EUI results and the typical office building EUI values.

Table 16 presents the benchmarking equation divided by end-use. Comparisons between results would be established against the lighting system, office devices and HVAC systems of this study.

Table 16 – Energy Use Intensity (kWh/m^2/year) by end-use according to the *Benchmarking de escritórios corporativos.*

Benchmark	Typical		Good Practice	
End Use	**Private Area**	**Public Area**	**Private Area**	**Public Area**
Lighting	29.89	5.27	22.42	3.93
Office Devices	$33.51 + C_3*(N_{f,media}-N_f)$	-	$33.51 + C_3*(N_{f,media}-N_f)$	-
Air Conditioning	$(C_0-87.66)+C_1*GHR$		$(C_0-73.75)+C_1*GHR$	

Source: Based on Benchmarking de escritórios corporativos (CBCS, 2015)

Where C_0, C_1 and C_3 are constant values, N_f = building population, $N_{f,media}$ = 11.1 m^2/person (office building population mean value), GHR=cooling degree-hours. Constant values used in the benchmarking are presented in Table 17.

Table 17 – Benchmarking Constant values

Constant Identification	Typical	Good Practice	Unit
C_0	145.15	111.31	kWh/m^2/year
C_1	0.39	0.33	kWh/m^2.(1000 GHR)/year
C_3	4.15	4.15	kWh/person/year

Source: Based on Benchmarking de escritórios corporativos (CBCS, 2015)

For this study, the archetype model would be considered valid if the archetype EUI results do not disagree with the benchmarking EUI results obtained by the authors to within 20% absolute typical EUI.

4.1.3 BELO HORIZONTE'S CASE STUDY: ENERGY CONSUMPTION BASELINE ESTIMATION

The BaseCase baseline of energy consumption was estimated considering the EUI simulated for each building archetype energy model, the existing built area from each class building and the growth rate indicated over the years by the SMAPU/PBH database as shown in Table 18. The growth rate was computed based on the Equation 20 presented in the general methodology. The overall growth area data of office floor spaces from the SMAPU/PBH database are presented in Appendix E.

Table 18 – Growth rate of the high-rise building stock from Belo Horizonte

	High-rise buildings areas (m²)	Cumulative sum of high-rise building area (m²)	Growth rate over the period
1940/1949	58,924.34	58,924.34	
1950/1959	102,111.62	161,035.96	10.58%
1960/1969	303,349.37	464,385.33	12.49%
1970/1974	153,030.70	617,416.03	5.86%
1975/1977	67,874.29	685,290.32	3.54%
1978/1979	60,043.67	745,333.99	4.29%
1980/1981	96,137.43	841,471.42	6.25%
1982/1984	118,463.84	959,935.26	4.49%
1985/1989	254,190.03	1,214,125.29	4.81%
1990/1994	566,795.06	1,780,920.35	7.96%
1995/1997	215,596.72	1,996,517.07	3.88%
1998/1999	185,050.04	2,181,567.11	4.53%
2000/2004	166,038.10	2,347,605.21	1.48%
2005/2011	160,909.01	2,508,514.22	0.95%

Source: Author's own elaboration based on SMAPU/PBH

4.2 RESULTS AND DISCUSSION

4.2.1 BELO HORIZONTE HIGH-RISE COMMERCIAL BUILDINGS: AN OVERVIEW OF LAND USE REGULATIONS AND BUILDING CONSTRUCTION CODES

The city of Belo Horizonte was founded in 1897 to be the political and administrative headquarter for the State of Minas Gerais, Brazil. The original city plan divided the city into three zones (urban, suburban and rural) and established a rational and orthogonal grid for the urban zone delimited by a so called *Avenida do Contorno* as shown in Figure 23.

The orthogonal original grid of the city is rotated 15 ° clockwise from North. There are three geometric shapes into the blocks in the urban zone: 120x120m (most common), 120x60m, and a triangular shape which were born from the inserts of some diagonal avenues in the orthogonal grid. These blocks are composed by 24 rectangular plot subdivisions with the same area but different shapes: 10x60m, 20x30m and 15x40m (NORONHA, 1999).

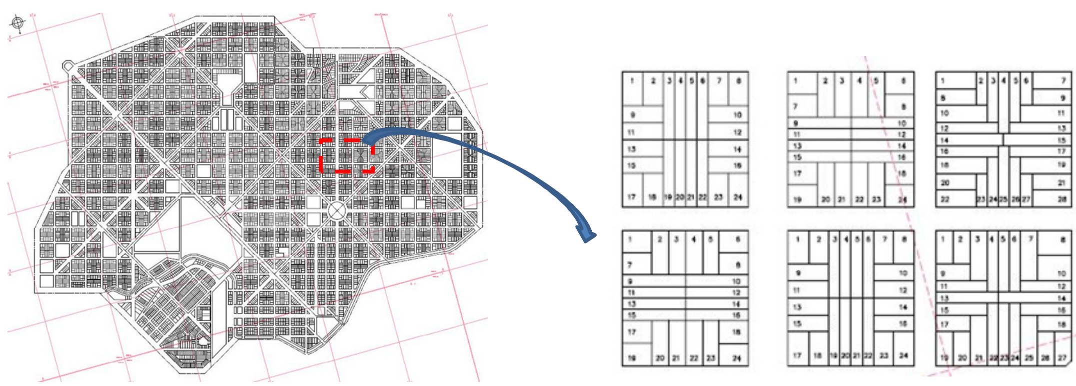


Figure 23 - Original city plan and land subdivisions.
Source: Online Digital Database (PBH, 2014)

From 1920s on, the city land use regulations provided specific criteria for vertical construction. However, high-rise commercial buildings effectively started to be built in the early 1940's due to a combination of aspects of the ongoing land use regulation permission with engineering knowledge and technological access (ex. vertical transportation).

Regarding the urban zone, in 1922 the land use regulation established a relationship between building height and street width. Buildings up to 25 floors were allowed in 25m wide streets and up to 35 floors in 35m wide Avenues. In 1930, the land use regulation introduced a height restriction related to perimeter distance based upon sky view angles (AGUIAR, 2004; NORONHA, 1999).

In 1933, a new Land Use Regulation subdivided the city into commercial, residential, suburban and rural zones. The building coverage ratio known as *Taxa de Ocupação* (TO), which regulates the maximum portion of the land that can be built upon, was introduced and set to 100% for commercial buildings in the commercial zone. Additionally, the new regulation removed height restrictions in the commercial zone, encouraging the emergence of high-rise commercial buildings (AGUIAR, 2004; NORONHA, 1999).

Yet in 1940, a Building Construction Code (PBH, 1940) defined general and specific rules to be followed during building design, construction, maintenance and use. From a building design point of view, this code set rules to minimum room areas, daylight and ventilation minimum fenestration areas. Natural ventilation was required in every room and a minimum window-to-floor area ratio was prescribed to ensure ventilation and daylight. Another daylighting design parameter was a room depth limit, introduced to allow a minimum access to daylight. For a room to be considered illuminated it should have a depth of no more than 2.5 its internal height. Regarding the high-rise commercial buildings, this resulted in the emergence of light courts and the use of E, H and U plan forms to optimize natural light in the buildings located in the commercial central zone. This construction code remained effective until the 2009 when it was replaced by a new Building Code (PBH, 2009), although for those mentioned ventilation and daylighting topics there were no conceptual changes.

The 50's, 60's and 70's decades were marked by sharp population growth and consequently an intense process of densification of the city (AGUIAR, 2004). Most of the high-rise commercial buildings built during those decades are located in the commercial central zone, in response to the land use legislation intention of transforming this area into a place of attraction for trade and urban services. Figure 24 illustrates the location of the high-rise commercial buildings from the 40's, 50's, 60's and 70's in the context of the city.

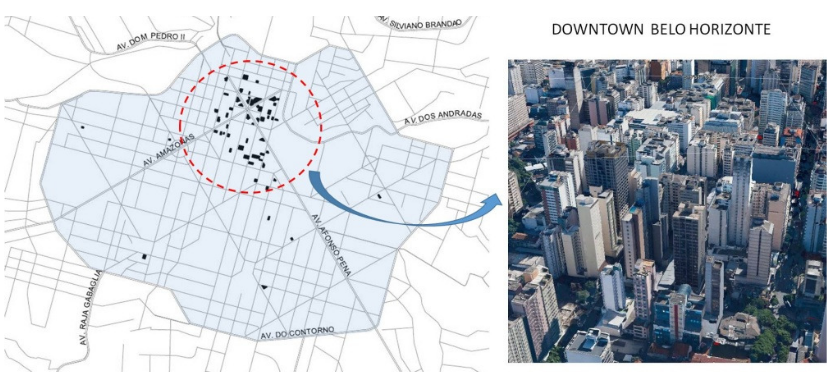


Figure 24 - 40's, 50's, 60's and 70's high-rise commercial building locations.

Source: Author's own elaboration based on the SMAPU/PBH database and Google Earth / Street View

In 1974, the creation of the Metropolitan Planning Authority (PLAMBEL) allowed the development of global urban studies which resulted in the approval in 1976 of the Law of Use and Land Use of Belo Horizonte - LUOS (PBH, 1976). The LUOS/76 established a regimented use of the urban space for the city. Thus, the permitted uses were defined by zones (residential, commercial, industrial and institutional) and occupation by settlement models. LUOS/76 was revised four times and each revision will be referred as LUOS/85, LUOS/96, LUOS/2000 and LUOS/2010 in this text.

Among the land use parameters established in the LUOS/76, three parameters are noted to affect building typology and consequently the street canyons formed by those buildings: a land utilization coefficient (CA), a building coverage ratio (TO) and a perimeter distance requirement (R). The coefficient CA determines the amount of floor space which would be allowed on that land (example: if a CA is defined as 8.0, means that 1m² of land allowed 8m² of floor space). In other words, a high CA coefficient means zone densification through vertical constructions. The R parameter is divided in Frontal (RF), Back (RB) and Lateral (RL) and means the minimum distance to be kept from the Frontal, Back and Lateral plot borders respectively. TO as explained earlier in this study is related to the maximum portion of the land that can be built upon. R and TO parameters are observed to be related to daylight and natural ventilation access. Figure 25 illustrates the developable volume allowed in the commercial central zone of the city based on the LUOS/76.

CA		8.0
TO	Ground Floor, 2°, 3°	100%
	4° Floor on	50%
RL	Blind Facade	0
	Regular Facade	1.5
RB	3° Floor on	5.0
RF	Ground Floor	4.0
	2°, 3° Floors	0
	4° Floor on	4.0

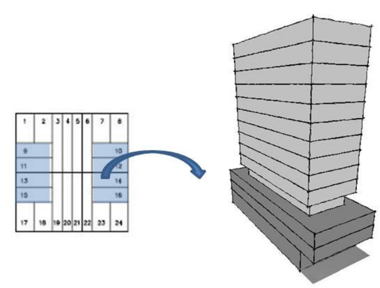


Figure 25 - Example of developable volume allowed in central area under LUOS/76 land use parameters for high-rise commercial buildings in zone ZC6. Example based on an original plot subdivision of 15x40m

Source: Author's own elaboration

The LUOS/85 (PBH, 1985) added more types of zoning such as Special Sectors (SE) and provided more detail on the end use categories. Generally, the CA, TO and R parameters related to commercial zoning remained unchanged. From the commercial building perspective, the LUOS/76 and LUOS/85 promoted the spread of the vertical construction inside the original city plan, especially along major avenues as shown in Figure 26.

Figure 26 - 80's, 90's high-rise commercial building locations

Source: Author's own elaboration based on the SMAPU/PBH database

The LUOS/96 (PBH, 1996) redefined the city zoning according to infrastructure availability, roads classification, environmental demands, historical, cultural and landscape preservation. In contrast with the previous legislation, the LUOS/96 allowed any end use in anywhere since end use activity was compatible to the road classification. Regarding high-rise commercial buildings, the major change occurred in the CA coefficient. The CA in the commercial central zoning and along major roads was reduced from 8 to 3, in an effort to stabilize and diminish densification. The R parameter in the LUOS/96 changed as well. The FR parameter for ground floors was now defined in relation to the road classification. RB and RL parameters previously fixed at 5m and 1.5m respectively were now related to building height. In general, the results were lower buildings and larger lateral and backside distances, meaning that vertical constructions would demand larger land areas. Figure 27 illustrates the developable volume allowed for commercial buildings based on the LUOS/96.

CA	3.0
TO	-
RL and RB	2.30 + $(H+12)/b$ Where H=building height and b = coefficient defined as 10 for central zoning and 4 elsewhere.
RF	Ground Floor defined as a relation to the road classification which means 4m for major roads and 3m for local roads. 2°, 3° Floors – no distance required 4° Floor on follows ground floor

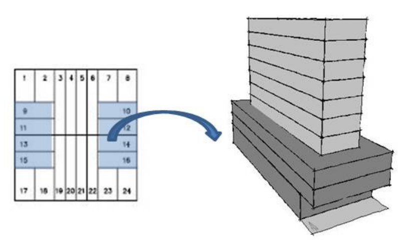


Figure 27 - Example of developable volume allowed for high-rise commercial buildings under LUOS/1996 land use parameters. Example based on an original plot subdivision (15x40m)

Source: Author's own elaboration

The LUOS/2000 (PBH, 2000) provided once more further detail on the end use categories and their negative impact across the city. For each negative impact a compensating measure should be introduced. In general, the CA and R parameters related to commercial end use in central area and major roads remained unchanged.

Although the legislation allowed commercial activity across the city, the high-rise commercial building remained linked to central commercial zones and major avenues. Major avenues were reinforced in the LUOS/96 and LUOS/2000 as a place of commercial activity.

The most significant change brought by LUOS/2010 (PBH, 2010) was a CA 10% reduction across the city. In simple terms, it kept the search for a balanced densification throughout the city. The LUOS/2010 is still in effect.

Figure 28 presents the timeline of land use regulations regarding the high-rise commercial building from Belo Horizonte.

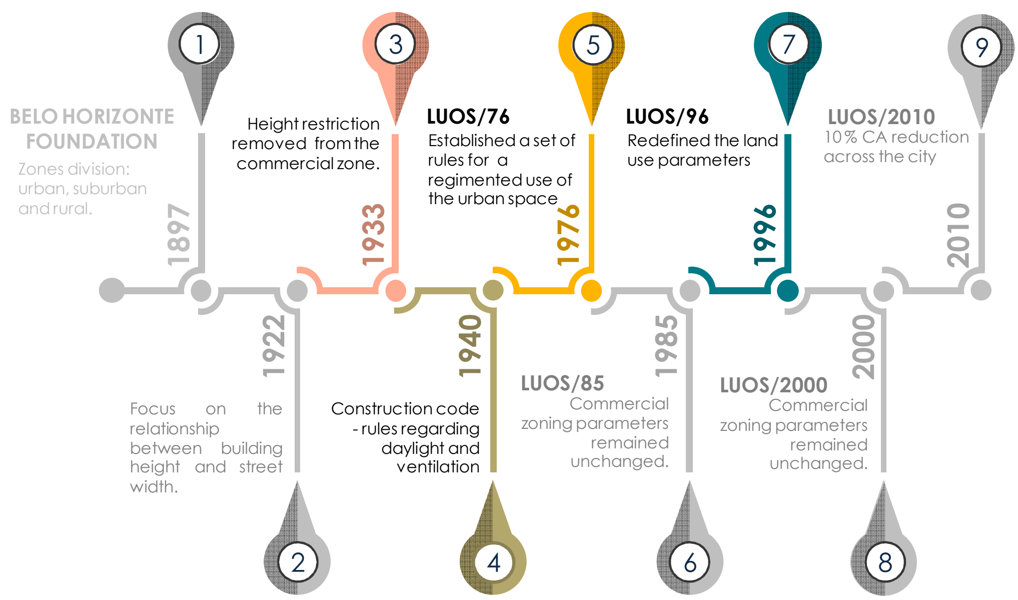


Figure 28 – Belo Horizonte's timeline of land use regulations

Source: Author's own elaboration

Summarizing the timeline of land use regulations in Belo Horizonte, two key points related to urban regulations were noted to influence the building typology and distribution across the city. Those were the introduction of the LUOS/76 and LUOS/96. The changes promoted by the LUOS/76 and LUOS/96 in the high-rise building volume and distribution over the city which led to different surrounding contexts were the starting points to propose the range of each building classification as illustrated in Figure 29. Three categories named *Class I, Class II* and *Class III* were identified and used to analyse the high-rise office building. The ones identified as *Class I* are related to buildings from the 40's, 50`s, 60`s and 70`s, the *Class II* are related to buildings from the 80`s and 90`s and the *Class III* are related to buildings from 2000's decades and on.

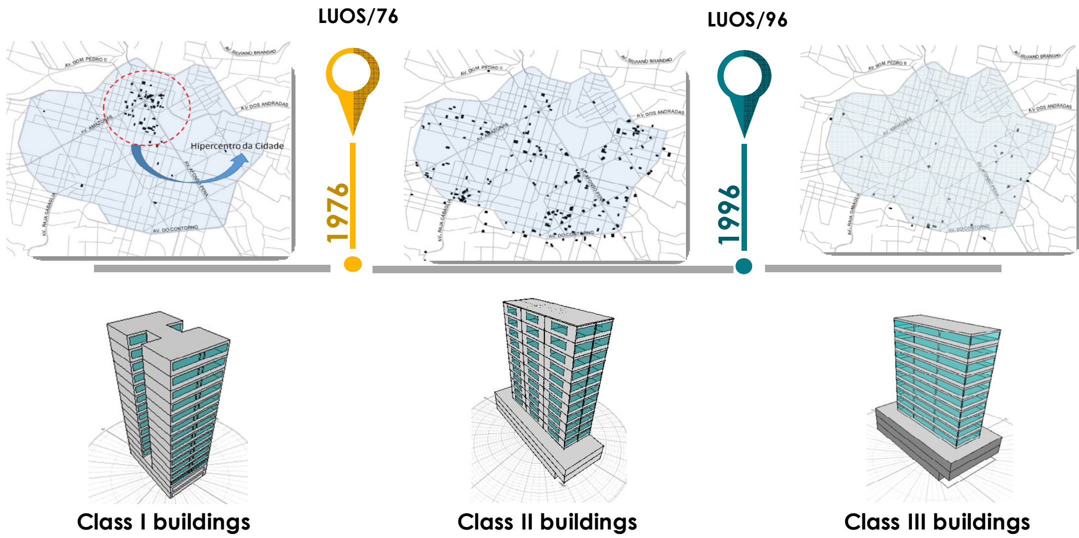


Figure 29 - Proposed range of building classification.

Source: Author's own elaboration

4.2.2 SMAPU/BH DATABASE ANALYSIS RESULTS

According to the SMAPU/PBH database, in 2011 Belo Horizonte city provided at about 4,577,000m^2 related to office floor spaces, from which approximately 20% represent the total commercial building stock. Most of the office floor spaces (approximately a 75% of the total area) are located inside or around the original city plan (Centro-Sul region), presenting evidences of the land use legislation intention of promoting the region as a place of attraction for trade and services as shown in Table 19. The overall area data is presented in Appendix E.

Table 19 – Office floor spaces per city regions and buildings height

	Office Building Area (m²)		
City Regions	**Up to 4 Floor**	**5 and 10 Floors**	**Over 10 Floors**
Centro-sul	468,543.18	1,111,558.84	2,464,147.15
Leste	231,867.76	32,356.46	40,015.76
Nordeste	41,214.85	43,560.27	1,484.00
Noroeste	173,781.52	45,286.49	3,855.45
Oeste	118,827.14	158,016.66	79,980.91
Venda-nova	14,989.74	2,278.46	0.00
Barreiro	46,780.99	30,422.95	13,684.26
Pampulha	147,968.91	38,405.71	10,999.69
Norte	25,160.06	4,327.01	0.00
Total	**776,858.15**	**1,291,710.85**	**2,508,514.22**

Source: Author's own elaboration based on the SMAPU/PBH database

Regarding office building heights, the SMAPU/PBH database indicates that approximately 17% of the total floor spaces are provided by buildings up to 4 floors, 28% by buildings between 5 and 10 floors, and 55% by buildings over 10 floors.

The age of the stock is shown in Figure 30. A significant expansion in the amount of office floor spaces can be seen from the 70's reaching its apex during the 90's years.

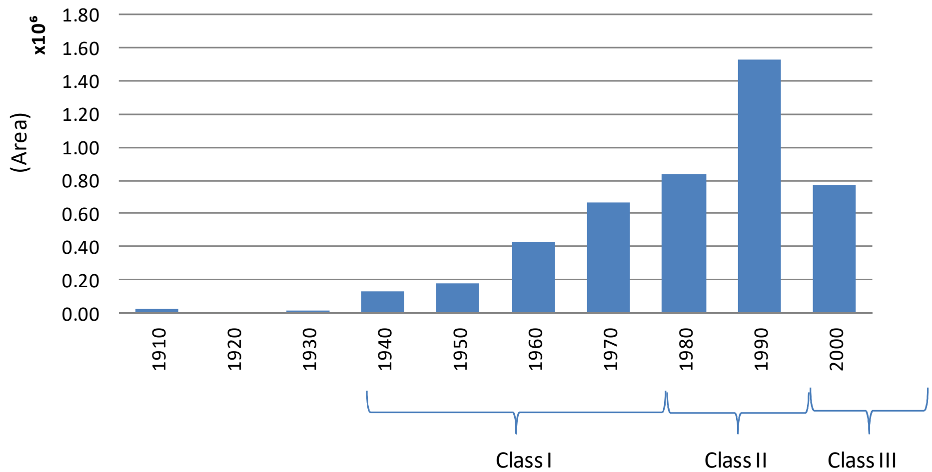


Figure 30 - Office floor spaces (m²) per Decade in Belo Horizonte

Source: Author's own elaboration based on the SMAPU/PBH database

Regarding high-rise office building areas and the proposed building classification, the database indicates the prevalence of the Class II buildings (52%), followed by the Class I buildings (27%) and the Class III buildings (21%) as shown in Figure 31. These areas were further used to scale up the energy consumption to the high-rise building stock.

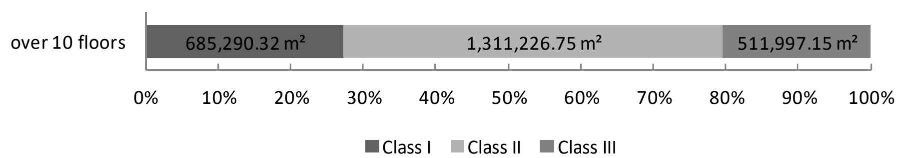


Figure 31 - High-rise office building area shares according to the building classification proposed

Source: Author's own elaboration based on the SMAPU/PBH database

Concerning high-rise office building size, buildings up to 5.000 m² are prevalent in Class I, II and III as shown in Figure 32. In the Class I buildings they represent 39% of the total share whereas in the Class II and III they represent 41% and 37% respectively.

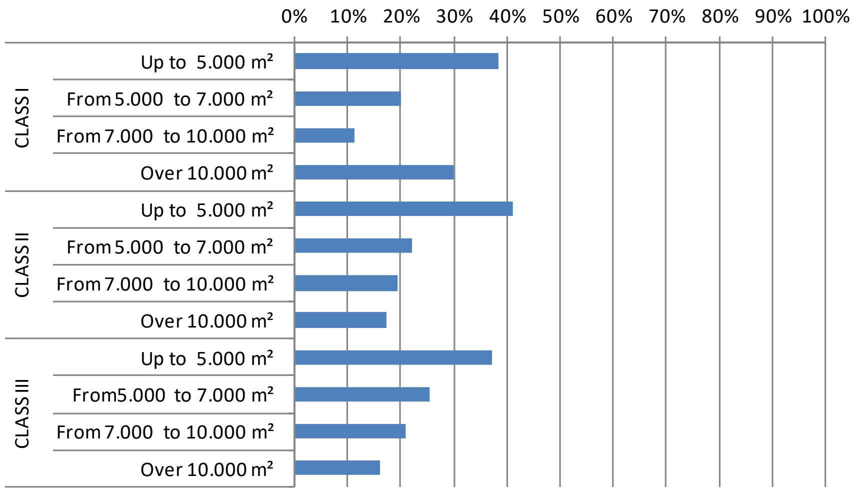


Figure 32 – High-rise building size per Class buildings

Source: Author's own elaboration based on the SMAPU/PBH database

In terms of internal high-rise office building concept, the SMAPU/PBH database also indicates that cellular office floor spaces are prevalent in buildings from the Class I and II while open office floor spaces are prevalent in buildings from the Class III as shown in Figure 33.

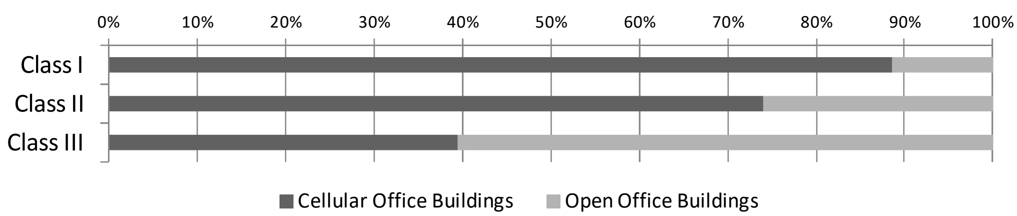


Figure 33 - Cellular and Open Buildings per Class buildings

Source: Author's own elaboration based on the SMAPU/PBH database

4.2.3 FIELD SURVEY ANALYSIS RESULTS

From the SMAPU/BH database, 298 buildings were analysed using the Adapted Morphological Diagrams (AMDs). Figure 34 shows the high-rise office buildings sample mapped in the city.

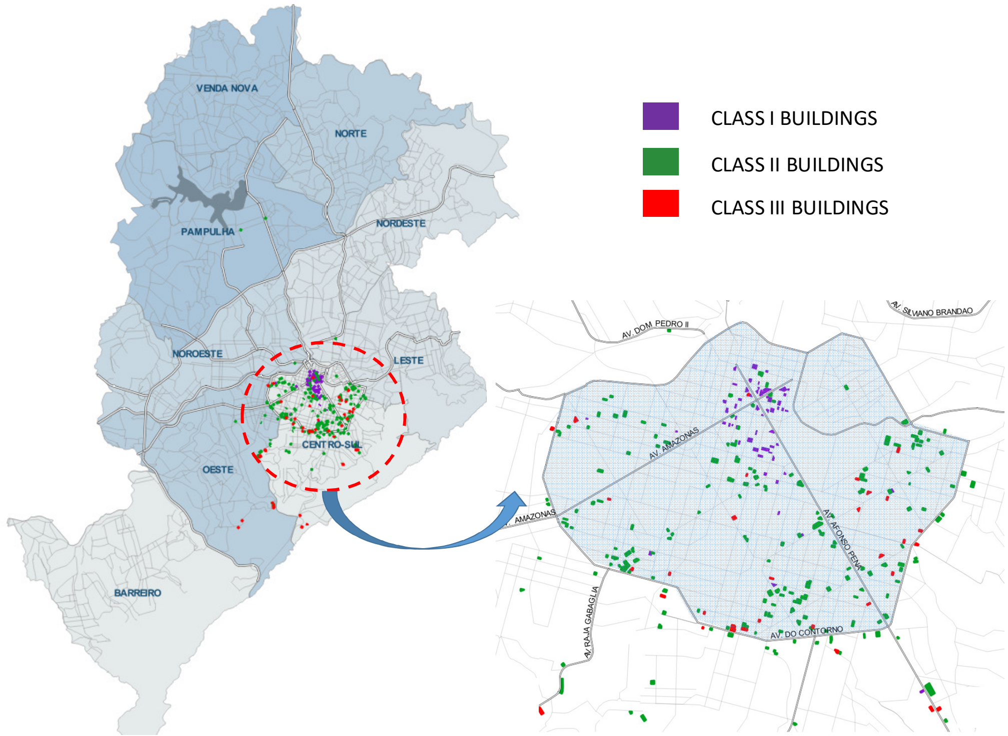


Figure 34 – Sample buildings location

Source: Author's own elaboration

A summary of the prevalent attributes of Class I, II and III buildings according to the AMDs is shown in Table 20. Detailed information about the results of the AMDs analysis is presented in Appendix F.

Table 20 - Prevalent attributes of the buildings Class I, II and III according to AMDs

		Class I	Class II	Class III
Street Width		between 10 to 20 meters	between 10 to 20 meters	between 10 to 20 meters
Sky View		up to 30°	between 30° to 60°	between 30° to 60°
Facade Reflectance		Medium	Front facade mixed colours, other facades medium	mixed colours – all facade
Roof Reflectance		Medium	Medium	Medium
Glazing colour		Transparent	Brown	Brown/green
Roof Characteristics		Single/multi plane roof	Single/multi plane roof	Concrete slab
Solar Orientation		no prevalent orientation	no prevalent orientation	no prevalent orientation
Number of Floors		15 floors	15 floors	13 floors
Building Shape		rectangular/light court	rectangular	rectangular
Ground floor characteristic		street store only	Street store/parking floor	Street store /parking floor
Window to wall ratio	**Front**	50%	50%	50%
	Left	blind	25%	50%
	Right	blind	25%	50%
	Back	50%	50%	50%
Window-facade distribution		Non uniform	Non uniform	Non uniform
Daylighting control		Internal curtain/blinds/venetian	Internal curtain/blinds/venetian	Internal curtain/blinds/venetian
Environmental conditioning strategy		Split/window Equipment	Split/window Equipment	Split/window Equipment /central air conditioning (Fain-coils/chillers)

Source: Author's own elaboration

According to the AMDs analysis, in terms of street width, 99% of the total buildings are located on streets wider than 10 meters. A closer view shows that 72% of the Class I buildings, 62% of the Class II buildings and 58% of the Class III buildings are located on streets between 10 and 20m. This situation historically reflects the city land use regulation that links commercial buildings to major traffic avenues.

Analysing the sky view parameter, the AMDs indicate that Class I buildings are located on vertical density areas (downtown area), while Class II and III buildings are spread along the city and located in a mid-rise urban context. This information was used to characterize the urban context of each building Class during the simulations.

In terms of building facade colours, Class II and III buildings display a diversity of materials and reflectance regarding the front facade. All facades from Class I buildings and the other facades from Class II and III buildings display medium colours, where due to the course of aging white/cream colour deteriorates.

Concerning roof reflectance, Class I, II and III buildings display medium colours, in most of the cases related to grey colours deteriorated by environmental pollution. The prevalent glazing colour is transparent for Class I buildings (84%), brown for Class II buildings (74%) and green for Class III buildings (52%).

In terms of roof system characteristics, single or multi plane roofs are prevalent in Class I buildings (70%) and Class II buildings (58%), whereas concrete flat slab is prevalent in Class III buildings (62%).

Regarding solar orientations, there is no prevalent building orientation. The average height in Class I and II buildings are 15 floors, while in Class III buildings are 13 floors. This difference can be understood as the influence of the CA parameter reduction in the building volume from 1996's and on.

The most common shape found in the sample is the rectangular one. In Class I buildings the rectangular shape is also associated with light courts. The heights of the surrounding buildings together with the lighting criteria established by the Building Construction Code/1940 are noted to be responsible for the presence of the light court in Class I buildings. The rectangular shape is frequent in 67% of the total Class II buildings and 69% of the total Class III buildings. In general, the predominance of the rectangular shape can be understood as a result of the renovation building process over an existing area where the original plot subdivision still remains.

Regarding ground floor features, 73% share of the total buildings use the ground floor for commercial proposals. In Class I buildings, less than 10% of the buildings present parking spaces in the 1^{st} and 2^{nd} floors. Differently, in Class II and III buildings approximately 74% and 68% of the buildings respectively present parking spaces located on the 1^{st} and 2^{nd} floors. Other 1st and 2nd floor characteristic is that they occupy a 100% of the plot perimeters. Ground, 1st and 2nd floor prevalent shapes are known to be linked to the land use parameters from the LUOS/76 on.

In terms of Wall to Window Ratio (WWR), the prevalent front and back facades account for 50% of the WWR in the Class I, II and III buildings. The prevalent lateral facades are considered blind in Class I buildings, in Class II buildings they account for 25% of WWR and in Class III buildings they account for 50% of the WWR. Increasing in glazing percentages is noted to be a tendency for contemporaneous buildings in the city.

Regarding daylighting control, curtains/blinds placed inside office rooms are the most common daylighting control found in Class I, II and III buildings. Daylight control components such as brises-soleil are found in 20% of the Class I buildings and in less than 5% in the Class II and III buildings.

In terms of air conditioning, 98% of the buildings present operable windows which enable natural ventilation. Window or split systems occur in 92% share of the total Class I buildings, 84% of the Class II buildings and 60% of the Class III buildings. Class III buildings present a significant increase in the use of central air conditioning systems (40% of the total share) and together with the concept of open office spaces they could be considered a trend in terms of office development in the context of Belo Horizonte. This tendency can be confirmed analysing recent commercial building developments found in the city (PERUCCI, 2016).

The identification of the window/split systems and the central air conditioning systems was based on images collected through the Google Earth® as shown in Figure 35. Regarding the central air conditioning systems, the prevalent system identified was the air condensed chillers/fain coil system. This identification was supported by an engineering specialist.

Figure 35 – Example of facade and roof images used to identify air conditioning systems

Source: Author's own elaboration based on Google earth

Continuing the field survey and in order to gather information to create the energy models related to cellular office buildings (Class I and II buildings), 60 office rooms were visited and the results presented in Figure 36.

The predominant artificial lighting system is the linear fluorescent lamp (78%), followed by compact fluorescent lamp 15% and LED lamp 7%. The data also indicates that among the tubular lamp systems the 40/20W lamp power (62%) is dominant, followed by 32 / 16W (30%) and the 28 / 14W (8%).

