Achieving energy efficiency in a hotel-office building under tropical Latin American climatic conditions

Luis Arias
Abstract

Latin America has become an objective for local and foreign investors over the last decade due to its relatively unexploited economic markets, and more important, due to the vast amount of natural resources present in this part of the planet that can bring definitely an important economic growth to almost every sector in industry. In order to provide ease in terms of commuting by business men and with the idea of saving time, efforts and money, combined hotel and offices buildings are a rapidly growing kind of construction project that is being benefitted with taxation exceptions at local government levels in Latin America.

The commonly large size of the new hotel-office buildings bring along high fuel consumption rates for them to function properly and provide occupants with thermal comfort. This fact is the reason for the development of this research, taking into account different engineering measures to reduce the energy consumption rates and therefore, reduce the environmental footprint due to CO₂ emissions. Different ventilations systems, lighting control, proper orientation of the main-façade of the building, different material combinations for external walls, different properties involved in glazing and shading devices were the measures used to aim at a significant reduction in the usage of resources from the design level.

The difficulty of the research, besides the selection of the appropriate measures for each city, relies on the fact that Latin America has a widely varied geography that affects the local weather variables and its influence on the indoors comfort conditions. Cities with different climatic conditions have been chosen: Bogotá (Cold and dry weather), Mexico City (Temperate and mid-humid) and Fortaleza (Hot and humid).

A computer model has been constructed using DesignBuilder software to design the building and simulate the different weather conditions for each city using the exact same building. The results show a significant reduction of approximately 50% in terms of fuel usage fulfilling in each case the desired thermal comfort levels.

Keywords: Latin America, Hotel-office building, fuel consumption, thermal comfort, environmental footprint, varied weather conditions, engineering measures, DesignBuilder.
# Table of Contents

Abstract .......................................................................................................................... 2
Glossary of Terms .......................................................................................................... 6
List of Tables .................................................................................................................. 7
List of Figures ................................................................................................................ 8
1 Introduction .................................................................................................................. 11
   1.1 Background ............................................................................................................ 11
   1.2 Objectives ............................................................................................................ 11
      1.2.1 General Objective .......................................................................................... 11
      1.2.2 Specific Objectives ....................................................................................... 12
   1.3 Method .................................................................................................................. 12
      1.3.1 Software ....................................................................................................... 12
      1.3.2 Energy performance and environmental impact ........................................... 12
      1.3.3 Thermal comfort .......................................................................................... 12
   1.4 Constraints ........................................................................................................... 12
2 Theoretical Information ............................................................................................... 14
   2.1 Energy consumption and utilisation in buildings in Latin America ....................... 14
   2.2 Modeling and simulation software .................................................................... 14
   2.3 Weather files ........................................................................................................ 16
   2.4 Latin American geography and basic information about it ................................ 17
      2.4.1 Geography of Mexico and weather overview ................................................. 17
      2.4.2 Geography of Colombia and weather overview ............................................ 18
      2.4.3 Geography of Brazil and weather overview .................................................. 18
   2.5 Building envelope definition and other parts of the construction of a building .. 18
      2.5.1 External walls ................................................................................................ 19
      2.5.2 Windows ........................................................................................................ 19
      2.5.3 Roof .............................................................................................................. 19
      2.5.4 Foundations and floors ............................................................................... 20
   2.6 Thermal Comfort ................................................................................................. 20
      2.6.1 Heat gains involved ...................................................................................... 21
   2.7 Heat transfer ......................................................................................................... 22
   2.8 Different systems inside the building .................................................................. 23
      2.8.1 Ventilation, HVAC systems .......................................................................... 23
      2.8.2 Electrical power systems ............................................................................. 25
      2.8.3 Lighting systems .......................................................................................... 25
3 Methodology ............................................................................................................... 27
   3.1 Case of study building ......................................................................................... 27
3.1.1 Building selection: ................................................................. 27
3.1.2 Building model ................................................................. 28
3.1.3 Latin American cities selection for the research ..................... 30
3.2 Design Builder modeling and simulation ................................... 32
3.2.1 Original input data for the building ..................................... 32
3.2.2 Schedules: ................................................................. 36
3.3 Simulation .............................................................................. 36
3.3.1 Hourly weather data for the selected cities ......................... 37
3.4 Different measures to achieve thermal comfort and energy efficiency .............................................................................. 38
3.4.1 Air conditioning and ventilation systems ................................ 38
3.4.2 Lighting control .................................................................... 38
3.4.3 Orientation of the main long side façade ............................... 39
3.4.4 Exterior Walls .................................................................... 39
3.4.5 Glazing .............................................................................. 39
3.4.6 Shading devices ................................................................. 40
3.5 Environmental Impact Assessment (CO₂ Emissions) .................. 40
4 Results and analysis ................................................................... 42
4.1 Bogotá (Colombia) .................................................................. 42
4.1.1 Original model results ........................................................ 42
4.1.2 Different scenarios to achieve an energy efficient building in Bogotá ............................................................. 45
4.1.3 Final Comparison between original and final building designs (Bogotá) ......................................................... 55
4.2 Mexico City (Mexico) ............................................................... 58
4.2.1 Original model results ........................................................ 58
4.2.2 Different scenarios to achieve an energy efficient building in Mexico City ............................................................. 60
4.2.3 Final Comparison between original and final building designs (Mexico City) ......................................................... 74
4.3 Fortaleza (Brazil) .................................................................... 76
4.3.1 Original model results ........................................................ 76
4.3.2 Different scenarios to achieve an energy efficient building in Fortaleza ............................................................. 77
4.3.3 Final Comparison between original and final building designs (Fortaleza) ......................................................... 88
5 Discussion ................................................................................. 91
5.1 Bogotá ................................................................................... 91
5.2 Mexico City ............................................................................ 91
5.3 Fortaleza ................................................................................. 92
6 Conclusions and recommendations ............................................. 93
7 Bibliography ............................................................................... 94
8 Appendix .................................................................................. 96
8.1 Design builder features .......................................................... 96
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1.1</td>
<td>Simulation and Design</td>
<td>96</td>
</tr>
<tr>
<td>8.1.2</td>
<td>Interface</td>
<td>97</td>
</tr>
<tr>
<td>8.1.3</td>
<td>Data</td>
<td>97</td>
</tr>
<tr>
<td>8.1.4</td>
<td>Visualisation</td>
<td>97</td>
</tr>
<tr>
<td>8.2</td>
<td>Views of the building</td>
<td>98</td>
</tr>
<tr>
<td>8.3</td>
<td>Building schedules per zone</td>
<td>99</td>
</tr>
<tr>
<td>8.4</td>
<td>Building area, volume and occupancy by zone</td>
<td>101</td>
</tr>
<tr>
<td>8.5</td>
<td>Chillers nominal capacity (kW) for Mexico City and Fortaleza</td>
<td>102</td>
</tr>
</tbody>
</table>
# Glossary of Terms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>AC</td>
<td>Air Conditioning; Air Conditioned</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>DWH</td>
<td>District Heating Water</td>
</tr>
<tr>
<td>MET</td>
<td>Metabolic Heat Rate</td>
</tr>
<tr>
<td>CLO</td>
<td>Clothing Factor</td>
</tr>
<tr>
<td>PMV</td>
<td>Predicted Mean Vote</td>
</tr>
<tr>
<td>LC</td>
<td>Lighting Control</td>
</tr>
<tr>
<td>SHGC</td>
<td>Solar Heat Gain Coefficient</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>VAV</td>
<td>Variable Air Volume</td>
</tr>
</tbody>
</table>
**List of Tables**

Table 1 - Typical metabolic heat generation rates. Source: ASHRAE. ........................................... 20
Table 2 - Fanger PMV Scale for thermal comfort. .............................................................................. 21
Table 3 - Values for solar radiation absorptivity for different materials. Source: KTH Energy Technology. ......................................................................................................................... 21
Table 4 - General Information related to the case of study cities. Source: www.weatherbase.com ....... 32
Table 5 - Input data related to lighting, equipment and ventilation ...................................................... 34
Table 6 - Natural ventilation set-points for different zones in the building ......................................... 35
Table 7 - Constitution of the building envelope used in the original building ..................................... 35
Table 8 - Information on DHW for the building .................................................................................. 36
Table 9 - Variables used in EnergyPlus software weather files. ......................................................... 37
Table 10 - Thermostat set-points in the three cities ......................................................................... 38
Table 11 - External walls technical information .............................................................................. 39
Table 12 - Glazing technical information .......................................................................................... 39
Table 13 - Diffusive blinds window shading devices technical information ....................................... 40
Table 14 - Slatted blinds window shading devices technical information ......................................... 40
Table 15 - Local shading devices technical information ................................................................... 40
Table 16 - CO2 Intensity from energy use in the three different cities .............................................. 41
Table 17 – Average operative temperature and average relative humidity for different zones under naturally ventilated conditions in Bogotá ................................................................. 44
Table 18 - Relative humidity (%) for critical zones after having implemented local exhaust fans ....... 49
Table 19 - Operative temperature and relative humidity for different zones under naturally ventilated conditions in Mexico City ............................................................... 59
Table 20 - Relative humidity (%) in meeting rooms on 4th, 5th, 6th and 7th floors under NV conditions in Mexico City ....................................................................................................... 60
Table 21 - Operative temperature and relative humidity for different zones with AC system and local exhaust fans conditions in Mexico City ................................................................. 61
Table 22 - Relative humidity (%) in meeting rooms on 4th, 5th, 6th and 7th floors with AC system installed in Mexico City .................................................................................................... 62
Table 23 - Fanger PMV comparison for the three external walls scenarios in hotel rooms for Mexico City ................................................................................................................................. 66
Table 24 - Comparison between NV scenario and AC scenario. Annual operative temperature and relative humidity in sample zones and meeting rooms in Fortaleza .................................................. 78
Table 25 - Occupancy schedule per zone ......................................................................................... 99
Table 26 - Occupancy schedule per zone (Continuation 1) .............................................................. 99
Table 27 - Occupancy schedule per zone (Continuation 2) .............................................................. 100
Table 28 - Area, volume and occupancy by zone ......................................................................... 101
Table 29 - chillers nominal capacity for Mexico City and Fortaleza .............................................. 102
List of Figures

Figure 1 - Typical end use consumption chart. Source: Jayamaha L. .................................................. 14
Figure 2 - energy flow paths and parts of a building. Source: Clarke, 2001......................................... 15
Figure 3 - (a) Design Builder Edit mode used for modeling purposes; (b) Design Builder Computational fluid dynamics option; (c) Design Builder Visualization Mode. Source: Design Builder website................. 16
Figure 4 - a) Political map of Latin America, Source: spanskespanol.wikispaces.com; b) Amazon, Source: www.dfocetblog.com; c) Andes Range, Source: www.bligo.com.................................................. 17
Figure 5 - Composite external wall and its different layers. Source: www.trusthousing.org................. 19
Figure 6 - Natural ventilation flow through the interior of a building. Source: www.aeieng.com........... 24
Figure 7 - (a) Basic window A/C unit; (b) Central air conditioner system; (c) Split A/C systems; (d) Packaged A/C systems. Source: LEED Practices, Certification and Accreditation Handbook ........................ 25
Figure 8 - Methodology representation. ......................................................................................... 27
Figure 9 - (a) Ceasar’s business Hotel (Rio de Janeiro, Brazil); (b) Oxo Center (Bogotá, Colombia); (c) Cúcuta Hotel y Centro de Negocios (Cúcuta, Colombia). Sources: www.tecnoglass.com, www.cucutahotel.com, www.hoteles.com.................................................. 28
Figure 10 - Detailed plan of the first floor of the building. Image extracted from Design Builder Software. .................................................................................................................. 29
Figure 11 - Detailed plan of the second and third floors of the building. Image extracted from Design Builder Software. ........................................................................................................ 29
Figure 12 - Detailed plan of the fourth, fifth, sixth and seventh floors of the building. Image extracted from Design Builder Software............................................................... 30
Figure 13 - General overview of the building designed on Design Builder........................................ 30
Figure 14 - Geographic Location of the three cities Bogotá, Fortaleza and Mexico City....................... 31
Figure 15 - Thermal operative temperatures for different clothing and activity levels (ISO, 2005).... 33
Figure 16 - Operative temperature and Outside dry bulb temperature per month for Bogotá ............ 42
Figure 17 - Fanger PMV levels for the building under NV conditions .............................................. 43
Figure 18 - Fuel breakdown in the building for Bogotá (kWh). ............................................................ 44
Figure 19 - Internal gains for the year in the building for Bogotá (kWh)............................................ 45
Figure 20 - Annual General lighting electricity consumption (kWh) influenced by the Orientation + LC in Bogotá................................................................. 46
Figure 21 - Fanger PMV Index of the building influenced by LC + SW Orientation.......................... 46
Figure 22 - Heat loss (kWh/year) due to conduction through the external walls in the sample hotel rooms. .................................................................................................................. 47
Figure 23 - Heat loss (kWh/year) due to conduction through the external walls in the sample offices.... 47
Figure 24 - Heat loss (kWh/year) due to conduction through the external walls in sample hotel rooms including ‘External Walls 3’................................................................. 48
Figure 25 - Monthly Fanger PMV Index for the three exterior walls options in Bogotá. ...................... 49
Figure 26 - Fanger PMV for the building after implementation of local exhaust fans.............................. 50
Figure 27 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the sample hotel rooms................................................................. 51
Figure 28 - Heat loss (kWh/year) through windows in the sample hotel rooms. ................................ 51
Figure 29 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the sample offices................................................................. 52
Figure 30 - Heat loss (kWh/year) through windows in the sample offices.......................................... 52
Figure 31 - Fanger PMV levels for the building with the addition of different glazing options in Bogotá................................................................. 53
Figure 32 - Annual Fanger PMV comparison when using Drapes or not as a shading device in the sample hotel rooms in Bogotá ............................................................. 54
Figure 33 - Annual Fanger PMV comparison when using Blinds as a shading device in the sample offices in Bogotá................................................................. 54
Figure 34 - Operative temperature comparison between original and final designs in Bogotá............. 55
Figure 35 - Fanger PMV comparison between original and final designs........................................56
Figure 36 - Fuel breakdown comparison between original and final designs in Bogotá.......................56
Figure 37 - CO2 Production comparison between original and final designs in Bogotá........................57
Figure 38 - Specific energy consumption evolution in the building influenced by the different measures applied during the analysis for the city of Bogotá.......................................................................................57
Figure 39 - Operative temperature and Outside dry bulb temperature per month for Mexico City........58
Figure 40 - Fanger PMV for the building under Natural ventilation conditions in Mexico City........59
Figure 41 - Annual Fuel breakdown (kWh) in the building for Mexico City with AC and exhaust fans.....61
Figure 42 - Annual Internal gains in the building (kWh) with AC and exhaust fans installed.............62
Figure 43 - Annual General lighting electricity consumption influenced by the Orientation + LC in Mexico City..................................................................................................................................................63
Figure 44 - Annual chillers electricity consumption influenced by the Orientation + LC in Mexico City...63
Figure 45 - Heat loss due to conduction through the external walls in sample hotel rooms in Mexico City.
..........................................................................................................................................................64
Figure 46 - Heat loss due to conduction through the external walls in sample offices in Mexico City.....64
Figure 47 - Electricity consumption due to chillers influenced by the external walls options..............65
Figure 48 - Heat loss due to conduction through the external walls in sample hotel rooms in Mexico City.
..........................................................................................................................................................65
Figure 49 - Annual electricity consumption due to chillers in the building depending on the external walls in Mexico City........................................................................................................................................66
Figure 50 - Annual heat gain through the internal floor on the 4th floor offices influenced by the usage of ‘External Walls 3’ in the hotel rooms on the 2nd and 3rd floors in Mexico City..............................................67
Figure 51 - Heat loss (kWh/year) through windows in the hotel rooms..............................................68
Figure 52 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the hotel rooms.................................................................68
Figure 53 - Influence of glazing on the thermal comfort perception by the sample hotel rooms occupants expressed in average annual Fanger PMV index in Mexico City.................................................................69
Figure 54 - Heat loss (kWh/year) through windows in the offices in Mexico City...............................69
Figure 55 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the same offices in Mexico City...............................................................................70
Figure 56 - Annual electricity consumption due to artificial lighting in the building influenced by the different glazing options in Mexico City................................................................................70
Figure 57 - Annual electricity consumption due to chillers in the building influenced by the different glazing options in Mexico City......................................................................................71
Figure 58 - Annual solar heat gains (kWh/year) in the sample offices with different window shading devices installed for Mexico City.........................................................................................71
Figure 59 - Artificial lighting annual electricity consumption with different window shading devices in Mexico City..................................................................................................................................................72
Figure 60 - Chillers annual electricity consumption with different window shading devices in Mexico City.
..........................................................................................................................................................72
Figure 61 - Annual solar heat gains (kWh/year) in the sample offices with ‘Inside shade rolls + overhangs’ installed for Mexico City..............................................................................................73
Figure 62 - Annual electricity consumption (kWh/year) in the building with ‘Inside shade rolls + overhangs’ installed for Mexico City..........................................................................................73
Figure 63 - Operative temperature comparison between original and final designs in Mexico City........74
Figure 64 - Fuel breakdown comparison between original and final designs for Mexico City............75
Figure 65 - CO2 Production comparison between original and final designs in Mexico City...............75
Figure 66 - Specific energy consumption evolution in the building influenced by the different measures applied during the analysis for Mexico City.................................................................75
Figure 67 - Operative temperature and Outside dry bulb temperature per month for Fortaleza...........76
Figure 68 - Fanger PMV for the building under Natural ventilation conditions in Fortaleza.............76
Figure 69 - Annual Internal gains in the building with AC installed in Fortaleza

Figure 70 - Annual Fuel breakdown in the building for Fortaleza with AC

Figure 71 - Annual general lighting electricity consumption influenced by the Orientation + LC in Fortaleza

Figure 72 - Annual chillers electricity consumption influenced by the Orientation + LC in Fortaleza

Figure 73 - Heat gain due to conduction through the external walls in the sample hotel rooms in Fortaleza

Figure 74 - Heat gain due to conduction through the external walls in the sample offices in Fortaleza

Figure 75 - Electricity consumption due to chillers influenced by the external walls options in Fortaleza

Figure 76 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the sample hotel rooms in Fortaleza

Figure 77 - Influence of glazing on the thermal comfort perception by the sample hotel rooms occupants expressed in Fanger PMV index in Fortaleza

Figure 78 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the same offices in Fortaleza

Figure 79 - Annual electricity consumption due to artificial lighting in the building influenced by the different glazing options in Fortaleza

Figure 80 - Annual electricity consumption due to chillers in the building influenced by the different glazing options in Fortaleza

Figure 81 - Annual Fanger PMV levels for sample hotel rooms with and without drapes installed for Fortaleza

Figure 82 - Artificial lighting annual electricity consumption with different window shading devices in Fortaleza

Figure 83 - Chillers annual electricity consumption with different window shading devices in Fortaleza

Figure 84 - Annual solar heat gain (kWh/year) comparison for the ‘Inside Shade Rolls’ window shading scenario in sample offices with ‘0.5m Overhangs’ and ‘1.0m Overhangs’ as local shading in Fortaleza

Figure 85 - Annual electricity consumption (kWh/year) in the building with ‘Inside shade rolls + 1.0 overhangs’ installed for Fortaleza

Figure 86 - Operative temperature comparison between original and final designs in Fortaleza

Figure 87 - Fuel breakdown comparison between original and final designs for Fortaleza

Figure 88 - CO2 Production comparison between original and final designs in Fortaleza

Figure 89 - Specific energy consumption evolution in the building influenced by the different measures applied during the analysis for the city of Fortaleza

Figure 90 - Front view of the building

Figure 91 - Back view of the building

Figure 92 - Side views of the building. Parking lot car entrance façade (Left); Hotel reception entrance façade (Right)
1 Introduction

1.1 Background

Industry has been experiencing a deep and constant change since the Industrial Revolution in the XVIII century. Different techniques have been adopted everyday in an evolving world with the aim of optimizing processes; but, unfortunately, not always taking into account the impact that these might have on the environment. For several decades, worldwide industry presented a high-rate economical growth powered by industrial evolution and eagerness to achieve more production than other nations, speaking from a local point of view. This has lead to a wide range of consequences such as higher concentration of people in large cities, loss of diversity in terms of local production, deforestation and deterioration of habitats, high levels of energy consumption and the irresponsible harm to the environment that we live in, which is at last the most powerful reason why green activists in every field have felt at some point the duty to do something and contribute to change the actual direction of events.