Apart of the *in loco* visit, a lighting supplier was consulted in order to obtain information regarding the lighting system used in 2000's buildings. The answer suggests the prevalence of linear tubular fluorescent 28/14W and a growth tendency in the use of LED technology (NOVAES, 2016).

In terms of lighting routine, in 47% of the work spaces visited there were no lighting circuit subdivision, meaning that the whole lighting system remains ON during room operation. The remaining 53% shows lighting circuit subdivision but no integration with natural lighting.

The survey also indicates the prevalence of mixed mode systems. In 82% of the office rooms visited, users only switch the air conditioning ON when they feel the room thermally uncomfortable. The predominant air conditioning system is the window equipment with 58%, followed by the Split equipment with 25%. Among those conditioning systems the predominant energy efficiency classes according to the Brazilian Labelling Program are B and C respectively.

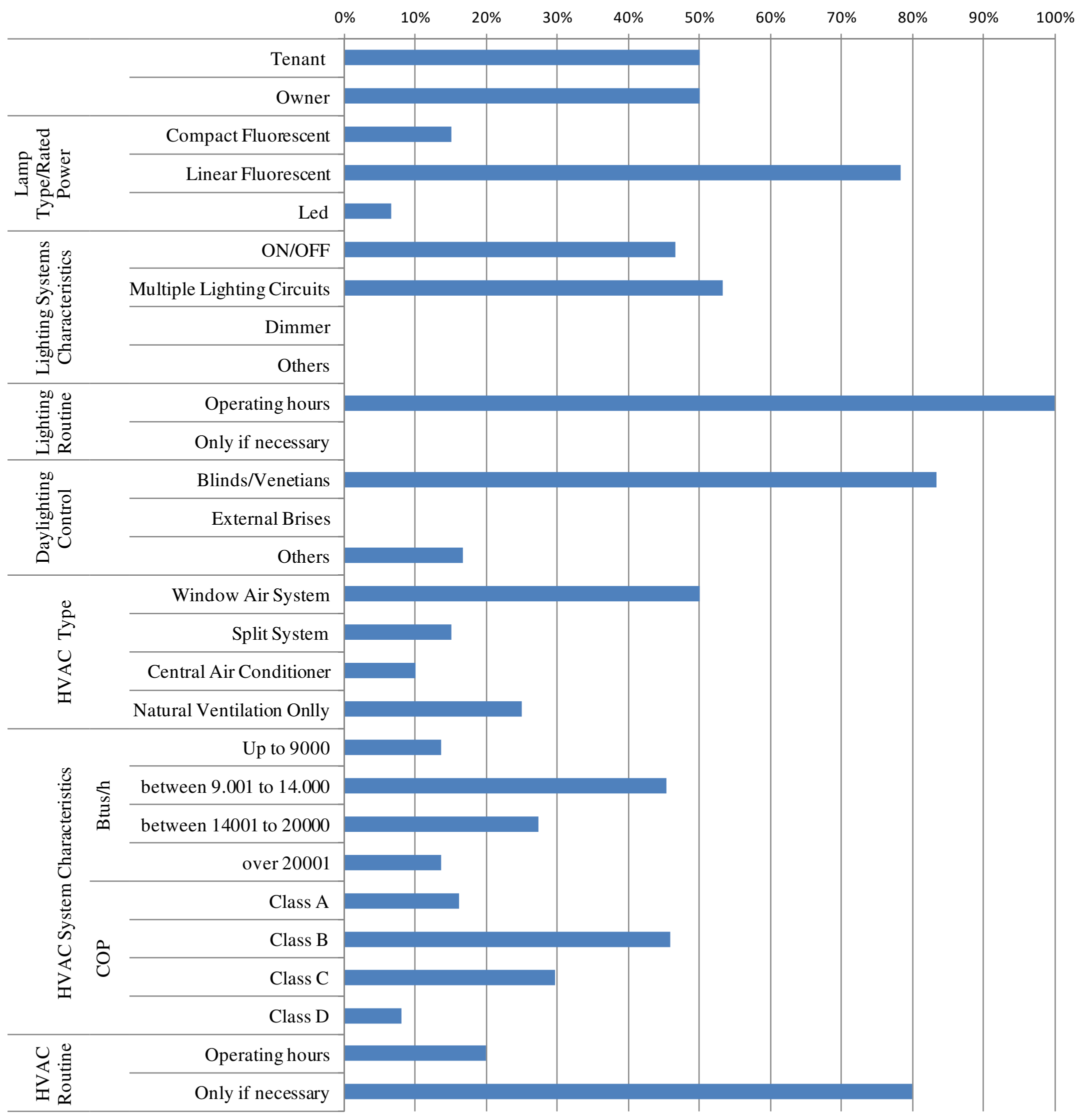


Figure 36 - Summary of *In loco* visit results

Source: Author's own elaboration

Completing the field study, a sample of 19 floor plans regarding Class I, II and III buildings was studied in terms of internal floor space distribution. The space distribution can be summarized as shown in Table 21. Approximately 15% of the plan floor is related to vertical and horizontal distribution (stairs, elevators, and halls), 5% to technical support areas and

80% to workspaces. Those dimensional proportions were used to describe plan floor on the archetype energy models.

Table 21 – Summary of floor plan distribution results

	Vertical distribution	Horizontal Distribution	Technical area	Working area
Sample 01	9%	9%	0%	83%
Sample 02	15%	7%	4%	75%
Sample 03	6%	4%	2%	88%
Sample 04	8%	11%	10%	71%
Sample 05	13%	8%	0%	80%
Sample 06	5%	5%	8%	82%
Sample 07	9%	3%	1%	88%
Sample 08	11%	10%	4%	75%
Sample 09	10%	12%	8%	70%
Sample 10	4%	3%	2%	87%
Sample 11	9%	8%	4%	79%
Sample 12	12%	4%	6%	82%
Sample 13	6%	4%	6%	83%
Sample 14	9%	7%	9%	74%
Sample 15	7%	14%	6%	73%
Sample 16	4%	3%	5%	88%
Sample 17	9%	4%	6%	82%
Sample 18	8%	3%	6%	82%
Sample 19	9%	6%	7%	78%
mean value	8%	7%	5%	80%
standard deviation	3%	3%	3%	6%

Source: Author's own elaboration

4.2.4 DYNNAMIC ARCHETYPE MODEL SIMULATION RESULTS

The archetype energy models were created gathering information from the results of the land use legislation, SMAPU/BH database and field survey. The general idea was to obtain one representative archetype energy model of each building Class. As explained earlier, the archetype energy model from the Class I buildings was named Archetype I, the archetype energy model from the Class II buildings was named Archetype II. However, to better characterize Class III buildings there was a need to create two archetype energy models: Archetype III_A and Archetype III_B.

In this study, it was found that a correlation between the internal building concept and air conditioning type can be established. Window and Split systems are usually associated to compartmented spaces whereas central air conditioning systems are associated to open office spaces.

In Class I and II buildings, it was possible to visualize this correlation through the comparison between the prevalent window/split systems from the AMD's analysis and the prevalent cellular buildings from the SMAPU/PBH database as shown in Figure 37.

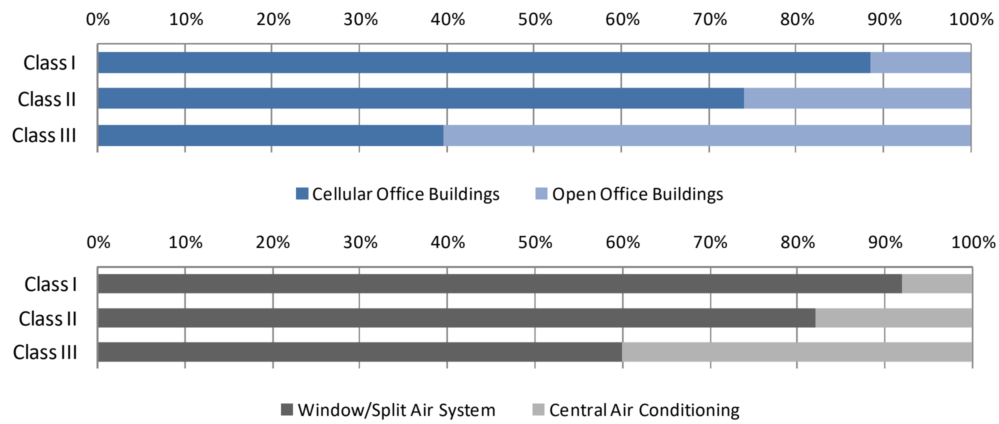


Figure 37 - Comparison between internal distribution concept (SMAPU/PBH) and air conditioning systems (AMDs)

Source: Author's own elaboration

This correlation was used to describe archetype energy models related to Class I and II buildings as mixed mode buildings, in other words a building that combines natural ventilation and window/split air conditioning. Differently, in Class III buildings this correlation was not straightforward. As presented in Figure 37 a 60% share of window/split systems didn't find a correspondence in the 40% share of the cellular office buildings. That suggests that only 40% of the Class III buildings could be described, in the context of this case study, as mixed mode buildings which led to the fact that the remaining 20% of window/split systems seemed to occur in open office buildings. In doing so, it was considered that in those open office buildings the window/split system operational routine was similar to the central air conditioning operational routine.

This was the starting point to creating the Archetype III_A and Archetype III_B and to assign a weight factor for each archetype energy model related to the Class III buildings. The Archetype III _A is representative of Class III cellular buildings and the Archetype III_B is representative of Class III open office buildings. The Archetype III_A weight factor assigned was 0.4 (representative of 40% of the building class) whereas the Archetype III_B weight factor was 0.6.

Tables 22 and 23 summarize all key attributes related to the Archetype I, II, III_A and III_B. Detailed information on the results from the AMDs analysis for the Archetype III_A and III_B used to characterize some attributes are presented in Appendix G. Archetype III_A LPD and COP value were assigned equal to Archetype II values due to the building systems and floor plan concept similarities.

Table 22 - Key attributes of the building envelope and physics

	Archetype I	Archetype II	Archetype III _ A	Archetype III_B
Floor plan concept	cellular office	cellular office	cellular office	open office
Floor plan dimension (m^2)	300	300	300	300
Building shape	rectangular light court	rectangular	rectangular	rectangular
Number of floors	15	15	13	13
Surrounding built environment	high-rise buildings	mid-rise buildings	mid-rise buildings	mid-rise buildings
WWR (Front/Back Facade)	50%	50%	50%	50%
WWR (Lateral Facade)	Blind (0%)	25%	50%	50%
Glass color	transparent	brown	brown	green
Glass thickness	6mm	6mm	6mm	6mm
Glass SHGC	0.81	0.62	0.62	0.56
External wall U - ($W/m^2.K$)	1.85	1.85	1.85	1.85
Internal wall U - ($W/m^2.K$)	2.39	2.39	2.39	2.39
Roof U - ($W/m^2.K$)	2.06	2.06	2.22	2.22
Wall Absorptance	0.4	0.4	0.5	0.5
Roof Absorptance	0.4	0.4	0.5	0.5

Source: Author's own elaboration

Table 23 - Key attributes of the building systems and operational routines

	Archetype I	Archetype II	Archetype III _ A	Archetype III_B
Lighting level required (lux)	500	500	500	500
Light power density -LPD (W/ m²)	19.04	19.04	19.04	10.5
Office devices density (W/ m²)	12	12	12	14
Air conditioning type	Direct expansion (window)	Direct expansion (window)	Direct expansion (window)	fain coil, water chiller, air cooler condenser
Air conditioning coefficient of performance -COP, (w/w)	2.94	2.94	2.94	3.20
Cooling Setpoint (°C)	25	25	25	25
Area Conditioned (%)	100% of the office rooms, no horizontal distribution included	100% of the office rooms, no horizontal distribution included	100% of the office rooms, no horizontal distribution included	100% of the office rooms, horizontal distribution included
Outdoor Air flow rate per person (L/s.person)	3.8	3.8	3.8	3.8
Space heating (yes/no)	No	No	No	No
Population (floor area per person)	7 m²	7 m²	7 m²	7 m²
Operational day time (hours)	10 (8h to18h)	10 (8h to18h)	10 (8h to18h)	14 (6h to 20h)
Lighting schedule (operating hours/year)	2500	2500	2500	3200
Office devices schedule (operating hours/year)	2500	2500	2500	2750
Air conditioning schedule (hours)	Mixed mode system schedule	Mixed mode system schedule	Mixed mode system schedule	14 (6h-20h)

Source: Author's own elaboration

Figures 38, 39 and 40 present information of the archetype geometry (a), the urban context (b), the site plan (c), Lateral and Front Facade views (d) and the floor plan zone subdivision simulated for Archetypes I, II and III_A and III_B respectively.

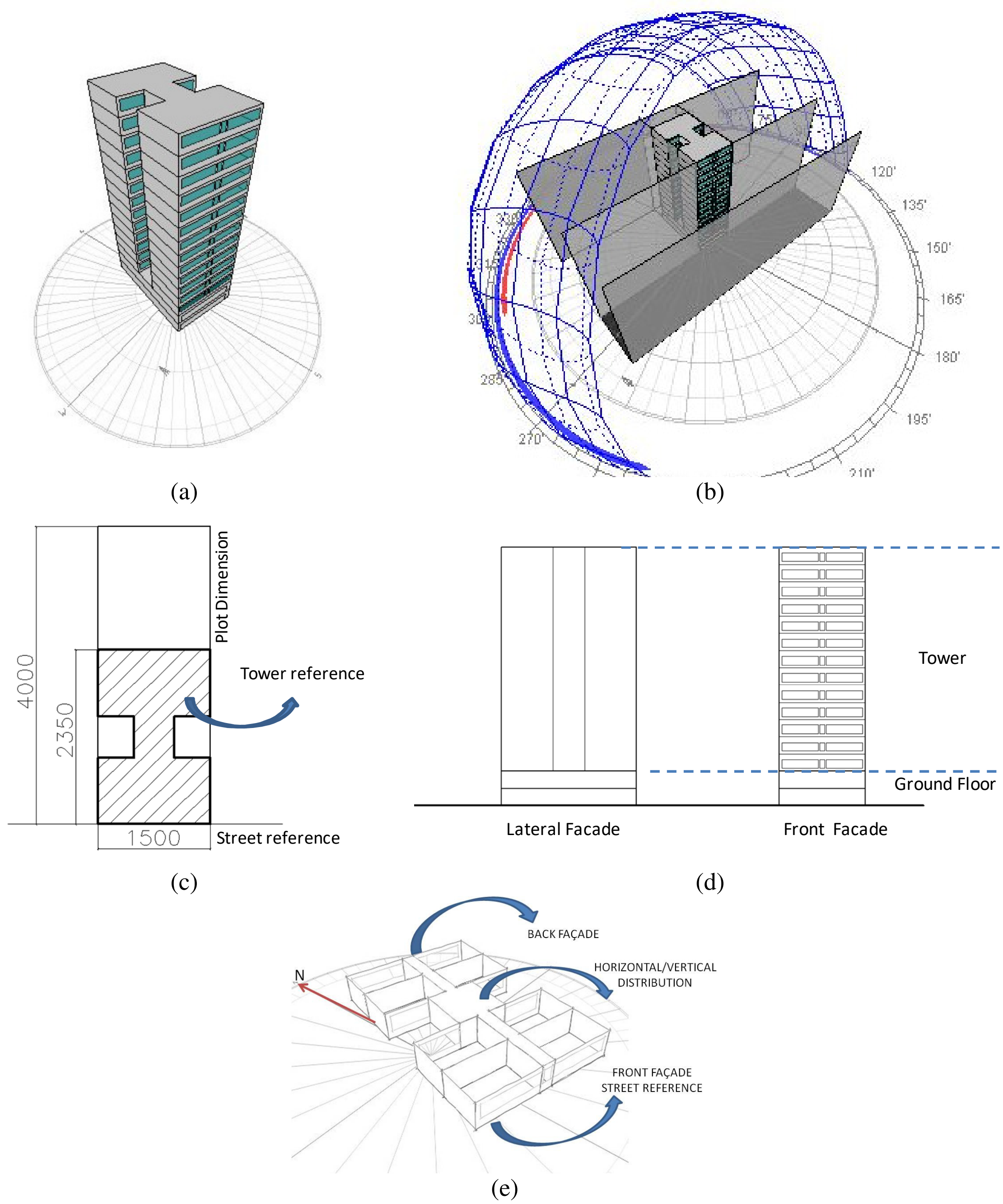


Figure 38 – (a) Archetype I geometry, (b) Urban Context, (c) Site plan, (d) Lateral and Front Facade views, (e) Floor Subdivision

Source: Author's own elaboration

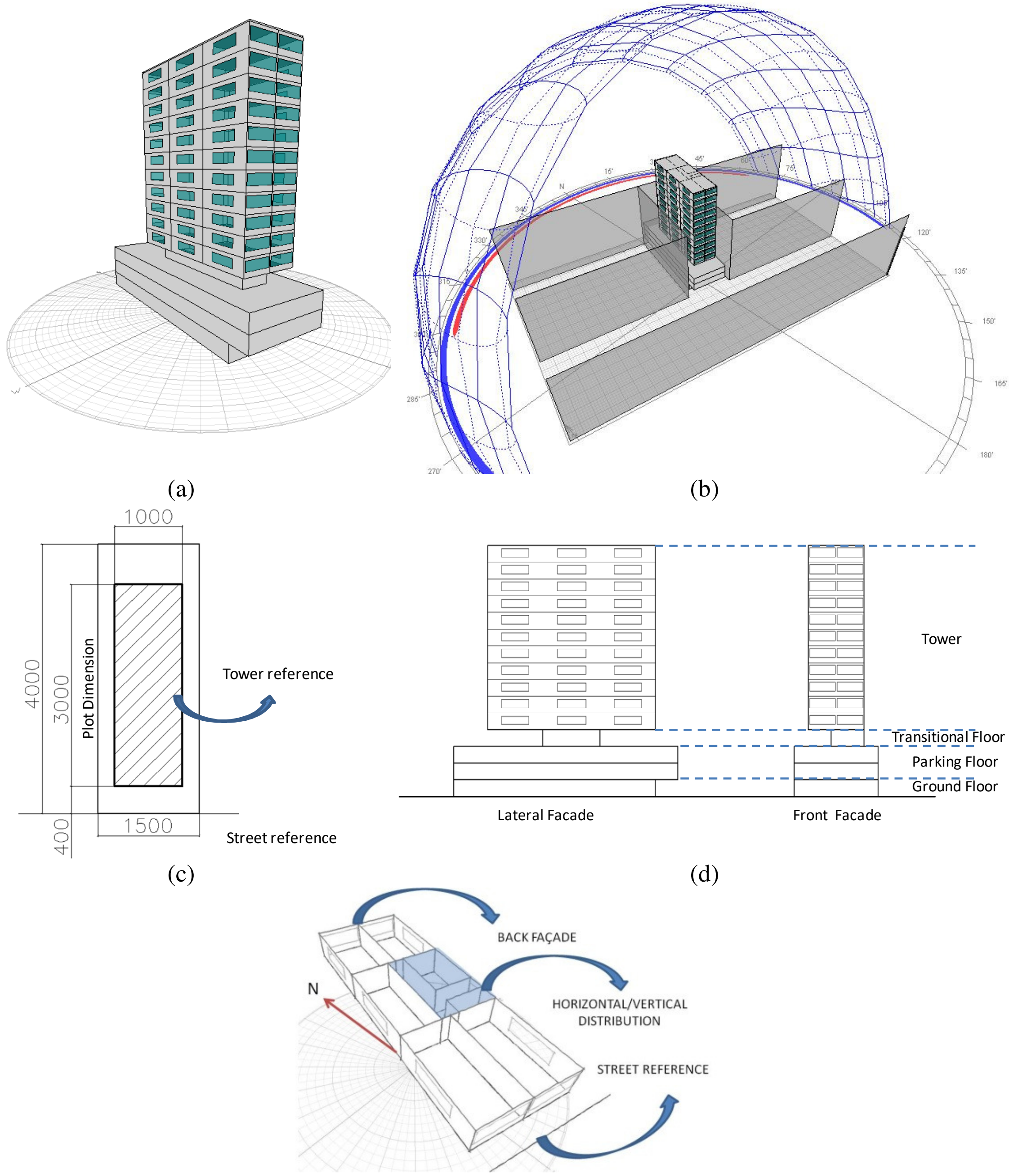


Figure 39 - (a) Archetype II geometry, (b) Urban Context, (c) Site plan, (d) Lateral and Front Facade references, (e) Floor Subdivision

Source: Author's own elaboration

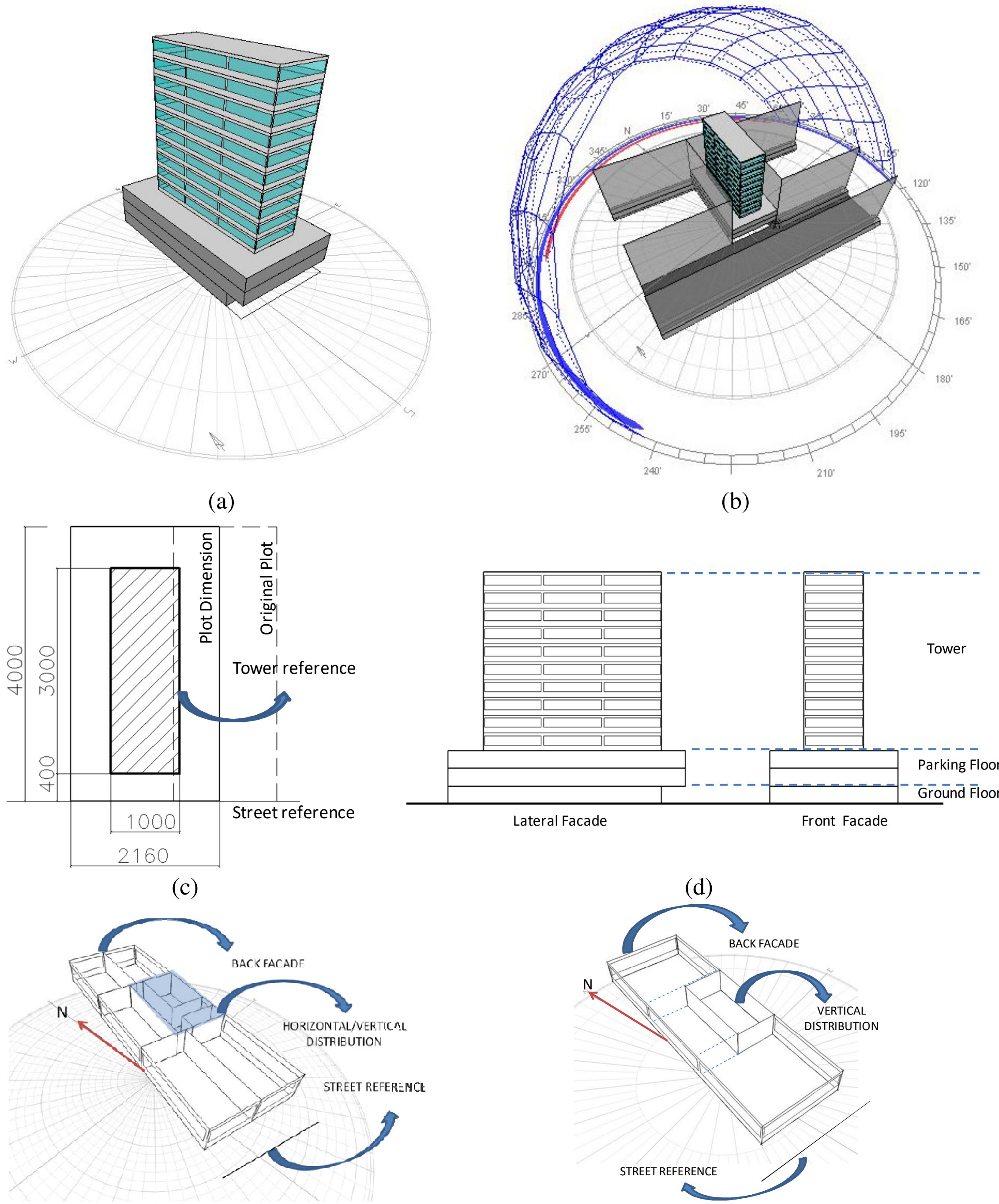


Figure 40 - (a) Archetype III_A and III_B geometry, (b) Urban Context, (c) Site plan, (d) Lateral and Front Facade references, (e) Floor Subdivision Archetype III_A, (f) Floor Subdivision Archetype III_B

Source: Author's own elaboration

An overview of Energy Use Intensity (EUI) indicates substantial differences between office floor spaces located within different archetypes. The EUI of Archetype I model is about 90.1 kWh/m²/year, the Archetype II model is about 83.1 kWh/m²/year, while in the Archetype

III_A and III_B models are about 92.6 and 141.9 kWh/m²/year respectively as shown in Figure 41.

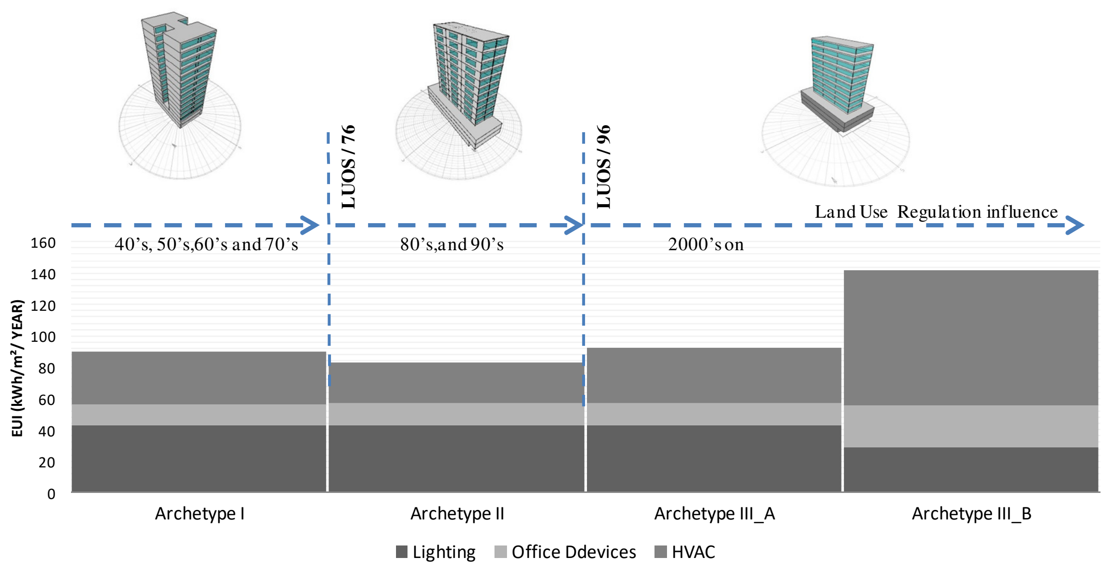


Figure 41 - EUI (kWh/ m²/year) per Archetype

Source: Author's own elaboration

Comparing EUI between archetypes, the Archetype III_B is about 54% more energetically intense than the Archetype III_A, 70% more energetically intense than the Archetype II and about 57% more energetically intense than the Archetype I; suggesting a growth tendency of energy consumption for forthcoming buildings. In this context, despite of the better performance of lighting (LPD) and HVAC (COP coefficient) systems, Archetype III_B is noted to consume more energy due to the intensive use of central air conditioning which is related to the open office internal concept.

The EUI difference among archetypes is noted to be mainly related to the electric energy consumption of the HVAC system as shown in Figures 41 and 42. In Archetype I, HVAC electric energy consumption corresponds to 37% of the overall EUI, in Archetype II to 31%, in Archetype III_A to 38% and in Archetype III_B to 60%. The natural ventilation strategy adopted in Archetypes I, II and III_A (mixed mode systems with control schedules based on thermal comfort) is observed to reduce the HVAC use and consequently air conditioning energy consumption, which would explain low EUI related to HVAC on these archetypes.

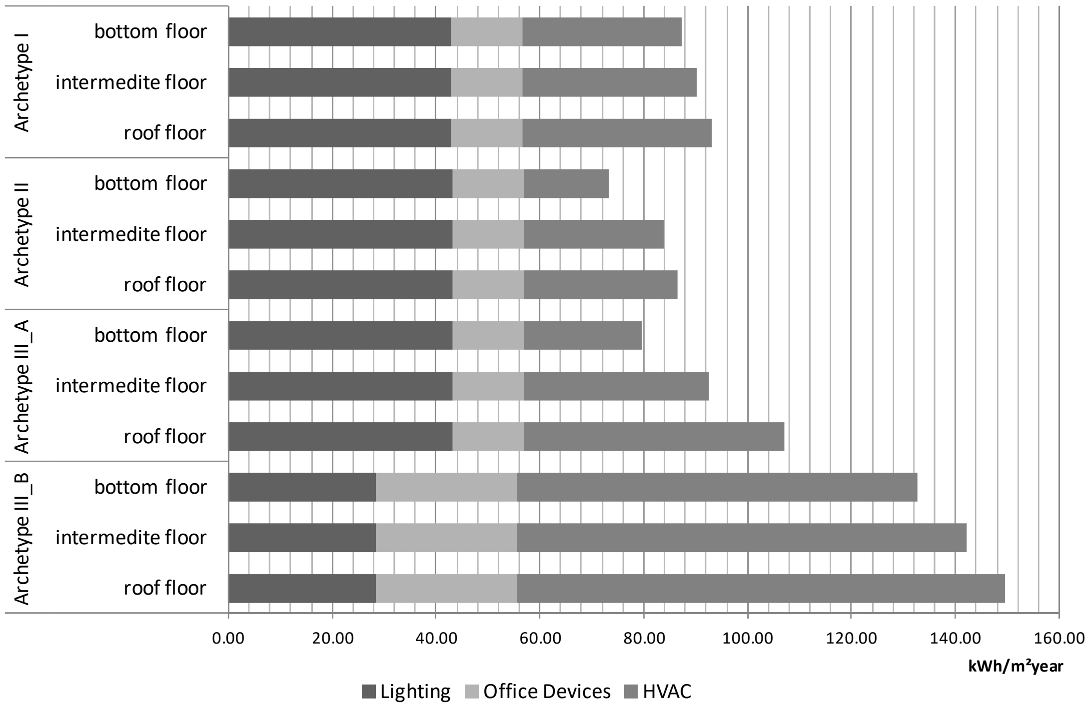


Figure 42 - EUI (kWh/ m²/year) per floor

Source: Author's own elaboration

Among those mixed mode buildings (Archetypes I, II and III_A) there are also thermal heat loads differences. The differences are supposed to be related to:

- The glazing system - there are value differences regarding the SHGC and WWR among archetypes;
- Building geometry - the Archetype I geometry differs from the other archetypes especially on front and back facade dimension providing to Archetype I greater glazing areas on those facades and Archetype II differs from the others due to the existence of a transitional floor between the parking floor and the tower (see Figure 39 item "c");
- Number of windows per zone - Archetypes II and III_A present zones with more than one window; while Archetype I presents zone with only one window.
- The urban canyons - there are surround context differences related to the height and perimeter distance in Archetypes I, II and III_A.

Analysing EUI in terms of floor level, the simulations indicated that the EUI varies according to the floor level as shown in Figure 42. In all archetypes, the roof floor presents the higher EUI, followed by the intermediate floor and then by the bottom floor. The EUI difference between roof and bottom floor is about 7% in Archetype I, 15% in Archetypes II, 25% in Archetype III_A and 11% in Archetype III_B.

Analysing thermal loads, the non-uniform solar access is the main explanation for EUI differences among floors related to a same archetype. As examples Figures 43, 44 and 45, 46 present the total heat gain rate through windows, internal and external surfaces of a # 5 zone positioned on the roof and the bottom floor of the Archetype II and III_A respectively. The simulated day was a typical summer day, corresponding to 21/02 in the Belo Horizonte's climate file. The simulation presented was the 15º North Orientation (to identify zone number and orientation see Appendix D).

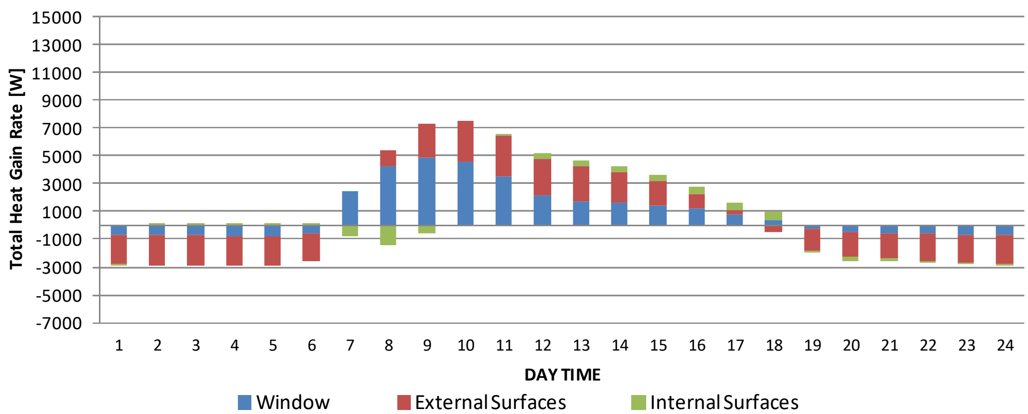


Figure 43 - Roof floor room surfaces total heat gain rate - # 5 zone, 15º North Orientation, Archetype II

Source: Author's own elaboration

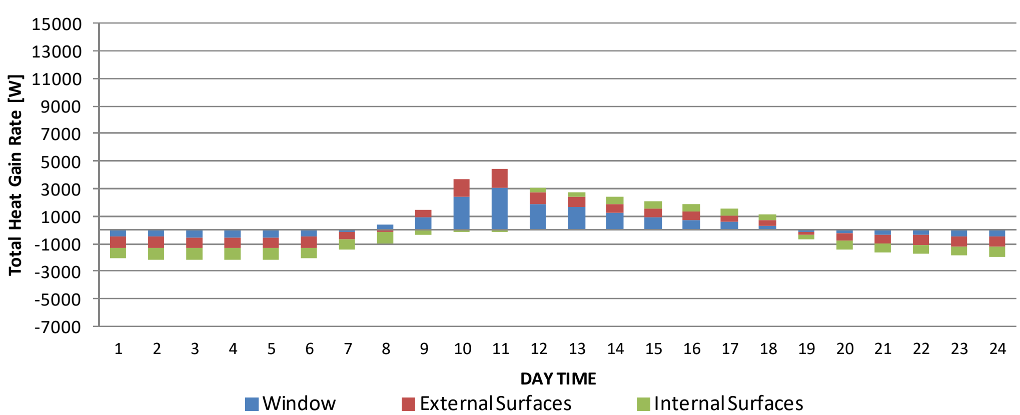


Figure 44 - Bottom floor room surfaces total heat gain rate - # 5 zone, 15º North Orientation, Archetype II

Source: Author's own elaboration

According to Figures 43 and 44 related to Archetype II, it is possible to identify during operational time a sharp influence of the non-uniform solar radiation on the windows and external surface heat gain rates. Regarding the windows, the non-uniform solar radiation is caused by the shading effect of the urban canyon on the bottom floor. Regarding the external surfaces, the difference is mainly related to the addition of the roof surface thermal loads contribution.

According to Figures 45 and 46 related to Archetype III_A, it is possible to identify the influence of the non-uniform solar radiation on the windows and external surfaces heat gain rate. In Archetype III_A, the significant difference between the roof and the bottom floor suggests that the WWR and the Roof U play an important role in the solar heat gain of the roof floor. This helps to explain the 25% EUI difference between the roof and bottom floor in Archetype III_A mentioned earlier in this study.

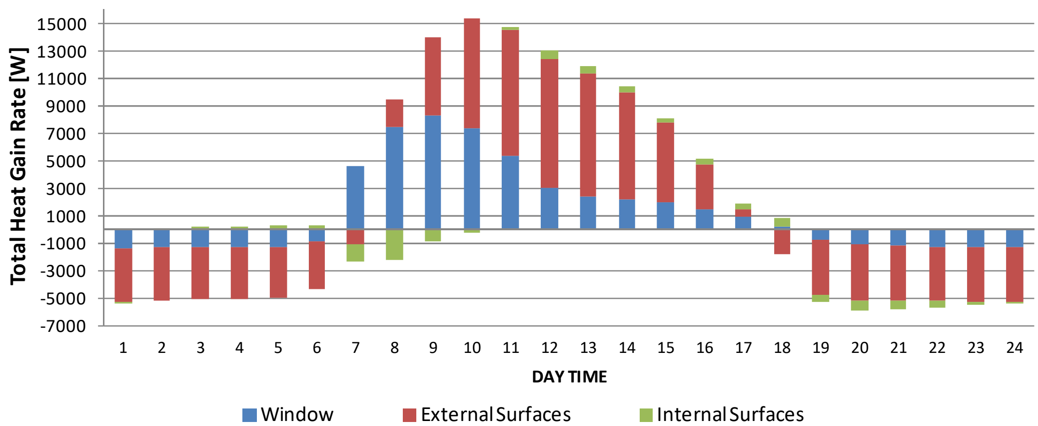


Figure 45 - Roof floor room surfaces total heat gain rate - # 5 zone, 15º North Orientation, Archetype III_A

Source: Author's own elaboration

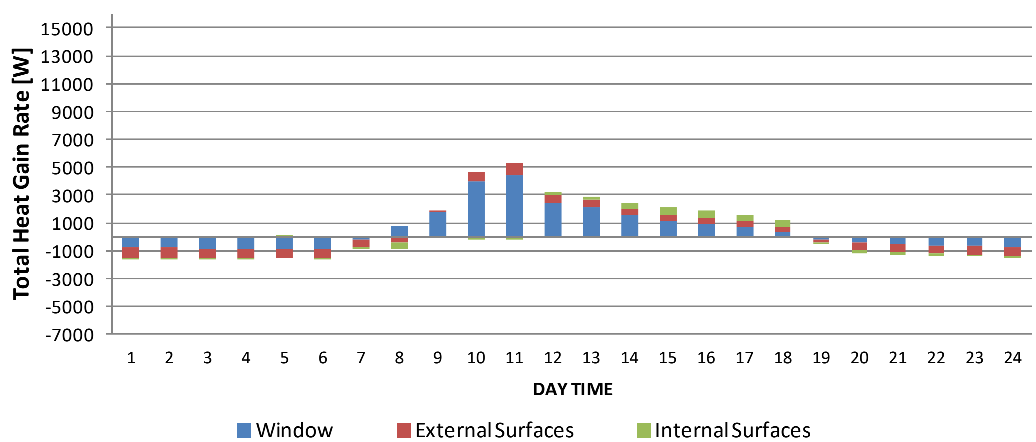


Figure 46 - Bottom floor room surfaces total heat gain rate - # 5 zone, 15º North Orientation, Archetype III_A

Source: Author's own elaboration

Regarding lighting, the EUI distribution analysis indicates that the artificial lighting system is the biggest electric energy consumer in Archetype I, II and III_A as shown in Figures 41 and 42. It is representative of approximately a 46% share of the total in Archetype I, a 52% in Archetype II and a 47% in Archetype III_A. Regarding Archetypes I, II and III_A, the impact of artificial lighting is explained by the lighting routine with no daylight integration and a high LPD. In Archetype III_B the lighting system is representative of approximately a 33% share of the total.

4.2.4.1 Validation

Due to the archetype characteristics found in the context of the city, it was possible to compare the results obtained in this thesis with the ones obtained in the *Benchmarking de escritórios corporativos* study (CBCS, 2015) only for Archetype III_B. Figure 47 shows the Archetype III_B EUI compared to the EUI from that benchmarking study. The Archetype III_B EUI value is noted to be close to the typical office building electric energy consumption found in the benchmarking study which is an indication that both studies work in a close agreement. The EUI difference between the typical office building and the Archetype III_B was 1.2%.

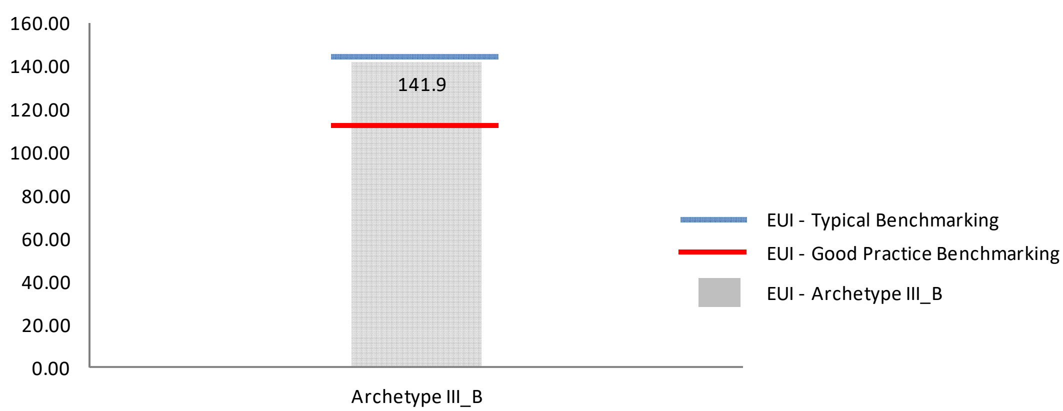


Figure 47 – The comparison between the Archetype III_B EUI value and the typical office building EUI value.

Source: Author's own elaboration

4.2.5 ENERGY USE INTENSITY BASELINE ESTIMATION

The BaseCase baseline of energy consumption was estimated considering the EUI of each building class and the growth rate of the existing office building stock indicated over the years by the SMAPU/PBH database as presented earlier in Table 18. Class I buildings had their energy consumption based on Archetype I EUI (90.1 kWh/m²/year), Class II on Archetype II EUI (83.1 kWh/m²/year). Class III energy consumption was estimated based on the weighting factor of the Archetype III_A (92.6 kWh/m²/year) and the Archetype III_B (141.9 kWh/m²/year) as follows:

$$\text{Class III EUI} = 0.4\ \text{EUI Archetype III\_A} + 0.6\ \text{EUI Archetype III\_B} \tag{27}$$

The EUI values of each building Class used to estimate the BaseCase baseline are:

- Class I buildings - 90.1 kWh/m²/year;
- Class II buildings - 83.1 kWh/m²/year;
- Class III buildings – 122.2 kWh/m²/year;

Figure 48 shows the estimated energy consumption baseline of the high-rise office floor space stock over the last 65 years in the city. The same growth rate computed in the 2005-2011 period was used to project the stock area to 2016. Figure 48 indicates that by 2016 Class II buildings would represent 49% of the overall energy consumption, followed by Class I buildings (29%) and Class III buildings (22%).

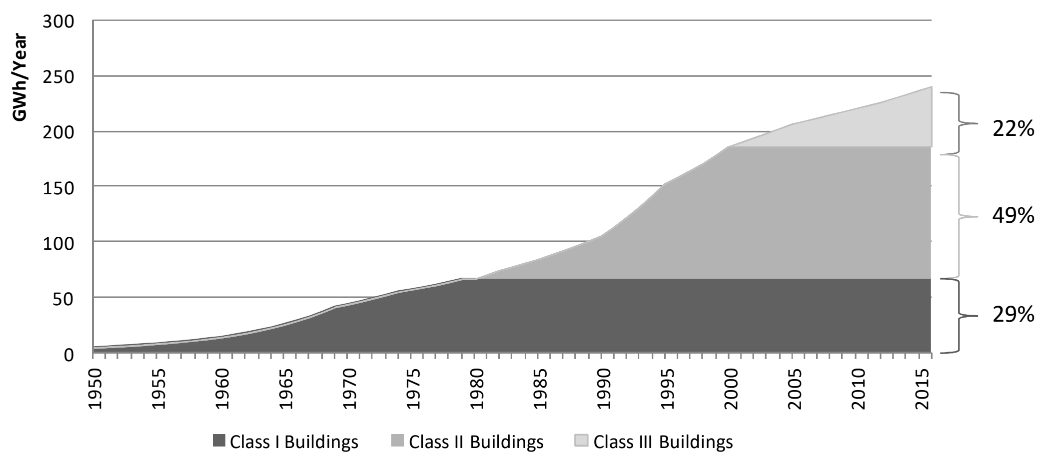


Figure 48 - Energy consumption BaseCase baseline of high-rise office spaces in Belo Horizonte.
Source: Author's own elaboration

Analysing the BaseCase baseline in terms of its energy saving potential, the baseline indicates that retrofit actions addressed to buildings Class I and II could have a substantial impact on energy savings of the high-rise office building stock once they together represent about 78% of their energy consumption.

Based on this understanding, this study next steps are focused on accessing the energy saving potential of Class I and II buildings and thus to assess the energy savings potential of the high-rise office building stock.

4.3 CONCLUSION AND REMARKS

The main goal of this chapter was to develop an energy consumption baseline of the existing high-rise office building stock. In order to reach this goal three methodological steps have been applied: the method for obtaining reference buildings, dynamic archetype simulations and the consumption baseline estimation.

The research steps described arrived to the following conclusions:

- The applied methodology demonstrated the capability of characterizing a building stock category without the need to rely on an existing building database.
- The methodology also captured the urban context which allows the inclusion of the shading effect from surrounding buildings in the dynamic model simulation.
- Studying land use regulations in a temporal and spatial perspective permitted to identify changes in the urban context, especially in building typologies. Land use parameters introduced as a form of city density control are noted to exist in most of the Brazilian cities which emphasizes that the framework proposed could be replicated nationwide, providing a novel approach to identifying reference buildings.
- High-rise buildings were observed to be linked to their urban context. The study showed evidences that the surrounding context could impact on solar radiation access and heat gain rates and consequently on building electric energy consumption. Being aware of this interaction is a way of better understanding high-rise building energy use intensity.
- The EUI results from the archetypes emphasized the role of technical choices, particularly when related to HVAC systems. Mixed mode systems as present in Archetypes I, II and III_A are noted to be an interesting technical approach in the context of Belo Horizonte due to their low energy consumption when compared to central air conditioning systems (Archetype III_B).
- Despite the higher performance of the HVAC system (COP coefficient) and the lighting system (LPD) in Archetype III_B, this study showed that office spaces represented by the Archetype III_B tend to be more energetically intense, demonstrating that high energy efficiency of individual systems do not necessarily

equate to low energy consumption of the building, a phenomenon known in the literature as the rebound effect (HERRING; ROY, 2007; MADLENER; ALCOTT, 2009). In that sense, buildings considered efficient and sustainable are, sometimes, among the largest consumers of energy which means that this discussion goes on beyond system performance and technological innovation.

- The energy consumption BaseCase baseline of the office building stock indicated the current representative weight of Class I and II buildings over the overall consumption. In that sense, retrofit actions addressed to buildings Class I and II might be decisive for a timely electric energy consumption reduction in the context of Belo Horizonte.

Remarks

- These methodological steps adopted a deterministic approach in order to estimate the energy consumption baseline of a building category. Traditionally, deterministic approaches have been used by researchers and technicians to model real patterns of energy demand due to their accuracy and ability of predicting the energy consumption of an existing building stock. At the aggregated level of large groups of buildings where uncertainties in occupant behaviour and operation tend to average out, previous validation works have reported acceptable errors in the total energy use from 4 to 20%, especially in warming climates (CAPUTO; COSTA; FERRARI, 2013; GALANTE; TORRI; OTHERS, 2012; HEIPLE; SAILOR, 2008; REINHART; CEREZO DAVILA, 2016; SHIMODA *et al.*, 2004). Despite the wide acceptance of the deterministic approach, it is important to mention that in recent years several researchers have proposed to include uncertainty analysis on building performance evaluation (CHOUDHARY, 2012; HOPFE; HENSEN, 2011; MENASSA, 2011; RASOULI *et al.*, 2013; TIAN; CHOUDHARY, 2012). The underlying argument is that large uncertainties exist for most of input parameters in building stock models. In that sense it seems to be more appropriated to inform performance values against the probability of their occurrence. However, quantifying uncertainties of systems and components parameters individually can be time-consuming and computationally expensive. Thus, incorporating uncertainty quantification in the building stock energy modelling process in a regular basis turns it into a real challenge. In the way forward, incorporating uncertainty analysis in the modelling process seems to be a natural development of this research.

- The lack of information on building energy consumption patterns in the context of Belo Horizonte city was one of the greatest challenges faced by this study. Additionally, no building construction databases were available which required combining multiple sources of information to characterize key building attributes. Thus, the whole process was time-consuming, especially when authorization to access a municipal database was needed.
- In this study, only the Archetype III_B energy model could be validated against the *Benchmarking de escritórios corporativos* study (CBCS, 2015). This lack of validation could be overcome by a baseline consumption validation, however in the context of the city there is no disaggregated office building stock energy consumption data available that enables to validate the energy consumption BaseCase baseline. These issues should be part of a future study.

5 THE ENERGY SAVINGS POTENTIAL OF HIGH-RISE OFFICE BUILDINGS: A CASE STUDY OF BELO HORIZONTE.

5.1 BELO HORIZONTE'S CASE STUDY METHODOLOGY

Figure 49 shows the last three methodological steps applied to the case study of Belo Horizonte: energy retrofit measures selection and a cost optimal pathway analysis, developing energy saving scenarios and estimating building stock energy savings potential. The three steps were the basis to estimate the energy savings potential of the high-rise office building stock from the city.

Concerning the energy retrofit measures selection, firstly potential retrofit measures were selected based on their technical feasibility and suitability. In the context of this study, retrofit measures were focused on Class I and II buildings due to the representativeness of these buildings in the estimated energy consumption BaseCase baseline. Secondly, a local sensitivity analysis was applied to prioritize the Class I and II building retrofit measures. The top four retrofit measures went through the sequential search method in order to identify the cost-optimal pathway for implementing the selected measures.

The cost optimal pathway results were the starting point to develop the energy saving scenarios. Three scenarios were estimated: Scenario 01 pursued the optimal retrofit package solution, Scenario 02 pursued the cost effective retrofit package solution, whereas Scenario 03 pursued the most efficient energy retrofit package solution related to Class I and II buildings.

Finally, all scenario projections were estimated and compared to the BaseCase projection in order to assess the energy savings potential of the high-rise office building stock from Belo Horizonte.

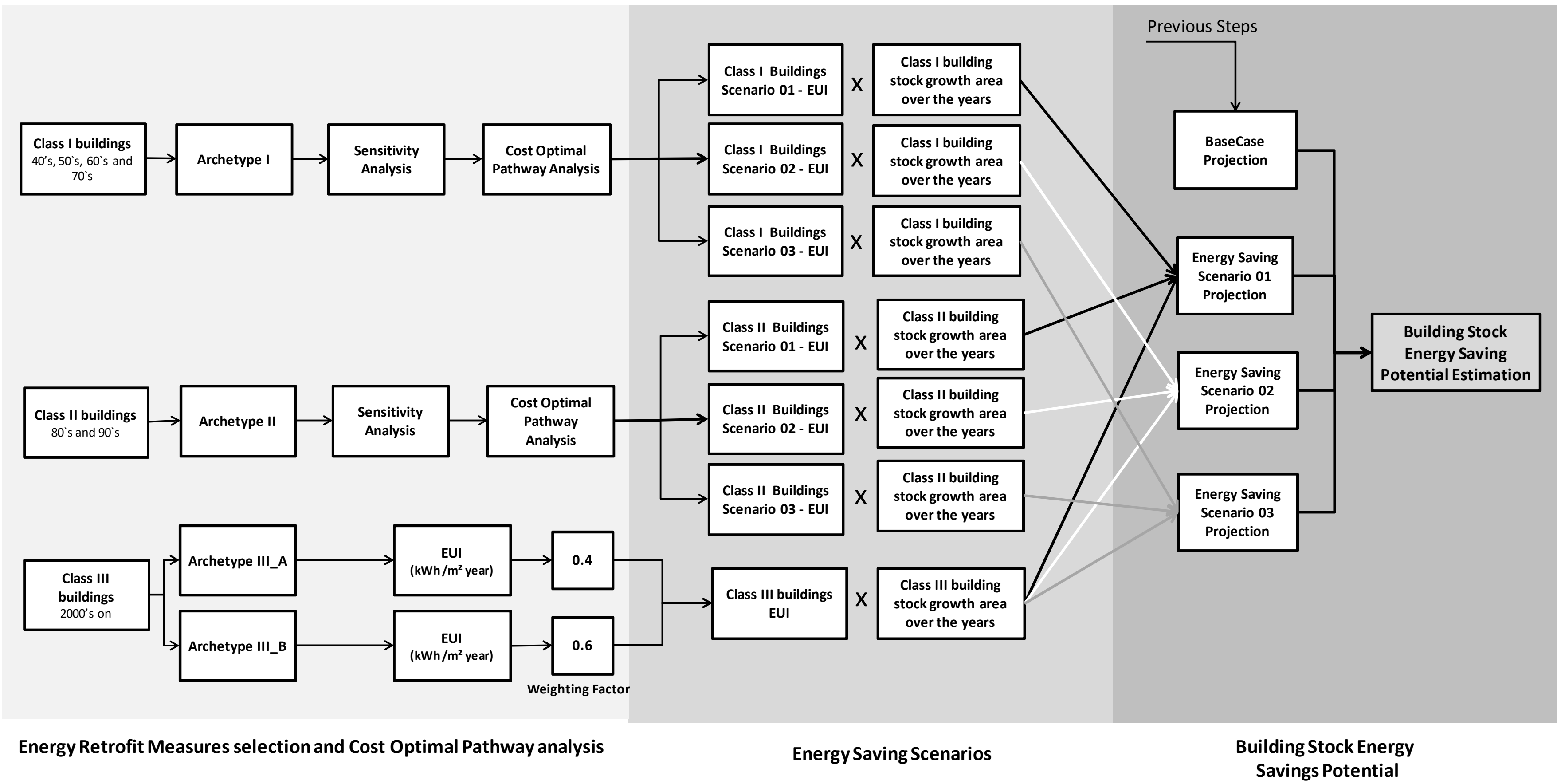


Figure 49 – Method for estimating the energy savings potential from Belo Horizonte's high-rise office buildings.

Source: Author's own elaboration

5.1.1 BELO HORIZONTE'S CASE STUDY: ENERGY RETROFIT MEASURES SELECTION AND A COST OPTIMAL PATHWAY ANALYSIS

5.1.1.1 Local Sensitivity Analysis (LSA)

For the archetype energy model related to Class I and II buildings, the first step was to determine input factor variations. The present study focused on factors which should be promising energy retrofit interventions. Input factors to be studied through LSA were selected based on their impact on the lighting and HVAC systems due the representativeness of those items on the Class I and II buildings EUI. Some input factors are numerical in nature while some are not, for example SHGC of windows is a numerical figure varying from 0 to 1 whereas the presence of window shading systems are non numerical and abstract in nature. For numerical and non numerical input factors, their ranges of perturbations were set based on the technical retrofit opportunities found in the high-rise office building stock.

Regarding Class I and II buildings, a total of seven retrofit measures were studied in terms of LSA:

1. Replace windows in order to diminish glazing SHGC;
2. Change exterior colours in order to obtain a lower wall absorptance;
3. Reduce envelope leakage (infiltration from external windows and doors);
4. Change window air conditioning in order to increase the coefficient of performance (COP);
5. Retrofit interior fixtures to reduce light power density (LPD);
6. Add a daylight harvesting system;
7. Add window shading devices;

Table 24 shows the resulting input parameters related to each retrofit measure, their BaseCase value and the perturbation performed. The perturbation values are to be explained in the following sections.

Table 24 – LSA Input Parameters, their base case and their perturbation related to Archetypes I and II

items	Parameter	Archetype I		Archetype II	
		range		range	
		Base Case	Perturbation	Base Case	Perturbation
1	**Glazing SHGC**	0.81	0.34	0.62	0.46
2	**Walls Absorptance**	0.40	0.15	0.40	0.15
3	**Exterior window/internal door Leakage** (kg/s m)	0.00041(windows) 0.00204 (doors)	0	0.00041(windows) 0.00204 (doors)	0
4	**Air conditioning coefficient of performance -COP, (w/w)**	2.94	3.28	2.94	3.28
5	**Light power density -LPD (W/ m²)**	19.04	8.1	19.04	9.3
6	**Daylight harvesting system**	no	yes	no	yes
7	**Window shading devices**	no	yes	no	yes

Source: Author's own elaboration

5.1.1.1.1 Glazing windows replacement

Glazing windows can account for a significant part of a building's heat loss and heat gain. There is a consensus that replacing inefficient glazing windows by better thermal performance system can reduce the building HVAC energy use.

In the context of this study, the glazing type as well as the WWR identified during field study, especially in Class I buildings, highlight a room for improvement that can impact on the existing building stock.

The glazing SHGC perturbation value of each archetype was selected from glazing technical catalogues keeping the BaseCase glazing colour reference. The selected glazing characteristics are presented in Table 25 as follows:

Table 25 – Glazing attributes

Parameters	Archetype I	Archetype II
Thickness	6mm	6mm
Colour	Transparent	Brown
Type	Float	Float
Product	COOL-LITE KNT 140	COOL-LITE ST 136
Glazing Supplier	Cebrace	Cebrace
Solar Transmittance at Normal Incidence (Tsol)	0.257	0.31
Visible Transmittance at Normal Incidence (Tvis)	0.411	0.37
Glazing U - (W/m².K)	3.485	5.566
SHGC	0.34	0.46

Source : Author's own elaboration based on the Thermal Proprieties Catalogue (INMETRO, 2013)

5.1.1.1.2 Changing exterior building colours

In general, the thermal energy gained through opaque walls via conduction accounts for a great percentage of the air conditioning demand in buildings. Diminishing wall absorptance can reduce the amount of heat transfer.

In this study, walls absorptance perturbation value considered the change from medium colours (aging light colour) to a new light colour painting. The value adopted was selected from the Thermal Proprieties Catalogue (INMETRO, 2013) and referenced by the name *Tinta Acrilica Branca*.

5.1.1.1.3 Reducing envelope leakage

Air leakage through the building envelope is usually a result of improper construction, lack of maintenance and degradation over the life of a building. Identifying significant air leaks in the building envelope and sealing them is observed to increase energy savings regarding the HVAC system.

In this study, the air mass flow coefficients when opening is closed (kg/s m) were set to zero.

5.1.1.1.4 Window Air conditioning replacement

Replacing equipment by ones with more efficient technologies improve the building energy performance. In this study, the COP perturbation value was chosen from the available COP list provided by the Brazilian Labelling Program in the Class A Window Air Conditioning Category ("Tabelas de consumo/eficiência energética - Condicionadores de Janela (Window Air Conditioning - Coefficient of Performance)", 2016).

5.1.1.1.5 Artificial Lighting retrofit

Artificial lighting accounts for a significant portion of overall energy use in a typical office building. In this study, lighting was noted to present the highest electric energy consumption percentage in Class I and II buildings. Utilizing lighting technologies more energy efficient to reduce the amount of energy related to the lighting end-use can result in significant energy savings at the existing building stock.

The LPD perturbation value was based on the installation of high-performance linear fixtures and LED lamps. Lighting power density (LPD) was estimated using the software DIALux 4 (DIALux, 2014). Table 26 shows the parameters used to calculate the LPD.

Table 26 – Parameters for LPD calculation

Items	Values
Height of the room (m)	2.8
Mounting Height (m)	2.8
Light loss factor	0.8
Surfaces reflectance p(%)	
Floor	30
Ceiling	80
Walls	50
Work plane height (m)	0.85
Luminaries Name	2005 LED (“Itaim Iluminação - Catálogo”, 2016)
LED Lamps (lm)	2990
LED Lamp Power (W)	31
Supplier	Itaim Iluminação

Source: Author’s own elaboration

5.1.1.1.6 Daylight harvesting System - Artificial and Daylighting integration

It is known that artificial lighting accounts for a significant portion of overall energy use in office buildings. In that sense, daylighting is becoming a key strategy to generate savings in the lighting end-use. This measure involves the installation of photocells to sense the space lighting level and to control the overhead lighting to maintain a constant light level in the space. This measure also requires introducing dimmable ballasts.

In this study the software used to carry out dynamic daylighting simulations was the DaySim 3.0 (DaySim, 2010). DaySim is a radiance-based daylighting analysis tool developed by the National Research Council Canada and the Fraunhofer Institute for Solar Energy Systems in Germany (REINHART, 2010). The simulation tool flow chart is presented in Figure 50. DaySim uses the Radiance algorithm coupled with a daylight coefficient approach proposed by Tregenza as a method to calculate indoor illuminance levels due to daylight under arbitrary sky conditions (TREGENZA; WATERS, 1983). DaySim imports an EnergyPlus weather file that contains hourly direct and diffuse irradiances. Using the Perez sky model these irradiances are first converted into illuminances and then into a series of sky luminous distributions of the celestial hemisphere for all sky conditions of the year (REINHART, 2010).

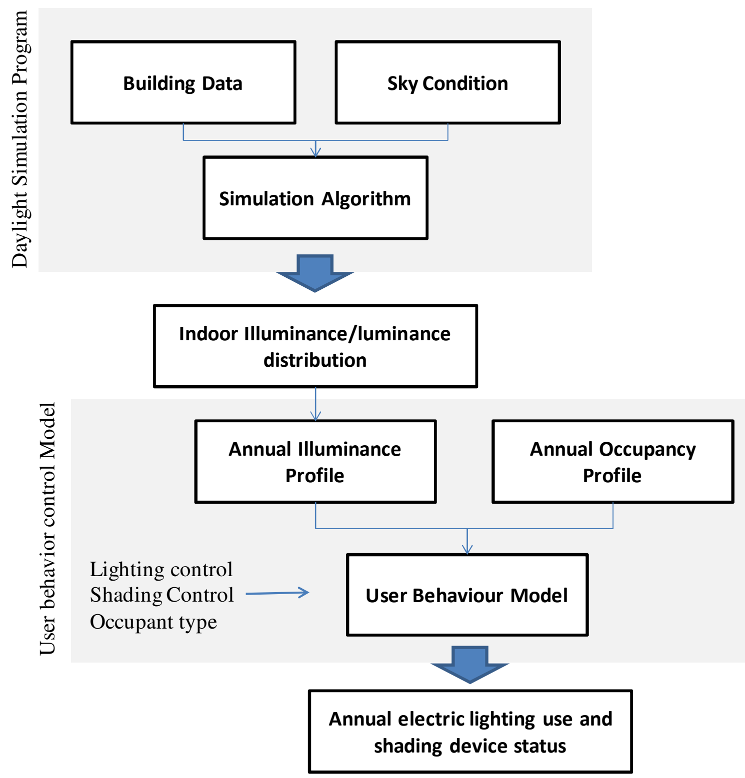


Figure 50 – Daysim simulation tool flowchart.

Source: Author's own elaboration based on Reinhart (2010)

The internal gains file provided at the end of dynamic daylighting simulation process was used as a lighting schedule file in the EnergyPlus simulations. The file contains hourly mean values of electric lighting (0 = off ...1=full on) generated from the predicted lighting zone at the work plane. Two work plane lighting sensors were simulated for each room. They were located in the middle of the room, over the longest axis and equidistant from the walls. At each time step, Daysim calculated the minimum illuminance of all work lighting plane sensors and this minimum work plane illuminance was used to determine whether the electric lighting is activated at a particular time step (REINHART, 2010). The sensors were defined as dimmable lighting sensors. For each room on the roof, intermediate and bottom floor a lighting schedule file was generated. The surrounding building context was taken into account during the simulation.

Table 27 shows the input parameters used to the dynamic daylighting simulation.

Table 27 - DaySim input parameters for daylighting simulation

Parameters		Definitions
Reflectance	Internal Wall	50%
	Floor	30%
	Ceiling	80%
	Surrounding Buildings	50%
Radiance Simulation Parameters		Scene Complexity 1
Operational Schedule		(8h-18h)
Minimum Illuminance Level		500 lux
Shading Device Model		Simplified dynamic shading device model
Occupant Behaviour		Active

Source: Author's own elaboration

Radiance Simulation Parameters described by Scene Complexity 1 suggest standard values of ambient bounces, ambient division/ambient sampling and ambient accuracy/resolution for a room without complicated facade elements. Figure 51 shows the values used during the simulation. Ambience bounces are related to the number of diffuse inter-reflections which will be calculated before a ray path is discarded, ambient division/ambient sampling is related to the number of sample rays that are sent out from a surface point during an ambient calculation, ambient accuracy/resolution provides a measure of how fine the luminance distribution in a scene is calculated.

ambient bounces	ambient division	ambient sampling	ambient accuracy	ambient resolution
5	1000	20	0.1	300

Figure 51 - Radiance Simulation Parameters for Scene Complexity 1

Source: Reinhart (2010)

Minimum Illuminance Level (500 lux) was based on the office room illuminance level values required by the ISO/CIE 8995-1 – Lighting for work spaces (ABNT, 2013a).

The simplified dynamic shading device model considers the effect of a generic venetian blinds system on the annual daylight availability. DaySim assumes that a generic blind system blocks all direct sunlight and transmits 25% of all diffuse daylight (REINHART, 2010).

The active occupant behaviour indicates that the user who operates the electric lighting in relation to ambient daylight conditions, opens the blinds in the morning, and partly closes them during the day to avoid direct sunlight.

5.1.1.1.7 Window shading Devices

In warm climates, external shading devices installed in glazing windows that receive direct sunlight can reduce the amount of solar heat gain, and therefore reduce the cooling load on the HVAC system.

The window shading devices proposed were designed to block direct sunlight during the operational time (8h-18h) throughout the year. Figure 52 shows the Stereographic Diagram for Belo Horizonte. The tinted area corresponds to the minimum shading mask that it is necessary to block direct sunlight over the year. The shading devices were designed for each facade and took into account the facade orientation and the surrounding building context of each archetype.

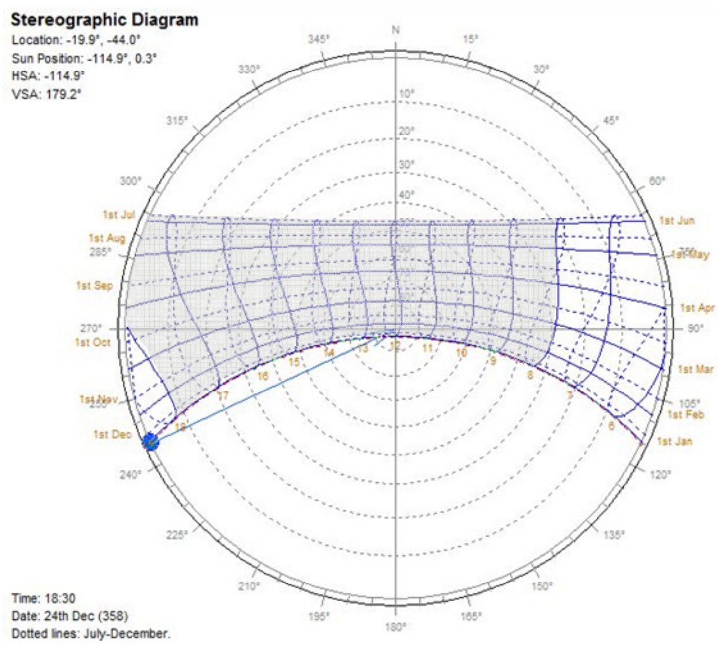


Figure 52 – Stereographic Diagram for Belo Horizonte.

Source: Author's own elaboration

Figure 53 shows possible shading device design solutions for different facade orientations. The archetype window shading masks used during the simulations are presented in Appendix H.