Proper use of the available resources and maximizing the outcome of using them to boost an important part of the society like construction, are actual concerns for almost every nation in the world, which have been realizing that investing in stopping the depletion of our limited resources actually represent a revenue in the long term, partially thanks to the effort made by International Institutions to regulate the different variables that affect the environment. It is a well-known fact that there are inefficiencies in industrial and technological processes. Identifying these flaws and achieving a reduction of these is, undoubtedly, one of the most important goals of today’s industry, not being the construction sector an exception. Taking into consideration the importance of this field in the actual society and the high sensitivity that it represents, have become a priority nowadays, giving society, and especially researchers, the possibility to isolate the climate conditions, environment characteristics and the engineering measures to make it possible to perform different activities (Industrial, educational, recreational, residential) in the different buildings used by human beings. That is when energy efficiency in buildings shows up: to improve the named engineering measures, including the envelope design, as well as the proper calculation of Heating, Cooling and Ventilating systems; to achieve better living conditions and productiveness creating a sustainable balance between the human interaction and the environment.

The importance of an energy efficiency research in the construction field relies on the many variables that influence the actual performance of these systems and how unexplored this problem is in many parts of the world. Almost every industrialized nation is located either above the Cancer Tropic in the Northern hemisphere or below the Capricorn Tropic in Southern hemisphere. This might be a trivial fact if looked at from a shallow perspective, but it actually means that the greater efforts to reduce the impact on the environment and improve energy efficiency have taken place in these regions since developed countries count with greater resources to undertake researches and offer industries more attractive incentives that make it possible for a turning point event to take place. Most developing countries are then located within the two tropic lines and present totally different climatic conditions than developed countries, affecting the energy performance within buildings in a different way for both cases. Making use of great educational tools, I decided to start this research in some tropical weather countries of Latin America, inquiring and scrutinizing as many variables as possible, stressing and analyzing whatever energy efficiency measure to be applied feasibly in this part of the world that is so behind in this field.

1.2 Objectives

1.2.1 General Objective

- Analyze the different factors involved in the energy consumption of a typical commercial modern building located in different cities within the tropical area of Latin America, considering the great
climatic diversity present in this part of the continent; and propose feasible solutions to achieve more efficient systems making use of the simple measures.

1.2.2 Specific Objectives

- Perform an energy analysis in the building model under each of the different tropical weather conditions for every city that allows to identify the flaws in terms of energy efficiency in the system, using the software Design Builder.
- Evaluate the performance and importance of the building envelope on the energy efficiency in tropical weather conditions for different cities in Latin America.
- Evaluate the performance of natural ventilation and air conditioning systems according to each different city and the importance of a proper selection on the energy consumption of the building.
- Propose different engineering alternatives to improve the energetic performance of the building.

1.3 Method

1.3.1 Software

In order to recreate the variables, zones and different weather conditions present in buildings interaction with the environment, a computer model has been done using the software Design Builder, identifying flaws regarding the electricity consumption and proposing feasible alternatives to these. Version 3 of Design Builder was used to model the different conditions related to the building and its locations, and simulate the energy consumption and thermal comfort performances. This software is approved by ASHRAE as a reliable program for building modeling, simulation and energy performance evaluation.

1.3.2 Energy performance and environmental impact

Considering the changes made and the measures taken to reduce the energy consumption for each of the scenarios, comparisons were made in order to analyze each scenario in a separate way, thus finding the best measures to create efficient alternatives to the original case. The environmental impact, which is measured in CO₂ emissions are commonly linked to the energy performance of the building, was compared and considered in the building’s analysis.

1.3.3 Thermal comfort

Taking for reference the ASHRAE 55-2004 standard, the building occupants’ thermal comfort was evaluated, using as a main guideline the Fanger PMV (Predicted mean vote). The operative temperature and the relative humidity are other factors that influence directly the thermal comfort perception, reason why the temperature set points were defined following the ISO 7730 standard for a Category B building.

1.4 Constraints

The original plan was to carry out this research with weather information for cities in the country of Colombia, but due to limitations at the institution in charge of registering and providing the weather information for this country, a decision of including different cities in Latin America with diverse climatic conditions and compare their energy performance was made. Since a large portion of Latin America is located within the Cancer and Capricorn tropics lines, it was a suitable alternative to choose cities with more complete weather databases than those existent in Colombia.
Also, one of the most important factors when performing energy analysis in buildings is the initial costs which were not included in the scope of this specific research due to the impossibility of carrying it out on an already existent building but on a theoretical one.
2 Theoretical Information

2.1 Energy consumption and utilisation in buildings in Latin America

Energy efficiency is defined as a reduction in the quantity of energy used to provide a service or product. This term can be applied to every sector that comes to mind: construction, production, transport, health. In buildings, energy is used for several purposes day after day, and it is important to understand when and where energy is being consumed. Studies have shown that energy consumption in a typical commercial building are divided by percentages of the total building energy consumption as follows (Jayamaha, 2007):

![Figure 1 - Typical end use consumption chart. Source: Jayamaha L.](image)

As seen in Figure 1, HVAC systems account for the largest share in the energy consumption in buildings. Being these in charge of removing the heat from the occupied spaces, they become essential for the well-functioning of the occupied spaces. Many factors influence the performance of HVAC systems and must be changed, at least partially, to improve the energy consumption. Some of these factors are: the building envelope quality, air leakages, solar gains inside the conditioned spaces, and radiation emitted by inefficient lighting, among others. There are measures available to be taken in order to implement a reduction in energy usage that leads for energy efficiency to start taking place; some are more complex than others (changing layers in the building envelope), but some others are simple (changing incandescent light bulbs for fluorescent ones). Some of these measures require a considerable investment for building already built (retrofitting procedure), but the main idea is that all of them are achievable and will pay off in the long term by reducing the electricity bills costs, and, the most important reason: by reducing the environmental impact.

Nowadays, the energy consumption in buildings is being assessed by teams that specialize in finding the weak points and identifying the potential areas for energy efficiency. A very important part of this activity takes place in field collecting all the data as it is possible, such as technical specifications of the machinery, utilities bills, schedules in which the different areas of the building operate, occupancies, etc. Nevertheless, there is also a very important part of this process and is the usage of software capable of modeling and simulating the building conditions in order to implement the changes that will lead to save energy taking into account the different variables that affect directly or indirectly the energy consumption in the building.

2.2 Modeling and simulation software

Computer models have become in an important tool for exploring new technologies and having a better understanding of the actual conditions that characterize different phenomena. In engineering, these can
recreate the performance of a whole set of variables and the influence that each one of them has on the final outcome, in order to correct, predict, suggest new alternatives, identify trends and failures at a low cost with very accurate results aiming at a more efficient technology (DesignBuilder, 2010).

Simulations are attempts to recreate the reality by using mathematical models, which in this case, represent possible energy flows and different interaction with the environment in buildings. At first, the simulations available were limited to only provide vague indications of the problems available, resulting in difficult to interpret due to the amount of limitations and assumptions used during the process. These first generation simulations evolved into a second generation more focused towards representing and analyzing the building constructive problems from the time perspective. Third generation simulations presented the assumption of space and time dimensions being independent variables, while all of the other were dependant. Later on, with the growing attention awakened by the evolving computer industry, more practitioners became interested in creating new developments such as more friendly interfaces for users.

Clarke (2001) represented the interaction between different variables and parts of the building, showing the different heat flow paths inside and outside the building and can be seen in Figure 2.

In order to understand simulations, it is needed to represent them as electrical circuits, in which building parts (or nodes) are capacitances; temperature and pressure are so called “variables of state” and are represented by voltage; energy transferred is represented by current and is a dynamic variable since each node captures and releases energy at different rates (Clarke, 2001).

![Figure 2 - energy flow paths and parts of a building. Source: Clarke, 2001](image)

DesignBuilder, Energy Plus and TRNSYS are some examples of software capable of recreating the slightest details such as transients, air movement and distribution inside the zones in the building. It is important to highlight that using software for construction and energy utilization analysis involves at least two stages:

- Modeling.
- Simulation.
During the building modeling process, it is required to take into account the constructive details of the building/floor/room space to simulate considering geometry, technical information available, resources consumption, type of materials and weather information. The simulation part is in charge of showing the performance of the geometry drawn under the effect of variables input previously, such as weather information making possible to identify the flaws and qualities of the existent space to evaluate. Figure 3 shows different features available in the software:

![Figure 3 - (a) Design Builder Edit mode used for modeling purposes; (b) Design Builder Computational fluid dynamics option; (c) Design Builder Visualization Mode. Source: Design Builder website.](image)

In order to simulate conditions that are the closest to reality as possible, DesignBuilder is a user interface of Energy Plus, which is another software that is used to model the performance of a building in order to improve the design and reduce the resources consumption. Among the information used by DesignBuilder there are the weather databases for different regions in the world, that constitute a very important part during the simulation stage, since external conditions influence in a direct way the performance of the mechanical systems inside the building that have the task to compensate the heating, cooling, air quality, cleanliness demands to provide thermal comfort, as it has been expressed above.

### 2.3 Weather files

All software simulation programs aim at representing the weather and climatic conditions that may influence the building models in one way or another. For many years, simulation programs have based their results taking into consideration just a few climatic variables: hourly temperature, humidity, wind speed and direction, atmospheric pressure, and solar irradiance. Nowadays, there are several weather data formats that are taken in an hourly basis at specific locations by meteorological offices, including American, Canadian and European institutions. Most times, information data is incomplete and does not include details that are important to take into account depending on the specific location of interest for the simulation and it has to be completed using old calculation methods like interpolation.

In this sense, Energy Plus databases offer a better scenario thanks to its generalized weather data format and information like location name, data source, geographic location, peak design conditions, holidays, etc at time steps of less than hourly to obtain more accurate results. Some of the databases formats adopted
by Energy Plus are: DOE-2, BLAST, ESP-r, E/E, SWERA, IWEC, TMY, TMY2, TMY3CWEC, ISHRAE, among others (NREL, 2006).

2.4 Latin American geography and basic information about it

The Latin American geography is similar to that in North America in the sense that these were formed approximately during the same age, with long ranges that cross this part of the American continent in longitudinal way. This is reflected in the high altitude in some points and the presence of plateaus and valleys. The eastern part of South America is constituted in its majority by plains and the Amazon forest. The Mexican geography will be explained below in a more detailed way, which is similar to that characteristic in Central America, since the Mexican southern ranges extend to this region, therefore, inheriting similar climatic conditions. The Equator line crosses South America, giving the possibility for almost all possible weather conditions to be in different areas of it. It is important to stress the fact that the main factor determining the climatic conditions in most of Latin America is the altitude above the sea level.

In order to clarify what has been explained above in text about Latin America, Figure 4 shows the countries that constitute this part of the world and some of its most representative geographic features:

![Figure 4 - a) Political map of Latin America, Source: spansk espanol.wikispaces.com; b) Amazon, Source: www.dforceblog.com; c) Andes Range, Source: www.bliggo.com](image)

2.4.1 Geography of Mexico and weather overview

Mexico is a vast state located in North America with several geographic events generally following the North-West to South-East directions of the country. The most important of these events is the Altiplano Mexicano (Mexican Plateau), which is an extensive rather flat land located within 1100 and 2000 meters above the sea level and in the middle of three important ranges: Sierra Madre Oriental, Sierra Madre Occidental and Sierra Madre del Sur, one located to the south and the others to the west and east of the Plateau. Some of these ranges peaks exceed the 3000 meters above the sea level and separate the plateau of the Pacific coast and the Gulf of Mexico.
These geographic conditions give Mexico varied climatic conditions: To the south and in the majority of the coastal zones the weather is tropical, with high temperatures and significant precipitations all year round. In the central region of the country, the weather becomes temperate due to the medium altitude above the sea level. In the Northern part of the Mexican territory, the weather is ruled by subtropical conditions, meaning high temperatures and few precipitations. Finally, in the Sonora desert and some isolated parts of the country there are desert conditions and inappreciable precipitations (La Patria, 2000).

2.4.2 Geography of Colombia and weather overview

Colombia is located between the Caribbean Sea and the Pacific Ocean. The Andes range crosses the country from South to North through the western part of its territory. The Colombian Andes divide into three smaller ranges: Cordillera Oriental, Cordillera Occidental and the Cordillera Central, with flat highlands in between the ranges where the main rivers rise and flow. Besides the mountainous regions in the country, there are important plains to the eastern side and also in the coastal zones.

The Colombian climate is known as tropical due to its geographical location near the Equatorial line and is characterized by the altitude above the sea level. From 0 to 1000 m, one can find the so called “hot lands” where the temperatures can easily exceed the 25°C. Between 1000 and 2000 m are the “temperate lands” where temperature oscillates between 17 and 23°C. The “cold lands” take place between 2000 and 3000 m, in these parts of the country, the temperature oscillates between 11 and 16°C. The rain precipitation varies depending on the region, but in general terms, Colombia is considered to have high levels of precipitation (more than 1000 mm per annum) (La Patria, 2000).

2.4.3 Geography of Brazil and weather overview

This country has a rather flat territory constituted by plains and plateaus. To the north of the country there is the Guayanas range and limits with the Amazon forest. The Amazon plain covers two thirds of the Brazilian area and is divided into two different zones: the Várzea which present floods periodically; and the mainland which is located at higher altitude. South to the Amazon is the Brazilian plateau and its large extension and is separated to the east by different mountain ranges like Do Mar and Da Mantiqueira.

Northern Brazil is located in or near the Equatorial line, influencing in the tropical climatic conditions in the majority of the country during most months of the year. On the other hand, Southern Brazil presents winter conditions during one season of the year between the months of May and August. The main regional differences from the climatic point of view rely on the amount of precipitations, which are really abundant to the north of the country and in the Amazon plain (More than 3000 mm per annum); less precipitation takes place in the Brazilian plateau (1200-1500 mm) and a really low precipitation number takes place in the northeastern part of the country (La Patria, 2000).

2.5 Building envelope definition and other parts of the construction of a building

Buildings are constituted by a group of parts that performs a different task to provide the occupant inside with some basic requirements for comfort to carry out activities normally. The building envelope is the term to define all the components that enclose the conditioned spaces of a building and separate them from the exterior conditions or the unconditioned spaces (Cleveland & Morris, 2009). The envelope is subdivided into walls, doors, roofs, floors and windows that make possible the heat transfer between the outside and the outside of the building. The construction materials and the way that envelopes are constructed have a direct influence on the ventilation systems, indoor air quality and maintenance costs. It is important to take into account that the process for improving the quality of building envelopes should be done during the design stage of a building project, since it can end up being really complicated task to
achieve once the building is already built, besides the fact that the cost would be much higher this way (Hastings & Wall, 2007).

2.5.1 External walls

Building envelope has the purpose of protecting the occupants from weather conditions providing thermal comfort and reducing the heat transmission losses between the inner space and the exterior. However, constructing an efficient high thermal resistant envelope implies investing on increasing the thermal resistance of exterior walls (Higher R-value). The other fact to take into consideration is that thermal mass in walls is proportionally related to thermal storage inside the building; therefore, the amount of thermal mass and thermal resistance surely depends on the exterior conditions and must be sized properly for optimal performance during extreme condition periods like summer or winter. Different layers, such as plaster, internal and external coatings, structure wall, insulation material, may constitute an external wall from inside of the building towards the outside, Figure 5 shows the distribution of these layers, which can of course be arranged in different ways (Wulfinghoff, 1999):

![Figure 5 - Composite external wall and its different layers. Source: www.trusthousing.org](image)

2.5.2 Windows

The roles of windows in building envelopes are diverse. Basically they are in charge of allowing light into the different spaces, admitting air for ventilation in case of operable windows and also acting as a resistant layer to energy movement and heat transfer. In order to consider windows successfully operable, there must be a balance between the amounts of light admitted and the heat gains that it allows into the space. Several factors influence the performance of windows as a part of the envelope (Kilbert, 2008):

- **Solar heat gain coefficient**: The value of this variable ranges between 0 and 1 and represents the fraction of solar heat that becomes into heat after entering through the window.