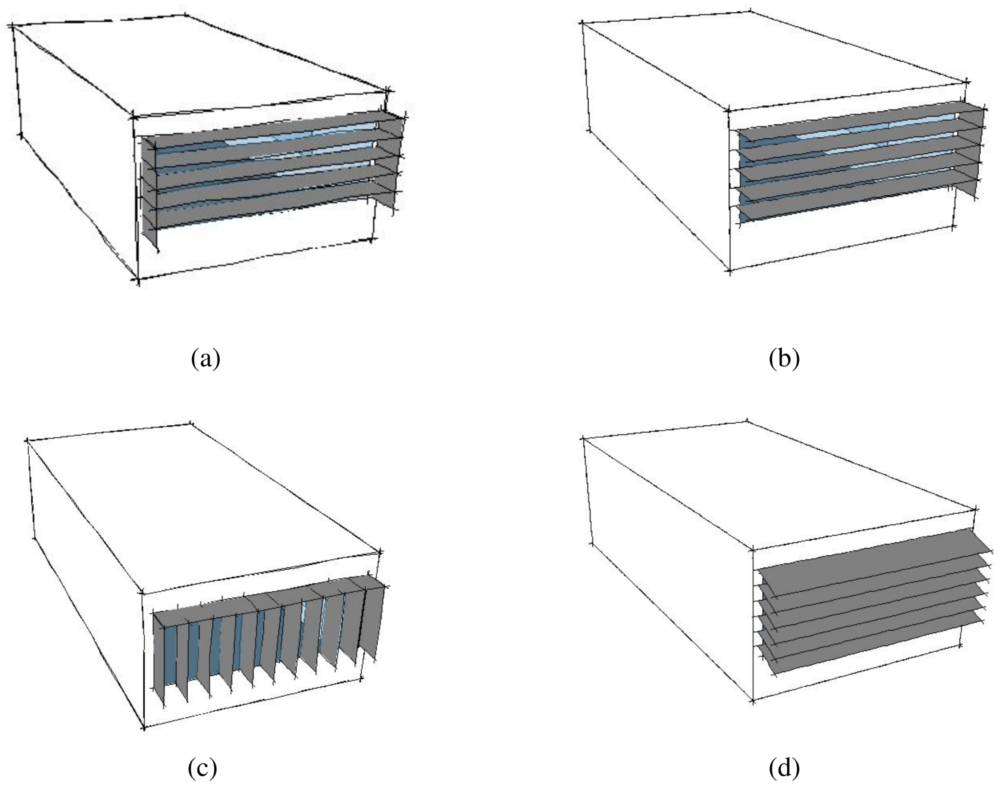


Figure 53 – (a) Shading devices designed for windows facing 15° North Orientation, (b) Shading devices designed for windows facing 105° North Orientation, (c) Shading devices designed for windows facing 195° North Orientation, (d) Shading devices designed for windows facing 285° North Orientation.

Source: Author's own elaboration

5.1.1.2 Cost Optimal Pathway Analysis

The cost optimal pathway analysis was developed according to the general methodology. Local sensitivity analysis results were the starting point to select the top 4 (four) retrofit measures that went through the sequential search method in order to identify the cost optimal pathway. In this study, two cost optimal pathways were developed: one related to Class I buildings and other related to Class II buildings.

5.1.1.2.1 Energy Retrofit Packages saving potential evaluation

The Energy Saving Potential (SP) of each Energy Retrofit Package (ERP) related to Class I and II buildings were calculated using Equation 22 indicated by the general methodology.

5.1.1.2.2 Economic Evaluation - Life-Cycle Cost (LCC) and Net Savings (NS) inputs

Life-Cycle Cost (LCC) and Net Savings (NS) were the economic methods used to evaluate the cost effectiveness of each ERP. In this study, the LCC and the NS were estimated for the building typical floor.

LCC and NS were calculated using Equations 23, 24 and 25 indicated by the general methodology. The inputs related to the city context are listed as follows.

Study Period

The LCC analysis study period is the time over which the costs and benefits related to a capital investment decision are evaluated. In this study, the study period used to compute the LCC of each ERP was 20 years.

Discount rate and Inflation rate

Building-related costs occurring at different points in time must be discounted to their present-value before they can be combined into an LCC analysis. In this study, the discount rate used to discount future cash flows to present value is 8% per year and it is based on the minimum acceptable rate of return for investments of equivalent risk in the construction and electricity sector (GATTO, 2009; TOLMASQUIM; GUERREIRO, 2013).

Inflation reduces the purchasing power of the money over time. To make a meaningful comparison between costs occurring at different points in time, those adjusts must be made for changes in the purchasing power. The general inflation rate used is 4.5% per year, based on the government target band (ROSEK, 2016).

Discount and Inflation- Adjustment formulas

The Present-Value (PV) formula used to discount one-time amounts is shown in Equation 15 presented earlier in this study.

The Present-Value (PV) formula for annually recurring non-uniform amounts used in this study is shown in Equation 28 as follows:

$$PV = F_t \cdot \frac{(1+e)}{(d-e)} \cdot \left[1 - \left(\frac{1+e}{1+d}\right)^t\right]$$

(28)

Where, PV = present-value, F_t = cash amount, e = escalation rate, d = discount rate, t=number of years.

Investment Costs

Quotes for purchase and installation costs of each ERP were obtained from local suppliers and construction cost-estimating guides such as *Planilha Referencial de Preços Unitários para Obras de Edificação e Infraestrutura - SETOP Central* (SETOP, 2016) and *Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil – SINAPI* (CEF, 2016).

Replacement Costs

The number and timing of capital replacements were estimated based on the useful life of the components. In this study, equipment useful lives were estimated based on producers' information and the normative instruction *IN SRF nº 162 Anexo I* (DOU, 1999) that estimates useful life and depreciation percentages for accounting purposes.

Quotes for purchase and replacement costs of each ERP were obtained from local suppliers and construction cost-estimating guides (SETOP Central and SINAPI).

Residual Values

In a LCC analysis, the residual value of a system or component is its remaining value at the end of the study or at the replacement time during the study period subtracted from disposal costs.

The method used to estimate the remaining value is the declining balance depreciation method that involves applying the depreciation rate against the non-depreciate balance. In this study, the depreciation rate were estimated based on the normative instruction *IN SRF nº 162 Anexo I* (DOU, 1999).

Operating, Maintenance and Repair Costs (OM&R)

OM&R costs are annually recurring costs related to operating, maintenance and repair costs. In this study, only annually maintenance costs were estimated. Quotes for maintenance costs of systems related to each ERP were obtained from local maintenance companies.

Energy Costs (kWh)

The quantity of energy estimated for each ERP alternative was based on the multiplication of the EUI of each ERP alternative per the building typical floor area (300m^2). The kWh value was based on the B3 electricity tariff (R$0,5312/kWh) billed by the Compahia Energética de Minas Gerais – Cemig. In this study, the electricity price escalation was expected to be equal to the general inflation.

5.1.2 BELO HORIZONTE'S CASE STUDY: DEVELOPING ENERGY SAVING SCENARIOS AND ESTIMATING BUILDING ENERGY SAVINGS POTENTIAL

The cost optimal pathway results from Class I and II building were the basis to develop three energy saving scenarios regarding the existing high-rise office building stock.

- Scenario 01 – Optimal Solution.

  The scenario represents the savings that would result if Class I and II buildings adopted the Optimal ERP solution.

- Scenario 02 – Cost Effective Solution.

  The scenario represents the savings that would result if Class I and II buildings adopted the Cost Effective ERP solution.

- Scenario 03 – Most efficient Solution.

  The scenario represents the savings that would result if Class I and II buildings adopted the Most Efficient ERP solution, regardless of cost.

All scenario projections were estimated for a period study of 20 years and compared to the BaseCase projection in order to assess the energy saving potential of the high-rise office building stock. The BaseCase projection represents the building stock consumption evolution without any building retrofit action.

As explained earlier, the EUI from the scenarios do not replaced the BaseCase EUI instantaneously, but rather was phased in over 20 years using a replacement rate of 5% year. The same growth rate computed for the 2005-2011 period was used to project the building stock area to 2036.

The high-rise office building stock saving potential was computed as being the difference between the BaseCase projection and the energy saving scenario projections.

5.2 RESULTS AND DISCUSSION

5.2.1 LOCAL SENSITIVITY ANALYSIS RESULTS

Local sensitivity analysis was carried out for 7 (seven) retrofit measures. Tables 28 and 298 show the Influence Coefficient (IC) computed for Class I and II buildings respectively. The tables present the IC values related to 15°North orientation, 105°North orientation, 195°North orientation, 285°North orientation as well as the IC mean values and the local sensitivity influence rank based on the mean values.

Table 28 – Class I building Influence Coefficients (IC)

	Factors	Archetype I					
		IC 15°	*IC* 105°	*IC* 195°	*IC* 285°	Mean value	Rank
1	**Glazing SHGC**	0.171	0.210	0.203	0.206	0.198	3
2	**Walls Absorptance**	0.085	0.101	0.100	0.099	0.097	5
3	**Exterior window/internal door Infiltration**	-0.016	-0.018	-0.018	-0.018	-0.017	7
4	**Air conditioning coefficient of performance -COP, (w/w)**	-0.139	-0.161	-0.160	-0.156	-0.154	4
5	**Light power density -LPD (W/ m²)**	0.561	0.524	0.542	0.525	0.537	1
6	**Daylight harvesting system**	0.263	0.200	0.225	0.234	0.230	2
7	**Window shading device**	0.042	0.076	0.065	0.071	0.064	6

Source: Author's own elaboration

Table 29 - Class II building Influence Coefficients (IC)

	Factors	Archetype II					
		IC 15°	*IC* 105°	*IC* 195°	*IC* 285°	Mean value	Rank
1	**Glazing SHGC**	0.140	0.148	0.144	0.138	0.142	4
2	**Walls Absorptance**	0.094	0.091	0.095	0.085	0.091	5
3	**Exterior window/internal door Infiltration**	0.002	0.002	0.002	0.002	0.002	7
4	**Air conditioning coefficient of performance -COP, (w/w)**	-0.244	-0.247	-0.246	-0.235	-0.243	3
5	**Light power density -LPD (W/ m²)**	0.608	0.608	0.606	0.615	0.609	1
6	**Daylight harvesting system**	0.236	0.274	0.219	0.255	0.2460	2
7	**Window shading device**	0.090	0.096	0.091	0.086	0.091	6

Source: Author's own elaboration

At the top of the Class I buildings ranking, there were two factors related to the lighting system: (1) the LPD and (2) the daylight harvesting system. The next five factors were related to solar heat gain: (3) the glazing SHGC, (4) the COP, (5) the walls absorptance, (6) the window shading device and (7) the infiltration. Regarding the Class I buildings, lighting system related factors are observed to be important due to the representative weight of the lighting on the Class I building EUI (about 47%).

Similarly, at the top of the Class II buildings ranking, there are two factors related to the lighting system: (1) the LPD and (2) the daylight harvesting system. The next five factors are related to solar heat gain: (3) the COP, (4) the glazing SHGC, (5) the walls absorptance, (6) the window shading device and (7) the infiltration.

Coincidently, the top 4 factors of both classes are the same: the LPD, the daylight harvesting system, the SHGC and the COP. The top 4 factors which are known to be related to retrofit measures are presented as follows:

1. ERP-01 LPD - Retrofit interior fixture by LED lamp/luminary systems with the purpose of reducing LPD;
2. ERP-02 Daylighting - Add daylight harvesting system through the use of dimmable lighting sensor in order to reduce lighting EUI;
3. ERP–03 SHGC - Replace windows to reduce glazing SHGC;
4. ERP-04 COP - Replace the window air conditioning by a Class A window air conditioning in order to increase the coefficient of performance (COP).

The four retrofit measures went through a sequential search method in order to identify the cost optimal pathway for implementing them.

5.2.2 COST OPTIMAL PATHWAY RESULTS

All measures were simulated one by one in the presence of an initial base case (BaseCase). The Energy Use Intensity (EUI), the Energy Saving Potential (SP), the Life-Cycle Cost (LCC) and the Net Savings (NS) of each option were computed and the most cost-effective (steepest slope) option was chosen as the optimal point for the iteration. The chosen option was then removed from future evaluations by the search. Remaining efficiency measures were simulated in the presence of this new optimal point and the iterative process repeated.

The sequential search method applied to the Class I and II building ERPs is presented in Figures 54 and 55.

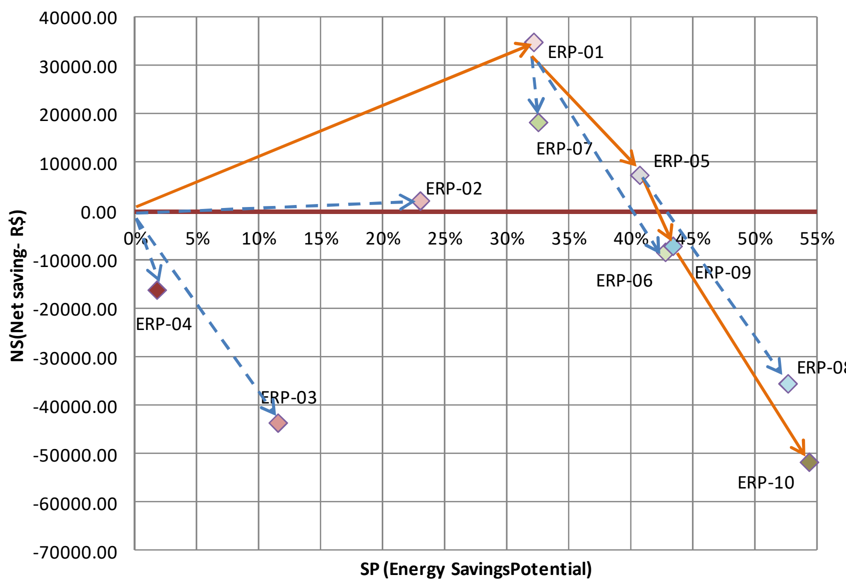


Figure 54 – Sequential search method applied to the Class I buildings top four retrofit measures.

Source: Author's own elaboration

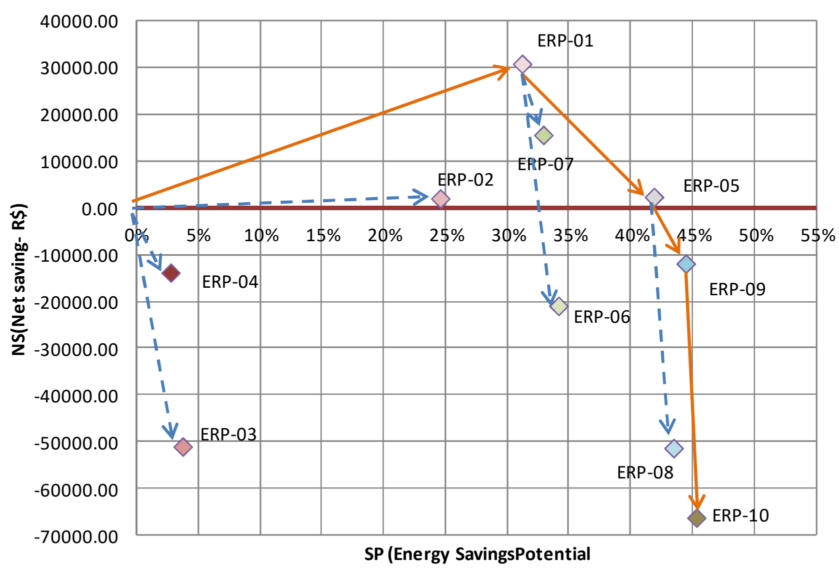


Figure 55 - Sequential search method applied to the Class II buildings top four retrofit measures.

Source: Author's own elaboration

Information regarding the EUI, SP, LCC and NS values used during the sequential search process are presented in Tables 30 and 31. Systems/components prices as well related services used to estimate the LCC are shown in Appendix I. Investment costs, replacement costs, residual values, electric costs and OM&R values used to compute the LCC of each ERP are presented in Appendix J as well as the year of occurrence of those cost events.

Table 30 – EUI, SP, LCC and NS values of each ERP related to Class I buildings

# of retrofit measures combination		Retrofit Measures	EUI (kWh/m²/ year)	SP (%)	LCC_20 (R$)	NS (R$)
	BaseCase		90.10	-	218590.50	
Individual Measure	ERP - 01	LPD	62.29	32.2%	183802.22	34788.28
	ERP - 02	Daylighting	69.36	23.0%	216347.54	2242.96
	ERP - 03	SHGC	79.75	11.5%	262291.95	-43701.45
	ERP - 04	COP	88.50	1.8%	234633.25	-16042.75
Two Combined Measures	ERP - 05	LPD + Daylighting	53.44	40.7%	211018.18	7572.32
	ERP - 06	LPD + SHGC	51.60	42.7%	226968.86	-8378.36
	ERP - 07	LPD + COP	60.85	32.5%	200114.41	18476.09
Three Combined Measures	ERP - 08	LPD + Daylighting + SHGC	42.60	52.7%	253954.27	-35363.77
	ERP - 09	LPD + Daylighting+ COP	51.03	43.4%	225792.56	-7202.06
Four Combined Measures	ERP- 10	LPD + Daylighting + COP + SHGC	41.15	54.3%	270238.43	-51647.93

Source: Author's own elaboration

Table 31 - EUI, SP, LCC and NS values of each ERP related to Class II buildings

# of retrofit measures combination		Retrofit Measures	EUI (kWh/m²/ year)	SP (%)	LCC_20 (R$)	NS (R$)
	BaseCase		83.15	-	209705.19	
Individual Measure	ERP - 01	LPD	57.23	31.2%	178887.45	30817.74
	ERP - 02	Daylighting	62.69	24.6%	207732.63	1972.56
	ERP - 03	SHGC	80.09	3.7%	260650.10	-50944.91
	ERP - 04	COP	80.81	2.8%	223443.55	-13738.36
Two Combined Measures	ERP - 05	LPD + Daylighting	48.34	41.9%	207390.78	2314.41
	ERP - 06	LPD + SHGC	54.75	34.2%	230730.27	-21025.07
	ERP - 07	LPD + COP	55.82	32.9%	194077.75	15627.44
Three Combined measures	ERP - 08	LPD + Daylighting + SHGC	46.99	43.5%	261015.61	-51310.41
	ERP - 09	LPD + Daylighting + COP	46.23	44.4%	221488.68	-11783.49
Four Combined measures	ERP- 10	LPD + Daylighting + COP + SHGC	45.49	45.3%	276070.10	-66364.91

Source: Author's own elaboration

Regarding individual measure packages related to Class I and II buildings, the improvement that led to the largest reduction in energy consumption and the highest NS was the artificial lighting system retrofit (ERP-01) as presented in Tables 30 and 31. The ERP-01 was then chosen as the new optimal point.

Concerning Two-Combined Measure packages, in Class I buildings the combination between the artificial lighting system and the window glazing retrofit (ERP-06) presented the most effective energy consumption reduction (42.7%) followed by the ERP-05 with reductions about 40.7%. However, as the ERP- 06 was not a cost effective package, the ERP-05 which was the combination between the artificial lighting system and the daylight harvesting system measures was then chosen as the new optimal point. In Class II buildings, the combination between the artificial lighting system and the daylight harvesting system (ERP-05) was considered the most efficient package with reductions about 41.9%, followed by the ERP-06 and the ERP-07 with reductions about 34.2% and 32.9% respectively. Regarding the economic evaluation, the ERP-07 was the most cost effective package followed by the ERP-05. However, as the ERP-05 presented greater energy savings it was chosen as the new optimal point.

It is important to observe that a close examination of the SP results reveals that combined measure savings are not a linear addition of individual measure savings. Effectiveness of multiple measures depends upon their interactive effects. For instance, as an individual measure, the ERP-01 (LPD) and the ERP-02 (Daylighting) energy saving potential in Class I buildings are about 32.2% and 23.0% respectively. As a combined measure the ERP-05 (LPD + Daylight) energy saving potential is about 40.7%. In this study, most of the retrofit sets presented this negative net effect. The most negative net effect occurred in the simultaneous implementation of measures that combines lamp/luminary retrofits and daylight strategies.

Regarding Three-Combined Measure packages, there were no cost effective packages regarding Class I and II buildings since there were no positive NS values. In Class I buildings, the combination of the artificial lighting system retrofit, the daylight harvesting system and the window glazing retrofit (ERP-08) was observed to have the highest energy saving potential (about 52.7%), followed by the ERP -09 with a reduction about 43.4%. However, as the ERP-09 showed better NS value, it was chosen as the new optimal point. In Class II buildings, the most efficient combination was the artificial lighting system retrofit, the daylight harvesting system and the window air conditioning retrofit (ERP-09) with reductions about 44%. The ERP-09 also presented the better NS value and in doing so it was chosen as the new optimal point.

Finally, the estimated consumption reduction of the Four-Combined Measure packages (ERP-10) was approximately 54.3 % for Class I buildings and 45.3% for Class II buildings. A close analysis suggests that the 9% difference between energy saving values of Class I and II buildings is due to the low impact of the window glazing retrofit on the energy saving potential of Class II buildings. In both cases, the ERP-10 was observed not to be cost effective which indicates that the savings in energy and OM&R relative to the BaseCase don't prevail over the additional costs related to the initial investment, replacement and residual values.

5.2.3 ENERGY SAVING SCENARIO RESULTS

Three scenarios based on the cost optimal pathway results were developed in order to estimate the energy savings potential of the high-rise office building stock. Figures 56 and 57 show the cost optimal pathway designed for Class I and II buildings.

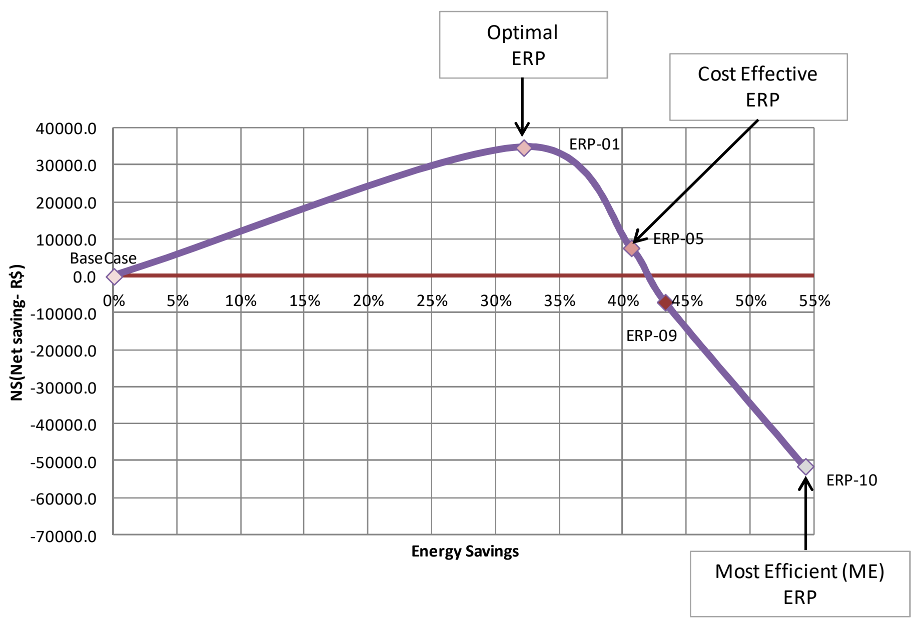


Figure 56 - Class I buildings cost optimal pathway

Source: Author's own elaboration

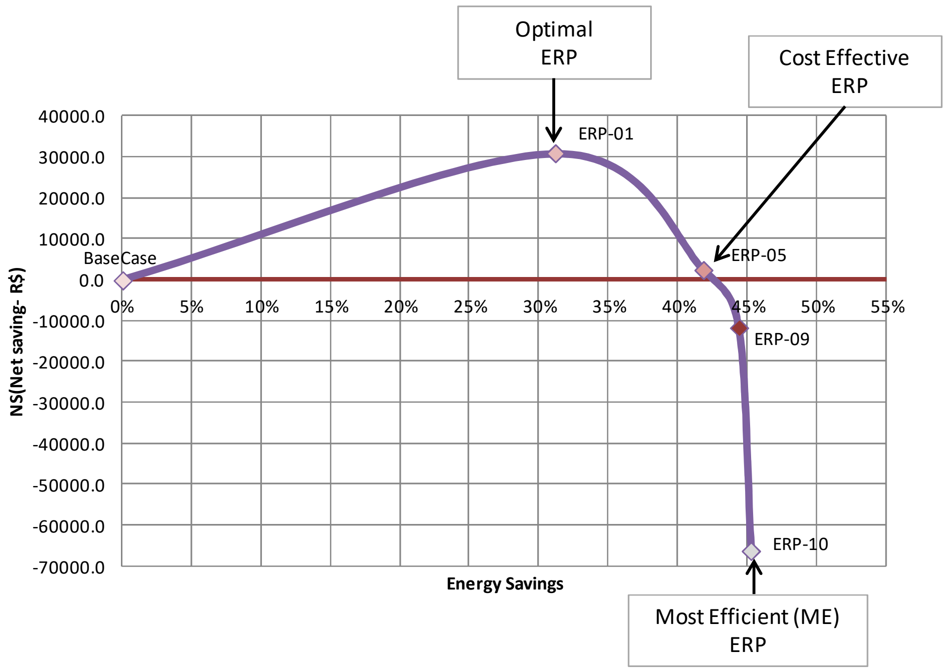


Figure 57 - Class II buildings cost optimal pathway

Source: Author's own elaboration

Scenario 01 explored the Optimal ERP solution. The Scenario 01 baseline represents the saving results from the implementation of the ERP-01 solution over the Class I and II building stock.

Scenario 02 explored the Cost Effective ERP solution. The Scenario 02 baseline represents the saving results from the implementation of the ERP-05 solution over the Class I and II building stock.

Scenario 03 explored the most efficient ERP solution. The projected baseline represents the saving results from the implementation of the ERP-10 solution over the Class I and II building stock.

Figure 58 shows the energy consumption projections regarding the BaseCase, the Scenario 01, Scenario 02 and the Scenario 03 for the next 20 years. Despite the simplicity of these projections, they are effective in illustrating the potential savings available in the existing high-rise office building stock. In the city context, going after Optimal and Cost Effective ERP solutions can lead to energy savings potential of approximately 18% and 24% respectively whereas pursing deeper retrofit packages can result in energy savings potential of approximately 28%.

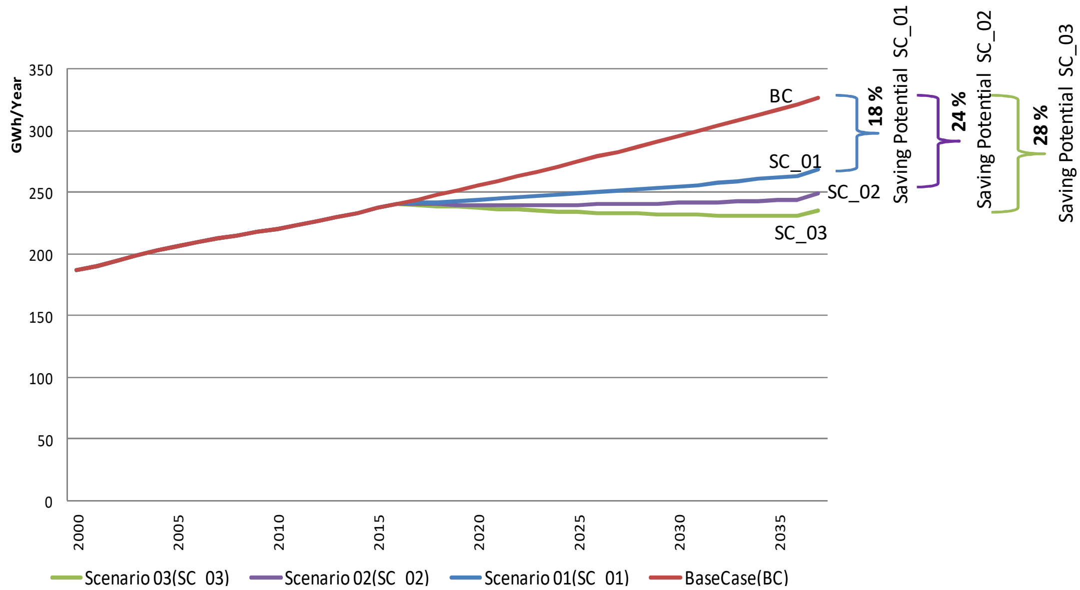


Figure 58 – Energy consumption Baseline projections - Comparison among the BaseCase, Scenario 01, Scenario 02 and Scenario 03

Source: Author's own elaboration

Figure 59 shows the BaseCase projection regarding the energy consumption of each building Class. The BaseCase projection, once again, represents the evolution of the consumption over the next 20 years without any constraint. By 2036, the BaseCase projection indicates that Class I and II buildings together would represent 58% of the total high-rise office building stock consumption. The BaseCase projection also indicates that the Class III building consumption could overcome the Class I building consumption by 2020 and the Class II building consumption by 2031 and, in doing so, it could become the most representative class building in the building stock consumption by 2036.

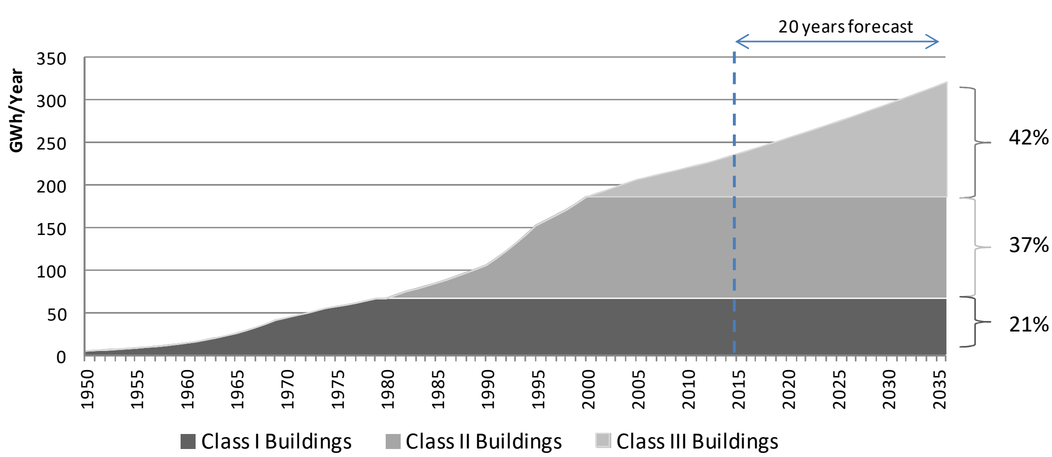


Figure 59 - Base Case energy baseline consumption over the next 20 years

Source: Author's own elaboration

Figure 60 presents the Scenario 01 projection concerning the energy consumption of each building Class. The savings from the optimal retrofit package implementation diminish considerably the overall high-rise office building consumption escalation for the next 20 years. By 2036, the Scenario 01 projection indicates that the Class I building consumption would represent 18% of the total high-rise office building stock consumption, whereas the Class II and III building consumptions would represent 31% and 51% of the total high-rise office building stock consumption respectively.

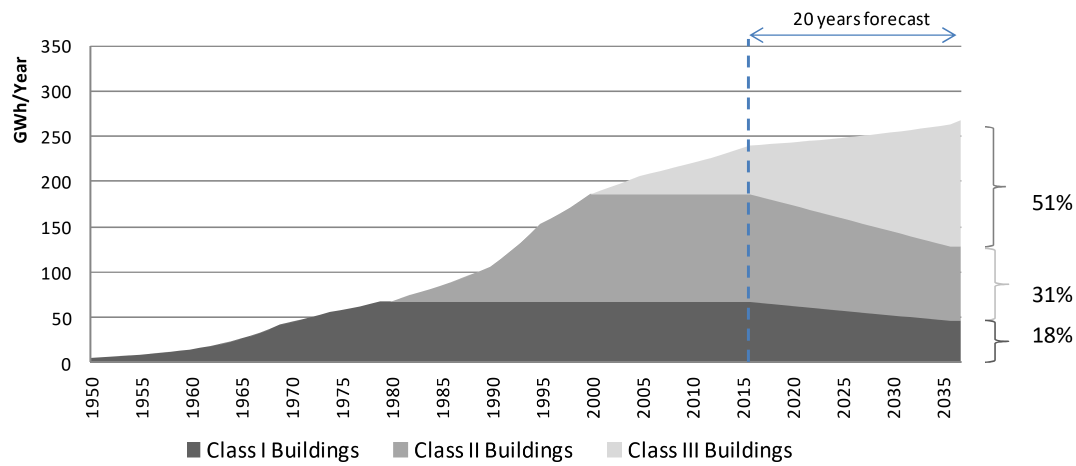


Figure 60 - Scenario 01 energy baseline consumption over the next 20 years

Source: Author's own elaboration

Figure 61 presents the Scenario 02 projection regarding the energy consumption of each building Class. The Scenario 02 projection shows that the implementation of the cost effective retrofit package over Class I and II buildings could practically reduce to zero the overall high-rise office building consumption escalation for the next 20 years. By 2036, the Scenario 02 projection indicates that the Class I building consumption would represent 16% of the total high-rise office building stock consumption, whereas the Class II and III building consumptions would represent 29% and 55% of the total high-rise office building stock consumption respectively.

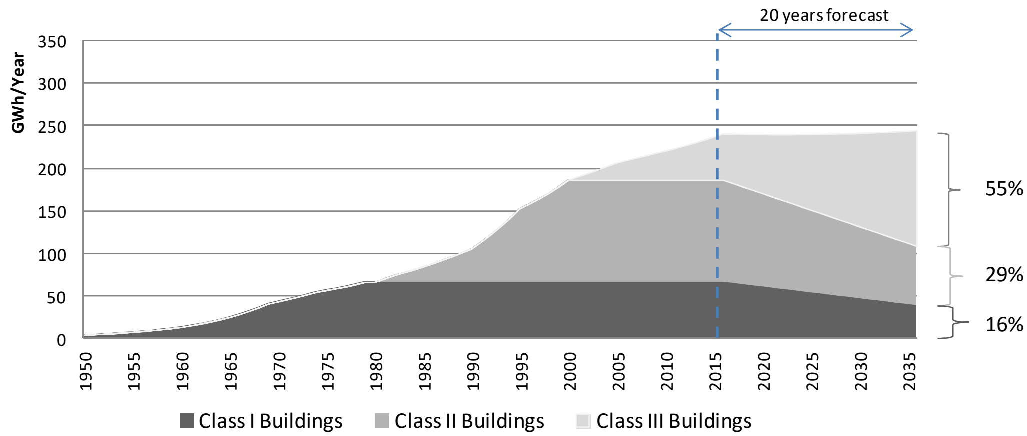


Figure 61 - Scenario 02 energy baseline consumption over the next 20 years

Source: Author's own elaboration

Figure 62 presents the Scenario 03 projection regarding the energy consumption of each building Class. The Scenario 03 projection shows that the implementation of the deeper retrofit package over Class I and II buildings could lead to a slightly decreased of the overall high-rise office building stock energy consumption. By 2036, the representativeness of Class I buildings on the overall building office energy consumption would be about 13%, Class II buildings would be about 28% and Class III buildings would be about 59%.

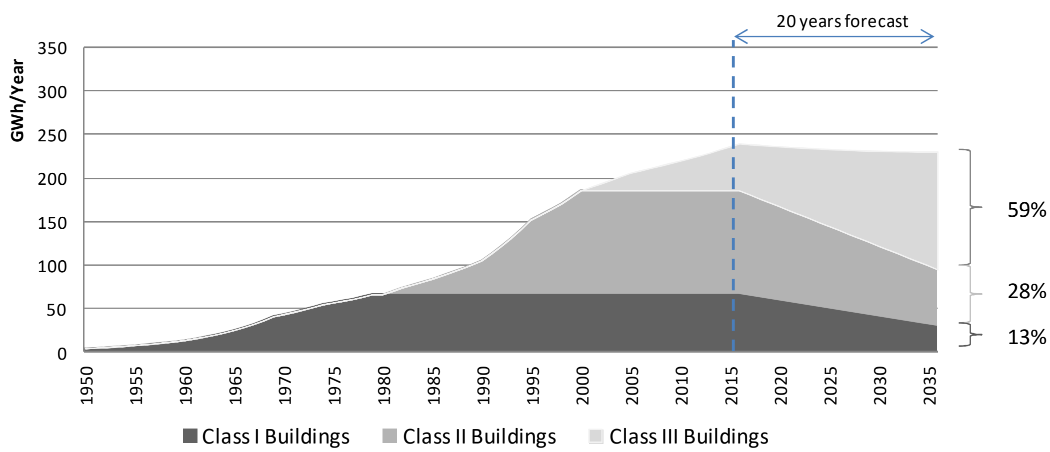


Figure 62 – Scenario 03 energy baseline consumption over the next 20 years.

Source: Author's own elaboration

Overall, these savings indicated by the scenarios are consistent with other worldwide works mentioned in this study. The disaggregated projections highlighted the importance of dealing with the existing building stock once they showed evidences that much can be achieved through the retrofit actions directed to them. Moreover, the projections also suggested that to be effective in the overall building stock energy consumption reduction (drop the further consumption to values lower than the current consumption), the policy makers must draw attention not only to the existing buildings but also to the upcoming buildings once, as identified in this research, the high-rise office buildings have become significantly more energy intensive over the last years.

5.3 CONCLUSION AND REMARKS

The main goal of this chapter was to estimate de energy savings potential from the high-rise office building stock of the city. In order to reach this goal three methodological steps have been applied: energy retrofit measures selection and a cost optimal path analysis, developing energy saving scenarios and estimating building stock energy savings potential.

The research steps described resulted in the following conclusions:

- In the city context, actions directed to reduce the lighting energy use intensity were the most cost effective in the goal of diminishing the office building stock energy consumption. Retrofit measures focused on the lighting system improvements (ERP-01) can unlock saving opportunities from the Class I and II buildings up to 32%.
- Despite the negative net effect, retrofit packages that combine lamp/luminary retrofits and daylighting strategies can become a key strategy to maximize savings in the lighting end-use. In the context of the city, this combination (ERP-05) was noted to be cost effective and present energy saving results up to 41%.
- Deeper retrofit packages (ERP-10) provided an opportunity for reducing energy consumption by over 50% in Class I buildings and by over 45% in Class II buildings. However, as deeper retrofit packages require a larger upfront investment, they were, in the context of this study, considered to be not cost effective.
- There are significant opportunities for energy efficiency improvements in the existing high-rise office building stock of the city. The energy saving scenario results indicated that pursing the Optimal and the Cost Effective ERP solutions implementation can lead to reductions up to 18% and 24% respectively, whereas pursuing deeper retrofit packages could unlock savings up to 28% of the overall high-rise office building stock by 2036.
- The disaggregated scenario projections emphasized the significance of tackling the existing high-rise office building stock (Class I and II) in order to achieve building energy consumption reductions in the city. Additionally, the disaggregated projections suggested that to shrink the current overall high-rise office building stock

consumption the policy makers must draw attention to the upcoming buildings once they are becoming significantly more energy intensive over the last years.

Remarks

- It is important to mention that some simplifications were necessary to develop the projections. In reality, over the years many Class I, II and III buildings will experience increases and decreases in the energy using intensity regardless of any energy policy. For instance, if in one hand the energy using equipment density increases (offices incorporate new products) on the other hand there is offsetting reduction due to the natural replacement of existing equipment (ex. as LED lamps turn less expensive they become the natural substitute of tubular lamps). These actions had not been taken into account in this study.
- This study focused on analysing retrofit measures specifically related to technical opportunities and therefore operation-related energy conservation opportunities such as energy management and occupancy interventions were not analysed. In recent years, several studies have emphasized that human actions are major determinants of energy use and could lead to significant savings potential (AZAR; MENASSA, 2012, 2014; EGBU *et al.*, 2009). However, due to the challenge of measuring operation-related energy conservation opportunities they are rarely integrated to a framework that quantifies energy savings. Future researches should focus on proposing a framework that would incorporate operational-related saving opportunities.
- In this study, a local sensitivity analysis was used to prioritize potential energy retrofit measures. Despite being widely used, this method shows some drawbacks. For instance, it explores only a reduced space of input factors around a base case and interactions among changed input factors could not be considered. In recent years, several studies have been concentrated on global methods because they can explore uncertain input factors over the whole input space as well as considering input interactions. Regression methods such as SRC are widely used for global sensitivity analysis in building energy analysis because they are considered fast to compute and easy to understand. Further studies should consider the possibility of introducing global sensitivity analysis to prioritize potential energy retrofit measures.
- The methodological steps adopted a deterministic approach in order to estimate the energy savings potential of the high-rise office building stock. As previous mentioned, incorporating uncertainty analysis seems to be a natural development of this study,

especially concerning energy building retrofit measures and LCC analysis. Making decisions on discount rate, inflation rate, etc. regarding a LCC analysis were noted to be a hard work in this study due to the current political and economic issues faced by the country. In that sense, further research should be done to investigate building energy retrofits under technical and economic uncertainty.

6 CONCLUSION

The general problems addressed in this thesis were how to access the energy performance and the energy savings potential of an existing building stock. Both topics are observed to be challenging especially in developing countries where the lack of available information about building energy consumption makes it hard to decide upon interventions in the building stock, as neither the existing nor the achievable energy performance are known.

At the basis of this discussion, there are two topics: (1) building stock energy modelling which allows the development of an energy consumption baseline and consequently the identification of energy consumption patterns and (2) building stock energy retrofits which permit to assess the energy savings potential of a building stock.

In order to develop structured knowledge regarding these topics, this research proposed a methodology for identifying and analysing the energy savings potential of an existing building stock category based on six steps: (1) a method for obtaining reference buildings, (2) dynamic archetype model simulations, (3) an energy consumption baseline estimation, (4) energy retrofit measures selection and a cost optimal path analysis, (5) developing energy saving scenarios and (6) estimating building stock energy savings potential. Each step had positive findings and drawbacks, indicating that the pathway to identify and analyse energy savings potential is not always straightforward. In order to examine the implementation of the methodology, a case study took place in Belo Horizonte, Minas Gerais, Brazil with the purpose of identifying and analysing the energy savings potential of the high-rise office building stock from Belo Horizonte.

Concerning the methodology, one of the most relevant contributions regards the method for obtaining reference buildings in their urban context. The lack of information about building energy consumption patterns in the context of the city was one of the greatest challenges faced by the case study, however, the methodology permitted to obtain reference buildings without having to study specific buildings in depth or to access existing building construction databases. In the methodology, the land use regulation investigation was introduced as the main tool to identify changes in the urban context, especially in building typologies and together with the land tax database and the field survey investigation allowed an efficient identification of the reference building attributes in the context of the city. Moreover, land use parameters introduced as a form of city pattern control are noted to be present in most of the Brazilian cities which emphasizes that the novel framework could have great applicability potential for other regional contexts and likely to other countries, especially underdeveloped ones.

Regarding the dynamic archetype model simulations, the urban context captured by the methodology enabled the inclusion of the shading effect from surrounding buildings in the dynamic model simulation. In Belo Horizonte's case study, the high-rise buildings were observed to be linked to their urban context and therefore the simulations showed evidences that the surrounding context could impact on the solar radiation access and heat gain rates and consequently on the energy consumption of office buildings. Being aware of these interactions is a way of better understanding the long lasting impact of the urban patterns on the city energy consumption.

Concerning the case study simulation results and the BaseCase baseline designed from these results, three main findings need to be addressed: the role of technical choices in the Archetype EUI results, the evidences that high-rise office buildings have become significantly more energy intensive and the representativeness of the existing buildings in the overall building stock consumption.

The Archetype EUI results emphasized the role of technical choices in reducing electric energy consumption, particularly when related to the HVAC system. Mixed mode systems (natural ventilation and mechanical cooling) as presented by Archetypes I, II and III_A are noted to be an interesting technical approach in the context of Belo Horizonte due to the capability of reducing the HVAC operation hours and consequently the energy consumption. Therefore, encouraging mixed mode systems might be decisive for a timely energy use reduction in the context of the city.

In the context of this study, there are growing evidences that the high-rise office buildings are becoming more energetically intense. Despite the improvement in energy efficiency of HVAC system (COP coefficient) and lighting system (LPD) found in the Archetype III_B, this study showed that contemporary office spaces tend to be more energy intensive, demonstrating that high energy efficiency of individual systems are not necessarily associated to low energy consumption of buildings. In that sense, policies and programs focused on energy efficiency improvements should target not only a given technology or end use but also the total energy intensity of buildings.

In the context of city, approximately 78% of the current high-rise office building electric energy consumption is related to office floor spaces aged more than 15 years. Given the representative weight of those buildings, focusing on improving energy efficiency of existing buildings is observed to be one of the most important means available to tackle the electric energy consumption reduction of the city. Directing energy policies and energy saving initiatives to the existing building stock is a growing tendency perceived in the entire world, especially in consolidate urban areas, and can be understood as an effort towards a more sustainable city.

It is important to point out that the archetype model validation process wasn't possible for all proposed archetypes in this case study. The mixed mode building models referenced by Archetypes I, II and III_A were not evaluated due to the lack of similar studies (local benchmark studies) and disaggregated office building stock consumption data in the context of the city. However, as the examination of the Archetype III_B model proved to be valid it suggests that the bottom up archetype modelling methodology is capable of identifying the energy use intensity of a reference building. Encouraging the development of large local data sets is essential to support existing building stock retrofit studies. More research on this topic needs to be undertaken in order to overcome this data limitation.

Identifying building stock retrofit measures that impact on the energy savings potential of the existing building stock was an important step of the methodology developed in this study. Two procedures were applied and noted to be valuable in the selection of retrofit measures and in the creation of retrofit packages: (1) a local sensitivity analysis and (2) a cost optimal pathway analysis. The local sensitivity analysis was used to prioritize the retrofit measures whereas the cost optimal pathway analysis was applied to optimize the search towards cost effective retrofit package solutions.

The introduction of the economic analysis finds support in several studies cited in this work that state that identifying cost effective strategies for retrofitting existing buildings is essential to increase the success of saving initiatives implementation. Moreover, this subject highlights an important question: the underinvestment in energy efficiency in existing buildings. The lack of investment in energy efficiency is frequently linked to the lack of sufficient information to make purchasing decision regarding costs and energy savings which leads to other important barrier, the principal-agent barrier also named the split incentive. The split incentive is one of the most important issues identified in the commercial building leasing market. It begins when the tenant pays the operation costs whereas the owner pays its capital costs and its energy-using equipment. Similarly, a split incentive barrier exists for businesses that do not expect to hold a property long enough to appreciate the full financial benefit of an energy efficiency measure. Policy experts agree that solutions to this barrier are not a single solution but a combination of different measures designed in a case-by-case basis. Therefore, in the context of this study, addressing all those questions was an important way of supporting further energy initiatives and policies implementation in an effort to target building energy consumption reduction in the city.

Regarding the case study energy retrofit measures selection and the cost optimal path analysis results, three main findings should be underlined: the representative weight of actions directed to decrease the lighting use intensity, the negative net effect of retrofit measure combinations and the non-cost-effectiveness of deeper retrofit packages.

Actions directed towards lighting energy use intensity reduction represent the optimal and the most cost effective initiatives in the effort to target the office building stock consumption reduction. Retrofit measures focused on the lighting system improvements (ERP-01 and ERP-05) can unlock saving opportunities from the Class I and II buildings as much as 32% and 41% respectively.

Combined measure savings are not a linear addition of individual measure savings. The case study revealed that the effectiveness of multiple measures depends upon their interactive effects. Moreover, these combined effects also play an important role in the retrofit measures selection of the cost optimal pathway. In this study, most of the retrofit sets presented a negative net effect. The most negative net effect occurred in the simultaneous implementation of measures that combined lamp/luminary retrofits and daylight strategies.

As for retrofit measures, the cost to implement and maximize saving benefits that can be achieved demands a more careful study. Deeper retrofit packages provide a substantial opportunity for reducing energy consumption; however as deeper retrofit packages require a larger upfront investment, they tend to become non cost-effective as they go deeper. Although important, the cost effectiveness of a retrofit measure is not the only dimension to be analysed in this equation. A growing body of evidences links elevated building performance to non energy benefits such as occupant comfort improvement, productivity and healthy, higher building occupancy rates, higher rents, and greater asset value. Being aware of those questions is a strong start to establish a holistic view regarding the topic building stock retrofits.

Based on the results of the cost optimal pathway analysis, the last steps of the methodology were developed: the energy saving scenarios and the building stock energy savings potential. There are several functions that scenarios could serve. Two of them were particularly important in this study: the use of scenarios as a public communication tool to draw attention to specific issues and the potential of examining the effectiveness of energy retrofit strategies over the existing building stock. In the context of this case study, three scenarios were developed and findings presented as follows.

The saving scenario results highlighted that there are significant opportunities for energy efficiency improvements in the existing high-rise office building stock of the city. Using current technology, cost effective energy savings of up to 24% would be possible in the high-rise office building stock by 2036. Regardless costs, by 2036, deeper retrofit packages could unlock savings up to 28%. Currently, there is no specific energy saving policy directed to existing buildings, therefore, none of those scenarios were developed under financial or technical incentives. Furthermore, to realize the saving scenarios potential energy policy makers must support building retrofit solutions that would target energy consumption reduction.

Overall, the disaggregated scenario projections over the next 20 years emphasized the significance of dealing with the existing high-rise office building stock in order to achieve building energy consumption reduction in the city. Although, the projections also suggested that to be effective in the overall office building stock energy consumption reduction (to shorten the current building stock consumption), the policy makers must pay close attention not only to the existing buildings but also to the upcoming buildings once as identified in this research, the high-rise office buildings have become significantly more energy intensive over the last years.

6.1 OPPORTUNITIES FOR FUTURE RESEARCH

The framework for identifying and analysing energy savings potential has been tested with one case study. Further case studies are needed to expand the understanding of the interdependencies among the inputs and the methodological steps. For instance, the complexities associated with the method for obtaining reference buildings should be tested in other building categories (e.g. Residential). The current study could be expanded to include not only technical saving opportunities but also operational-related saving opportunities in order to expand the savings potential of the building stock. Uncertainties related to the building physics and building operation could be considered in the inputs.

The next paragraphs will identify directions for further research in order to improve the framework proposed.

This thesis applied a deterministic approach in all methodological steps in order to estimate the energy consumption baseline of a building category. Despite the wide acceptance of the deterministic approach, there is a growing tendency of studies that believe to be more appropriate to inform performance values against the probability of their occurrence. In a further study, the deterministic approach used to estimate the reference building energy use intensity as well as the LCC values and the retrofit measures could be then improved by including sources of uncertainties in their inputs.

The archetype model validation was limited to public data available and did not allowed evaluated all proposed archetypes. Similarly, the lack of disaggregated energy consumption data did not enable to validate the energy consumption BaseCase baseline. Future research would be required to gather data which would allow to develop a validation method that may result in an improved energy model.

A local sensitivity analysis was used in this study to prioritize potential energy retrofit measures. Despite being widely used in the field of building energy analysis, this method shows drawbacks such as it only explores a reduced space of the input factor around a base case and the interactions among changed input factors cannot be considered using this method. Further studies should consider the possibility of introducing global sensitivity analysis to prioritize potential energy retrofit measures in order to develop a more informative and robust sensitivity analysis.

This thesis focused on analysing retrofit measures related specifically to technical opportunities. In recent years, several studies have emphasized that human actions are major determinants of energy use and could lead to significant savings potential. Further researches should focus on proposing a framework that would incorporate operational-related saving opportunities that might result in greater building stock energy savings.

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APPENDIX A – Adapted Morphological Diagram (AMD)

INFORMATION								
LEVEL	**PARAMETERS**	**SUBCATEGORIES**						
		F	**RS**	**LS**	**B**		**Description**	
Urban	Street width					A1	up to 10 m	
						A2	between 10 and 20	
						A3	over 20 m	
	Sky view					B1	angle < 30°	
						B2	30 < angle < 60°	
						B3	60 < angle < 90°	
						B4	Others	
Building	Facade Reflectance					C1	specular	
						C2	high reflectance	
						C3	Medium reflectance	
						C4	Low reflectance	
						C5	Heterogeneous	
						C6	Others	
	Roof Reflectance					D1	High reflectance	
						D2	Medium reflectance	
						D3	Low reflectance	
	Glazing Color					E1	Transparent	
						E2	Brown	
						E3	Green	
						E4	Other	
	Roof System					F1	Concrete slab	
						F2	Single/multi plane roof	
						F3	Other	
	Solar orientation					G		
	Number of Floors					H		
	Building Shape					I1	Square	
						I2	Triangular	
						I3	Rectangular	
						I4	Light court	
						I5	others	
	Ground floor characteristic					J1	building tower entrance	
						J2	street store only	
						J3	Street store plus parking floor	
						J4	Other	
	Window to wall ratio					L1	Up to 25%	
						L2	Between 25% and 50%	
						L3	Between 50 % and 75%	
						L4	Over 75%	
						L5	Blind	
	window - facade distribution					M1	Uniform	
						M2	Non uniform	
						M3	others	
	Daylight control					N1	balcony	
						N2	Brise	
						N3	Blinds/venetian	
						N4	others	
	Environmental Conditioning strategy					O1	Natural ventilation	
						O2	Window or split air conditioning	
						O3	Central air conditioning	
						O4	others	

F - front facade, RS - right side facade, LS - left side facade, B - back facade

APPENDIX B – Sample Building List

	YEAR OF CONSTRUCTION	AREA	ADDRESS/ZONE		
1	1943	15,648.96	AVE	AFONSO PENA	ZHIP
2	1947	12,456.17	RUA	DOS CARIJOS	ZHIP
3	1947	2,235.00	RUA	RIO DE JANEIRO	ZHIP
4	1947	7,713.00	RUA	ESPIRITO SANTO	ZHIP
5	1949	8,852.00	AVE	AFONSO PENA	ZHIP
6	1951	13,256.47	AVE	AFONSO PENA	ZHIP
7	1951	4,001.39	AVE	AMAZONAS	ZHIP
8	1952	4,053.31	RUA	DOS CARIJOS	ZHIP
9	1952	3,137.00	RUA	DOS CARIJOS	ZHIP
10	1952	4,307.35	RUA	DA BAHIA	ZHIP
11	1952	4,306.00	RUA	SAO PAULO	ZHIP
12	1953	18,709.00	AVE	AMAZONAS	ZHIP
13	1954	8,100.47	RUA	CURITIBA	ZHIP
14	1958	7,104.40	RUA	DOS GOITACAZES	ZHIP
15	1958	12,156.91	AVE	AMAZONAS	ZHIP
16	1960	4,147.20	RUA	DOS TAMOIOS	ZHIP
17	1960	7,411.91	AVE	AMAZONAS	ZHIP
18	1960	13,264.78	RUA	DOS CARIJOS	ZHIP
19	1960	15,352.91	RUA	RIO DE JANEIRO	ZHIP
20	1960	16,046.00	RUA	RIO DE JANEIRO	ZHIP
21	1960	13,807.14	RUA	DOS CAETES	ZHIP
22	1960	15,383.00	RUA	ESPIRITO SANTO	ZHIP
23	1960	5,996.55	RUA	SAO PAULO	ZHIP
24	1961	4,577.92	RUA	DOS TUPINAMBAS	ZHIP
25	1961	5,291.00	RUA	CURITIBA	ZHIP
26	1961	6,895.40	RUA	SAO PAULO	ZHIP
27	1962	6,795.28	RUA	DOS GOITACAZES	ZHIP
28	1962	4,671.00	RUA	DOS CAETES	ZHIP
29	1962	5,943.51	RUA	DOS TAMOIOS	ZHIP
30	1962	5,485.52	RUA	DA BAHIA	ZHIP
31	1963	2,761.46	RUA	DOS TUPINAMBAS	ZHIP
32	1963	4,308.41	RUA	DA BAHIA	ZHIP
33	1963	5,490.88	RUA	CURITIBA	ZHIP
34	1964	2,396.00	RUA	DA BAHIA	ZHIP
35	1964	5,452.38	RUA	CURITIBA	ZHIP
36	1964	2,144.00	RUA	DA BAHIA	ZHIP
37	1965	9,617.90	RUA	DOS GOITACAZES	ZHIP
38	1965	5,574.04	AVE	AMAZONAS	ZHIP
39	1965	2,803.00	RUA	DOS TUPIS	ZHIP
40	1965	10,100.98	RUA	ESPIRITO SANTO	ZHIP
41	1966	4,814.00	AVE	JOAO PINHEIRO	ZHIP
42	1966	11,141.06	RUA	SAO PAULO	ZHIP
43	1968	5,219.78	RUA	DOS TUPIS	ZHIP
44	1968	4,740.59	RUA	RIO DE JANEIRO	ZHIP
45	1968	13,773.64	RUA	DOS TUPIS	ZHIP
46	1969	6,087.31	AVE	AFONSO PENA	ZHIP
47	1969	5,777.02	RUA	DA BAHIA	ZHIP
48	1970	7,510.00	RUA	DOS CARIJOS	ZHIP
49	1970	11,847.35	AVE	JOAO PINHEIRO	ZHIP
50	1970	17,742.04	AVE	AFONSO PENA	ZHIP
51	1971	13,130.13	RUA	DOS TUPIS	ZHIP
52	1971	2,727.64	RUA	ARAGUARI	ZHIP
53	1972	4,305.00	RUA	CURITIBA	ZHIP
54	1972	4,141.78	RUA	SAO PAULO	ZHIP
55	1972	4,276.29	RUA	DA BAHIA	ZHIP
56	1973	14,032.94	AVE	AMAZONAS	ZHIP
57	1974	16,267.05	RUA	DOS GOITACAZES	ZHIP
58	1974	14,736.00	RUA	ESPIRITO SANTO	ZHIP

59	1975	18,307.18	RUA	RIO DE JANEIRO	ZHIP
60	1976	19,196.26	AVE	AMAZONAS	ZHIP
61	1976	4,826.29	RUA	DOS GOITACAZES	ZHIP
62	1976	4,681.56	AVE	CRISTOVAO COLOMBO	ZCBH
63	1977	3,836.00	RUA	RIO GRANDE DO SUL	ZHIP
64	1978	1,984.98	PCA	CARLOS CHAGAS	ZCBH
65	1978	5,350.19	PCA	CARLOS CHAGAS	ZCBH
66	1978	2,821.00	RUA	TENENTE BRITO MELO	ZCBH
67	1978	9,762.00	RUA	DOS GUAJAJARAS	ZHIP
68	1978	4,989.15	RUA	ESPIRITO SANTO	ZHIP
69	1979	2,988.46	AVE	BRASIL	ZCBH
70	1979	3,106.92	RUA	DOS AIMORES	ZCBH
71	1979	2,016.00	RUA	ARAGUARI	ZCBH
72	1979	2,495.00	AVE	BRASIL	ZCBH
73	1979	6,230.00	AVE	AFONSO PENA	ZA
74	1980	6,967.00	RUA	LEVINDO LOPES	ZCBH
75	1980	7,445.50	AVE	CRISTOVAO COLOMBO	ZCBH
76	1980	5,537.00	RUA	TOME DE SOUZA	ZCBH
77	1980	14,104.31	AVE	ALVARES CABRAL	ZCBH
78	1980	2,480.00	AVE	GETULIO VARGAS	ZCBH
79	1980	3,461.33	AVE	DO CONTORNO	ZA
80	1981	3,118.87	RUA	DO OURO	ZA
81	1981	4,909.00	RUA	PADRE ODORICO	ZA
82	1981	4,601.00	RUA	LEVINDO LOPES	ZCBH
83	1981	9,707.00	AVE	ALVARES CABRAL	ZHIP
84	1981	4,625.00	RUA	PADRE MARINHO	ZCBH
85	1981	8,520.66	AVE	GETULIO VARGAS	ZCBH
86	1981	5,556.00	RUA	ESPIRITO SANTO	ZHIP
87	1982	30,433.65	RUA	DOS GUAJAJARAS	ZHIP
88	1982	6,473.27	AVE	BRASIL	ZCBH
89	1982	6,704.79	RUA	MATO GROSSO	ZCBH
90	1982	6,727.00	RUA	ESPIRITO SANTO	ZHIP
91	1982	12,401.00	RUA	RIO DE JANEIRO	ZHIP
92	1982	3,025.01	AVE	BRASIL	ZCBH
93	1983	3,419.45	RUA	DOS GUAJAJARAS	ZHIP
94	1983	3,163.00	AVE	BRASIL	ZCBH
95	1983	6,668.21	RUA	TOME DE SOUZA	ZCBH
96	1983	6,130.20	RUA	PARAIBA	ZCBH
97	1984	3,509.72	RUA	ANTONIO DE ALBUQUERQUE	ZCBH
98	1984	3,396.40	RUA	PERNAMBUCO	ZCBH
99	1984	6,907.00	AVE	AUGUSTO DE LIMA	ZCBH
100	1984	2,652.00	AVE	BRASIL	ZCBH
101	1984	4,323.69	AVE	DO CONTORNO	ZA
102	1985	2,914.12	RUA	ALAGOAS	ZCBH
103	1985	3,748.18	RUA	ALAGOAS	ZCBH
104	1986	14,910.71	RUA	COELHO DE SOUZA	ZCBH
105	1986	2,879.94	RUA	GENTIOS	ZA
106	1986	2,645.55	RUA	TENENTE BRITO MELO	ZCBH
107	1986	8,411.03	AVE	ALVARES CABRAL	ZCBH
108	1986	5,886.72	RUA	RIO GRANDE DO NORTE	ZCBH
109	1986	4,865.63	RUA	JUIZ DE FORA	ZCBH
110	1986	7,418.93	RUA	DA BAHIA	ZHIP
111	1987	3,005.44	RUA	RAUL POMPEIA	ZA
112	1987	2,444.87	AVE	FRANCISCO SALES	ZCBH
113	1987	18,527.84	RUA	PARAIBA	ZCBH
114	1987	7,010.64	RUA	DOS TIMBIRAS	ZCBH
115	1988	8,281.60	RUA	MATIAS CARDOSO	ZCBH
116	1988	7,674.00	RUA	MARTIM DE CARVALHO	ZCBH
117	1988	7,403.69	RUA	PARACATU	ZCBH
118	1988	5,181.08	RUA	DOMINGOS VIEIRA	ZCBH
119	1988	3,464.13	RUA	PADRE ROLIM	ZCBH
120	1988	4,939.59	RUA	RIO GRANDE DO NORTE	ZCBH
121	1988	3,517.47	RUA	DOS TIMBIRAS	ZCBH

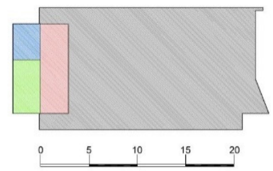
122	1989	5,727.66	RUA	CEARA	ZCBH
123	1989	6,387.39	RUA	DOS TUPIS	ZHIP
124	1989	10,789.09	AVE	ALVARES CABRAL	ZHIP
125	1989	624.28	RUA	DOS OTONI	ZCBH
126	1989	7,098.31	AVE	AMAZONAS	ZHIP
127	1989	14,005.75	RUA	SAO PAULO	ZHIP
128	1989	6,871.04	RUA	DOS TIMBIRAS	ZHIP
129	1989	5,722.24	AVE	DO CONTORNO	ZA
130	1989	4,983.07	AVE	DO CONTORNO	ZCBH
131	1989	2,913.39	AVE	DO CONTORNO	ZCBH
132	1989	3,047.94	AVE	DO CONTORNO	ZA
133	1990	2,679.01	RUA	LAVRAS	ZA
134	1990	2,557.68	RUA	VICOSA	ZA
135	1990	3,566.57	RUA	PROFESSOR MORAES	ZCBH
136	1990	14,793.97	RUA	DOS OTONI	ZCBH
137	1990	5,283.99	RUA	SERGIPE	ZCBH
138	1990	5,643.70	AVE	AFONSO PENA	ZCBH
139	1990	6,268.20	AVE	DO CONTORNO	ZCBH
140	1990	12,822.67	AVE	AFONSO PENA	ZCBH
141	1990	6,504.39	AVE	AFONSO PENA	ZCBH
142	1990	2,786.17	AVE	DO CONTORNO	ZCBH
143	1990	17,402.01	AVE	DO CONTORNO	ZCBH
144	1991	3,525.05	AVE	GETULIO VARGAS	ZCBH
145	1991	2,576.72	RUA	ULHOA CINTRA	ZCBH
146	1991	2,384.91	RUA	RODRIGUES CALDAS	ZCBH
147	1991	3,032.65	AVE	BIAS FORTES	ZCBH
148	1991	6,136.82	AVE	ANTONIO ABRAHAO CARAM	ZP2
149	1991	2,022.50	RUA	PARACATU	ZCBH
150	1991	5,371.46	RUA	FERNANDES TOURINHO	ZCBH
151	1991	11,702.08	AVE	PRUDENTE DE MORAIS	ZA
152	1991	7,574.72	AVE	RAJA GABAGLIA	ZA
153	1991	5,646.78	RUA	DOS TIMBIRAS	ZHIP
154	1992	7,646.67	RUA	PIAUI	ZCBH
155	1992	3,066.59	RUA	SANTA RITA DURAO	ZCBH
156	1992	7,964.89	AVE	BRASIL	ZCBH
157	1992	4,899.78	RUA	FERNANDES TOURINHO	ZCBH
158	1992	4,287.50	RUA	GERMANO TORRES	ZA
159	1992	3,707.65	RUA	DOMINGOS VIEIRA	ZCBH
160	1992	9,569.35	AVE	GETULIO VARGAS	ZCBH
161	1992	6,232.20	RUA	DOMINGOS VIEIRA	ZCBH
162	1992	8,502.01	AVE	GETULIO VARGAS	ZCBH
163	1992	3,917.87	AVE	PROFESSOR MAGALHAES PENIDO	ZAP
164	1992	7,040.25	RUA	RODRIGUES CALDAS	ZCBH
165	1992	5,207.18	RUA	GRAO PARA	ZCBH
166	1992	6,451.83	RUA	TOMAZ GONZAGA	ZCBH
167	1992	12,986.73	RUA	DOS GUAJAJARAS	ZHIP
168	1992	4,159.14	RUA	DOS INCONFIDENTES	ZCBH
169	1992	6,815.01	RUA	GONCALVES DIAS	ZCBH
170	1992	2,869.15	AVE	FRANCISCO SA	ZA
171	1992	8,496.19	RUA	PARAIBA	ZCBH
172	1992	7,662.56	RUA	CEARA	ZCBH
173	1992	9,850.94	AVE	BRASIL	ZCBH
174	1992	12,863.52	RUA	DOS TIMBIRAS	ZHIP
175	1993	4,209.12	AVE	NOSSA SENHORA DO CARMO	ZA
176	1993	4,440.60	RUA	DOMINGOS VIEIRA	ZCBH
177	1993	4,809.40	AVE	FRANCISCO SALES	ZA
178	1993	7,698.15	RUA	BARAO DE MACAUBAS	ZA
179	1993	3,100.84	AVE	BERNARDO MONTEIRO	ZCBH
180	1993	13,117.05	RUA	PARAIBA	ZCBH
181	1993	14,899.02	AVE	RAJA GABAGLIA	ZAR2
182	1993	3,116.68	RUA	PARACATU	ZCBH
183	1993	3,212.49	RUA	TENENTE BRITO MELO	ZCBH
184	1993	16,056.49	RUA	DOS GOITACAZES	ZCBH