- **Visible transmittance**: Ranges between 0 and 1 and represents the fraction of the visible spectrum (from 380 to 720 nanometers) that is transmitted through the window.

- **U value of the window assembly**: This number is a reference to estimate how effective is the heat conduction through the materials that constitute the window assembly. The lower the U value is, the lower the heat gain through conduction will be.

- **Air leakiness characters of the window assembly**.

2.5.3 Roof

The importance of the roof space on the energy efficiency of buildings relies on the fact that it presents a large area for heat transmission due to its direct exposure to the sun, reaching temperatures of
approximately 83°C during summer season in large structures like office buildings, shopping centers and warehouses. An effective way to counteract this phenomenon is to have light-colored roofs, this way reflecting a large share of the solar radiation, reducing the energy consumption of the equipment in charge of removing these loads inside the building (Kilbert, 2008).

2.5.4 Foundations and floors

These are parts of the building envelope that are often not taken into account, but can result in great energy savings and more comfortable indoor environments for occupants. As for floors, warm air locates higher in the zones, increasing the heat transfer due to conduction to above floors, which leads to make proper insulation of these a priority in early stages during the design and construction of the building (Kilbert, 2008).

2.6 Thermal Comfort

According to the ASHRAE Standard 55-2004, thermal comfort refers to that state of mind that expresses satisfaction with the thermal environment, both physiological and psychologically. The ASHRAE standard specifies six primary essential variables for thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity (ASHRAE, 2004). Table 1 shows some values for metabolic heat generation rates due to the physical activity:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Metabolic Rate</th>
<th>Activity</th>
<th>Metabolic Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MetUnits</td>
<td>W/m² (Btu/h･ft²)</td>
<td></td>
</tr>
<tr>
<td>Resting</td>
<td>-</td>
<td>-</td>
<td>Miscellaneous Occupation Activities</td>
</tr>
<tr>
<td>Cooking</td>
<td>0.7</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Housekeeping</td>
<td>0.8</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Sodden, house</td>
<td>1</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Standing, rest</td>
<td>1.2</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Walking (on level surface)</td>
<td>2</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>1.2 m/s (4.3 km/h)</td>
<td>2.6</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>1.8 m/s (6.8 km/h)</td>
<td>3.8</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>Office Activities</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Seated, reading or writing</td>
<td>1</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous Leisure Activities</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Typing</td>
<td>1.1</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Filming, editing</td>
<td>1.2</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Film, standing</td>
<td>1.4</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Working, riding</td>
<td>1.7</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Walking, other</td>
<td>2.1</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Driving, Flying</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Typical metabolic heat generation rates. Source: ASHRAE

The amount of heat that is generated and dissipated by the bodies varies with age, activity, size and gender (Jonsson & Bohdanowicz, 2010). The conditions required for comfort vary from person to person since it depends on the heat exchanges between the surroundings and the person; nevertheless, some researches have been done in order to conclude which are the approximate conditions that represent thermal comfort for a major part of occupants within a space of the individuals. The Fanger Predicted Mean Value (PMV) scale shown in Table 2, represent different levels of discomfort perceived by occupants:
2.6.1 Heat gains involved

In some cases, the air conditioning process is required due to the presence of cooling loads generated inside the space of interest. Since this space is not isolated, it interacts with its surroundings, but also interior factors such as technological devices and occupants influence the change of the interior conditions. The most representative parameters usually considered are (Jonsson & Bohdanowicz, 2010):

- **Heat transmission through the envelope:** This gain is originated due to heat flow through the floor, walls, ceiling and windows of the space. The heat transmission depends on the temperature difference of each of these components of the envelope and the interior of the room. Solar irradiation contributes with this heat load by being absorbed partly, depending on the absorption coefficient or absorptivity, by the material in the surface of the exterior part of the envelope. The latter has a direct relation with the glazing of the building and the quality of it depending on the needs. Table 3 shows some values for absorptivity for different materials.

```
<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment</th>
<th>Absorptivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>Polished</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Anodized</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Foil</td>
<td>0.15</td>
</tr>
<tr>
<td>Bricks, red</td>
<td>---</td>
<td>0.63</td>
</tr>
<tr>
<td>Concrete</td>
<td>---</td>
<td>0.6</td>
</tr>
<tr>
<td>Galvanized sheet</td>
<td>Clean</td>
<td>0.65</td>
</tr>
<tr>
<td>metal</td>
<td>Oxidized, weathered</td>
<td>0.8</td>
</tr>
<tr>
<td>Paint</td>
<td>Black</td>
<td>0.9-0.98</td>
</tr>
<tr>
<td></td>
<td>White (Acrylic)</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>White (Zinc Oxide)</td>
<td>0.16</td>
</tr>
<tr>
<td>Ice or Snow</td>
<td>---</td>
<td>0.13-0.33</td>
</tr>
</tbody>
</table>
```

Table 3 - Values for solar radiation absorptivity for different materials. Source: KTH Energy Technology.

- **Heat gains as a result of ventilation and air infiltration:** Ventilation refers to the means of improving the air quality by removing stale polluted air and replacing it with better quality air; also it can be used to modify the air indoor conditions. On the other hand, air infiltration refers to the entry of unwanted air from opening in the building, which is an uncontrollable phenomenon. When a space is air conditioned, there is always a need to replace constantly the air in order to provide good indoor air quality. Basically, heat gains/losses take place when there are air
infiltrations from the outside ambient at different conditions to the conditioned space, creating a load to be removed by the ventilation equipment.

- **Internal heat generation:** This item refers to the loads generated within the air conditioned space. There are different aspects that contribute to make this load higher, such as: lighting, occupants, appliances and other machinery. This problem leads to higher electricity consumption, since the machinery and other devices involved use energy to perform their different purposes and there is a greater effort made by the ventilation and air conditioning unit to remove the heat created during the accomplishment of these different tasks.

### 2.7 Heat transfer

There are different ways to transfer heat: conduction, convection and radiation; and there is an essential factor needed for heat transfer to happen and it is a temperature difference between the spaces involved. **Conduction** refers to the heat transfer that takes place due to a temperature difference in a solid material and many factors are involved, such as the internal properties of the material, the area in which heat transfer occurs, the wall thickness and the value that represents the temperature difference. Walls, roofs and floors are the parts of the building through conduction heat transfer takes place. Equation 1 expresses the mathematical equation and the different variables (Jonsson & Bohdanowicz, 2010):

\[
Q_{\text{cond}} = -kA \frac{dT}{dx} \quad (\text{Equation 1})
\]

Where, \( k \) = Thermal conductivity of the material;
\( A \) = Area (Perpendicular to heat flow);
\( dT \) = Temperature gradient;
\( dx \) = Thickness

Heat transfer due to **Convection** takes place when a fluid and a surface are in contact and there is a temperature difference between them. The factors that influence this kind of heat transfers are: the surface area, the value for temperature gradient between the surface and the fluid, and the convective heat transfer coefficient (also depends on the properties of the fluid, the kind of flow and the properties of the surface in contact with the fluid). In buildings, convective heat transfer takes place at inner and outer surfaces. Equation 2 shows the different variables involved (Jonsson & Bohdanowicz, 2010):

\[
Q_{\text{conv}} = h_c A (T_s - T_f) \quad (\text{Equation 2})
\]

Where, \( h_c \) = Surface heat transfer coefficient;
\( A \) = Surface area;
\( T_s \) = Surface temperature;
\( T_f \) = Fluid temperature

Finally, **Radiation** is the heat transfer that occurs between two radiant surfaces due to electromagnetic waves, which from the building energy analysis perspective come mainly from the solar radiation that enter through the windows. The factors influencing this type of heat transfer are: the absolute temperatures (K) of the radiant surfaces and the area of the surface that presents a higher temperature. Equation 3 shows the different variables (Jonsson & Bohdanowicz, 2010):

\[
Q_{\text{rad}} = \sigma A_1 \varepsilon_1 (T_1^4 - T_2^4) \quad (\text{Equation 3})
\]

Where, \( \sigma \) = Stefan-Boltzmann constant;
\( \varepsilon_1 \) = Emissivity of surface 1;
Air leakage from inside the building is named exfiltration, whilst air leakage from outside to the inside of the building is named infiltration. This phenomenon is important since it represents the unbalance of supply and exhaust air. *Infiltration* takes place when there is a negative pressure in buildings due to the wrong sizing of the ventilations systems for the different zones within the building, letting unconditioned air to enter the building. *Exfiltration* takes place when there is an unbalance between the supply air and exhaust air flows, the latter being lower. Wind pressure difference in different facades of the building that leads for air to pass through the building and the named “stack effect” due to cold air from the outside entering the lower levels of the building and replacing the warm air that tends to move upwards, are other causes of air leakage from either inside, or outside the building, which has to be compensated every time by the interior air conditioning systems. Some measures to reduce the air leakage in both directions are: weather-stripping seals, automatic doors, vestibules and air curtains (Jayamaha, 2007).

### 2.8 Different systems inside the building

In order for the building to work properly and providing the required needs by occupants, there are different systems designed to perform different tasks:

#### 2.8.1 Ventilation, HVAC systems

Ventilation is the process of circulating air from the outside to an enclosed space to adjust it to certain parameters depending on the space. Air conditioning is, then, a way to provide control over temperature of the air supplied, moisture content, air quality and cleanliness of it required by the occupants or the processes that take place in the specific space (Cleveland & Morris, 2009). Proper ventilation can be achieved by natural means, such as wind velocity, wind direction and pressure difference between the interior and the exterior of the buildings; however, in the majority of cases for large complex buildings it is needed to make use of mechanical systems to ventilate and condition the air to make the interior environment more comfortable.

##### 2.8.1.1 Natural Ventilation

Natural ventilation takes place when the wind pressure forces are used to move air through the building, also making use of the stack effect generated in the interior of the building thanks to the air temperature difference and its different densities, leaving place for outside cooler air to enter the building. The other reason why wind flows through the building after coming in through doors, windows or openings in general, is due to the pressure difference created between the façade that the wind goes in direction of, and the opposite to this one. Figure 6 shows in a more clear way the airflow inside buildings using natural ventilation.
This kind of ventilation is not suitable for all climates, but only for mild climate zones since different seasons may affect indirectly factors like Indoor air quality, relative humidity and extreme air temperatures. Proper natural ventilation can be achieved using different methods (Khan, et al, 2008):

- Window openings.
- Atriums and courtyards.
- Wing walls.
- Chimneys and exhaust openings.
- Wind towers.
- Double skinned facades.
- Wind catchers.
- Wind floor and air inlets.

2.8.1.2 Mechanical ventilation

Along with this idea, technology has been advancing in such a way, that ventilation systems have evolved up to a point where larger and more complex buildings are being designed and built fulfilling the thermal comfort requisites. There are different types of air conditioning systems but they all have in common the usage of cooling coils in the systems in order to reduce the air temperature for the conditioned space.

But just like it happens with any other mechanical system, there are different factors that influence the actual performance of these Heating, Ventilating and Air Conditioning (HVAC) units and inefficiencies show up, leading to unplanned levels of energy consumption. This is one of the reasons why there are several options when it comes to choosing which HVAC to use when designing a new project: Through the wall or window electric air-conditioning units are used for single zones applications and do not require to be linked to a central air handling unit. This kind of A/C units is mostly used for small buildings, houses, apartments and trailers. Central air conditioning systems are commonly used in office buildings, public buildings and restaurant. These systems provide heating, ventilation and air conditioning in a controlled-centralized way and are used for cooling and dehumidifying during the summer season; and for heating and humidifying during winter season. It consists of: condenser and compressor (Outdoor unit), blower coil and evaporator (Indoor unit) and indoor thermostats. The final design of a centralized A/C system will depend on the specific demands of each of the spaces to be cooled. Figure 7 shows the different mechanical ventilation systems named above:
Split systems refer to two different sets located in different places of the building: one is outside and it contains the condenser and compressor; and the other one is located inside the building and contains the evaporator and the thermostat. This system can also be used as a heat pump system and be reversed by using a furnace in the indoor set. The condensing unit is usually located on the roof of the buildings due to the large size it can present sometimes. Packaged systems are used for applications in which there is a need to supply several rooms on the same floor. Packaged units are located with all of its components in an outdoor mechanical equipment room, providing supply air to the conditioned spaces through ducts in all-air systems and air-water systems, or by fan coil units located in the conditioned spaces for all-water systems although these are the most expensive ones to install (Kubba, 2010).

2.8.2 Electrical power systems

These systems are in charge of controlling and distributing the energy required for all other systems to work inside the building, such as lighting, heating cooling and mechanical ventilation, amongst others. Electrical energy is first delivered from the distribution line to the transformers at a really high voltage (2400 to 4160 volts), and then dropped to the building by wiring. The voltage and the number of phases vary widely depending on the application (residential, commercial or industrial) and the country. Residential electrical systems are rather simple, but on the other hand, commercial and industrial systems are complex and often need transformers and other heavy equipment for them to function (Kubba, 2010).

2.8.3 Lighting systems:

Amongst the electricity systems, lighting accounts for the greatest load, needing to be monitored constantly. These systems not only consume energy to generate light, but also generate heat that must be removed by the air conditioning equipment in order to maintain thermal comfort conditions. Despite of being a sensible system for its named electricity consumption and heat generation, lighting is needed in
buildings in order to provide visual comfort and higher productivity for the building occupants. There are different types of lamps that are commonly used (Jayamaha, 2007):

- Incandescent lamps.
- Halogen lamps.
- Fluorescent lamps (Linear and compact).
- High intensity discharge lamps.
3 Methodology

In order to carry out this research, several steps had to be taken to come up with valid results on the influence that the building envelope and HVAC systems have on the overall energy efficiency in buildings in three tropical Latin American cities, which, represent three specific weather cases. Figure 8 shows the named steps followed during this research:

Before starting the draft proposal of any project to do, it is important to review thoroughly the literature existent and make some clear ideas on what the project is going to be, identify an important problematic for society and define the objectives to achieve with the research by the end of it. Basics on building construction and different parts that constitute it, heat transfer, HVAC systems, energy simulation software and a quick overview about its more important features, besides background information about what has been done in the past by other researchers in subjects related; have been reviewed as a way to start this project.

3.1 Case of study building

3.1.1 Building selection:

Considering the trend in actual society of expanding each day the range of different business to other cities and countries, it has become more common to start construction projects on buildings that allow fulfilling the needs of investors and companies representatives, such as suitable spaces for negotiations and expositions of different products and services; or simply to establish different headquarters in different locations for multinational companies. Latin America has become into a really attractive place to invest on during the last years, since markets in this part of the world have been somewhat unexploited over history and also, because of its richness in terms of natural resources availability. Local governments are aware of this and want to boost the construction sector focused on hotel buildings by reducing the taxation normally charged to these projects (Norte de Santander).
A type of building that fulfills these requirements would be a mix between office and hotel buildings. In large cities like Bogotá (Colombia), Panamá City (Panamá), Rio de Janeiro (Brazil) and Mexico City (México) these projects have had great acceptance so far and new projects are being constructed. Some of these mixed-use buildings in Latin America are shown in Figure 9:

![Figure 9](a) Ceasar's business Hotel (Rio de Janeiro, Brazil); (b) Oxo Center (Bogotá, Colombia);(c) Cúcuta Hotel y Centro de Negocios (Cúcuta, Colombia). Sources: www.tecnoglass.com, www.cucutahotel.com, www.hoteles.com.

### 3.1.2 Building model

As stated above, the case of study building is one that integrates accommodation and business activities. The building used in this research is not real and was designed with the aim of recreating different zone areas and distributions on the different floors in order to assess the interaction between outdoors climatic conditions in different tropical cities and indoor zones. The building has 8 floors including the roof space, where there is a machinery room and large space for other purposes like a green roof. Each floor is equipped with a Data Centre and a deposit. The first floor is mainly constituted by two different receptions: one for the offices part of the building and another one for the hotel, besides common areas like restaurant, stairs, parking lot, meeting rooms, bathrooms and different administrative offices.

The building's floor area is 9479.62 square meters. Each floor has 2.95m of height from floor to ceiling. More detailed information about the building’s zones area and volume can be found on Table 28 in Appendix 8.4. The detailed first floor plan made in Design Builder is shown in Figure 10:
The second and third floors constitute the hotel part of the building, and each one of these floors has 19 rooms with a bathroom included in each. The common areas are stairs, elevators and hallways. It is important to stress that these floors are identical. Figure 11 shows the zone distribution on the floors more clearly and also the sample rooms, which will be used later on when presenting simulation results, in red shades and red font:

The fourth, fifth, sixth and seventh floors are the office part of the building. Each floor has 4 offices, two meeting rooms, elevators, stairs and communal bathroom. The sample offices, to be used during the results and analysis, are shown as the red shadow zones with red font. The space distribution in these floors can be seen in Figure 12.
Figure 12 - Detailed plan of the fourth, fifth, sixth and seventh floors of the building. Image extracted from Design Builder Software.

The main façade of the building modeled has been assumed to be facing the Westward direction. The final overview of the building designed on DesignBuilder is shown in Figure 13.

Figure 13 - General overview of the building designed on Design Builder.

Different views of the building can be seen in Figures 90, 91 and 92 in Appendix 8.2.

3.1.3 Latin American cities selection for the research

What is known as Latin America is that group of countries in the American continent that speak Romance roots languages as native, which includes from Mexico to Chile and Argentina in the Southernmost region of the continent. The Latin American region weather is directly influenced by its diverse geography and
also by the fact that the majority of it is located within the Tropic of Cancer and Tropic and Capricorn lines, which is the case of study of this research.

The Andes range covers the western part of South America, resulting in high altitude places and cities where the weather conditions are cold; however, the coastal areas present warmer and humid conditions. Mexico is a country where the presence of several mountains ranges like Sierra Madre Occidental, Sierra Madre Oriental and Sierra Madre del Sur; the flat regions between them, the Pacific Coast and the Caribbean Sea makes the weather conditions really influenceable by different factors. On the other hand, Central America is a geologically active region with several mountain ranges like Cordillera de Talamanca and Cordillera Isabelia.