185	1993	2,341.09	RUA	CEARA	ZCBH
186	1993	4,263.47	AVE	DO CONTORNO	ZA
187	1993	11,055.11	AVE	DO CONTORNO	ZA
188	1993	3,122.41	AVE	DO CONTORNO	ZA
189	1994	4,733.84	RUA	DO URUGUAI	ZA
190	1994	5,798.77	RUA	GOIAS	ZHIP
191	1994	3,384.13	RUA	UBERABA	ZCBH
192	1994	4,307.32	RUA	DOS GOITACAZES	ZHIP
193	1994	11,095.21	RUA	RIO GRANDE DO SUL	ZCBH
194	1994	4,070.43	RUA	FRANCISCO DESLANDES	ZCBH
195	1994	5,767.49	RUA	PARAIBA	ZCBH
196	1994	5,045.63	RUA	ALAGOAS	ZCBH
197	1994	3,447.50	RUA	SAO PAULO	ZHIP
198	1994	13,021.93	AVE	GETULIO VARGAS	ZCBH
199	1994	3,459.72	AVE	ALVARES CABRAL	ZCBH
200	1994	7,600.63	AVE	FRANCISCO SALES	ZCBH
201	1994	13,422.49	AVE	ALVARES CABRAL	ZCBH
202	1994	10,741.38	AVE	DOS ANDRADAS	ZCBH
203	1994	4,711.04	AVE	AFONSO PENA	ZA
204	1994	5,192.06	AVE	DO CONTORNO	ZA
205	1994	5,798.77	AVE	DO CONTORNO	ZCBH
206	1995	7,774.01	AVE	PASTEUR	ZCBH
207	1995	2,992.11	RUA	PERNAMBUCO	ZCBH
208	1995	9,529.30	RUA	TEIXEIRA DE FREITAS	ZA
209	1995	25,011.05	AVE	AUGUSTO DE LIMA	ZHIP
210	1995	4,287.98	RUA	AMERICO LUZ	ZA
211	1995	2,748.35	RUA	PARACATU	ZCBH
212	1995	9,904.47	RUA	DOS OTONI	ZCBH
213	1995	3,398.16	RUA	CATETE	ZA
214	1995	7,834.85	RUA	ALAGOAS	ZCBH
215	1995	8,095.02	AVE	RAJA GABAGLIA	ZAR2
216	1995	4,161.05	AVE	BRASIL	ZCBH
217	1995	12,077.35	RUA	DOS TIMBIRAS	ZHIP
218	1995	6,055.74	AVE	DO CONTORNO	ZCBH
219	1995	64,556.00	AVE	AFONSO PENA	ZA
220	1995	2,797.58	AVE	DO CONTORNO	ZA
221	1995	4,306.41	AVE	DO CONTORNO	ZCBH
222	1996	6,526.47	RUA	JUIZ DE FORA	ZCBH
223	1996	12,064.11	RUA	TENENTE GARRO	ZA
224	1996	8,349.53	AVE	PROFESSOR ALFREDO BALENA	ZCBH
225	1996	7,760.98	AVE	ALVARES CABRAL	ZHIP
226	1996	3,741.54	AVE	ALVARES CABRAL	ZHIP
227	1996	8,129.50	RUA	PARAIBA	ZCBH
228	1996	6,701.66	AVE	CRISTIANO MACHADO	ZAP
229	1996	5,594.36	RUA	DOS GUAJAJARAS	ZCBH
230	1996	6,151.44	AVE	NOSSA SENHORA DO CARMO	ZA
231	1996	4,394.24	AVE	AFONSO PENA	ZA
232	1997	3,890.98	RUA	DO OURO	ZA
233	1997	11,963.63	AVE	PRUDENTE DE MORAIS	ZA
234	1997	2,491.00	AVE	DOM PEDRO II	ZA
235	1997	3,359.02	RUA	TENENTE BRITO MELO	ZCBH
236	1997	3,033.63	AVE	ALVARES CABRAL	ZCBH
237	1997	10,392.38	RUA	DA BAHIA	ZCBH
238	1998	3,975.39	RUA	JUIZ DE FORA	ZCBH
239	1998	9,252.01	RUA	TOME DE SOUZA	ZCBH
240	1998	13,186.05	RUA	PERNAMBUCO	ZCBH
241	1998	4,574.48	RUA	ANTONIO DE ALBUQUERQUE	ZCBH
242	1998	8,547.63	RUA	DOS GUAJAJARAS	ZHIP
243	1998	3,967.91	AVE	BRASIL	ZCBH
244	1998	8,735.00	AVE	AFONSO PENA	ZCBH
245	1998	5,458.70	AVE	DO CONTORNO	ZA
246	1998	5,157.40	AVE	DO CONTORNO	ZA
247	1998	5,399.09	AVE	DO CONTORNO	ZCBH

248	1999	2,558.07	RUA	PROFESSOR MAGALHAES DRUMOND	ZA
249	1999	5,342.14	RUA	HERCULANO DE FREITAS	ZA
250	1999	7,856.87	RUA	BERNARDO GUIMARAES	ZCBH
251	1999	7,454.20	RUA	ARAGUARI	ZCBH
252	1999	9,205.97	AVE	GETULIO VARGAS	ZCBH
253	1999	3,784.16	AVE	ALVARES CABRAL	ZCBH
254	1999	8,570.77	AVE	RAJA GABAGLIA	ZA
255	1999	4,461.71	RUA	PERNAMBUCO	ZCBH
256	1999	6,845.46	RUA	ALVARENGA PEIXOTO	ZCBH
257	1999	15,373.44	AVE	BRASIL	ZCBH
258	1999	5,217.25	AVE	AFONSO PENA	ZCBH
259	1999	9,083.26	AVE	BARAO HOMEM DE MELO	ZAR1
260	2000	5,057.66	RUA	POUSO ALTO	ZA
261	2000	6,620.66	RUA	JORNALISTA DJALMA ANDRADE	ZP2
262	2000	3,967.93	RUA	RIO GRANDE DO NORTE	ZCBH
263	2000	3,001.79	RUA	MARCO AURELIO DE MIRANDA	ZAR2
264	2000	7,675.76	RUA	DESEMBARGADOR JORGE FONTANA	ZP3
265	2000	3,808.03	RUA	FELIPE DOS SANTOS	ZCBH
266	2000	9,180.92	AVE	AFONSO PENA	ZHIP
267	2000	8,001.30	AVE	BARAO HOMEM DE MELO	ZAR1
268	2000	9,946.34	AVE	DO CONTORNO	ZA
269	2000	6,253.63	AVE	DO CONTORNO	ZA
270	2001	6,585.98	RUA	DOS AIMORES	ZCBH
271	2001	6,678.04	RUA	ANTONIO DE ALBUQUERQUE	ZCBH
272	2001	2,746.96	RUA	DOS GUAJAJARAS	ZHIP
273	2001	3,980.38	RUA	SERGIPE	ZCBH
274	2001	4,364.82	AVE	AFONSO PENA	ZCBH
275	2001	6,464.49	AVE	AFONSO PENA	ZA
276	2002	6,762.44	AVE	PRUDENTE DE MORAIS	ZA
277	2002	3,470.74	RUA	PADRE ROLIM	ZCBH
278	2002	4,089.24	RUA	FELIPE DOS SANTOS	ZCBH
279	2002	3,390.66	RUA	FERNANDES TOURINHO	ZCBH
280	2002	2,765.57	AVE	PROFESSOR MARIO WERNECK	ZAR2
281	2003	6,895.88	AVE	LUIZ PAULO FRANCO	ZP3
282	2003	6,300.55	RUA	ALVARES MACIEL	ZCBH
283	2003	3,400.02	RUA	OURO PRETO	ZCBH
284	2004	10,157.88	AVE	BIAS FORTES	ZCBH
285	2004	9,033.63	RUA	FRANCISCO DESLANDES	ZA
286	2006	7,484.42	RUA	ANDALUZITA	ZA
287	2006	9,669.08	RUA	UBERABA	ZCBH
288	2006	2,764.90	AVE	BRASIL	ZCBH
289	2006	14,765.40	AVE	RAJA GABAGLIA	ZAR2
290	2006	3,087.33	RUA	SERGIPE	ZCBH
291	2006	24,008.11	AVE	DO CONTORNO	ZCBH
292	2007	32,842.92	AVE	RAJA GABAGLIA	ZAR2
293	2007	11,295.68	AVE	AFONSO PENA	ZA
294	2008	5,149.90	AVE	BERNARDO MONTEIRO	ZCBH
295	2009	4,159.04	RUA	GONCALVES DIAS	ZCBH
296	2009	13,572.00	RUA	LEVINDO LOPES	ZCBH
297	2009	8,409.52	RUA	MATO GROSSO	ZCBH
298	2010	8,285.75	AVE	BARAO HOMEM DE MELO	ZAR1

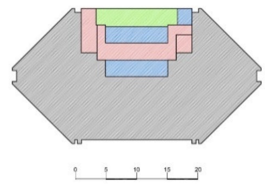
Sample 1

Description		(M^2)	(%)
Vertical Distribution		16	5%
Horizontal Distribution*		11	3%
Technical Area		27	9%
Working Area		252	83%
Floor Area		**305**	



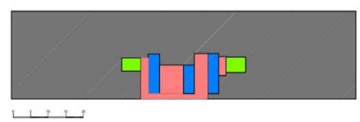
Sample 2

Description		(M^2)	(%)
Vertical Distribution		101	15%
Horizontal Distribution*		48	7%
Technical Area		26	4%
Working Area		520	75%
Floor Area		**695.14**	



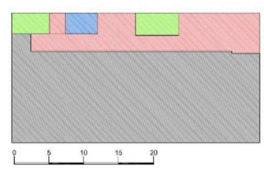
Sample 3

Description		(M^2)	(%)
Vertical Distribution		141	6%
Horizontal Distribution*		103	4%
Technical Area		55	2%
Working Area		2115	88%
Floor Area		**2414.05**	



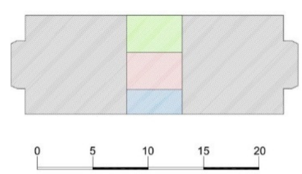
Sample 4

Description		(M^2)	(%)
Vertical Distribution		49	8%
Horizontal Distribution*		74	11%
Technical Area		65	10%
Working Area		466	71%
Floor Area		**654.1**	



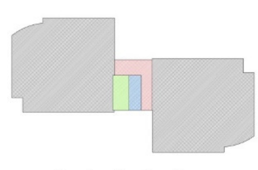
Sample 5

Description		(M^2)	(%)
Vertical Distribution		28	13%
Horizontal Distribution*		17	8%
Technical Area		0	0%
Working Area		172	80%
Floor Area		**215.6**	

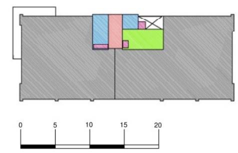


Sample 6

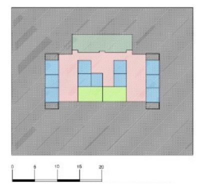
Description		(M^2)	(%)
Vertical Distribution		29	5%
Horizontal Distribution*		28	5%
Technical Area		44	8%
Working Area		478	83%
Floor Area		**579**	



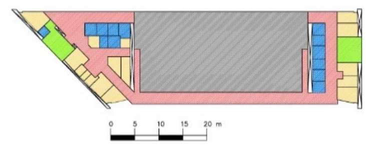
Sample 7		
Description	**(M^2)**	**(%)**
Vertical Distribution	32	9%
Horizontal Distribution*	10	3%
Technical Area	2	1%
Working Area	325	88%
Floor Area	**369.19**	



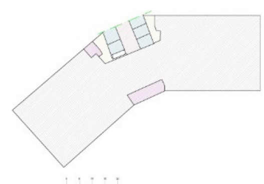
Sample 8		
Description	**(M^2)**	**(%)**
Vertical Distribution	143	11%
Horizontal Distribution*	136	10%
Technical Area	53	4%
Working Area	1005	75%
Floor Area	**1336.5**	



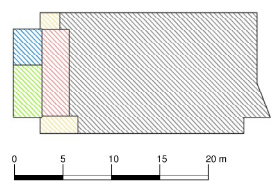
Sample 9		
Description	**(M^2)**	**(%)**
Vertical Distribution	118	10%
Horizontal Distribution*	293	25%
Technical Area	181	15%
Working Area	583	50%
Floor Area	**1174.96**	



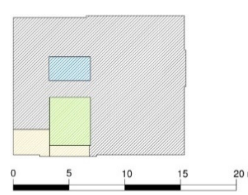
Sample 10		
Description	**(M^2)**	**(%)**
Vertical Distribution	121	4%
Horizontal Distribution*	69	2%
Technical Area	179	6%
Working Area	2540	87%
Floor Area	**2909.33**	



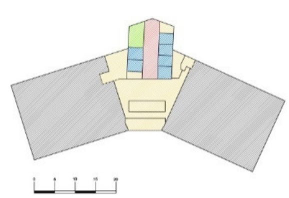
Sample 11		
Description	**(M^2)**	**(%)**
Vertical Distribution	27	9%
Horizontal Distribution*	25	8%
Technical Area	11	3%
Working Area	242	79%
Floor Area	**304.87**	



Sample 12		
Description	**(M^2)**	**(%)**
Vertical Distribution	24	12%
Horizontal Distribution*	-	#VALOR!
Technical Area	11	6%
Working Area	158	82%
Floor Area	**192.47**	

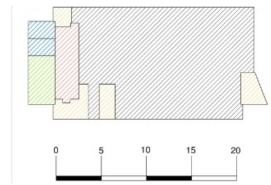


Sample 13		
Description	**(M^2)**	**(%)**
Vertical Distribution	82	6%
Horizontal Distribution*	54	4%
Technical Area	240	19%
Working Area	910	71%
Floor Area	**1284.97**	



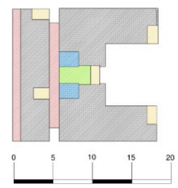
Sample 14

Description	(M²)	(%)
Vertical Distribution	27	9%
Horizontal Distribution*	22	7%
Technical Area	28	9%
Working Area	223	74%
Floor Area	**301**	



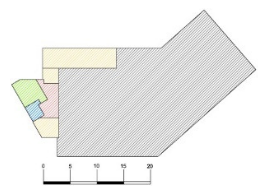
Sample 15

Description	(M²)	(%)
Vertical Distribution	19	7%
Horizontal Distribution*	35	14%
Technical Area	15	6%
Working Area	188	73%
Floor Area	**256.92**	



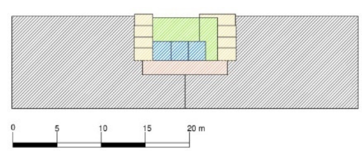
Sample 16

Description	(M²)	(%)
Vertical Distribution	29	4%
Horizontal Distribution*	20	3%
Technical Area	75	10%
Working Area	595	83%
Floor Area	**718.6**	



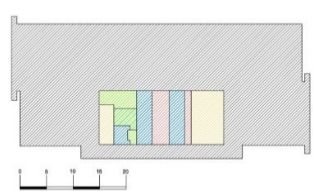
Sample 17

Description	(M²)	(%)
Vertical Distribution	35	9%
Horizontal Distribution*	15	4%
Technical Area	23	6%
Working Area	332	82%
Floor Area	**404.53**	



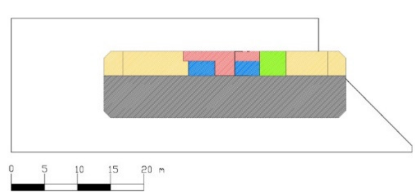
Sample 18

Description	(M²)	(%)
Vertical Distribution	110	8%
Horizontal Distribution*	45	3%
Technical Area	83	6%
Working Area	1097	82%
Floor Area	**1335.2**	



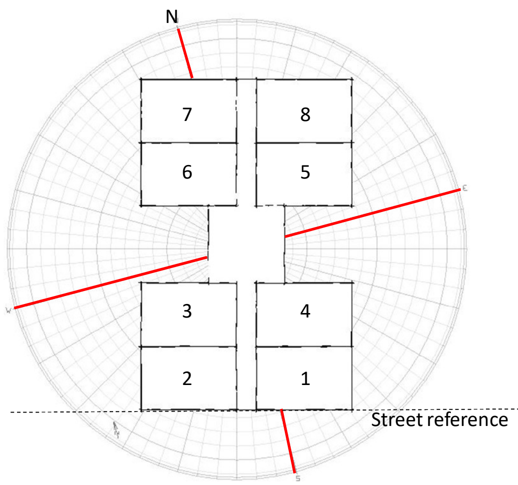
Sample 19

Description	(M²)	(%)
Vertical Distribution	31	9%
Horizontal Distribution*	23	6%
Technical Area	77	21%
Working Area	231	64%
Floor Area	**363**	

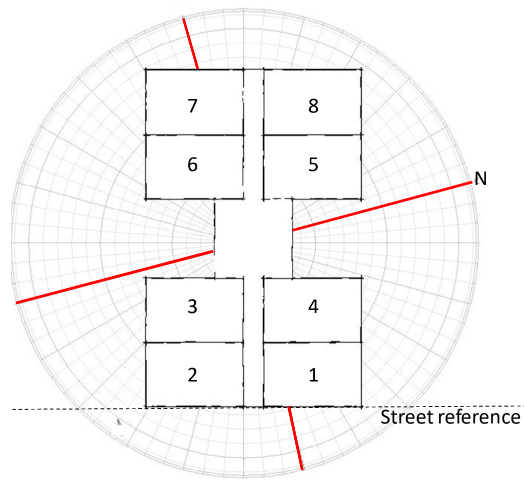


* Considered only public horizontal distribution

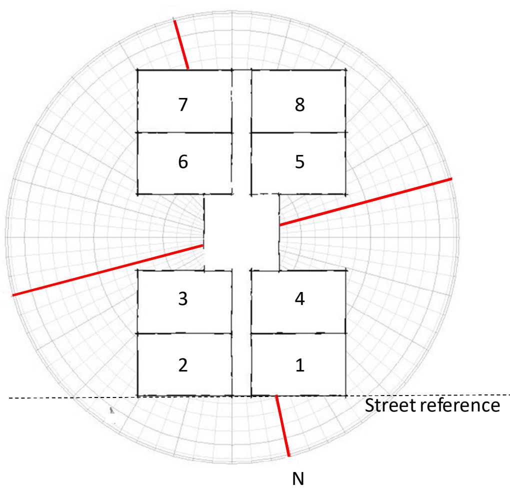
Archetype I orientations used during the simulations



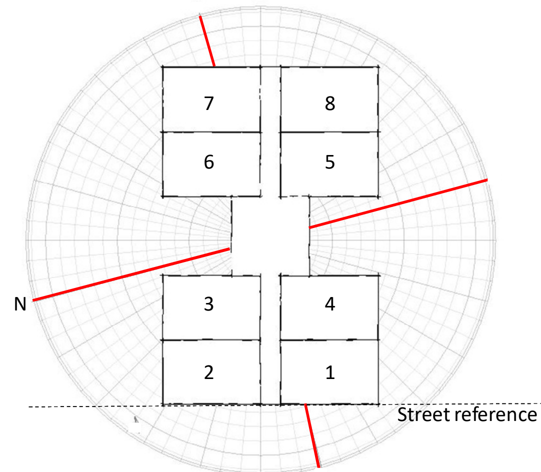
15° North Orientation



105° North Orientation

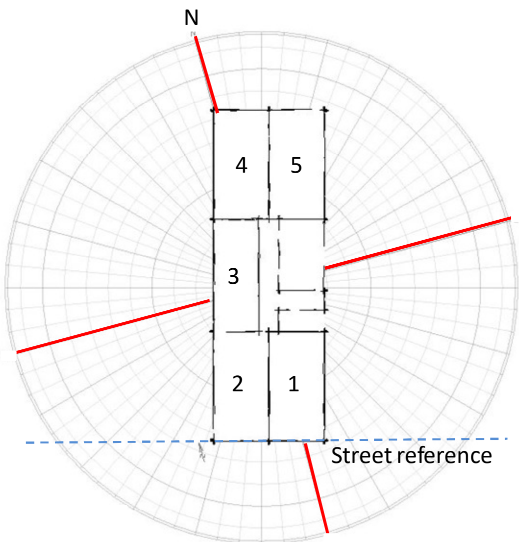


195° North Orientation

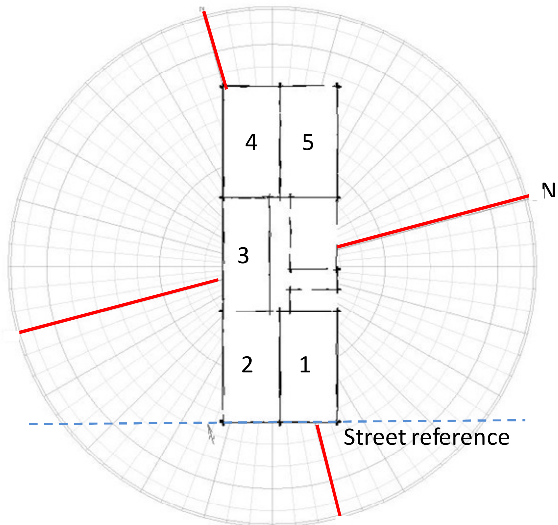


285° North Orientation

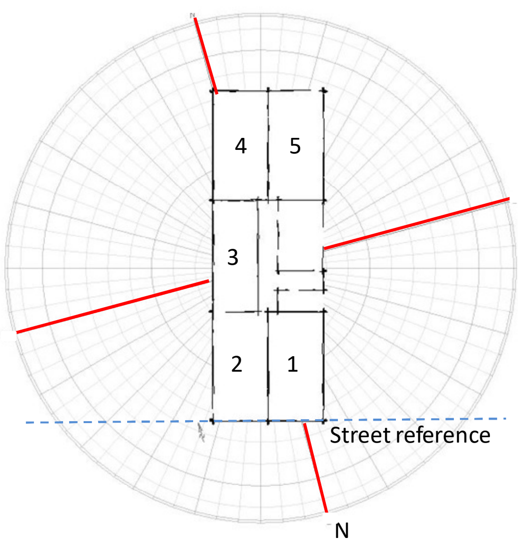
Archetype II and III_ A orientations used during the simulations



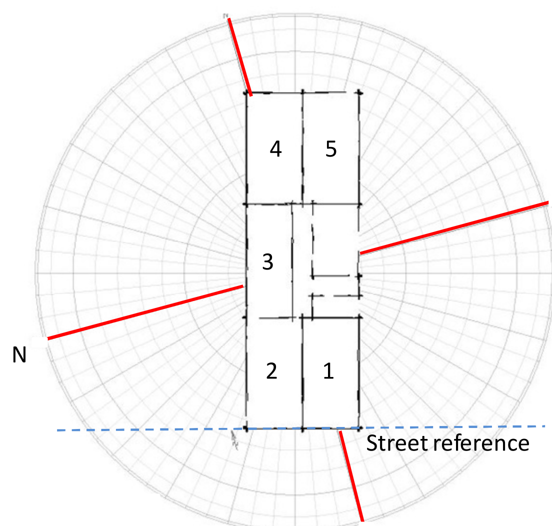
15° North Orientation



105° North Orientation

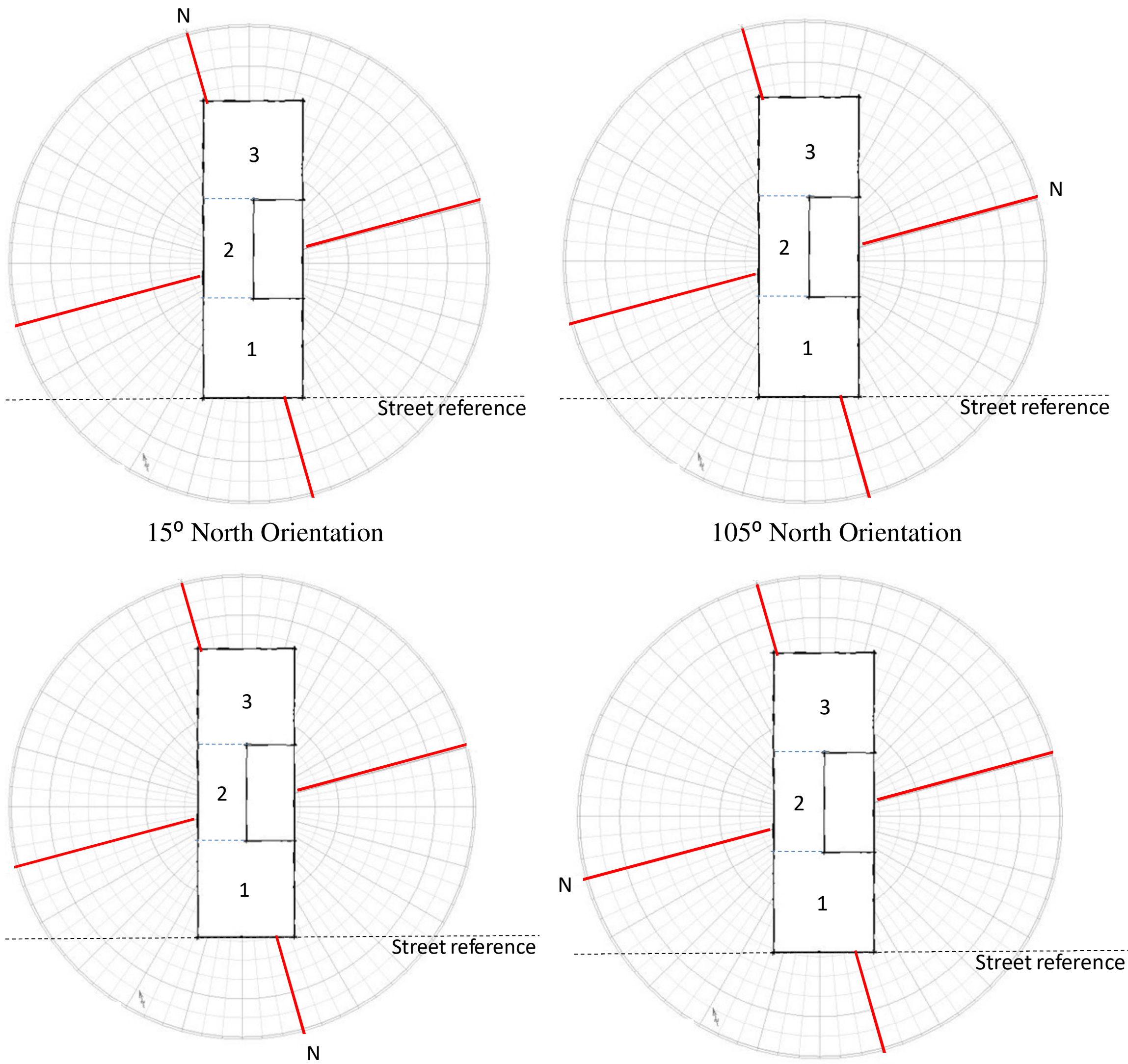


195° North Orientation



285° North Orientation

Archetype III_ B orientations used during the simulations



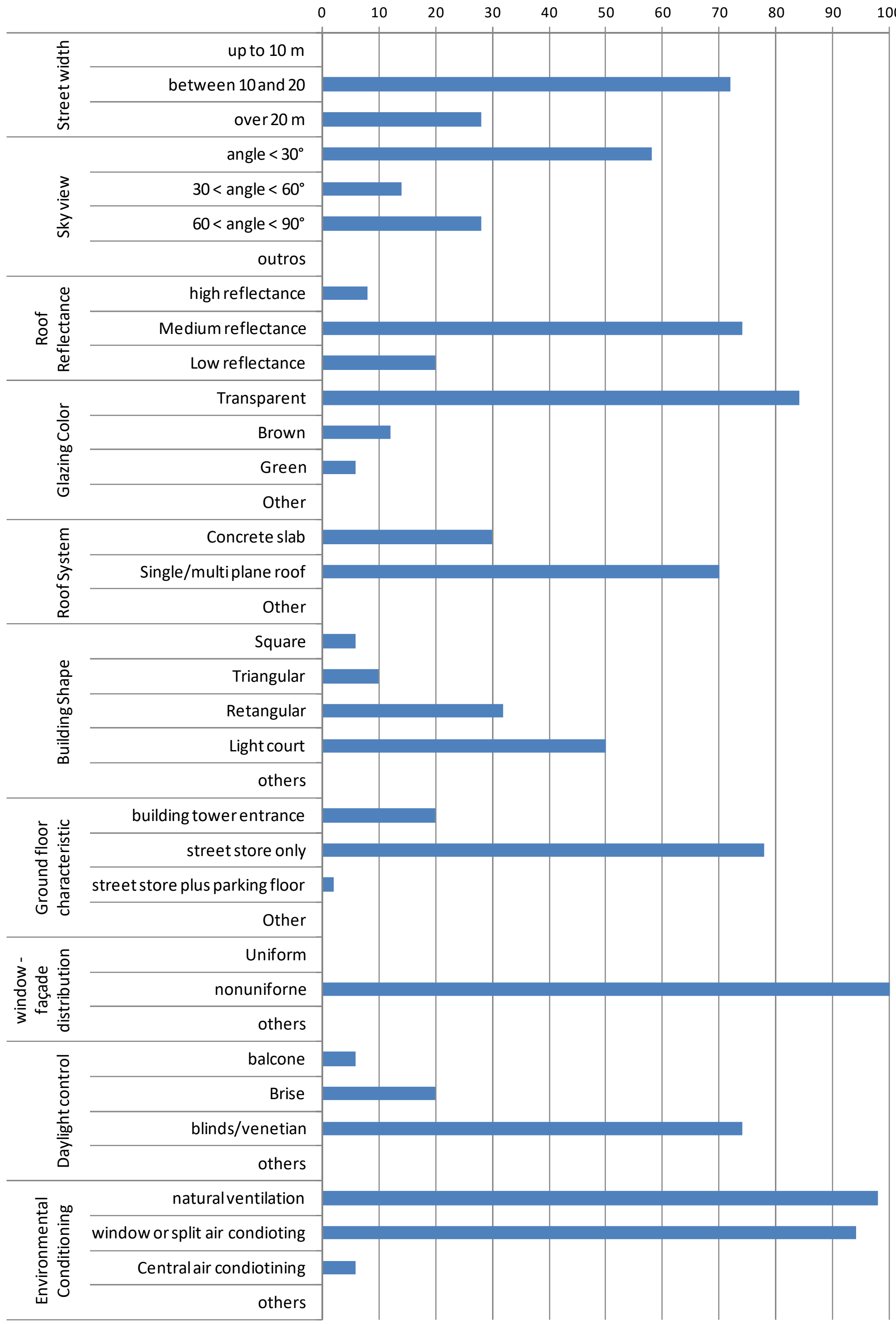
15º North Orientation 105º North Orientation

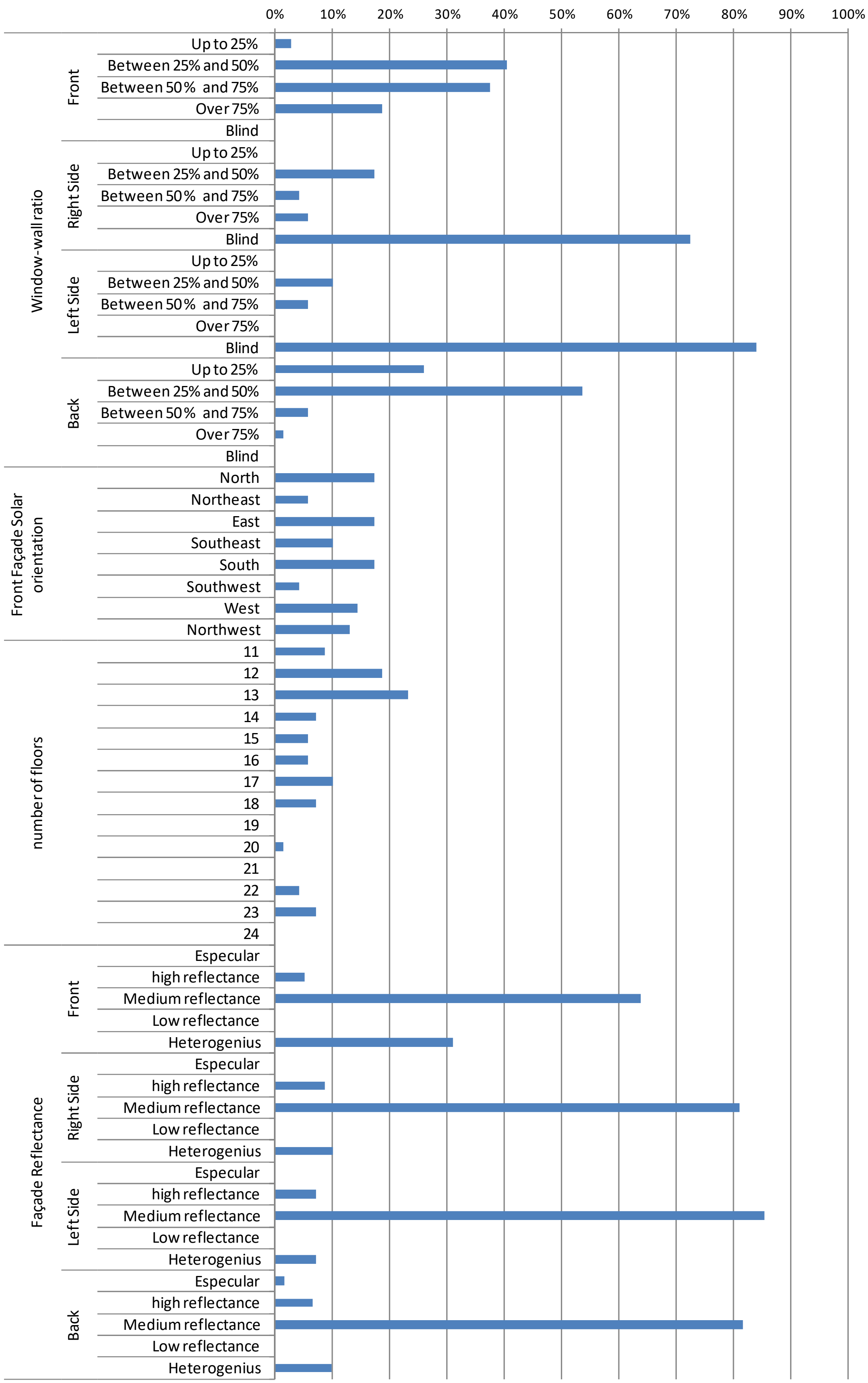
195º North Orientation 285º North Orientation