The great geographical variation of Latin America results then in a challenge in order to select the three cities for this research, but with the idea of representing the most determining weather conditions of this region, the three cities selected and the area within the Tropic of Cancer and the Tropic of Capricorn are shown in Figure 14.

![Figure 14 - Geographic Location of the three cities Bogotá, Fortaleza and Mexico City.](image)

As stated above, the three cities have different climate conditions:

- **Fortaleza**: Hot and humid climate.
- **Bogotá**: Cold. Humidity alternates between high and low throughout the year.
- **Mexico City**: Temperate and mid-humid conditions during the majority of the year. Stronger seasonal influence than in Bogotá and Fortaleza due to its geographic location far from the Equatorial Line.

Table 4 shows relevant general data to take into account in order to give the reader a better idea of the conditions for each of the cities involved in this research:
3.2 Design Builder modeling and simulation

3.2.1 Original input data for the building

In order to represent the building original conditions close to reality, initial data must be defined and input in the software. It is important to take into account that this kind of project is rather new in Latin America, reason why the designs are kept as simple as possible and with initial low investment on lighting, ventilation, glazing, envelope, etc.

3.2.1.1 Operative temperature and relative humidity ranges for thermal comfort

The PMV (Predicted mean vote), which according to the standard ISO 7730 (ISO, 2005) should range between -0.5 and 0.5 for a category B building in order for the building to be considered thermally comfortable (Ashrae, 2004); and the PPD (Predicted percentage dissatisfied) should be less than 10%. However, given that the PPD is a dependant variable of the PMV, it is not shown in the results.

The overall operative temperature range of the building was defined following the ISO 7730 standard. Different MET and CLO numbers were assumed depending on the city:

- Bogotá: MET=0.9; CLO=1.0.
- Mexico City: During Summer MET=0.9; CLO=0.8; During Winter MET=0.9; CLO=1.00.
- Fortaleza: MET=0.9; CLO=0.7.

Figure 15 shows the interaction of the named variables in order to define the operative temperature range for the research:

<table>
<thead>
<tr>
<th>General Information</th>
<th>FORTALEZA</th>
<th>BOGOTA</th>
<th>MEXICO CITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinates</td>
<td>3°43'53&quot;S 38°32'34&quot;W</td>
<td>4°35'53&quot;N 74°4'33&quot;W</td>
<td>19°3'52&quot; N 99°7'37&quot;</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>24</td>
<td>2547</td>
<td>2239</td>
</tr>
<tr>
<td>Annual Average Temperature (°C)</td>
<td>27</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Annual Average High Temperature (°C)</td>
<td>30</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Annual Average Low Temperature (°C)</td>
<td>23</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Annual Precipitation (mm)</td>
<td>1460</td>
<td>950</td>
<td>682</td>
</tr>
<tr>
<td>Average Morning Relative Humidity (%)</td>
<td>89</td>
<td>92</td>
<td>85</td>
</tr>
<tr>
<td>Average Evening Relative Humidity (%)</td>
<td>66</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>Average Dew Point (°C)</td>
<td>22</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Average Wind Speed (km/h)</td>
<td>16</td>
<td>12</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 4 - General Information related to the case of study cities. Source: www.weatherbase.com
According to Figure 15, the optimal operative temperature in the three cities should be:

- **Bogotá:**
  \[
  T_{\text{operative (Summer and Winter)}} = 23.8^\circ C \pm 2.0^\circ C
  \]
  \[
  21.8^\circ C < T_{\text{operative (Summer)}} < 25.8^\circ C
  \]

- **Mexico City:**
  - During Summer:
    \[
    T_{\text{operative (Summer)}} = 24.9^\circ C \pm 1.5^\circ C
    \]
    \[
    23.4^\circ C < T_{\text{operative (Summer)}} < 26.4^\circ C
    \]
  - During Winter:
    \[
    T_{\text{operative (Winter)}} = 23.8^\circ C \pm 2.0^\circ C
    \]
    \[
    21.8^\circ C < T_{\text{operative (Summer)}} < 25.8^\circ C
    \]

- **Fortaleza:**
  \[
  T_{\text{operative (Summer and Winter)}} = 25.5^\circ C \pm 1.5^\circ C
  \]
  \[
  24.0^\circ C < T_{\text{operative (Summer)}} < 27.0^\circ C
  \]

Relative humidity is also recommended by the ISO 7730 standard to be kept between 40% and 60%.

### 3.2.1.2 General parameters and input data used for the original building:

These variables are determined essentially by the activity carried out at the different areas that constitute the building. Table 5 shows input data for different zones; the minimum fresh air requirements were extracted from the ASHRAE Standard 62.1-2007 (Ashrae, 2007); also occupancy per square meter:
### 3.2.1.3 Information on lighting:

The list of variables used for lighting for the original building, which remain unchanged is:

- Lighting energy gains: \( \frac{3.4 W}{m^2 \cdot 100 \text{Lux}} \)
- Radiant fraction: 0.420
- Visible fraction: 0.180
- Luminaire type: Suspended.
- Lighting control: No.

Target Illuminance (Lux) required in the different zones of the building are shown in Table 5.

### 3.2.1.4 Information on equipment:

The equipment considered for the building research is constituted mainly by computers, printers, scanners, photocopiers, shredders, hair dryers, TV, cooking. Radiant fraction from equipment is assumed to be 0.2. More detailed information on the equipment and computers gains depending on the zones can be seen in Table 5.

### 3.2.1.5 Information on ventilation:

Traditionally, this type of ventilation has been used for years in construction projects in most parts of Latin America, reason why it was chosen as the original way to provide indoor thermal comfort in the building. The idea was to compare the natural ventilation scenario with those when using air conditioning and conclude about the most suitable option taking into account fuel costs and thermal comfort. The building design presents large window areas with the idea of taking advantage of natural lighting and natural ventilation, as well. The natural ventilation set point temperatures used in different areas of the original design building can be seen in Table 6:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Target Illuminance (Lux)</th>
<th>People density (People/m²)</th>
<th>Minimum Fresh Air (l/s·person)</th>
<th>Minimum Fresh Air (l/s·m²)</th>
<th>Equipment Gains (W/m²)</th>
<th>Computer Gains (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communal Bathrooms</td>
<td>200</td>
<td>0.124</td>
<td>12</td>
<td>~</td>
<td>5.48</td>
<td>~</td>
</tr>
<tr>
<td>Data centre</td>
<td>500</td>
<td>0.1</td>
<td>5</td>
<td>0.6</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Elevators</td>
<td>100</td>
<td>0.5</td>
<td>2.5</td>
<td>0.3</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Stairs</td>
<td>100</td>
<td>0.1</td>
<td>3.8</td>
<td>0.3</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Mail Room</td>
<td>400</td>
<td>0.05</td>
<td>2.5</td>
<td>0.3</td>
<td>11.77</td>
<td>5</td>
</tr>
<tr>
<td>Meeting Rooms</td>
<td>400</td>
<td>0.3</td>
<td>2.5</td>
<td>0.3</td>
<td>~</td>
<td>5</td>
</tr>
<tr>
<td>Reception</td>
<td>200</td>
<td>0.1</td>
<td>2.5</td>
<td>0.3</td>
<td>4.72</td>
<td>~</td>
</tr>
<tr>
<td>Halls</td>
<td>200</td>
<td>0.1</td>
<td>3.8</td>
<td>0.3</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Kitchen</td>
<td>500</td>
<td>0.108</td>
<td>25</td>
<td>~</td>
<td>42.24</td>
<td>~</td>
</tr>
<tr>
<td>Restaurant</td>
<td>150</td>
<td>0.7</td>
<td>3.8</td>
<td>0.9</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Hotel Rooms</td>
<td>100</td>
<td>0.11</td>
<td>2.5</td>
<td>0.3</td>
<td>3.15</td>
<td>~</td>
</tr>
<tr>
<td>Roof Equipment Room</td>
<td>200</td>
<td>0.01</td>
<td>~</td>
<td>0.6</td>
<td>52.5</td>
<td>~</td>
</tr>
<tr>
<td>Offices</td>
<td>400</td>
<td>0.05</td>
<td>2.5</td>
<td>0.3</td>
<td>11.77</td>
<td>5</td>
</tr>
<tr>
<td>Deposit Rooms</td>
<td>300</td>
<td>0.11</td>
<td>~</td>
<td>0.6</td>
<td>~</td>
<td>~</td>
</tr>
</tbody>
</table>

Table 5 - Input data related to lighting, equipment and ventilation.
Table 6 - Natural ventilation set-points for different zones in the building

<table>
<thead>
<tr>
<th>Zone</th>
<th>Natural Ventilation Setpoint (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communal Bathrooms</td>
<td>22</td>
</tr>
<tr>
<td>Data centre</td>
<td>22</td>
</tr>
<tr>
<td>Elevators</td>
<td>22</td>
</tr>
<tr>
<td>Stairs</td>
<td>22</td>
</tr>
<tr>
<td>Mail Room</td>
<td>22</td>
</tr>
<tr>
<td>Meeting Rooms</td>
<td>22</td>
</tr>
<tr>
<td>Receptions</td>
<td>23</td>
</tr>
<tr>
<td>Halls</td>
<td>20</td>
</tr>
<tr>
<td>Kitchen</td>
<td>20</td>
</tr>
<tr>
<td>Restaurant</td>
<td>24</td>
</tr>
<tr>
<td>Hotel Rooms</td>
<td>24</td>
</tr>
<tr>
<td>Roof Equipment Room</td>
<td>22</td>
</tr>
<tr>
<td>Offices</td>
<td>20</td>
</tr>
<tr>
<td>Deposit Rooms</td>
<td>22</td>
</tr>
</tbody>
</table>

Some specific areas that require a special environment, such as kitchen, and the restaurant were equipped with extraction fans. For Data Centers, a variable air volume system was installed in order to maintain the desired operative temperature and the relative humidity below 60%. Also, it is important to mention that the air infiltration rate for the building is 4.75 m³/h/m² at 50 Pa (Infiltec) and is a value that remains unchanged during the whole research.

Ventilation rates for all the zones in the building were defined, as it was stated before, according to the ASHRAE Standard 62.1-2001 and can be seen in Table 5.

### 3.2.1.6 Information on building envelope:

The different specifications for the original building envelope assessed in all cities and scenarios are shown in Table 7.

<table>
<thead>
<tr>
<th>Item</th>
<th>Layers</th>
<th>Thickness (m)</th>
<th>U-Value (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External Walls</strong></td>
<td>Brickwork Outer Leaf</td>
<td>0.1</td>
<td>1.498</td>
</tr>
<tr>
<td></td>
<td>Air Gap</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete Block (Medium)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum Plastering</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td><strong>Internal Partitions</strong></td>
<td>Plaster (Lightweight)</td>
<td>0.013</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>Brickwork Inner Leaf</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plaster (Lightweight)</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td><strong>External Windows</strong></td>
<td>Single Pane Green</td>
<td>0.003</td>
<td>6.257</td>
</tr>
<tr>
<td><strong>Internal Floors</strong></td>
<td>Ceramic/Clay Tiles</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cast Concrete</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air Gap</td>
<td>0.016</td>
<td>1.291</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td>Asphalt</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>MW Glass Wool (Rolls)</td>
<td>0.2512</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air Gap</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td><strong>Ground Floor</strong></td>
<td>Plasterboard (Ceiling)</td>
<td>0.01</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Timber Flooring</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floor/Roof Screed</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cast Concrete</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urea Formaldehyde Foam</td>
<td>0.2393</td>
<td></td>
</tr>
</tbody>
</table>

Table 7 - Constitution of the building envelope used in the original building.
Taking into account that the tropical area of Latin America presents rather warm climate conditions throughout the year, the original building model is assumed to have single pane glazing; on the other hand, external walls, internal walls and internal floors are not insulated with any material.

### 3.2.1.7 Information on hot water:

Hot water constitutes an important factor to take into account during the research since it has a direct effect on the natural gas consumption rates for each city. The fuel consumption and environmental impact due to hot water depend exclusively on the location where the energy is used. Table 8 shows the assumed water mains supply temperature and water delivery temperature for each city:

<table>
<thead>
<tr>
<th>City</th>
<th>Water Mains Supply Temperature (°C)</th>
<th>Water Delivery Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogotá</td>
<td>15</td>
<td>55</td>
</tr>
<tr>
<td>Mexico City</td>
<td>15</td>
<td>55</td>
</tr>
<tr>
<td>Fortaleza</td>
<td>18</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 8 - Information on DHW for the building.

Some technical information about the hot water system used in the building is shown below:

- Type: Instantaneously hot water.
- DHW COP= 0.85
- Fuel: Natural gas.

### 3.2.2 Schedules:

In order to optimize the resources and plan out the best approach to have an efficient-operating building, different schedules must be plan out for the functioning of the building. As explained above, the case of study building is used for two different activities: accommodation and business purposes, therefore, schedules for lighting, equipment and occupancy for the different zones were included in the original design.

The different schedules adopted for this research were taken from the United Kingdom National Calculation Methodology (UK NMC) for the Energy Performance of Buildings Directive, which is defined by the Department of Communities and Local Government. The NCM allows energy calculations to be performed by different approved simulation software programs, in this case Design Builder (NMC, 2010).

Tables 25, 26 and 27 in Index 8.3 show the different lighting, equipment and occupancy schedules used during the development of this project; the fractions shown beside the time intervals represent the percentage of operation in each zone during the different periods of time in the day, this way having more accurate values for heat gains, water consumption, occupancy, heating demands, cooling demands and energy consumption.

### 3.3 Simulation

After having defined all the parameters and design conditions, simulation is the next step in order to assess the energy performance and the thermal comfort in the building. The simulations for Bogotá, Mexico City and Fortaleza were done for a complete year, with annual, monthly and daily intervals focused on obtaining results in terms of internal heat gains, comfort, ventilation, temperature and envelope performance at building level and zone levels.
The indoor operative temperature control calculation was based on the Operative temperature in the different zones analyzed, which is the average between the mean radiant temperature and the ambient air temperature; and the number of time steps per hour were 4 (Number of times the building thermal network is solved).

### 3.3.1 Hourly weather data for the selected cities

As stated in Chapter 5, there are different weather sources to simulate the behavior of building models done in a software program and the influence that external conditions have on these. The EnergyPlus database provides complete hourly weather information for Mexico City, Fortaleza and Bogotá; however, it was collected by different institutions, presenting slightly different variables. Information for Bogotá and Mexico City was originally provided in format IWEC, Fortaleza information was provided in format TMY3.

#### 3.3.1.1 IWEC Data files

These data files are suitable for energy simulations in buildings and cover 227 locations outside the U.S.A and Canada. The database has been done after over 18 years of data collection archived at the U.S.A National Climatic Data Center. ASHRAE rules and licenses the usage of IWEC weather data files (Energy Plus).

#### 3.3.1.2 TMY3 Data Files

This data files are arranged in hourly values of solar radiation and meteorological information for a one year period, and are intended for computer simulations of buildings, enabling to make performance comparisons of different systems and arrangements. The institution in charge of ruling the usage of TMY3 information is the National Renewable Energy Laboratory in the U.S.A. For this specific case, the hourly weather data used for the city of Fortaleza (Brazil) was collected by the SWERA Project (Solar and Wind Energy Resource Assessment), which develops weather information for 14 developing countries in the world (EnergyPlus).

Both types of files are converted into EPW files (EnergyPlus Weather) in order to be used by Design Builder and the program simulations. The different variables used in EPW files are shown in Table 9:

<table>
<thead>
<tr>
<th>EPW Files</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Direct Normal illuminance</td>
</tr>
<tr>
<td>Day</td>
<td>Diffuse horizontal illuminance</td>
</tr>
<tr>
<td>Hour</td>
<td>Zenith illuminance</td>
</tr>
<tr>
<td>Minute</td>
<td>Wind direction (degrees)</td>
</tr>
<tr>
<td>Dry bulb temperature</td>
<td>Wind Speed</td>
</tr>
<tr>
<td>Dew Point temperature</td>
<td>Total sky cover</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Opaque sky cover</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>Visibility</td>
</tr>
<tr>
<td>Extraterrestrial horizontal radiation</td>
<td>Ceiling height (m)</td>
</tr>
<tr>
<td>Extraterrestrial normal radiation</td>
<td>Present weather observation</td>
</tr>
<tr>
<td>Horizontal infrared radiation from sky</td>
<td>Present weather codes</td>
</tr>
<tr>
<td>Global horizontal radiation</td>
<td>Precipitable water (mm)</td>
</tr>
<tr>
<td>Normal radiation</td>
<td>Aerosol optical depth</td>
</tr>
<tr>
<td>Diffuse horizontal radiation</td>
<td>Snow depth</td>
</tr>
<tr>
<td>Global Horizontal illuminance</td>
<td>Days since last snowfall</td>
</tr>
</tbody>
</table>

Table 9 - Variables used in EnergyPlus software weather files.
3.4 Different measures to achieve thermal comfort and energy efficiency

In order to improve the performance of the buildings for the cities selected, different scenarios were simulated and analyzed. This gives the chance of choosing the best possible combination to find an energy efficient building that provides thermal comfort to its occupants and emits less CO₂ to the atmosphere, at a feasible price. The idea during the analysis process was to show the progress of the different measures taken with regards to thermal comfort perception by occupants, as well as the fuel consumption to achieve it.

3.4.1 Air conditioning and ventilation systems

As stated above, all the cities included in the research use natural ventilation as the first scenario, then, if needed and depending on the weather conditions for each city, a different cooling and ventilation system was installed to meet the thermal comfort requirements. The AC set-points used in the different zones of the building for each city are seen in Table 10:

<table>
<thead>
<tr>
<th>Zone</th>
<th>AC Setpoints per City (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bogotá</td>
</tr>
<tr>
<td>Office Bathrooms</td>
<td>-</td>
</tr>
<tr>
<td>Data centre</td>
<td>26</td>
</tr>
<tr>
<td>Elevators</td>
<td>-</td>
</tr>
<tr>
<td>Stairs</td>
<td>-</td>
</tr>
<tr>
<td>Mail Room</td>
<td>-</td>
</tr>
<tr>
<td>Meeting Rooms</td>
<td>-</td>
</tr>
<tr>
<td>Receptions</td>
<td>-</td>
</tr>
<tr>
<td>Halls</td>
<td>-</td>
</tr>
<tr>
<td>Kitchen</td>
<td>-</td>
</tr>
<tr>
<td>Restaurant</td>
<td>-</td>
</tr>
<tr>
<td>Hotel Rooms</td>
<td>-</td>
</tr>
<tr>
<td>Roof Equipment Room</td>
<td>-</td>
</tr>
<tr>
<td>Offices</td>
<td>-</td>
</tr>
<tr>
<td>Deposit Rooms</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 10 - Thermostat set-points in the three cities.

The type of chiller used in all cities is named ‘DOE-2 Centrifugal/5.50COP’, some technical information about it is presented below:

- Chilled water set-point temperature: 7.2 °C.
- Condenser water set-point temperature: 29.4°C.
- Cooling tower type: Single speed.
- Reference COP: 5.50
- Water Cooled.

3.4.2 Lighting control

Controlling the artificial lighting usage in the building when natural lighting is available is one way to reduce direct electricity consumption for this purpose, beside the additional thermal load due the artificial lighting that has to be removed by the ventilation system in order to maintain the operative temperature and relative humidity needed to provide thermal comfort amongst the occupants.

In this case, the artificial lighting control method used was the so called “Continuous/Off”, which operates dimming the lights in a continuous and linear way as the daylight iluminance increases, finally switching these off when the minimum dimming point is reached (Minimum input power fraction=0.1; Minimum output fraction=0.1).
3.4.3 Orientation of the main long side façade

This measure is directly linked with the “Lighting Control” measure, since the aim of these has to do with taking advantage of the natural lighting availability depending on the geographical location of the building and the position of the sun in the sky during the year. The orientations simulated were every 45°, which means: East, North-East, North, North-West, West, South-West, South, and South-East. Depending on the results, the orientation that represented the least electricity usage for artificial lighting; the least electricity usage for chillers; and a suitable solar gain value through exterior windows in every city, was chosen to continue with the further energy saving measures.

3.4.4 Exterior Walls

Depending on the weather conditions in each of the cities, different combinations for exterior walls were used in order to find the best performance. Exterior walls combinations were assumed, and so their U-Values, due to the lack of related national standards in the different countries where the research was performed. These are named ‘External Walls 1’, ‘External Walls 2’ and ‘External Walls 3’. The different material layers and U-Value of the combination of these materials are shown in Table 11:

<table>
<thead>
<tr>
<th>External Walls</th>
<th>Layers</th>
<th>Thickness (m)</th>
<th>U-Value (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Walls 1</td>
<td>Brickwork, Outer Leaf</td>
<td>0.1</td>
<td>1.493</td>
</tr>
<tr>
<td></td>
<td>Air Gap</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete Block (Medium)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum Plastering</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>External Walls 2</td>
<td>Brickwork, Outer Leaf</td>
<td>0.1</td>
<td>2.071</td>
</tr>
<tr>
<td></td>
<td>Brickwork, Inner Leaf</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum Plastering</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>External Walls 3</td>
<td>Brickwork, Outer Leaf</td>
<td>0.1</td>
<td>0.934</td>
</tr>
<tr>
<td></td>
<td>Brickwork, Inner Leaf</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>XPS Extruded Polystyrene - CO2 Blowing</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gypsum Plastering</td>
<td>0.013</td>
<td></td>
</tr>
</tbody>
</table>

Table 11 - External walls technical information.

3.4.5 Glazing

Different window arrangements were selected to reduce the solar transmittance heat gains and or to reduce the heat loss inside the building depending on the city. Glazing combinations were assumed, and so their U-Values, due to the lack of related national standards in the different countries where the research was performed. The options used to assess the influence of glazing on the building energy performance are shown in Table 12:

<table>
<thead>
<tr>
<th>Glazing</th>
<th>Layers</th>
<th>Thickness (m)</th>
<th>Total Solar Transmission (SHGC)</th>
<th>Direct Solar Transmission</th>
<th>Light Transmission</th>
<th>U-Value (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Green 3mm</td>
<td>Generic Green</td>
<td>0.003</td>
<td>0.722</td>
<td>0.635</td>
<td>0.822</td>
<td>6.257</td>
</tr>
<tr>
<td>Single Green 6mm</td>
<td>Generic Green</td>
<td>0.006</td>
<td>0.623</td>
<td>0.487</td>
<td>0.749</td>
<td>6.121</td>
</tr>
<tr>
<td>Sgl.Le (c=2-0.2) Clr 3mm</td>
<td>Generic PIR B Clear 3mm</td>
<td>0.003</td>
<td>0.768</td>
<td>0.741</td>
<td>0.821</td>
<td>4.306</td>
</tr>
<tr>
<td>Dbl Clr 3mm/13mm Arg</td>
<td>Generic Clear</td>
<td>0.003</td>
<td>0.764</td>
<td>0.705</td>
<td>0.812</td>
<td>2.596</td>
</tr>
<tr>
<td>Dbl Clr 3mm/13mm Arg</td>
<td>Argon</td>
<td>0.013</td>
<td>0.764</td>
<td>0.705</td>
<td>0.812</td>
<td>2.596</td>
</tr>
</tbody>
</table>

Table 12 - Glazing technical information.
3.4.6 Shading devices

Shading devices were used with the aim of reducing the heat gains due to solar irradiance and provide occupants with visible comfort by reducing glare when it surpasses a maximum allowable level of 22 (Viracon, 2010). The different shading devices installed during the research can be seen in Tables 13, 14 and 15:

- **Window shading:**

<table>
<thead>
<tr>
<th>Shading Device</th>
<th>Thickness (m)</th>
<th>Conductivity (W/m·K)</th>
<th>Solar Transmittance</th>
<th>Solar Reflectance</th>
<th>Visible Transmittance</th>
<th>Visible Reflectance</th>
<th>Long-wave Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drapes close weave medium</td>
<td>0.003</td>
<td>0.1</td>
<td>0.05</td>
<td>0.3</td>
<td>0.05</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Shade Rail-Light Translucent</td>
<td>0.002</td>
<td>0.1</td>
<td>0.4</td>
<td>0.45</td>
<td>0.4</td>
<td>0.45</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 13 - Diffusive blinds window shading devices technical information.

<table>
<thead>
<tr>
<th>Shading Device</th>
<th>Blind-to-glass Distance (m)</th>
<th>Slat Orientation</th>
<th>Slat Width (m)</th>
<th>Slat Separation (m)</th>
<th>Slat Thickness (m)</th>
<th>Slat Angle (°)</th>
<th>Slat Conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blind with high reflectivity</td>
<td>0.015</td>
<td>Horizontal</td>
<td>0.025</td>
<td>0.0188</td>
<td>0.001</td>
<td>45</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 14 - Slatted blinds window shading devices technical information.

- **Local shading:**

<table>
<thead>
<tr>
<th>Shading Device</th>
<th>Projection (m)</th>
<th>Vertical Offset from Window Top (m)</th>
<th>Blade Material</th>
<th>Louvers</th>
<th>Side louvers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhangs</td>
<td>0.5</td>
<td>0</td>
<td>Steel</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Overhangs</td>
<td>1</td>
<td>0</td>
<td>Steel</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 15 - Local shading devices technical information.

3.5 Environmental Impact Assessment (CO₂ Emissions)

The environmental impact of the original building, as well as the new values after having applied all the different energy-saving measures in the building vary significantly depending on the location where the fuel is used and the source of it. In other words, electricity and heat generation have a great impact on the environment, even higher given the size of a building project like the one this research is about (IEA, 2011).

The amount of CO₂ emissions annually can be calculated by using the following equations (Arias, 2011):

\[
\text{Emissions CO}_2 (Electricity) = E L \times I E L \quad \text{(Equation 4)}
\]

\[
\text{Emissions CO}_2 (Heat) = Heat \times I E L \quad \text{(Equation 5)}
\]

\[
\text{Emissions CO}_2 (Cool) = m. losses \times G W P_{r e f r i g e r a n t} \quad \text{(Equation 6)}
\]

Where,

EL is the annual electricity usage in kWh;

IEL is the CO₂ intensity of fuel in kg CO₂/kWh (Depends on the fuel and country);

Heat is the heat usage in kWh;

m.losses is the mass flow of lost refrigerant in kg/Year;

GWP_{refrigerant} is the global warming potential of the refrigerant in kg CO₂/kg refrigerant.
It is important to clarify that Equation 6 was not used since it was assumed that no refrigerant leakage took place in any scenario for the research. The \( IEL \) values from electricity and heat generation were extracted from the IEA Statistics book for 2011 and can be seen in Table 16 depending on the country:

<table>
<thead>
<tr>
<th>Country</th>
<th>CO(_2) Intensity from electricity generation (g CO(_2)/kWh)</th>
<th>CO(_2) Intensity from heat generation (kg CO(_2)/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colombia</td>
<td>135</td>
<td>490</td>
</tr>
<tr>
<td>Mexico</td>
<td>90</td>
<td>441</td>
</tr>
<tr>
<td>Brazil</td>
<td>455</td>
<td>412</td>
</tr>
</tbody>
</table>

Table 16 - CO\(_2\) Intensity from energy use in the three different cities.
4 Results and analysis

Before showing and analyzing the results, it is important to remind some key assumptions made for the original building scenario:

- It is modeled under naturally ventilated conditions.
- Kitchen and restaurant have exhaust fans. Data centers in all floors are conditioned spaces in order to maintain the temperature below 26ºC.
- Main long-side façade faces westward direction.
- Relative humidity is meant to be kept within 40<R<60%.
- Room electricity consumption and district hot water (DHW) consumption remain constant in all measures taken for the cities.

4.1 Bogotá (Colombia)

4.1.1 Original model results

The city of Bogotá presents suitable climatic conditions for natural ventilation, since the monthly average air temperature ranges between 12ºC and 14ºC and the relative humidity rarely exceeds 60%, except during the rainy season, which takes place between the months of March and May, October and November. Several factors influence directly the indoor conditions of the building, such as outdoor outside relative humidity and dry bulb temperature, occupancy, solar heat gains, equipment heat gains that somehow will modify the local environment and, therefore, the comfort perception amongst the occupants. Figure 16 shows the outdoor dry bulb temperature and the indoor operative temperature for Bogotá, the latter after being influenced by the named factors above:

![Figure 16 - Operative temperature and Outside dry bulb temperature per month for Bogotá.](image)

This scenario is the starting point for the research that aims at turning the building into thermally comfortable by modifying different key factors that end up influencing the energy distribution and, also, by optimizing the fuel consumption that make it possible for the building to function properly.
In terms of thermal comfort, such a large naturally ventilated building turns out to be hard to control, since some specific zones are within the \(-0.5<\text{PMV}<0.5\) level, but at the same time the majority of the building is way out of this range making the local environment really uncomfortable or not adjusted to the defined requirements by Category B buildings, requiring further measures to equilibrate the conditions. With the aim of getting an idea of the thermal comfort perception, overall results for the building in terms of PMV index are shown in Figure 17:

![Figure 17 - Fanger PMV levels for the building under NV conditions](image)

It can be noted from Figure 17 that the comfort requirements for a Category B building are not fulfilled in any of the months of the year looking at the whole building perspective, making the comfort perception high in general terms; however, when analyzing the different zones of the building, it is evident that there are two different situations depending on the part of the building: the hotel rooms present high relative humidity and low operative temperatures, since these are occupied mostly only during the night time and, also, the heat load for equipment is considerably low as compared to the offices part of the building. On the other hand, some zones from the fourth floor to the seventh floor, especially offices, bathrooms and meeting rooms, present high operative temperatures due to the high concentration of occupants and the large heat gains due to computers and office equipment and also high relative humidity levels. High relative humidity levels might result into harmful effects like mildew growth (EPA). Relative humidity and operative temperature are key variables to monitor in order to provide a proper thermal environment, reason why further measures will be taken to adjust them. Table 17 shows operative temperature and relative humidity values for different zones on all floors of the building, including the sample zones stated in the Methodology in Chapter 3:
Table 17 – Average operative temperature and average relative humidity for different zones under naturally ventilated conditions in Bogotá.

From Table 17 it is noticeable that 2nd floor presents high relative humidity levels throughout the year. Similar values are registered in zones on the 4th, 5th, 6th and 7th floor that correspond to the offices part of the building, with really high operative temperature values, as well. On the 1st and 3rd floor relative humidity these levels are lower, but are considerably high taking into account the recommended range for relative humidity of 40%<RH<60%; and in some months exceeding 60%. It can be concluded that the most critical zones in terms of relative humidity are the 2nd floor rooms, the meeting rooms and bathrooms on the 4th, 5th, 6th and 7th floors.

In order to analyze the building’s energy performance, it is important to stress that there are different end uses for the energy consumed in the building that are kept as a reference throughout the whole research. These are shown in Figure 18 on an annual basis:

![Fuel Breakdown](image)

Figure 18 - Fuel breakdown in the building for Bogotá (kWh).
The results shown in Figure 18 represent the fuel breakdown of the building. The “Room electricity” category remains constant for all the different scenarios modeled in this project, since it represents the energy usage by cooking, office equipment, room equipment, etc and are out of the scope for the research. Also ‘DHW (Gas)’ is constant for the rest of the research for this city. ‘Chillers’ include the consumption due to pumps and fans used for air conditioning and ventilation. An important fact to stress is that zone heating was not taken into account during the simulations performed since the operative temperatures indoors remain at acceptable levels regardless the outdoor temperatures, except for isolated zones like the parking lot and the emergency stairs where the operative temperature reaches slightly lower values at night time.

The internal gains inside the building are distributed as shown in Figure 19:

![Graph showing internal gains](image)

Figure 19 - Internal gains for the year in the building for Bogotá (kWh).

‘Computer + Equipment’ remains constant for the rest of the scenarios. On the other hand, ‘General lighting’ is a variable that can be reduced; ‘Solar gains through exterior windows’ can be reduced or kept at an acceptable level in order to maintain the heat balance indoors. It is important to notice that the values for ‘Room electricity’ from the fuel breakdown chart (Figure 18) and ‘Computer + Equipment’ from the Internal Gains chart (Figure 19) are the same, since the Second Law of Thermodynamics implies a constant final outcome of equilibrium in systems expressed as heat; thus, light, motion and even sound will end up transformed into heat when interacting with the different surfaces and elements present in the surroundings. The same phenomenon takes place with ‘Lighting’ from the fuel breakdown chart (Figure 18) and ‘General Lighting’ from the internal gains chart (Figure 19).

### 4.1.2 Different scenarios to achieve an energy efficient building in Bogotá

#### 4.1.2.1 Lighting control and main long-side façade orientation

Proper orientation of the façade with the largest window area is a known measure to take into account when designing a building (Ecowho, 2012). After having looked into the yearly climatic conditions for Bogotá, it was concluded that unconditioned air from the outside fulfills the requirements to ventilate the building in a successful way. These climatic conditions show that Bogotá presents cold temperatures throughout the year, reason why solar irradiance was needed to stabilize the indoor temperatures in some areas, like hotel rooms.
Having clear that air from the outside was used as the direct supply air for the different spaces and no air conditioning is used (except for data centers), solar heat gains are not the main criteria for deciding the main long-side façade orientation of the building, since these contribute to achieve a passive solar heating system for some zones that need it, but the amount of natural lighting that can be taken advantage of, by using Lighting control in addition to orientation, reducing the electricity consumption due to artificial lighting. Figure 20 shows the annual energy consumption for artificial lighting depending on the orientation of the main long-side façade:

![Figure 20](image)

**Figure 20 - Annual General lighting electricity consumption (kWh) influenced by the Orientation + LC in Bogota.**

It can be noted from the Figure 20 that South-West orientation represents the least electricity consumption in terms of general lighting, which is the reason why it is used for the rest of the measures to achieve energy efficiency in the building for the Bogotá case. The annual Fanger PMV Index for the building after having applied lighting control and having chosen the South-West orientation can be seen in Figure 21:

![Figure 21](image)

**Figure 21 - Fanger PMV Index of the building influenced by LC + SW Orientation.**

4.1.2.2 **Exterior walls**

Lighting electricity consumption is the factor that made possible to choose South-West orientation as the most suitable for this city. It has been explained that the building is highly influenced, in terms of thermal comfort distribution, by the occupancy, activity performed and amount of equipment usage in the
different zones. This makes for cold 2nd and 3rd floors (Hotel); and hot 4th, 5th, 6th and 7th floors (Offices), resulting in thermal discomfort in both cases. Taking into account the importance of building envelope in the interaction between the inside and the outside of the building, exterior walls play an important role in balancing the thermal perception of the occupants. This is the reason why two different options for exterior walls have been selected to assess the benefits that one has over the other for the city of Bogotá.

Figure 22 and Figure 23 show the comparison between the two types of external walls and the influence that these have on the heat balance for different sample zones in the building:

![Figure 22](image1.png)

Figure 22 - Heat loss (kWh/year) due to conduction through the external walls in the sample hotel rooms.

![Figure 23](image2.png)

Figure 23 - Heat loss (kWh/year) due to conduction through the external walls in the sample offices.