APPENDIX E - Office Building Stock Areas by year, city neighbourhood and building height

city neighbohood	centro-sul			leste			nordeste			noroeste			oeste			venda nova			barreiro			pampulha			norte			
	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	up to 4 floors	between 5 and 10	ove 10 floors	
1889/1919	8,000			14,219																								22,219
1920/1929							745																					745
1930/1939	2,866	1,388								442			5,870															10,566
1940/1949	22,873	45,750	58,924							1,242			1,471															130,260
1950/1959	20,183	54,480	102,112		2,308					1,094			82															180,259
1960/1969	40,258	78,239	303,349	874						1,587			2,542	1,915		1,015			973									430,753
1970/1974	39,825	23,159	153,031							2,116			428							123								218,681
1975/1977	37,396	115,193	67,874	200						600			1,715	1,710														224,689
1978/1979	22,899	117,413	60,044	252						1,969	1,187		2,068	6,631		136			2,897			4,229						219,725
1980/1981	25,923	73,189	92,676		3,478					1,396	879		1,553	2,367	3,461				1,726			3,383						210,032
1982/1984	21,189	64,970	114,140		332	4,324				908				1,110					6,340	4,408		2,146	4,590		432			224,888
1985/1989	26,589	64,925	245,420	3,738	830	5,722	1,792	217		10,782	1,588		1,798	8,695	3,048	1,774			1,638			23,092	794		1,231			403,671
1990/1994	59,116	112,317	527,086	4,615	6,291	9,478	3,891	7,382		13,718	5,291		3,840	8,007	16,123	1,359			1,652		4,053	12,887	3,985	10,055	4,411			815,557
1995/1997	25,842	63,320	179,194	4,151	467	18,766	2,535	831		10,611	4,951	2,491	5,283	24,080	10,144	2,908			1,866	1,762	5,002	10,663	1,194					376,060
1998/1999	16,021	79,705	151,186	1,450	3,393	1,726	3,954			5,762	4,323	1,364	6,129	10,856	26,145	3,447			618	6,961	4,629	3,914	1,798		946	1,569		335,896
2000/2004	27,430	59,168	144,978	10,979	9,866		5,505			8,105	6,037		37,204	63,040	21,060	4,351			1,302			12,265	8,107		6,442			425,840
2005/2011	42,676	97,593	160,909	1,310	5,392		4,647	1,989		1,652	3,206		10,101				2,278		1,552	1,117		9,252	2,616			952		347,243
	439,086	1,050,809	2,360,923	41,788	32,356	40,016	23,070	10,419	0	61,983	27,462	3,855	80,084	128,410	79,981	14,990	2,278	0	20,565	14,370	13,684	81,831	23,085	10,055	13,462	2,521	0	**4,577,083**
	3,850,818			114,160			33,489			93,300			288,475			17,268			48,619			114,970			15,983			

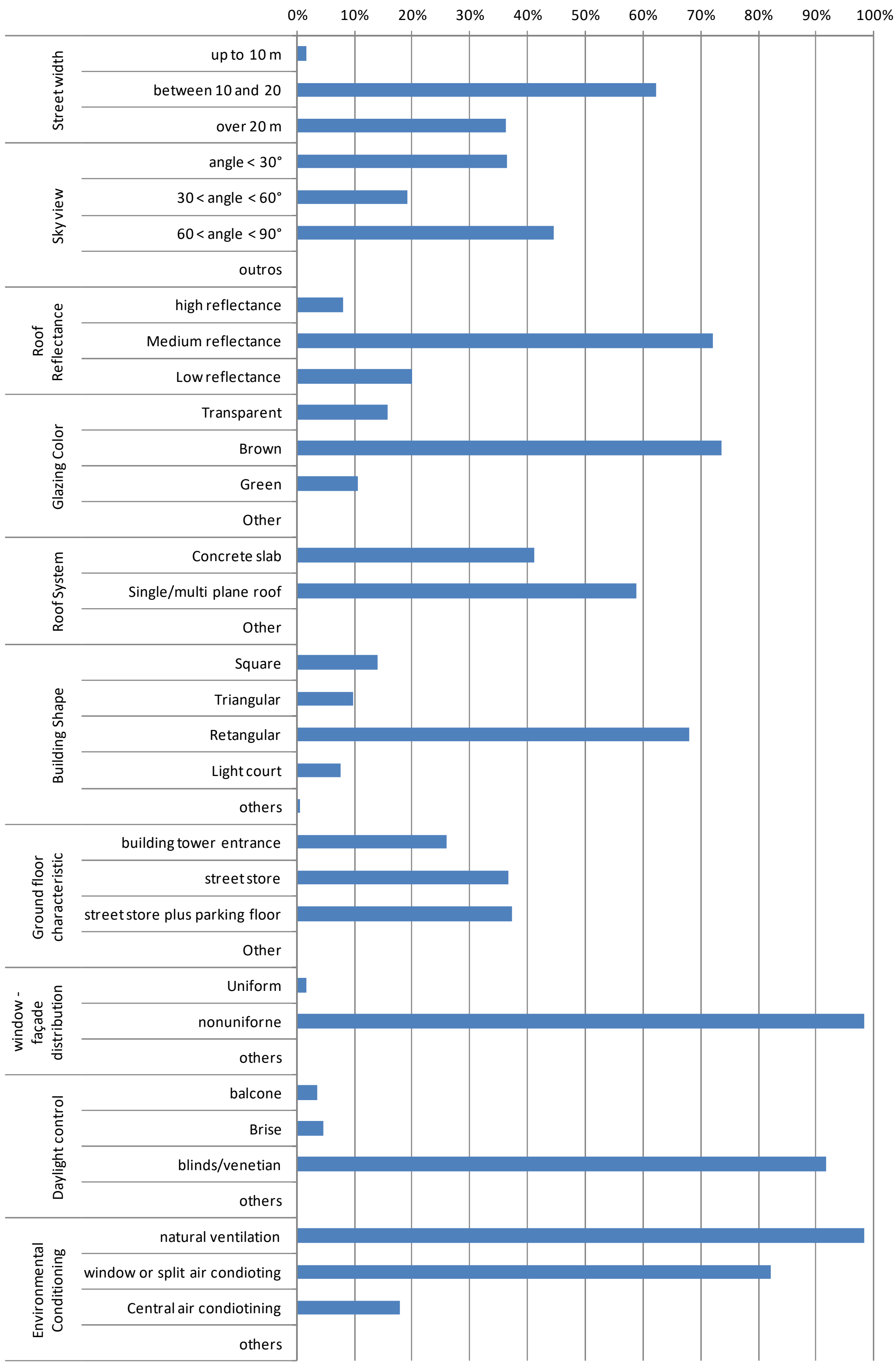
AMDs results of Class I buildings (% value)

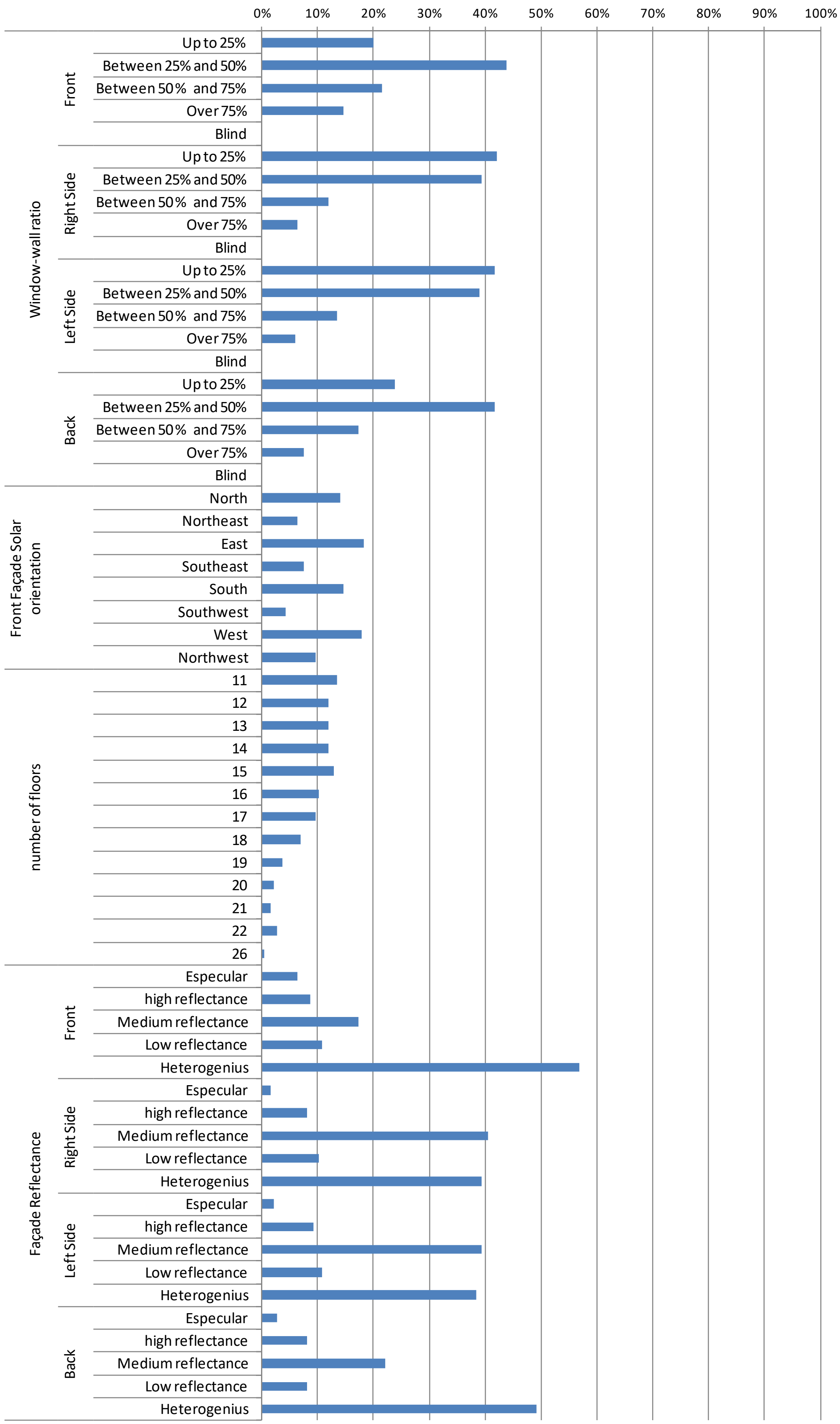




0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Window-wall ratio
Front
Right Side
Left Side
Back
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Front Façade Solar orientation
North
Northeast
East
Southeast
South
Southwest
West
Northwest
number of floors
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Façade Reflectance
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius

AMDs results of Class II buildings (% value)

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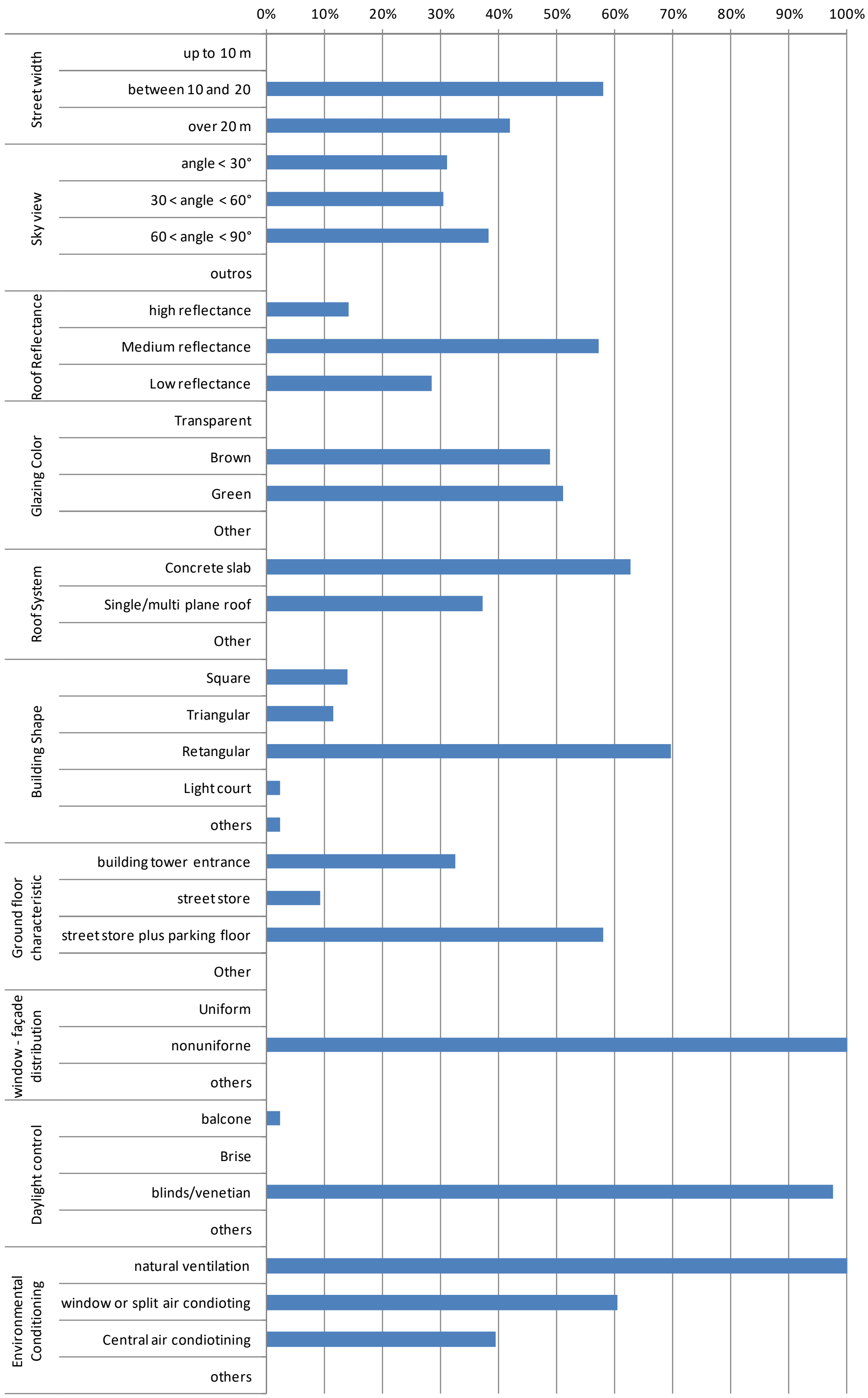
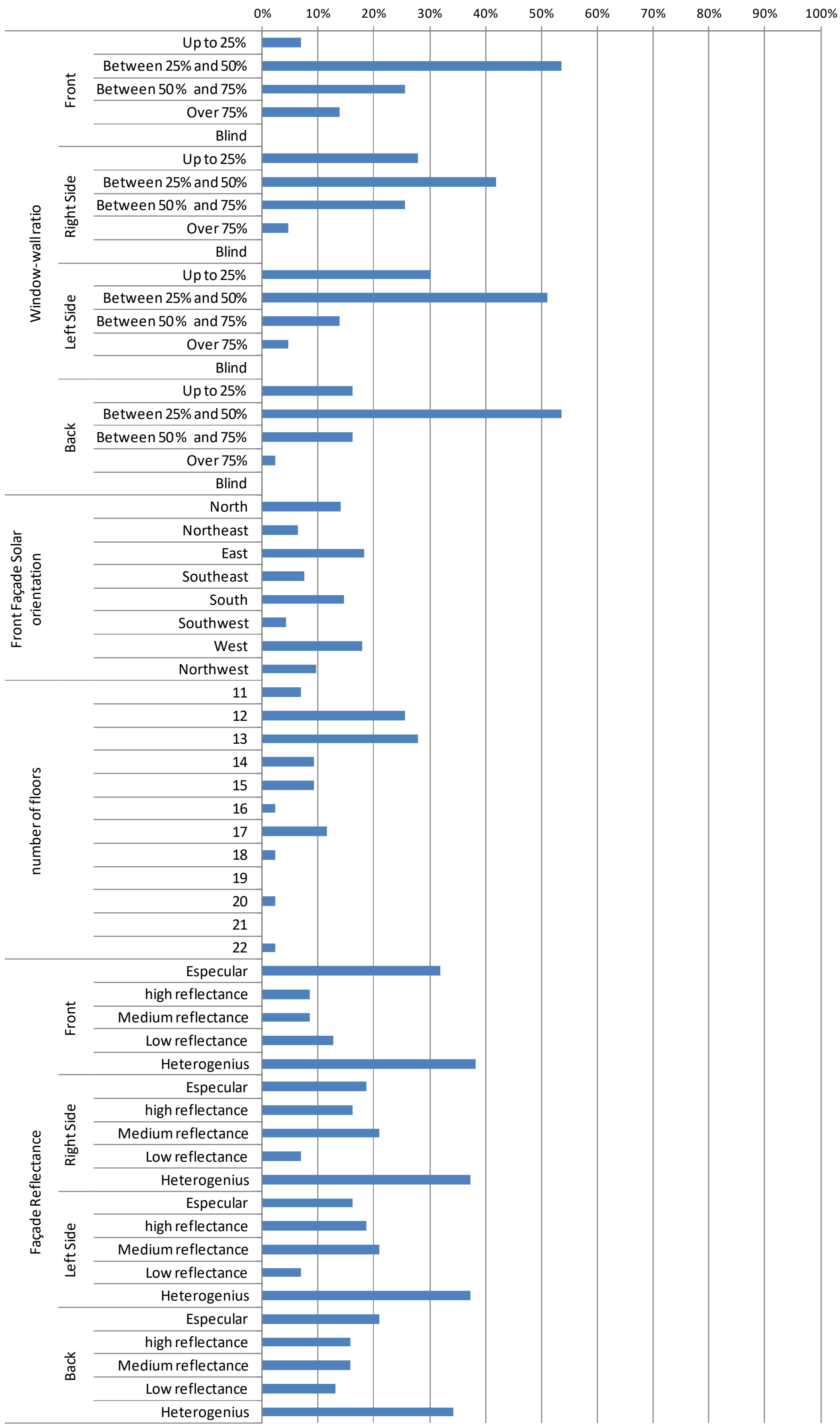
30%
40%
50%
60%
70%
80%
90%
100%
Window-wall ratio
Front
Right Side
Left Side
Back
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Front Façade Solar orientation
North
Northeast
East
Southeast
South
Southwest
West
Northwest
number of floors
11
12
13
14
15
16
17
18
19
20
21
22
26
Façade Reflectance
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius

AMDs results of Class III buildings (% value)




0%
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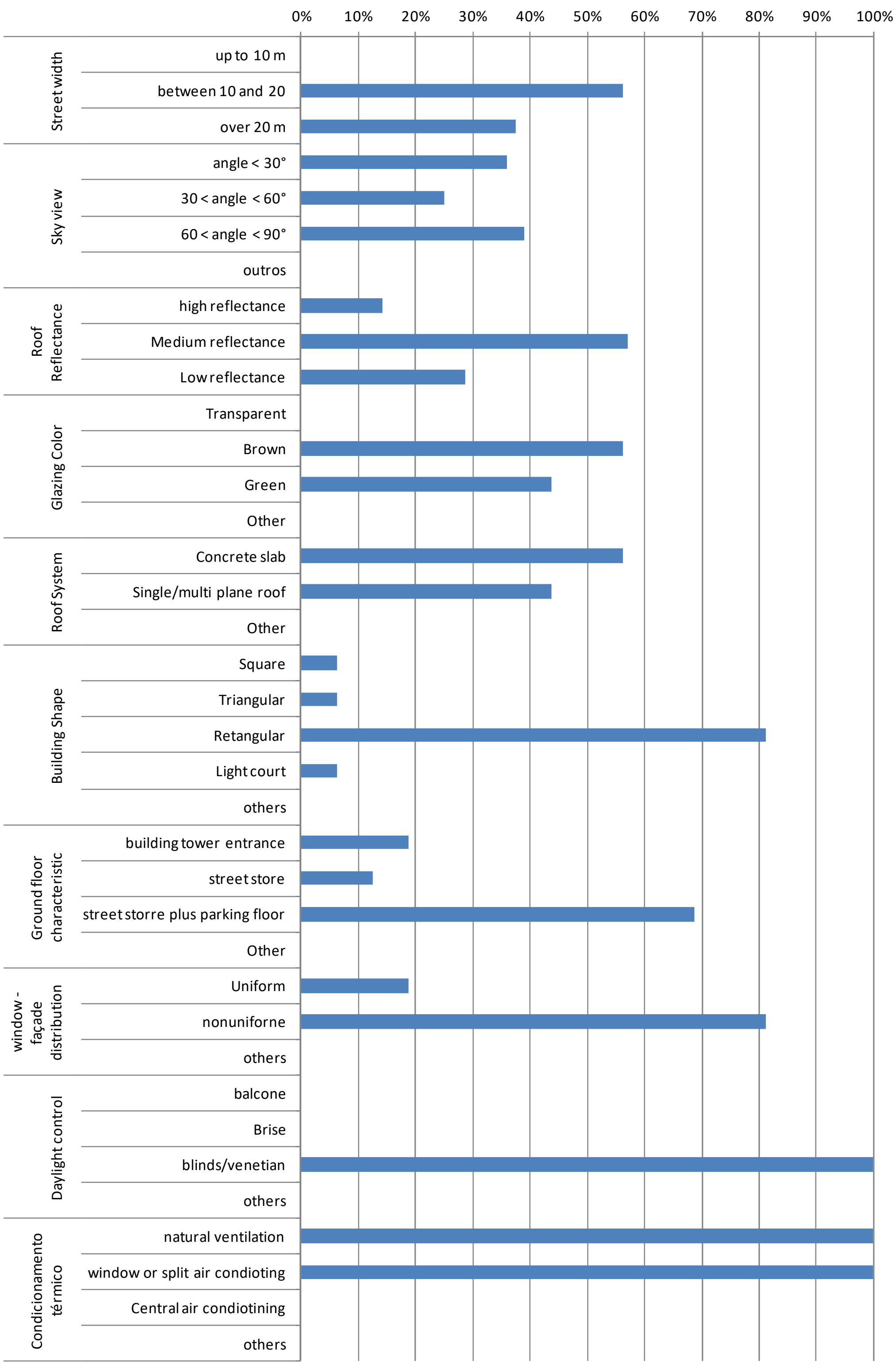
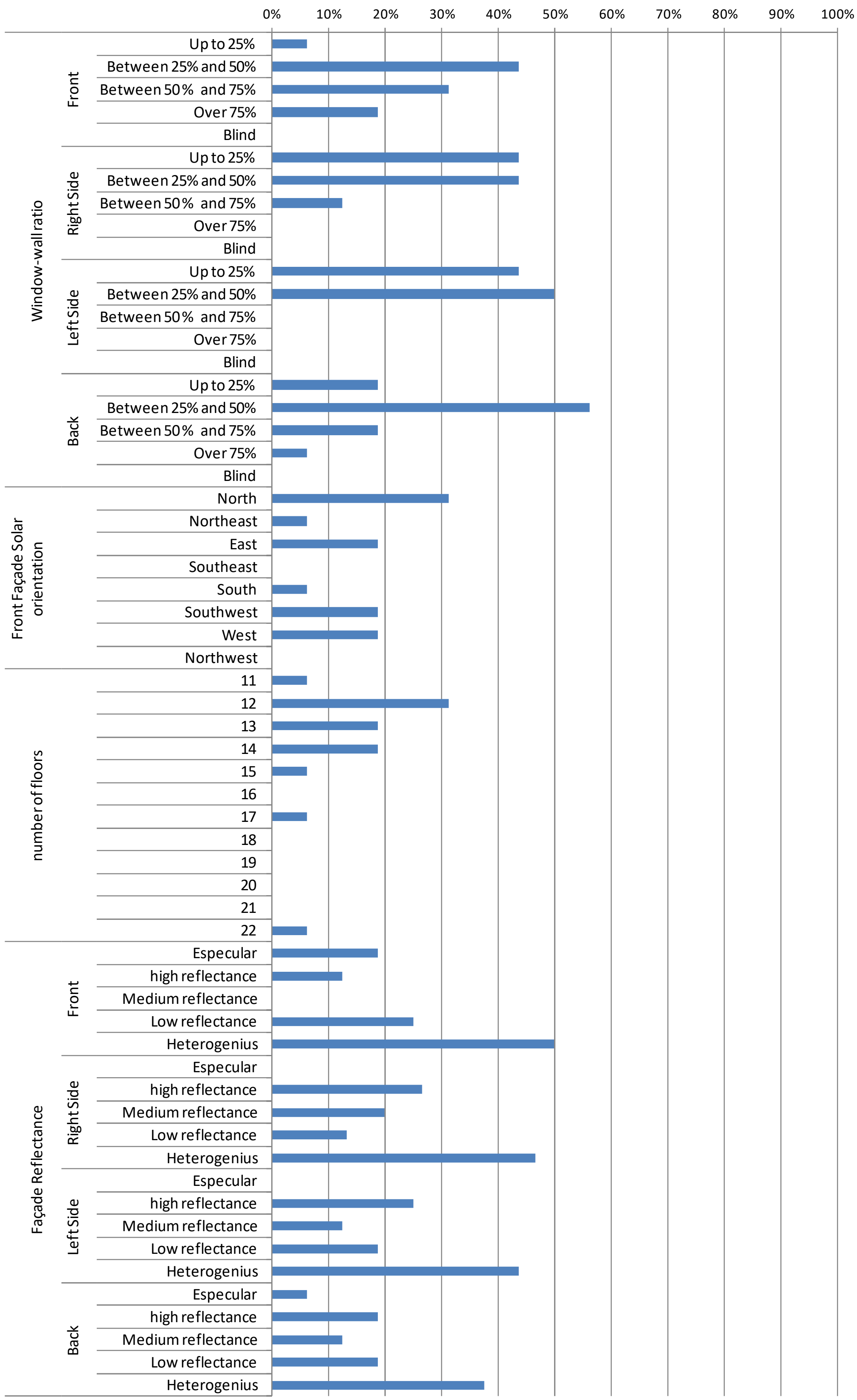
60%
70%
80%
90%
100%
Window-wall ratio
Front
Right Side
Left Side
Back
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Front Façade Solar orientation
North
Northeast
East
Southeast
South
Southwest
West
Northwest
number of floors
11
12
13
14
15
16
17
18
19
20
21
22
Façade Reflectance
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius

AMDs results of Class III_A buildings (% value)




0%
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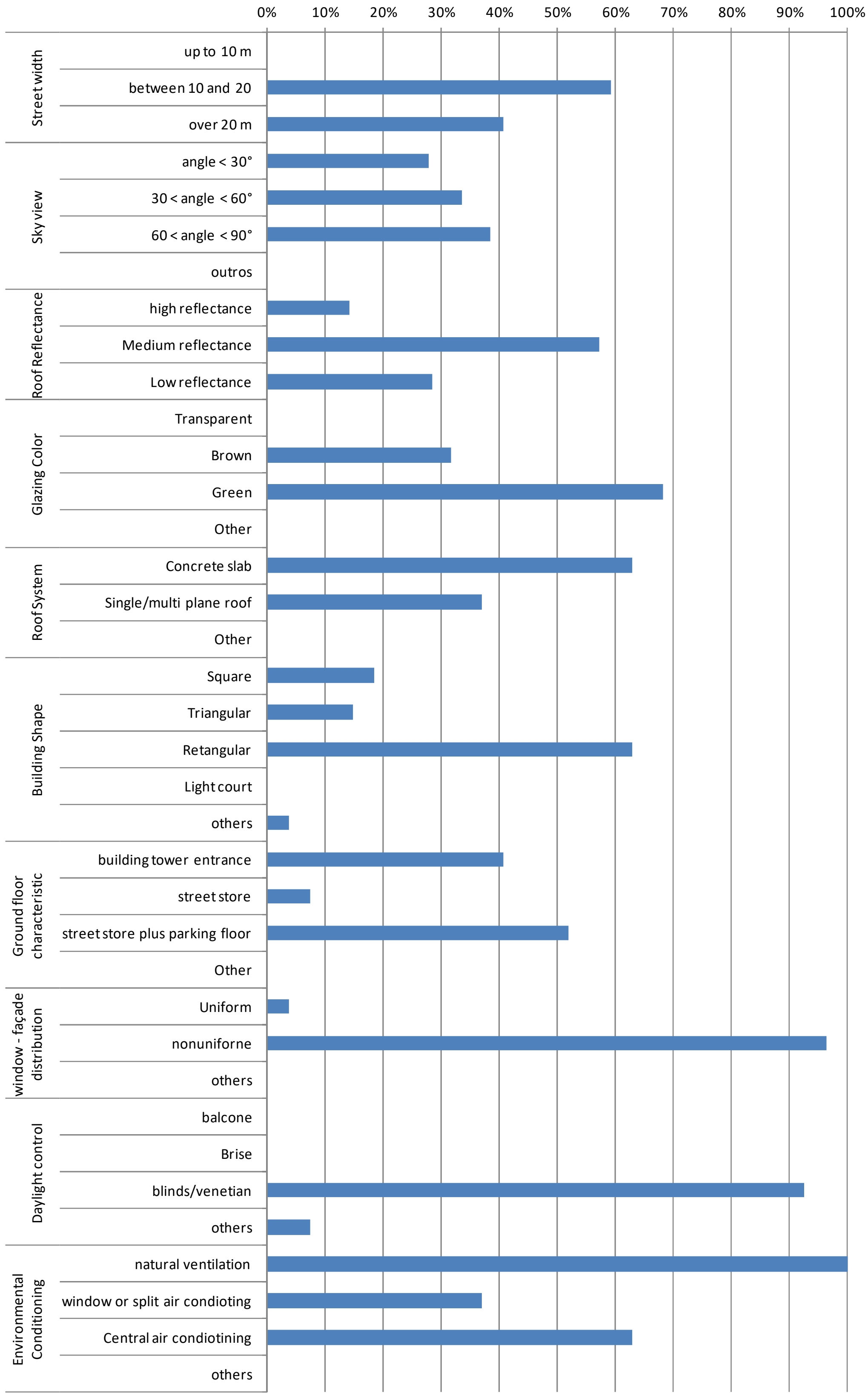
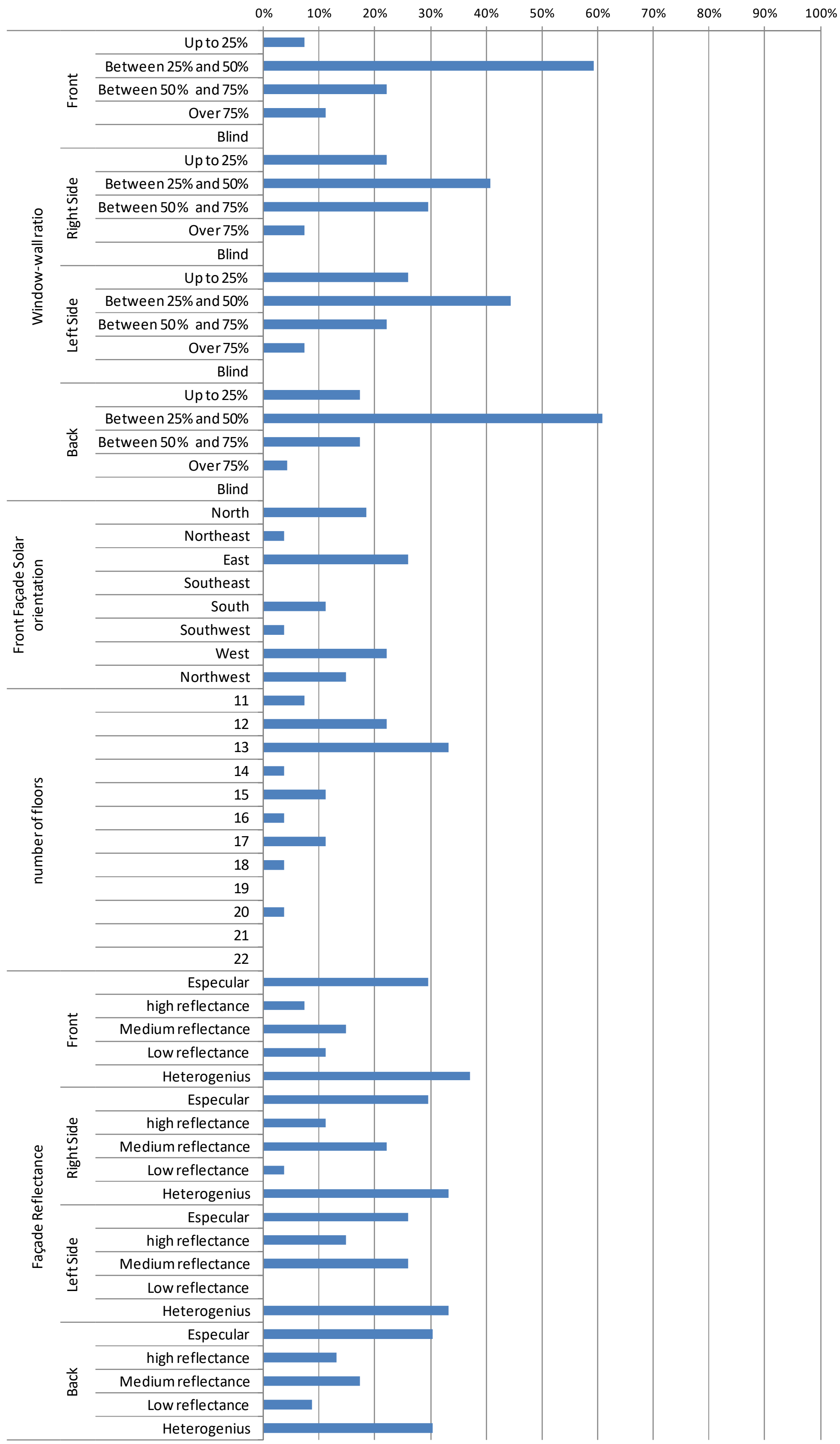
50%
60%
70%
80%
90%
100%
Window-wall ratio
Front
Right Side
Left Side
Back
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Front Façade Solar orientation
North
Northeast
East
Southeast
South
Southwest
West
Northwest
number of floors
11
12
13
14
15
16
17
18
19
20
21
22
Façade Reflectance
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius

AMDs results of Class III_B buildings (% value)

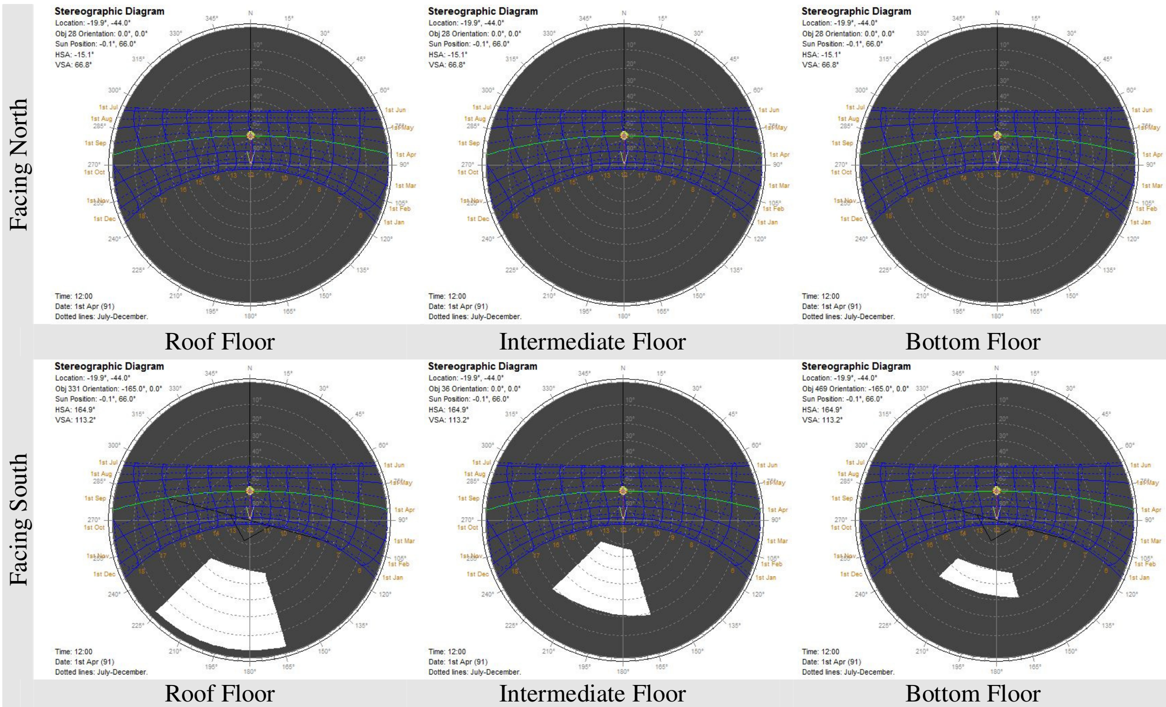




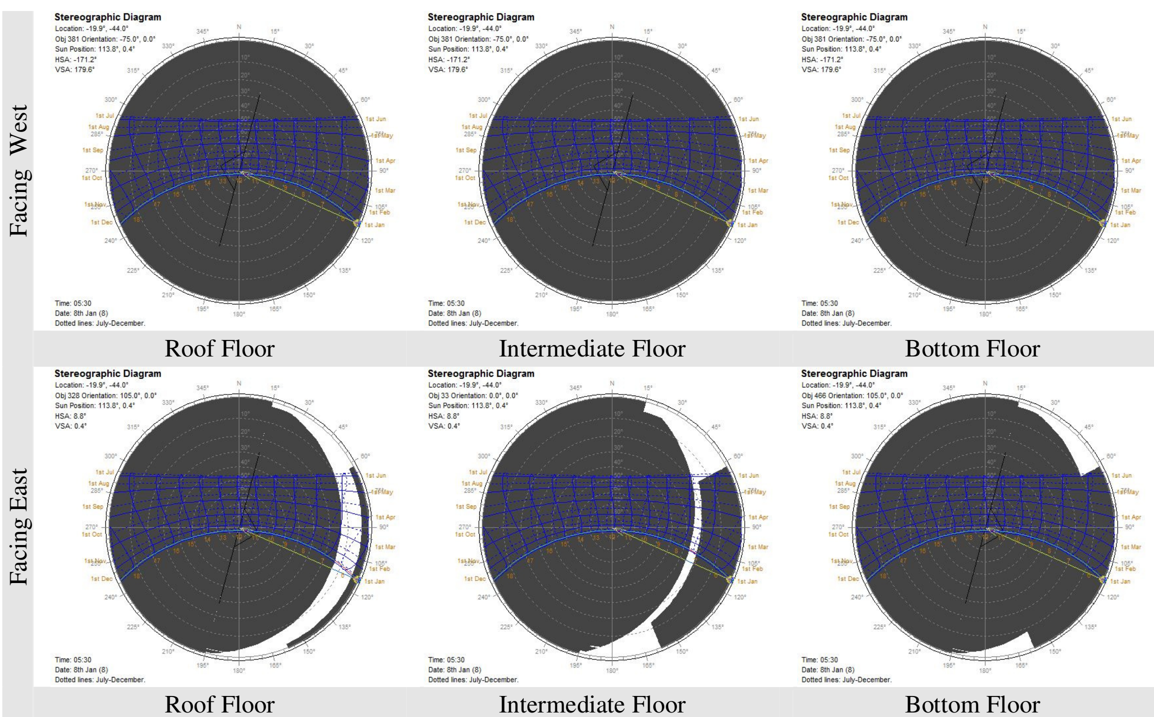
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Window-wall ratio
Front
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Right Side
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Left Side
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Back
Up to 25%
Between 25% and 50%
Between 50% and 75%
Over 75%
Blind
Front Façade Solar orientation
North
Northeast
East
Southeast
South
Southwest
West
Northwest
number of floors
11
12
13
14
15
16
17
18
19
20
21
22
Façade Reflectance
Front
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius
Right Side
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius
Left Side
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius
Back
Especular
high reflectance
Medium reflectance
Low reflectance
Heterogenius

Archetype I shading mask (based on the geometric centre of the window)

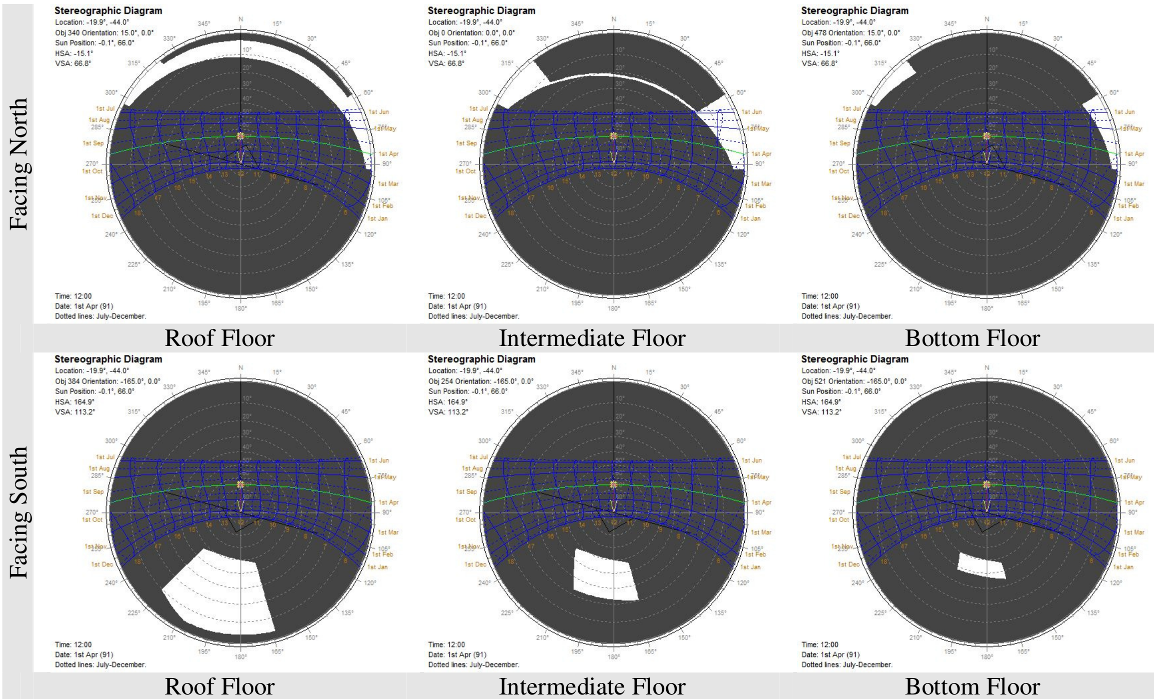
15° North Orientation



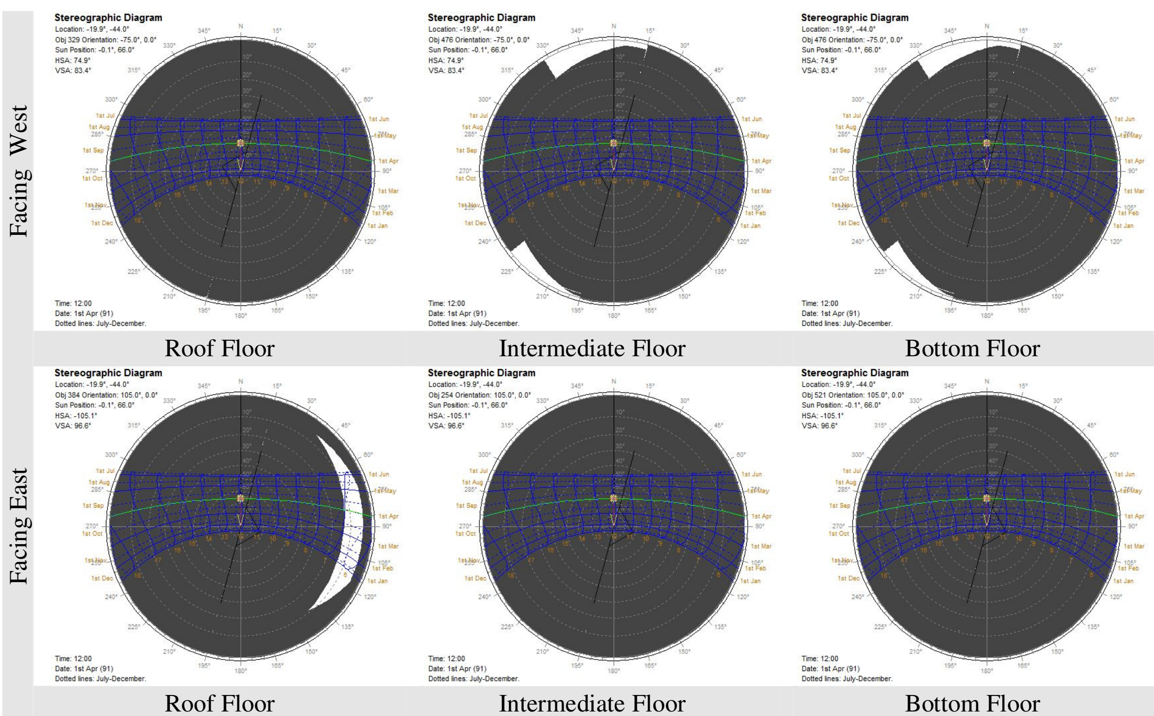
105° North Orientation



195° North Orientation

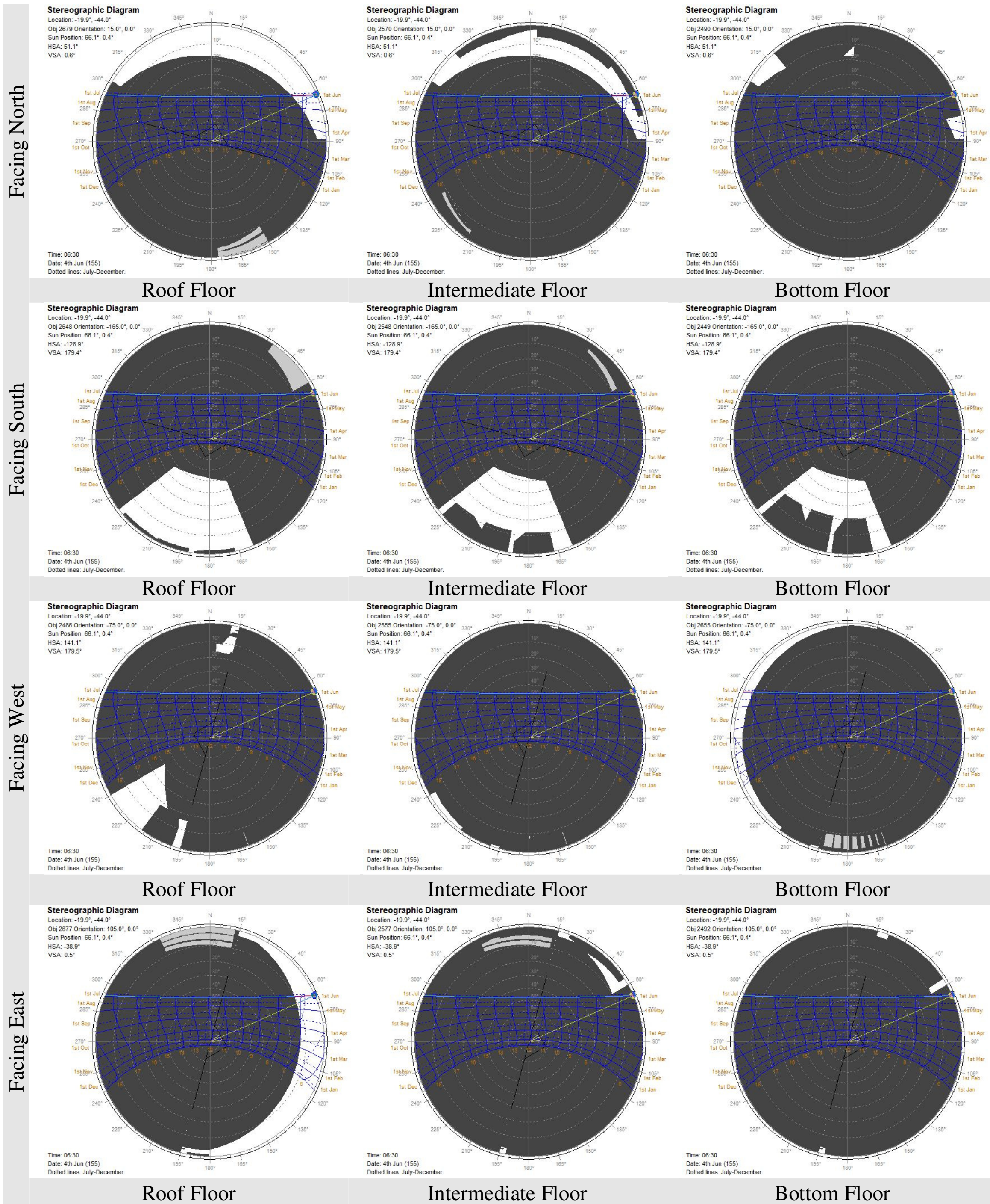


285° North Orientation

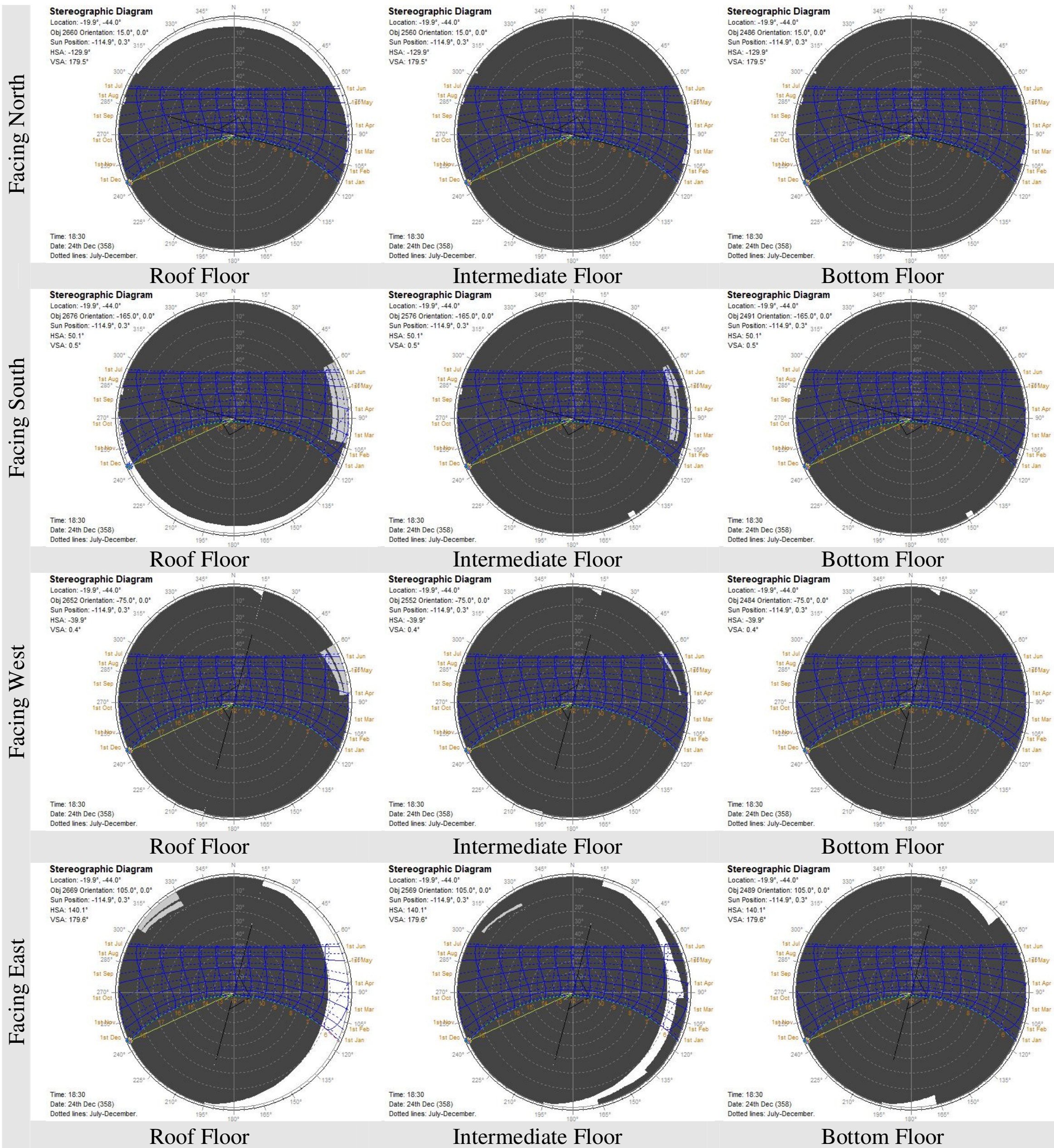


Archetype II shading mask (based on the geometric centre of the window

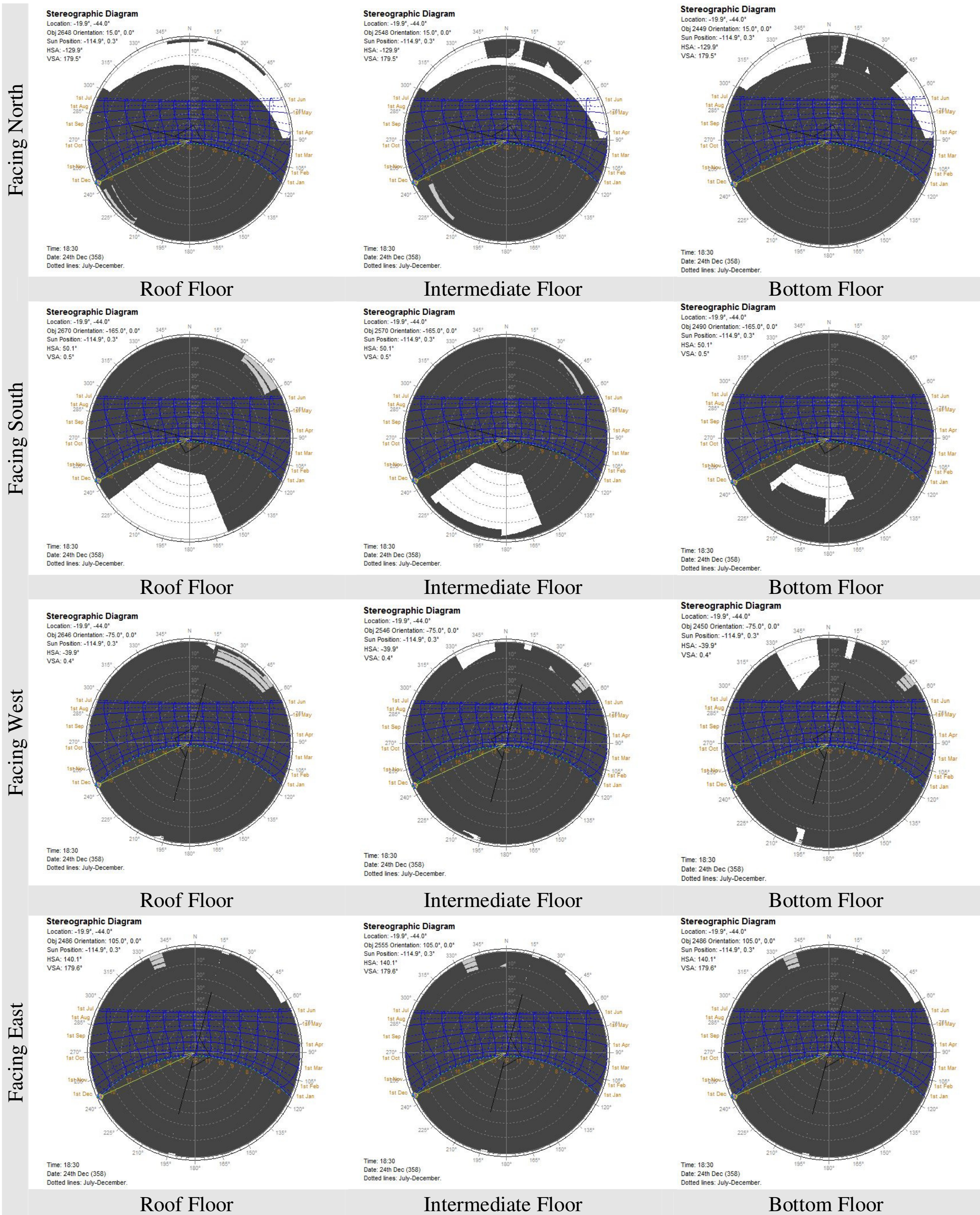
15° North Orientation



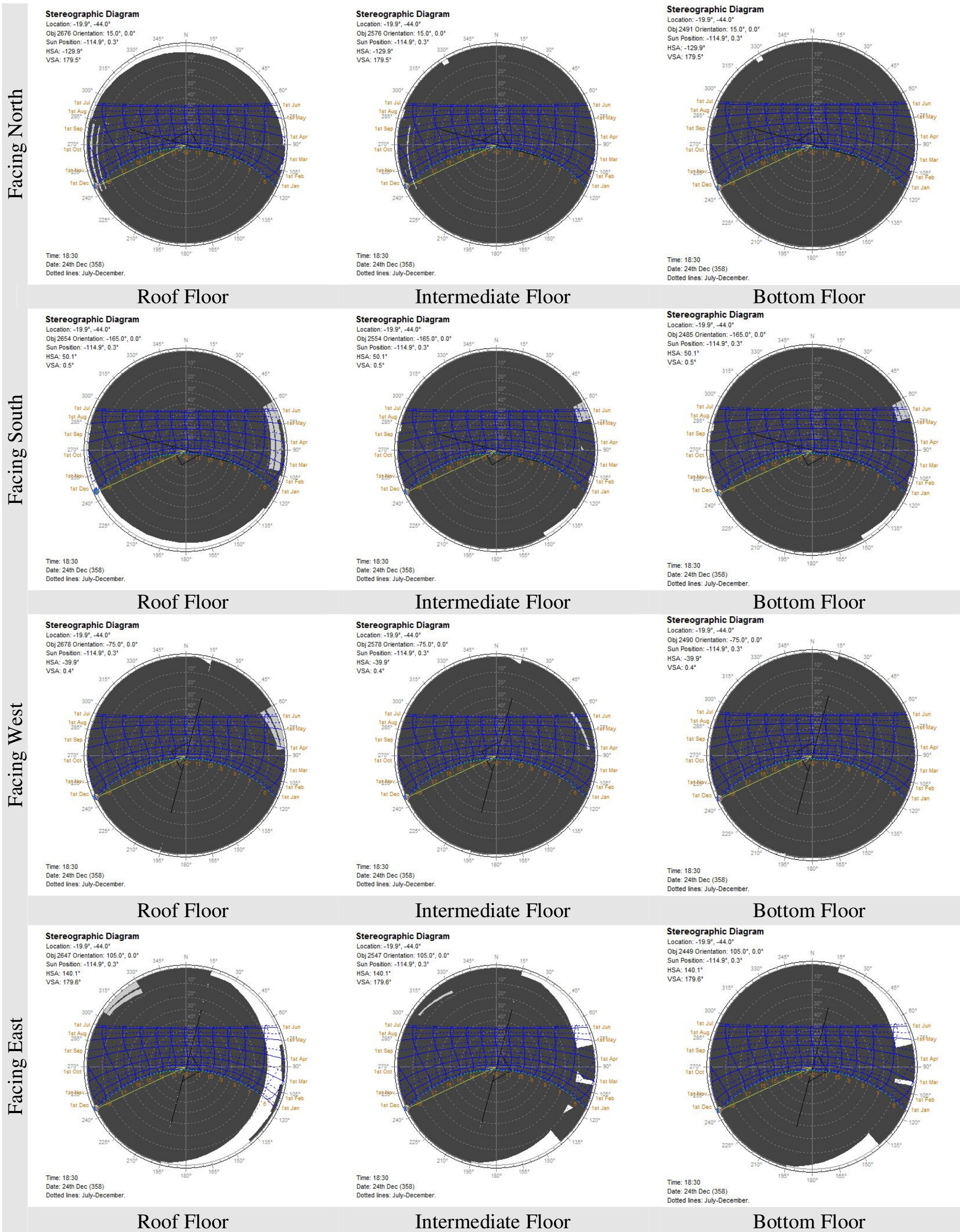
105° North Orientation



195° North Orientation



285° North Orientation



APPENDIX I - LCC reference items description and quotation

Items description	Unit	R$	Source
Fluorescent Lamp - equipment only	unit	6,39	83469/ SINAPI
Electronic Ballast for 2 tubular lamp - equipment only	unit	36,.04	83391/ SINAPI
Dimmable Ballast for 2 tubular lamp – equipment onlly	unit	75,00	Quotation/ Loja elétrica
Luminary for two tubular lamps - equipment only	unit	145,00	Quotation/ Loja elétrica
Luminary for two tubular lamps - disposal	unit	12,22	DEM-LUM-005/SETOP
Luminary replacement - service only	unit	32,00	Quotation /electrical services company
Lamp replacement - service only	unit	20,00	Quotation /electrical services company
Ballast replacement - service only	unit	30,00	Quotation /electrical services company
Led Lamp - 31W	unit	160,00	Quotation / Itaim supplier
Luminary - LED 2005 (Itaim Industria)	unit	154,00	Quotation /Itaim supplier
LED drive	unit	80,00	Quotation/ Loja elétrica
Dimmable LED drive	unit	161,45	Quotation / Itaim supplier
Lighting sensor	unit	274,00	Quotation /electrical services company
Lighting sensor installation	unit	35,00	Quotation /electrical services company
Luminary maintenance	unit	20,98	74086 /SINAPI
Glazing window System - CEBRACE Cool Lite 6 mm (material and installation)	m^2	830,00	Quotation /Cebrace Suppliers
Glazing window maintenance	m^2	4,45	SER-VED-005/SETOP
Glazing window system removal	m^2	26,00	85334/SINAPI
Regular Glazing window system 6mm (material and installation)	m^2	149,28	VID-LIS-015/SETOP
Window insulation maintenance	m^2	15,86	LIM-VID-005/SETOP
Air conditioning maintenance	unit	90,00	Quotation /HVAC Suppliers
Window Air conditioning - equipment only	unit	1085,00	Quotation /HVAC Suppliers
Window Air conditioning - installation only	unit	350,00	Quotation /HVAC Suppliers
Window Air conditioning disposal	unit	150,00	Quotation /HVAC Suppliers

APPENDIX J - LCC calculation

Data Summary for Class I LCC calculation

# of retrofit measures combination		Retrofit Measures	Present Value					LCC_20 (R$)
			Initial Investment cost (R$)	Capital Replacement (R$)	Residual Value (R$)	Electricity (R$)	OM&R (R$)	
		Base Case	0.00	42577.41	3365.34	140976.20	38402.23	218590.50
Individual Measure	ERP - 01	LPD	31290.00	24879.78	8227.51	97457.72	38402.23	183802.22
	ERP - 02	Daylighting	11984.00	46379.79	5418.51	108521.25	54881.01	216347.54
	ERP - 03	SHGC	61501.56	42577.41	4972.43	124783.18	38402.23	262291.95
	ERP - 04	COP	21359.84	42577.41	6169.05	138462.82	38402.23	234633.25
Two Combined Measures	ERP - 05	LPD + Daylighting	54508.30	30673.58	12661.33	83616.61	54881.01	211018.18
	ERP - 06	LPD + SHGC	92791.56	24879.78	9834.60	80729.89	38402.23	226968.86
	ERP - 07	LPD + COP	52649.84	24879.78	11031.22	95213.78	38402.23	200114.41
Three Combined Measures	ERP - 08	LPD + Daylighting + SHGC	116009.86	30673.58	14268.42	66658.24	54881.01	253954.27
	ERP - 09	LPD + Daylighting + COP	75868.14	30673.58	15465.04	79834.87	54881.01	225792.56
Four Combined Measures	ERP - 10	LPD + Daylighting + SHGC + COP	137369.70	30673.58	17072.13	64386.27	54881.01	270238.43

Data Summary for Class II LCC calculation

# of retrofit measures combination	Retrofit Measures		Present Value Initial Investment cost (R$)	Capital Replacement (R$)	Residual Value (R$)	Electricity (R$)	OM&R (R$)	LCC_20 (R$)
	Base Case		0.00	44036.99	3372.09	130094.02	38946.27	209705.19
Individual Measure	ERP - 01	LPD	34866.00	24316.78	8789.94	89548.34	38946.27	178887.45
	ERP - 02	Daylighting	11340.00	47060.93	5211.58	98088.30	56454.98	207732.63
	ERP - 03	SHGC	57222.60	44036.99	4867.36	125311.61	38946.27	260650.10
	ERP - 04	COP	20024.85	44036.99	6000.57	126436.01	38946.27	223443.55
Two Combined Measures	ERP - 05	LPD + Daylighting	59042.85	29616.21	13349.67	75626.42	56454.98	207390.78
	ERP - 06	LPD + SHGC	92088.60	24316.78	10285.21	85663.83	38946.27	230730.27
	ERP - 07	LPD + COP	54890.85	24316.78	11418.42	87342.26	38946.27	194077.75
Three Combined Measures	ERP - 08	LPD + Daylighingt + SHGC	116265.45	29616.21	14844.95	73523.92	56454.98	261015.61
	ERP - 09	LPD + Daylighting + COP	79067.70	29616.21	15978.15	72327.94	56454.98	221488.68
Four Combined Measures	ERP - 10	/LPD + Daylighting + SHGC + COP	136290.30	29616.21	17473.43	71182.04	56454.98	276070.10

Year of Occurrence - Data Summary.

Cost Item		Year of Occurrence				
		Initial Investment cost	Capital Replacement	Residual Value	Electricity	OM&R
1	Lighting System – Tubular Lamp	Base Date	3[6]	20	Annual	Annual
2	Ballast	Base Date	10[7]	20	Annual	Annual
3	Lighting System – Led Lamp/Led Drive	Base Date	17[8]	At replacement time	Annual	Annual
4	Luminaries	Base Date	10[9]	At replacement time	Annual	Annual
5	Lighting sensor	Base Date	10[10]	At replacement time	Annual	Annual
6	Glazing Window system	Base Date	No replacement [11]	20	Annual	Annual
7	Window Air Conditioning	Base Date	10[12]	At replacement time	Annual	Annual

[6] Based on based on 7.500 useful life hours

[7] Based on 35.000 useful life hours

[8] Based on 50.000 useful life hours

[9] Based on the normative instruction *IN SRF nº 162 Anexo I*

[10]Based on the normative instruction *IN SRF nº 162 Anexo I*

[11]Based on the normative instruction *IN SRF nº 162 Anexo I*

[12] Based on the normative instruction *IN SRF nº 162 Anexo I*