From Figures 22 and 23, it is noticeable the greater amount of heat dissipated to the environment through the ‘External Walls 2’ combination, which corresponds to a reduction in the heat load in the zones of around 20% for the hotel rooms and 7-10% for the offices. This phenomenon results into a more comfortable environment in the case of the offices; nevertheless, it is prejudicial for the hotel rooms since the operative temperature drops even more than it previously was with the ‘External Walls 1’ combination.
With the aim of solving the low operative temperatures in the hotel rooms, and at the same time being careful to not modify dramatically the envelope design of the building, a 20mm layer of expanded polystyrene was added to the ‘External Walls 2’ combination exclusively in the hotel rooms (‘External Walls 3’). By doing this, the external walls of the building in the rooms present a lower U-Value and maintain the heat inside, especially at night when the outside temperature drops dramatically and it is easier for heat to transfer though the walls due to conduction. This final design makes for a lighter building envelope than ‘External Walls 1’ with regards to the materials used, but keeping cooler the areas that are the most occupied with greater heat gains from occupancy and equipment; and, at the same time, keeping warmer the hotel rooms. Figure 24 shows the results for heat loss in the sample hotel rooms with the ‘External Walls 3’ combination:

![Figure 24 - Heat loss (kWh/year) due to conduction through the external walls in sample hotel rooms including ‘External Walls 3’.](image)

It can be noted in Figure 24 that even though the ‘External Walls 3’ is a light-weight combination, it gives better results when it comes to maintaining the heat indoors when compared to ‘External Walls 1’. The amount of heat that is kept from being wasted corresponds to approximately 40% in the hotel rooms taking as reference the ‘External Walls 1’. The best indicator to understand these results more clearly would be the comparison of the overall monthly PMV Comfort levels for the three external walls options at building level. These can be seen in Figure 25:

![Figure 25 - Overall monthly PMV Comfort levels for the three external walls options.](image)
It is noticeable in Figure 25 that the usage of ‘Exterior Walls 3’ in the hotel rooms and ‘Exterior Walls 2’ for all the other zones in the building represent a good balance in terms of thermal comfort, reason why this combination has been chosen as the most suitable for continuing the research with further measures to turn this building into an energy efficient one.

4.1.2.3 Ventilation modifications

In the original model results section of the city of Bogotá, the fact that relative humidity levels were reaching really high values, even higher than those recommended to prevent the zones from formation of mildew and therefore harmful diseases, is translated into a need to make the air circulate more efficiently. Taking into account that natural ventilation is suitable for Bogotá and has actually been selected as the type of ventilation; local exhaust fans in hotel rooms, bathrooms, meeting rooms and offices were installed (Ashrae, 2010). Table 18 shows the impact that this measure has on the relative humidity levels for the most critical zones in the building:

![Table 18 - Relative humidity (%) for critical zones after having implemented local exhaust fans](image)

From Table 18 it can be concluded that the presence of local exhaust fans does have a direct effect on the relative humidity levels and in this case, reduce it to acceptable levels in order to fulfill minimum ventilation requirements. This measure was then included in the building design for the rest of the measures to be taken in Bogotá. Figure 26 shows the evolution of the overall monthly Fanger PMV Index of the building influenced by this measure:
It is important to clarify that even though offices did not have any kind of problem regarding being out of the suggested range for relative humidity, exhaust fans were also installed in these zones with the aim of making the outside air circulate easier. This is the reason why Figure 26 shows a drop in Fanger PMV levels, since offices are definitely the warmest zones in the building.

4.1.2.4 **Glazing**

The next measure to carry out was a glazing change, since fenestration is one of the key factors with regards to energy efficiency in buildings, if not the most important. So far in the analysis, it has been evident that there were two main divisions in the building with different requirements for thermal comfort: hotel rooms require keeping heat indoors in order to stabilize the operative temperature; while offices require heat to constantly flow in the outdoors direction in order to maintain good thermal comfort conditions. Having this fact clear, the approach followed in terms of glazing was the same as the one followed in the other measures applied so far, selecting high SHGC windows for the hotel rooms, as well as low U-Values to reduce the heat flow to the outside; on the other hand, low SHGC and high U-Value windows for the upper floors (4th, 5th, 6th and 7th) which correspond to the offices, meeting rooms and bathrooms with the aim of reducing the operative temperatures.

The glazing type chosen for hotel rooms was ‘Double Clear 3mm/13mm Arg’. Figure 27 shows the comparison of the chosen glazing option with the ‘Single 3mm’, which was originally installed in the building, in terms of internal heat gains through them in the sample hotel rooms:
From Figure 27 it is noticeable that the heat gain due to solar radiation transmission is higher by around 8-10% when using ‘Dbl Clr 3mm/13mm Arg’ in the hotel rooms. Even though this is a pretty important fact for increasing the operative temperature in these zones, the benefits of using this new glazing are more easily appreciated when analyzing the amount of heat lost through it, since one special feature of double glazed argon-filled windows is its capacity to reduce the heat transfer due to its low U-Value. Figure 28 shows the heat loss through the newly installed glazing in sample hotel rooms:

It can be seen in Figure 28 that using ‘Dbl Clr 3mm/13mm Arg’ glazing reduces the heat loss in about 30%, this way making the environment warmer and the operative temperature higher in the hotel rooms, thus giving the expected performance. On the other hand, ‘Sgl Green 6mm’ windows were installed on 4th, 5th, 6th, 7th floors (except stairs and emergency stairs which remained with ‘Sgl Green 3mm’ glazing)
and all data centers, with the aim of reducing the transmission solar heat gains indoors. Figure 29 shows the comparison between ‘Sgl Green 3mm’ and ‘Sgl Green 6mm’ windows in terms of solar heat gains for the sample offices:

A great reduction of approximately 26% in solar transmission heat gains can be observed in Figure 29, resulting in a cooler environment with lower operative temperatures. Following the same procedure as with the hotel rooms, the heat loss through windows was also analyzed for the sample offices, which can be seen in Figure 30:

A great reduction of approximately 26% in solar transmission heat gains can be observed in Figure 29, resulting in a cooler environment with lower operative temperatures. Following the same procedure as with the hotel rooms, the heat loss through windows was also analyzed for the sample offices, which can be seen in Figure 30:

An interesting phenomenon can be seen in Figure 30, since the heat losses using ‘Sgl Green 6mm’ are lower by approximately 14% than when using ‘Sgl Green 3mm’. It can be explained partly due to the slightly higher U-Value of the ‘Sgl Green 6mm’ (6.121 W/m²-K), compared to ‘Sgl Green 3mm’ one (6.257 W/m²-K); but also due to the large amount of heat that was kept from entering these zones by
improving the glazing type, which can be understood, as expressed above, in much lower operative temperatures and heat concentrations inside.

As a way to keep track of the evolution in terms of internal thermal conditions and perception by the occupants, Figure 31 shows the Fanger PMV Index of the whole building after having applied different glazing options for the hotel rooms and the offices, meeting rooms and bathrooms in upper floors:

![Figure 31 - Fanger PMV levels for the building with the addition of different glazing options in Bogotá.](image)

An increase in the overall Fanger PMV levels is noticeable, but this fact shows how effective the installation of ‘Dbl Clr 3mm/13mm Arg’ glazing was in the hotel rooms. It is also observed that despite this increase, the Fanger PMV levels remain within the Category B building.

### 4.1.2.5 Shading devices

Shading devices are a handy option in order to reduce the solar transmission heat gains in warm zones of the building, especially when the sun radiation is higher at times of the day around noon. Shading devices give the possibility to provide visual comfort by reducing the glare levels during some hours of the day due to a direct solar light entrance (Viracon, 2010) also, these are useful as an extra obstacle to keep heat from flowing outwards in some zones when the outdoor temperature is low, this way maintaining the operative temperature indoors at acceptable levels.

In the hotel rooms, a ‘Drapes – close weave medium’ mechanism was installed indoors that works according to the occupancy schedule so that it could block the artificial lighting from the outside of the building at night time and, at the same time preventing heat to flow outdoors during the night, this way recreating the building as realistic as possible.

The influence of the shading devices installed is assessed in terms of local Fanger PMV levels for the selected sample rooms in an annual basis. Figure 32 shows these values:
From Figure 32 it can be concluded that Rooms 307 and 308 are the ones closer to being in a perfect equilibrium in terms of thermal comfort. Rooms 202 and 212 are the ones further away from this equilibrium and the reason for it is their corner location in the building, this way having the largest wall area amongst all the rooms and the least window area. This restricts the solar transmission gains, therefore lowering the operative temperature and Fanger PMV index. Figure 32 also shows the slight improvement in thermal comfort perception when using drapes as window shading at night time.

Offices are also critical zones that have the opposite scenario as the hotel rooms, as it has been explained throughout this chapter. Figure 33 shows the effects that different window shading devices have on the thermal comfort perception by occupants:

‘Outside blinds’ provide a suitable solution for glare discomfort and also contributes to decrease the thermal perception in the offices, as shown in Figure 33. The opposite is seen in ‘Inside blinds’ and ‘Inside shade rolls’, since these represent an obstacle for heat to leave these zones. There is no need for local...
shading devices in Bogotá, since the weather conditions are rather cloudy and cold, where solar heat gains do not contribute much on the indoor conditions; besides, the thermal comfort conditions are already in the Category B Building range. On the other hand, local shading would reduce significantly the natural light entering the zones, increasing the electricity consumption due to artificial lighting. ‘Outside blinds’ completes the shading devices measures to turn this building into a comfortable and energy-efficient project under the weather conditions of the city of Bogotá.

4.1.3 Final Comparison between original and final building designs (Bogotá)

The most important objective when modifying the project building and analyzing the performance of different measures in it, is undoubtedly how thermally comfortable the building can be while savings as many resources as possible at the same time. It is important to take a look at the direct comparison between the original proposed model and the final outcome after having implemented several measures to achieve that goal. Figure 34 shows the comparison between one another in terms of operative temperature taking as reference the outside dry bulb temperature:

Figure 34 - Operative temperature comparison between original and final designs in Bogotá.

Figure 35 represents the same comparison in terms of Fanger PMV levels perceived by the occupants:
It is noticeable from Figure 34 and Figure 35 how successful the different measures to provide comfort and reduce the energy consumption were. Outdoor conditions clearly benefited the performance showed by the new building design and made possible to make use of natural ventilation, which in the end represents an important way of saving money by reducing the electricity consumption and therefore, reducing the environmental impact. The fuel consumption comparison by both scenarios is shown in Figure 36:

The significant reduction in energy consumption for artificial lighting purposes can be noted in Figure 36, which represents around 61% in savings. Lighting control in all zones of the building, orientation of the main long-side façade and glazing were responsible for this important reduction. On the other hand there is the approximately 21% reduction in chillers electricity, which was achieved thanks to the glazing and external walls modifications in data centers, since these were the only air conditioned spaces in the
building. Regarding DHW natural gas consumed, it remained unchanged as expected because there were no changes made in terms of neither delivery and supply water temperatures nor water consumption rates by the occupants. The same situation takes place with ‘Room Electricity’ since it remained unchanged during the whole process.

As stated above, all the energy consumption reductions achieved during the implementation of the different measures described in this chapter influence directly the CO₂ emissions. The amount of grammes of CO₂ emitted per kWh produced varies depending on the country or region, since the source of these fuels are different (Hydro, Coal, Natural gas, Diesel, etc). The environmental impact comparison left by the fuel consumed in the building for both scenarios is represented in Figure 37:

![Figure 37 - CO2 Production comparison between original and final designs in Bogotá.](image)

Even though the CO₂ emissions from natural gas for hot water remain the same at 118.5 Tonnes of CO₂ emitted, it is an acceptable value for such a large building. On the other hand, the approximately 28.8% reduction in CO₂ emissions due to electricity usage represents a very important reduction in environmental impact and thus making the building more efficient.

As a final way to conclude about the energy analysis results, Figure 38 shows the specific energy consumption evolution in the building as new measures were taken in order to provide the best thermal comfort conditions as possible, as well as reducing the energy consumption:

![Figure 38 - Specific energy consumption evolution in the building influenced by the different measures applied during the analysis for the city of Bogotá.](image)
The evolution in specific energy consumption shown in Figure 38 depicts the benefits of the measures taken to reduce the energy consumption, but most important, the supply of thermal comfort to the occupants.

### 4.2 Mexico City (Mexico)

#### 4.2.1 Original model results

Mexico City climatic conditions are temperate during most of the year with an average temperature outside of 16°C. The rainy season starts in June until September. Due to the city's location far from the Equator line, seasonal variation is more noticeable than in the other two cities case of study in this project, being reflected on a wider outside temperature range during the year; and the availability of solar light and radiation depending on the month. Figure 39 shows the influence of external conditions on the operative temperature in the building for the original design:

![Operative temperature and Outside dry bulb temperature per month for Mexico City.](image)

It is worth to remind that the main factor that led to make different changes to the building design is thermal comfort when this was not met. The performance of this building under naturally ventilated conditions in terms of thermal comfort is shown in Figure 40:
Figure 40 shows how far the Fanger PMV values for the building are from the acceptable range (-0.5< Fanger PMV<0.5) for Category B buildings. These results are directly linked to the outdoor conditions, and even though there were no problems in terms of relative humidity surpassing the allowable 60% limit in the hotel part of the building, some areas in upper floors did present really high temperatures and relative humidity values that natural ventilation clearly could not alleviate. Table 19 shows annual values for operative temperature and relative humidity in the same sample zones as used in the analysis for Bogotá, so that it is easier to identify the problematic areas and propose a solution:

![Figure 40 - Fanger PMV for the building under Natural ventilation conditions in Mexico City.](image)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Operative Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Zone</th>
<th>Operative Temperature (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room 202</td>
<td>26.674</td>
<td>47.068</td>
<td>Office 401</td>
<td>31.354</td>
<td>46.196</td>
</tr>
<tr>
<td>Room 203</td>
<td>26.249</td>
<td>45.358</td>
<td>Office 402</td>
<td>31.834</td>
<td>45.550</td>
</tr>
<tr>
<td>Room 207</td>
<td>28.294</td>
<td>44.098</td>
<td>Office 403</td>
<td>30.326</td>
<td>46.741</td>
</tr>
<tr>
<td>Room 208</td>
<td>27.801</td>
<td>44.801</td>
<td>Office 404</td>
<td>30.633</td>
<td>45.502</td>
</tr>
<tr>
<td>Room 212</td>
<td>27.182</td>
<td>43.073</td>
<td>Office 501</td>
<td>30.976</td>
<td>45.681</td>
</tr>
<tr>
<td>Room 213</td>
<td>27.575</td>
<td>44.275</td>
<td>Office 502</td>
<td>31.355</td>
<td>44.724</td>
</tr>
<tr>
<td>Room 216</td>
<td>28.305</td>
<td>45.976</td>
<td>Office 503</td>
<td>32.150</td>
<td>44.823</td>
</tr>
<tr>
<td>Room 217</td>
<td>27.859</td>
<td>45.346</td>
<td>Office 504</td>
<td>32.777</td>
<td>43.818</td>
</tr>
<tr>
<td>Room 302</td>
<td>27.879</td>
<td>44.661</td>
<td>Office 601</td>
<td>31.020</td>
<td>45.551</td>
</tr>
<tr>
<td>Room 303</td>
<td>27.351</td>
<td>43.471</td>
<td>Office 602</td>
<td>31.438</td>
<td>44.535</td>
</tr>
<tr>
<td>Room 307</td>
<td>29.326</td>
<td>43.193</td>
<td>Office 603</td>
<td>32.220</td>
<td>44.620</td>
</tr>
<tr>
<td>Room 308</td>
<td>29.502</td>
<td>43.055</td>
<td>Office 604</td>
<td>32.873</td>
<td>43.577</td>
</tr>
<tr>
<td>Room 312</td>
<td>28.868</td>
<td>41.295</td>
<td>Office 701</td>
<td>30.461</td>
<td>35.873</td>
</tr>
<tr>
<td>Room 313</td>
<td>29.966</td>
<td>42.778</td>
<td>Office 702</td>
<td>30.969</td>
<td>35.459</td>
</tr>
<tr>
<td>Room 316</td>
<td>29.069</td>
<td>44.945</td>
<td>Office 703</td>
<td>31.518</td>
<td>34.094</td>
</tr>
<tr>
<td>Room 317</td>
<td>29.305</td>
<td>44.104</td>
<td>Office 704</td>
<td>32.153</td>
<td>32.818</td>
</tr>
</tbody>
</table>

Table 19 - Operative temperature and relative humidity for different zones under naturally ventilated conditions in Mexico City.

According to Table 19, hotel rooms present acceptable values for both, operative temperature and relative humidity, which can be easily adjusted by implementing measures such as orientation of the main façade, lighting and exhaust fans. However, offices in 4th, 5th, 6th and 7th show really high operative temperatures, and in some cases, like the 7th floor, the relative humidity levels are low. On the other hand, meeting
rooms in these same floors present uncomfortably high relative humidity values except for those located on the 7th floor, as can be seen in Table 20:

<table>
<thead>
<tr>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meeting Room 4-1</td>
</tr>
<tr>
<td>Meeting Room 4-2</td>
</tr>
<tr>
<td>Meeting Room 5-1</td>
</tr>
<tr>
<td>Meeting Room 5-2</td>
</tr>
<tr>
<td>Meeting Room 6-1</td>
</tr>
<tr>
<td>Meeting Room 6-2</td>
</tr>
<tr>
<td>Meeting Room 7-1</td>
</tr>
<tr>
<td>Meeting Room 7-2</td>
</tr>
</tbody>
</table>

Table 20 - Relative humidity (%) in meeting rooms on 4th, 5th, 6th and 7th floors under NV conditions in Mexico City.

Table 19 and Table 20 make evident the need for a different ventilation system for the upper floors (Office part of the building) in order to reduce the high operative temperatures and the relative humidity problems in the meeting rooms; as well as a modification in the hotel rooms to make air circulate easily.

4.2.2 Different scenarios to achieve an energy efficient building in Mexico City

4.2.2.1 Ventilation systems

Considering the results for the original building design scenario shown above, new ventilation systems were the next measure to undertake in the research. Hotel rooms in the 2nd and 3rd floors, as well as most zones on the first floor, remained using natural ventilation but with the addition of continuous local exhaust fans (Ashrae, 2010) in order to make stale air exit the room in a controlled and efficient way, leaving space for fresh air to enter through windows. Also, meeting rooms, offices and bathrooms on the 4th, 5th, 6th and 7th floors, as well as stairs, elevators and hallways on 2nd and 3rd floors have been equipped with a dual duct VAV air conditioning system in order to control important variables such as operative temperature and relative humidity that were reaching high levels in the previous scenario, as shown in Table 19 and Table 20 above.

It is worth to clarify that since the usage of an air conditioning system implies much more electricity consumption, the performance of further measures to achieve thermal comfort and energy efficiency in the building were be compared to this scenario where AC and local exhaust fans were installed, not the naturally ventilated one, whose results have been previously presented. Figure 41 shows the annual fuel breakdown for this new scenario:
It can be noted from Figure 42 that ‘Room electricity’, ‘Lighting’ and ‘DHW’ remain the same as with the city of Bogotá case, and for the rest of the analysis carried out for this city. Also, Figure 41 shows how high of a value ‘Chillers’ represent in this scenario, including the electricity consumed by fans and pumps in the AC system. It is clear that even though the installation of AC reduced considerably the high operative temperature and relative humidity values in the offices part of the building, as can be seen in Table 21, further measures were required in order to decrease the electricity consumption. Table 20 also shows the new performance in hotel rooms after local exhaust systems have been installed:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Operative Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Zone</th>
<th>Operative Temperature (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room 201</td>
<td>24.322</td>
<td>40.629</td>
<td>Office 401</td>
<td>24.544</td>
<td>40.941</td>
</tr>
<tr>
<td>Room 203</td>
<td>24.260</td>
<td>40.023</td>
<td>Office 402</td>
<td>24.677</td>
<td>40.687</td>
</tr>
<tr>
<td>Room 207</td>
<td>24.788</td>
<td>37.886</td>
<td>Office 403</td>
<td>24.294</td>
<td>41.362</td>
</tr>
<tr>
<td>Room 208</td>
<td>25.238</td>
<td>38.979</td>
<td>Office 404</td>
<td>24.439</td>
<td>40.972</td>
</tr>
<tr>
<td>Room 212</td>
<td>25.089</td>
<td>38.752</td>
<td>Office 501</td>
<td>24.219</td>
<td>41.307</td>
</tr>
<tr>
<td>Room 213</td>
<td>25.141</td>
<td>39.222</td>
<td>Office 502</td>
<td>24.436</td>
<td>40.972</td>
</tr>
<tr>
<td>Room 216</td>
<td>25.475</td>
<td>38.733</td>
<td>Office 503</td>
<td>24.537</td>
<td>40.950</td>
</tr>
<tr>
<td>Room 217</td>
<td>25.115</td>
<td>39.280</td>
<td>Office 504</td>
<td>24.692</td>
<td>40.663</td>
</tr>
<tr>
<td>Room 302</td>
<td>24.398</td>
<td>40.523</td>
<td>Office 601</td>
<td>24.299</td>
<td>41.349</td>
</tr>
<tr>
<td>Room 303</td>
<td>24.203</td>
<td>40.175</td>
<td>Office 602</td>
<td>24.423</td>
<td>40.989</td>
</tr>
<tr>
<td>Room 307</td>
<td>25.652</td>
<td>38.124</td>
<td>Office 603</td>
<td>24.498</td>
<td>41.023</td>
</tr>
<tr>
<td>Room 308</td>
<td>25.593</td>
<td>38.254</td>
<td>Office 604</td>
<td>24.649</td>
<td>40.738</td>
</tr>
<tr>
<td>Room 312</td>
<td>25.242</td>
<td>38.405</td>
<td>Office 701</td>
<td>24.104</td>
<td>40.017</td>
</tr>
<tr>
<td>Room 313</td>
<td>25.360</td>
<td>38.972</td>
<td>Office 702</td>
<td>24.332</td>
<td>39.785</td>
</tr>
<tr>
<td>Room 316</td>
<td>25.341</td>
<td>38.897</td>
<td>Office 703</td>
<td>24.207</td>
<td>39.882</td>
</tr>
<tr>
<td>Room 317</td>
<td>25.449</td>
<td>38.651</td>
<td>Office 704</td>
<td>24.343</td>
<td>39.753</td>
</tr>
</tbody>
</table>

Table 21 - Operative temperature and relative humidity for different zones with AC system and local exhaust fans conditions in Mexico City.

Previously, Table 20 in Page 59 showed meeting rooms in the office part of the building (4th, 5th, 6th and 7th floors) as the most critical zones in terms of high relative humidity. Table 22 shows the improvement shown by these zones after the installation of an AC system:
The internal gains in the building are distributed as follows in Figure 42:

<table>
<thead>
<tr>
<th>General Lighting</th>
<th>Computer + Equip</th>
<th>Occupancy</th>
<th>Solar Gains Exterior Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>292097.15</td>
<td>816097.26</td>
<td>222109</td>
<td>500977.8</td>
</tr>
</tbody>
</table>

Figure 42 - Annual Internal gains in the building (kWh) with AC and exhaust fans installed.

It is important to identify the distribution of internal gains since they give a hint regarding which aspects to change in order to decrease the fuel consumption of different systems. ‘Lighting’ and ‘Solar Gains through Exterior Windows’ are aspects that can be reduced by using lighting control and re-orientation of the main long-side façade of the building. These correspond to the next measure undertaken to improve the performance of the building.

4.2.2.2 Lighting control and main long-side façade orientation

As explained during the energy analysis of the building under the external conditions of Bogotá, lighting control is a very helpful way to reduce direct energy consumption used for artificial lighting by measuring the amount of natural light entering the different zones where these devices are installed, and dimming the electrical output used to compensate for lighting when required. Besides reducing the electricity consumption, LC helps reduce the internal heat gains due to artificial lighting. Orientation of the main long-side façade gives the chance to position the building in such a way that allows to take advantage of natural lighting and also, avoiding solar heat gains as much as possible, since the project building has a large amount of windows on all the facades. Figure 43 shows the influence of the orientation and LC on the energy consumption due to artificial lighting.
From Figure 43, it can be concluded that ‘South’ and ‘South West’ orientations are the least energy consuming for general lighting purposes, with almost identical values of approximately 77.18 MWh/Year. As stated above, the energy consumption due to chillers is also an important criterion when deciding which orientation suits the best Mexico City and its external weather conditions. Figure 44 shows the chillers energy consumption on an annual basis depending on the orientation of the main long-side façade:

From Figure 43 and Figure 44 it can be concluded that ‘South’ direction is the most suitable orientation for the building in Mexico City.
4.2.2.3 Exterior Walls

Exterior walls, along with glazing, represent that important boundary that divides the indoors and outdoors in edifications. Indoors, different factors affect the thermal conditions and therefore, the thermal comfort perceived by the occupants. Outdoors corresponds to a highly changing environment influenced by the weather conditions, season of the year and even the time of the day. In order to analyze that balance between indoors and outdoors, two different exterior wall combinations were used, and the performance of both is shown in Figure 45 and Figure 46 in terms of heat loss for the different sample zones previously defined:

![Figure 45 - Heat loss due to conduction through the external walls in sample hotel rooms in Mexico City.](image)

![Figure 46 - Heat loss due to conduction through the external walls in sample offices in Mexico City.](image)

When dealing with air conditioned spaces, like this building in Mexico City (contrary to the case of Bogotá), it is important to choose exterior walls that represent the most comfort to occupants, but also those that represent the least electricity consumption due to chillers. It can be noted from Figure 45 and Figure 46 that ‘External Walls 1’ restricts heat to flow outwards by 15% more than ‘External Walls 2’ does, fact that can be slightly beneficial for the unconditioned floors of the building (2nd and 3rd floors)
and that are clearly the coolest zones; however, this phenomenon is prejudicial for the air conditioned spaces since it increases the heat loads that have to be removed by the chillers. The comparison in terms of electricity consumption for both cases, ‘External Walls 1’ and ‘External Walls 2’ can be seen in Figure 49:

![Graph showing electricity consumption for 'External Walls 1' and 'External Walls 2']

Figure 47 - Electricity consumption due to chillers influenced by the external walls options.

It is clear that ‘External Walls 2’, besides being lighter in weight and having a higher U-Value, has a better performance for the whole building when looking at its lower electricity consumption due to chillers, as shown in Figure 47. However, the unconditioned part of the building, and more specifically, the hotel rooms, results directly affected by implementing this external walls option since it increases the heat flow to the outside, directly affecting the operative temperature in these zones. This is the reason why the performance of ‘Exterior Walls 3’ is compared with the other two exterior walls to see the benefits it brings to the hotel rooms. The heat loss through exterior walls for the three scenarios can be seen in Figure 48:

![Graph showing heat loss through external walls in sample hotel rooms in Mexico City.]

Figure 48 - Heat loss due to conduction through the external walls in sample hotel rooms in Mexico City.

It can be concluded that using ‘External Walls 3’ clearly reduces the heat loss by around 40% in sample hotel rooms if compared to ‘External Walls 1’, which gives an improved perception of thermal comfort, as can be seen in Table 23, expressed in annual Fanger PMV index:
Table 23 - Fanger PMV comparison for the three external walls scenarios in hotel rooms for Mexico City.

From Table 23, it is important to stress the positive influence of insulating layers in the performance of the building when the outside conditions are rather cold. In this case, a 20mm insulating layer of Extruded Polystyrene made a notorious improvement in the thermal conditions of the hotel rooms, without having to modify the design and construction of exterior walls for the rest of the building. This way, ‘External Walls 2’ was the option chosen for the building, except for the hotel rooms, which have ‘External Walls 3’.

As stated before, fuel consumption is the other important criterion, beside thermal comfort, for assessing the different scenarios to achieve an energy efficient building. Figure 49 shows the electricity consumption comparison due to chillers for the three options considered as external walls:

![Figure 49](image)

**Figure 49 - Annual electricity consumption due to chillers in the building depending on the external walls in Mexico City.**

The 9.84 MWh/Year difference between using ‘External Walls 2’ and the combination of ‘External Walls 2’ in the building and ‘External Walls 3’ in hotel rooms is due to the increase in operative temperature on
the 2nd and 3rd floors, which directly affects the heat transfer through ceiling/floor between 3rd floor hotel rooms and 4th floor offices. This phenomenon can be more easily appreciated in Figure 50:

![Figure 50](image)

**Figure 50 – Annual heat gain through the internal floor on the 4th floor offices influenced by the usage of ‘External Walls 3’ in the hotel rooms on the 2nd and 3rd floors in Mexico City.**

### 4.2.2.4 Glazing

The glazing option to be installed in the two different parts of the building (hotel and offices) varies depending on the needs of each of them. It is also important to take into account that the offices part of the building is air conditioned and deals with much more heat loads than the hotel.

As seen in the glazing analysis for the city of Bogotá, the default glazing of the original building is ‘Sgl Green 3mm’ is a slightly colored type of glazing that aims at reducing the solar gains thanks to its relatively low SHGC coefficient of 0.705 when comparing it with clear glass. Also, its high U-value of 6.257 W/m²/K makes for an easy flow of internal heat to the outside.

Hotel rooms require a type of glazing that helps keeping heat inside throughout the year. Since the occupancy schedule of this part of the building is higher at night time, it is not important if the glazing light transmission coefficient is low. Also, the SHGC coefficient is not wanted to be low so that passive heating can help regulate the operative temperature in the zones. Undoubtedly, the most important factor for the glazing selection in hotel rooms is a balanced U-Value that helps maintaining comfortable the indoors conditions depending on the season of the year. All of these aspects were taken into account and the outcome was that ‘Sgl LoE e2=0.2 Clr 3mm’ was the glazing that fulfilled the requisites (SHGC=0.763; Light transmission coefficient=0.821; U-Value=4.306 W/m²-K). The performance comparison for the new glazing and the original glazing in the hotel rooms can be seen in Figure 51 in terms of annual solar transmittance heat gains through them:
Figure 51 - Heat loss (kWh/year) through windows in the hotel rooms.

It can be noted from Figure 51 that thanks to the ‘Sgl LoE e2=0.2 Clr 3mm’ glazing, approximately 15% less heat flows outwards, this way increasing the operative temperature and improving the thermal comfort perception. The other important factor taken into account for choosing this new glazing was its capacity to transmit solar heat to the inside, which represents an increase of around 17% as compared to the former ‘Sgl Green 3mm’ glazing. This can be seen in Figure 52 as annual solar heat gains:

Figure 52 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the hotel rooms.

As it has been mentioned previously, hotel rooms did not represent any change in terms of chillers electricity consumption (since these are unconditioned zones); however, there was a slight increase in the usage of artificial lighting when changing the glazing, which can be supported due the difference in light transmission coefficients for both options of glazing, and also, because of the far location of Mexico City from the Equatorial line, which is a reason for daylight time to be longer than in Bogotá and Fortaleza during summer time. The thermal comfort perception by the occupants did vary and the new results are shown in Figure 53:
On the other hand, offices present an interesting challenge since it requires a versatile type of glazing with different characteristics:

- High U-Value so that internal heat is conducted outwards easily.
- High light transmission coefficient in order to make proper use of natural light during working hours, saving electricity due to artificial lighting.
- Low SHGC in order to reduce the solar heat gains in the zones, saving electricity due to chillers.

The most suitable glazing for offices would be one with low SHGC but without sacrificing much of the entry of natural lighting, reason why ‘Sgl Green 6mm’ has been chosen. It presents a high U-Value of 6.121 W/m²-K, low SHGC of 0.591 but a lower light transmission coefficient of 0.749. Figure 54 shows the performance of ‘Sgl Green 3mm’ and ‘Sgl Green 6mm’ glazing in terms of annual heat loss through windows:

The reduction in the amount of heat lost with the ‘Sgl Green 3mm’ as compared to the default ‘Sgl Green 3mm’ corresponds to approximately 22% in the offices. This can be explained partly due to the lower U-
Value; but most important due to the great reduction in solar transmittance heat gains that corresponds to a percentage of about 27%, as shown in Figure 55:

![Figure 55](image)

**Figure 55** - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the same offices in Mexico City.

From the results shows above, it can be concluded that there was an appropriate performance by the new glazing, ‘Sgl LoE e2=0.2 Clr 3mm’ for hotel rooms and ‘Sgl Green 6mm’ for offices. It is important to stress that glazing has a direct effect on the energy consumption of the air-conditioned zones, since less heat loads have to be removed by the AC system; also, glazing has a direct influence on the artificial lighting, due to the light transmission coefficient, which varies according to the glass thickness, and color (O’Connor, n.d). The influence on the energy consumption due to artificial lighting and chillers is showed in Figure 56 and Figure 57:

![Figure 56](image)

**Figure 56** - Annual electricity consumption due to artificial lighting in the building influenced by the different glazing options in Mexico City.
It is observed in Figures 56 and 57 that even though the change to ‘Sgl Green 6mm’ glazing presents a slight increase of approximately 3% (2442 kWh/year) in artificial lighting, it is compensated when looking at the electricity savings due to chillers thanks to the usage of this same glazing, which represents savings of approximately 4% (23699 kWh/year).

### 4.2.2.5 Shading devices

These devices were installed in the building as a way to reduce glare from solar light and, also, to reduce the thermal heat load in some areas of the building during the warmest months of the year. In the hotel rooms, only drapes were installed and no significant change, neither in thermal comfort perception nor electricity consumption, was expected in these zones. The drapes mechanism was meant to function according to the night time schedule.

The different scenarios analyzed for the offices, meeting rooms and bathrooms in upper floors (from 4th to 7th), were more complex, since these influence directly the electricity consumption due to artificial lighting and chillers in the air conditions zones. Different mechanisms were assessed in order to figure out the best combination: inside blinds, outside blinds, light-translucent shade rolls and overhangs. Before taking a look at the fuel breakdown in these zones, it is worth to make an idea regarding the solar heat gains of the sample zones on the upper floors when using the different shading devices, which can be seen in Figure 58:
It can be seen that the performance of the three shading devices is rather similar and vary slightly depending on the different floor (Levels) height, because the solar incidence angle also varies with it increasing or decreasing the amount of solar energy reflected, emitted and transmitted to the zone of interest. The important analysis has to do with the actual location of the shading device and how internal or external devices influence the heat concentration in the offices. Another important factor is how much of natural light can still be taken advantage of when using these shading devices. Results on electricity consumption due to artificial lighting and chillers influenced by the different window shading options are shown in Figures 59 and 60:

![Figure 59 - Artificial lighting annual electricity consumption with different window shading devices in Mexico City.](image)

![Figure 60 - Chillers annual electricity consumption with different window shading devices in Mexico City.](image)

A better performance by the ‘Inside shade rolls’ is seen above. The main reason for this is the translucent material of what the shade rolls are made of, preventing short-wave energy to enter the room but allowing approximately 40% of the visible light to enter when the glare index of 22 is reached, reducing the usage of artificial lighting and, at the same time, reducing the zones’ heat load to be removed by the AC system due to artificial lighting and solar transmitted gains. With the idea of reducing even more the solar heat gains an external local device was installed, along with the ‘Inside Shade rolls’. Two options were considered: ‘0.5m Overhangs’ and ‘1.0m Overhang’ on the superior part of the windows in 4th, 5th, 6th and 7th floors. Following the same procedure as with the internal window shading devices, solar heat gains in the sample offices are shown in Figure 61:
Comparing the results shown in Figure 61, ‘1.0m Overhangs’ were a better option since they were more effective by approximately 22% than ‘0.5m Overhangs’ when it comes to reducing solar transmittance heat gains. The addition of local shading has significant influence on the electricity consumption by both, artificial lighting and chillers, as can be seen in Figure 62:

Local shading was installed on the main long-side façade, as well as on the two side facades because these are the ones with the largest amount of windows. It is important to mention that local shading was also installed in meeting rooms in upper floors, as well as in bathrooms besides the offices. Figure 62 shows an increase in electricity consumption of 13.8% (13,458 MWh/year) in terms of artificial lighting when compared to the scenario that did not include local shading (‘Inside shade rolls’ only). However, there is an important reduction in terms of chillers electricity consumed of 13.3% (74,143 MWh), thanks to the action of overhangs reducing the direct incidence of solar radiation. The latter clearly compensates the rise in artificial lighting usage and constitutes an appropriate shading devices combination for the building under the existent conditions.
4.2.3 Final Comparison between original and final building designs (Mexico City).

As it was stated in the beginning of the analysis for Mexico City, the original design was considered to be when air conditioning and local exhaust fan extractions were installed. Figure 63 shows the comparison between the operative temperature in the original and final design in the building, taking as reference the outside dry bulb temperature:

![Figure 63 - Operative temperature comparison between original and final designs in Mexico City.](image)

The indoor operative temperature did not change much throughout the whole process of making the building more efficient under the available weather conditions in Mexico City. However, the original model had some problems that were successfully solved, like relative humidity and the low operative temperatures in hotel rooms. In terms of electricity usage, the building did follow some steps in order to increase the savings and, at the same time, reduce the environmental impact. The fuel breakdown comparison between the original and final designs is shown in Figure 64:

![Fuel consumption chart](image)
Figure 64 - Fuel breakdown comparison between original and final designs for Mexico City.

Figure 64 is really important because it shows the impact that different measures had on the fuel consumption in the building. ‘Lighting’ reduced its electricity usage to 38% of what it used to be in the beginning of the analysis. ‘Chillers’ electricity usage is 53.9% of the original consumption value. ‘DHW’ remains the same, because it was assumed to be a constant. The important electricity consumption reductions show how effective these measures can be and highlight the importance of an appropriate and responsible design in early stages for construction projects like this one. On the other hand, the environmental impact was reduced significantly, as shown in Figure 65:

![Figure 65 - CO2 Production comparison between original and final designs in Mexico City.](image)

From Figure 65 it is important to note the CO₂ emissions reduction due to natural gas when compared to the analysis for Bogotá, which has an explanation exclusively because of the amount of grammes of CO₂ per kWh generated in the Mexican country. On the other hand, the CO₂ emissions reduction due to electricity corresponds to approximately 39% when compared to the original design, which is an important value taking into account the size of the building and the amount of zones that constitute it.

Finally, Figure 66 represents the specific energy consumption in the building as a result of the different measures taken to reduce both, thermal discomfort and energy consumption:

![Figure 66 - Specific energy consumption evolution in the building influenced by the different measures applied during the analysis for Mexico City.](image)
Just as in the analysis performed in Bogotá, Figure 66 shows the evolution in specific energy consumption in terms of kWh/m² in the building. Again, the main criteria for this analysis were energy savings and thermal comfort perception by the occupants.

4.3 Fortaleza (Brazil)

4.3.1 Original model results

Fortaleza has a tropical weather with high temperature and relative humidity levels during most of the year. The average air temperature ranges between 27 and 30°C and the rainy season takes place from February to May, affecting even more the humid conditions in the city. Just to get an idea of the influence of the outdoor conditions on the building, the operative temperature of the naturally ventilated modeled building is shown in Figure 67, along with the outdoor dry bulb temperature:

![Operative temperature and Outside dry bulb temperature per month for Fortaleza.](image)

The effect of occupancy, equipment, computers, lighting, solar heat gains and the high relative humidity makes for a really high operative temperature in the building, as shown in Figure 67. The actual thermal comfort levels of this initial design are shown in Figure 68:

![Fanger PMV for the building under Natural ventilation conditions in Fortaleza.](image)

Figures 67 and 68 show how critical the conditions are in the building and how necessary it is to condition the air to provide the occupants with thermal comfort. Such high Fanger PMV levels cannot be lowered.
under natural ventilation conditions given the outdoor conditions, reason why the other measures that were taken in the analysis of Fortaleza to make the building energy efficient and thermally comfortable, were compared to the scenario where a VAV dual duct air conditioned system was installed, which is the one presented below, and not the naturally ventilated one so that the final comparison between original and final designs could be more realistic.

4.3.2 Different scenarios to achieve an energy efficient building in Fortaleza

4.3.2.1 Ventilation systems

In order to mitigate the thermal discomfort, high relative humidity and high operative temperatures; a new ventilation system was added to the building design. Considering the large size of the building, a dual duct VAV system was considered to be suitable. As stated above, the relative humidity is a major factor in the analysis for Fortaleza, since it is located in a coastal zone next to the Atlantic Ocean; therefore, an additional factor was included in this segment of the analysis and was the usage of a humidity control process for the most critical zones in the building, in order to maintain the RH below 60%. Table 24 shows annual operative temperature and relative humidity values for different zones in the building, as a way to compare the NV scenario with the new AC scenario:

![Table 24](image-url)
Table 24 - Comparison between NV scenario and AC scenario. Annual operative temperature and relative humidity in sample zones and meeting rooms in Fortaleza.

From Table 24 it can be seen the effect of air conditioning in the reduction of operative temperature and relative humidity. It is worth to clarify that hotel rooms do not count with humidity control since it was not necessary; however, offices and meeting rooms do. Other zones in which humidity control was included are: stairs, data centers, elevators, hallways on the 2nd and 3rd floors, kitchen, restaurant, receptions, bathrooms and offices on the 1st floor.

Having clear that at least the indoor conditions were balanced and thermal comfort perception has been provided, it is important to take into account that this was achieved thanks to the AC system installed and there is always a high cost to pay to provide these conditions. Figure 69 shows the internal heat gains in the building that are removed by the AC system:

![Figure 69 - Annual Internal gains in the building with AC installed in Fortaleza.](image)

From Figure 69, it is important to identify which of these variables can be reduced by changing and optimizing the design of the building under Fortaleza’s weather conditions. ‘General Lighting’ and ‘Solar Gains Exterior Windows’ are to be reduced by taking different measures. ‘Computer+Equipment’ remains unchanged during the analysis for Fortaleza. ‘Occupancy’ sensible gains depend on the interior conditions and will vary according to the influence that the different measures to be taken has on, mainly, operative temperature and relative humidity. After identifying the interior heat gains, to be removed by the AC system, it is important to take a look at the final end usages of the fuels used to supply the demands existent in the building for it to function properly. Figure 70 shows the fuel breakdown for Fortaleza with the new AC scenario:
The effects of the outdoor weather conditions were reflected on the really high electricity consumption due to chillers, as seen in Figure 70. ‘Room electricity’ was not affected by any of the measures taken during the analysis for Fortaleza, as well as ‘DHW (Gas)’, therefore, remained unchanged. ‘Lighting’ presented high electricity consumption; however, this is expected to be changed by installing lighting control devices and re-orienting the main long-side façade of the building, taking advantage of natural lighting. It is expected that ‘Chillers’ electricity consumption can be reduced thanks to the combination of these measures, too. The electricity consumption due to AC system pumps and fans were included in ‘Chillers’ from the fuel breakdown chart.

4.3.2.2 Lighting control and main long-side façade orientation

As explained previously, this measure aims at reducing the electricity consumption due to artificial lighting by measuring the illuminance levels and compensating with artificial lighting to fulfill the appropriate illuminance level according to the zones, which has already been defined for each zone. Besides reducing the direct electricity consumption, it helps reducing the heat load in the zones to be removed by the AC system. On the other hand, orientation of the main long-side façade allows to find an optimum position of the building so that natural light can be used as much as possible. Figure 71 shows the results in terms of annual artificial lighting electricity consumption for different orientations:
In Figure 72, annual electricity consumption results due to chillers for different orientations are shown:

Figure 72 - Annual chillers electricity consumption influenced by the Orientation + LC in Fortaleza.

Figure 71 and 72 show how ‘West’ and ‘East’ are the least artificial lighting electricity consumption presenting 77.96 and 77.66 MWh/year respectively. However, when taking a close look at Figure 72, it can be concluded how these two orientations present the most electricity consuming scenarios due to chillers with 963.43 MWh/year for ‘West’ and 959.95 MWh/year for ‘East’, which makes sense due to the high solar transmittance heat gains. There is no doubt about the strong influence of the ‘West’ and ‘East’ orientation on the artificial lighting consumption in Equatorial latitudes, where the duration of solar light during the day varies slightly throughout the year properly illuminating the majority of zones in the buildings; but greatly contributing to increase the solar heat gains through transmission. On the other hand, ‘South’ orientation consumes 79.26 MWh/year due to lighting, but it is the least consuming due to chillers with 864.58 MWh/year, which clearly compensates for the artificial lighting consumption for this orientation. This way, ‘South’ is chosen as the most suitable orientation for this city.

4.3.2.3 Exterior Walls

Just as it was expressed in the analysis for Mexico City, external walls play a really important role in all air-conditioned buildings depending on the characteristic weather for different site locations. There must be a balance between indoor desired conditions and outdoors weather conditions in order to provide thermal comfort, which is of course the main objective, but always considering the electricity consumption due to chillers as an important factor, too. This balance might be tricky to find when analyzing such a large building, in which different activities are performed from zone to zone, with varied schedules for occupancy.

The best indicator to conclude about the heat balance of the building and its interaction with the outdoors is through directly comparing the performance of the two external walls options presented in the methodology. Figure 73 shows this comparison for the sample hotel rooms, which are known to be the coolest zones in the building due to its low occupancy during most of the day and the lack of significant equipment gains, in terms of heat gains through conduction from the outside:
Figure 73 - Heat gain due to conduction through the external walls in the sample hotel rooms in Fortaleza.

The same comparison for the sample offices is shown in Figure 74:

Figure 74 - Heat gain due to conduction through the external walls in the sample offices in Fortaleza.

Figure 73 and Figure 74 show the behavior of the two different external walls options available, showing a greater amount of heat gain through ‘External Walls 2’, which correspond to the lightest composition of the two options; and a higher U-Value (2.071 W/m²-K). It is worth to mention how the heat gain through external walls phenomenon in Fortaleza is completely the opposite as the behavior presented by the same external wall options in Bogotá and Mexico City, since for these cities there was a heat loss instead. In other words, the heat transfer between the inside and the outside of the building changed direction because the outdoor temperature in Fortaleza is higher than the desired operative temperatures in the different indoor zones, reason why the heat transfer takes place from the outside to the inside of the building.

‘External Walls 1’ presents a lower U-Value (1.498 W/m²-K) and reduces the heat gains through conduction indoors in about 30% in hotel rooms; and 20% in offices. This is reflected in the electricity consumption due to chillers, shown in Figure 75:
Figure 75 shows that the usage of ‘External Walls 1’ instead of ‘External Walls 2’ reduces the amount of electricity used due to chillers in approximately 3% (24 MWh/year), directly saving fuel, money and reducing the ecological footprint due to carbon emissions.

4.3.2.4 Glazing

Glazing is definitely a key factor to create a proper equilibrium between the indoor conditions to provide occupants with thermal comfort; and the electricity consumption due to chillers. The characteristics of the ‘Sgl Green 3mm’ glazing have been explained in the previous analysis for Bogotá and Mexico City. ‘Sgl Green 3mm’ presents a high U-Value (6.257 W/m²-K) that allows for easier heat transfer between the inside and the outside, reflecting an acceptable amount of short-wave solar energy that may be also interpreted as heat in the different zones (SHGC=0.705). It also provides good transmittance for long-wave energy, or light (Light transmission coefficient=0.822).

Even though Fortaleza presents really high outdoor temperatures throughout the year, with the addition of air conditioning in the whole building to equilibrate the operative temperatures, hotel rooms present a rather cool situation when using the ‘Sgl Green 3mm’ glazing due to the low occupancy levels and low heat gains due to equipment. Figure 76 shows a comparison in terms of internal gains due to solar transmission for the different glazing options:

Figure 76 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the sample hotel rooms in Fortaleza.
In Figure 76 it can be noted how ‘Sgl LoE e2=0.2 Clr 3mm’ heat gains from solar transmittance are higher by approximately 17%. This increase in solar heat gains in sample rooms has a direct impact on the comfort perception which can be seen in Figure 77:

![Figure 77 - Influence of glazing on the thermal comfort perception by the sample hotel rooms occupants expressed in Fanger PMV index in Fortaleza.](image)

Figure 77 shows and improvement in Fanger PMV comfort levels in most of the areas that made possible for the zones to be within the -0.5<PMV<0.5 range for Category B buildings. However, the price to be paid for these more comfortable conditions in the hotel rooms is in terms of higher electricity consumption due to chillers, which can be seen in Figure 80, on page number 83, as a comparison of chillers consumption as the new glazing types are definitely installed.

As it known from the previous analysis performed in Bogotá and Mexico City, the scenario presented inthe upper floors, and more specifically in the offices, is completely different that in the hotel rooms. Computers, equipment and the large occupancy concentration contribute with high heat gains that turn these areas in the most critical when it comes to the chillers electricity consumption. Glazing plays an important role in these areas because with a proper reduction of solar transmittance heat gains, the heat loads to be removed by the air-conditioning systems will be much lower. Other zones in which ‘Sgl Green 6mm’ was installed are: data centers, bathrooms on 4th, 5th, 6th and 7th floors, meeting rooms and stairs. Figure 78 shows the comparison in terms of internal heat gains through different glazing options:

![Figure 78 - Internal heat gains (kWh/year) due to short-wave solar radiation transmission through windows in the same offices in Fortaleza.](image)
From Figure 78, the solar transmittance heat gains when using ‘Sgl Green 6mm’ were reduced by 25%, since the SHGC is lower (0.591) than for ‘Sgl Green 3mm’ (0.705). The glazing changes made in both, hotel rooms and offices floors, had a direct effect on the electricity consumption due to lighting and chillers. The comparison in terms of fuel consumption due to artificial lighting is shown in Figure 79:

![Figure 79 - Annual electricity consumption due to artificial lighting in the building influenced by the different glazing options in Fortaleza.](image)

From Figure 79 ‘Sgl Green 3mm’ and ‘Sgl LoE (e²=0.2) Clr 3mm’ present the same electricity consumption due to artificial lighting. The reason for that phenomenon is that the occupancy schedule for hotel rooms has been assumed as constant for all rooms and is only at night, therefore, rooms are not occupied during the day which is when lighting control takes advantage of natural lighting and compensates for the lack of it with artificial lighting. After installing ‘Sgl Green 6mm’ in the offices, the artificial lighting electricity consumption increases by around 2.6% because of its lower light transmission coefficient (0.749); however, this measure is needed in order to reduce the chillers consumption, as will be seen in the following figure.

On the other hand, chillers electricity are definitely affected by the glazing change in hotel rooms from ‘Sgl Green 3mm’ to ‘Sgl LoE (e²=0.2) Clr 3mm’, due to the higher solar transmittance gains during the day that allows to balance the operative conditions in the rooms in order to make them more comfortable. The latter can be appreciated in Figure 80:

![Figure 80 - Annual electricity consumption due to chillers in the building influenced by the different glazing options in Fortaleza.](image)
Figure 80 shows that, as expected, a slight increase in the chillers electricity consumption when using ‘Sgl LoE (e2=0.2) Clr 3mm’ in the hotel rooms. This increase corresponds to only 0.25%, however, since thermal comfort is the main design criteria, ‘Sgl LoE (e2=0.2) Clr 3mm’ is chosen as the new glazing to be used in hotel rooms; thus increasing the Fanger PMV levels in hotel rooms as it was required. Office floors and the other zones where ‘Sgl Green 6mm’ do represent a significant decrease in chillers consumption, which corresponds to approximately 2% when compared to the scenario where ‘Sgl LoE (e2=0.2) Clr 3mm’ was installed in hotel rooms. Both glazing types chosen as new, accomplished the building requirements which were: slightly increasing the operative temperature in hotel rooms without increasing much the chillers electricity consumption; and reduce as much as possible the general electricity consumption.

4.3.2.5 Shading devices

Under such warm weather conditions, shading devices represent an important source of electricity and money savings. The same principles were used when choosing the appropriate shading devices for hotel rooms that present low operative temperature; and for upper floors, especially meeting rooms and offices, where the heat gains are massive from different sources, such as occupancy, equipment, computers and solar. The idea was to avoid as much as possible for heat to flow outwards in hotel rooms when these are occupied, which is at night and the outdoor temperature is below the 26ºC, which is the desired operative temperature. The idea with upper floors was to reduce as much as possible the solar transmittance heat gains, but at the same time, making the best use of natural light to perform the different activities indoors.

The performance of the drapes installed in the hotel rooms, which act as a shading device from external artificial light since these are only used at night time, can be seen in Figure 81 as a comparison with no drapes installed at all in terms of Fanger PMV comfort levels:

![Figure 81 - Annual Fanger PMV levels for sample hotel rooms with and without drapes installed for Fortaleza.](image)

It can be noted how the mere addition of drapes with a usage schedule of night time exclusively, improves the thermal perception by approximately 2%, due to the extra ‘barrier’ for heat to cross represented by the drapes fabric. The last fact is beneficial especially for the coldest rooms: 213, 217, 313 and 317. Even though this 2% increase in thermal comfort perception can be also translated into higher electricity consumption due to chillers, but it is neglectable if compared to the effect that shading devices have in upper floors, where the heat loads are much higher and it is needed to maintain low chillers electricity consumption.

However, as it has been mentioned before during the research, the sense of comfort by occupants is the priority and solar glare can be considered as an uncomfortable factor when performing office activities.
Figure 82 and Figure 83 show the influence that different window shading devices installed in upper floors (Offices floors) have on the building’s electricity consumption due to chillers, taking into account that the three options accomplish the same objective of reducing solar glare when surpassing the level of 22.

The performance shown in Figure 82 by ‘Inside shade rolls’ with regards to artificial lighting consumption and chillers electricity consumption is rather variable from one to the other. In terms of artificial lighting, its electricity consumption is approximately 5.5% (5.31 MWh/Year) less than when using ‘Inside blinds’; nevertheless, when looking at Figure 83 it is noticeable that ‘Inside shade rolls’ represent the most electricity consumption option out of the three available. The latter value is higher by 0.25% (2.11 MWh/Year) than the value presented by ‘Inside blinds’, which leads to conclude that the savings achieved by using ‘Inside shade rolls’ due to artificial lighting compensate for the slight increase in chillers consumption, reason why this mechanism was chosen as the window shading device for the upper floors in Fortaleza.

Just as it was seen previously in the analysis performed for Mexico City, the importance of using a mix between window shading and local shading is relevant when the solar transmittance heat gains are high. Implementing local shading increases the artificial lighting consumption, but saves large amounts of energy in terms of chillers. Since ‘Inside shade rolls’ scenario corresponds to the best window shading option, it was complemented with two different options for local shading: ‘0.5m Overhangs’ and ‘1.0m...
Overhangs". The comparison between these two options is shown in Figure 84 in terms of solar heat gains through the windows in the sample offices:

![Figure 84](image)

Figure 84 - Annual solar heat gain (kWh/year) comparison for the 'Inside Shade Rolls' window shading scenario in sample offices with '0.5m Overhangs' and '1.0m Overhangs' as local shading in Fortaleza.

The approximately 15% reduction in solar transmittance heat gains in the sample offices shown in Figure 84, makes evident the better performance by the '1.0m Overhangs' mechanism, showing an inverse proportion between the longitude of the overhangs blade and the solar heat gains in zones. Even though such a significant reduction in solar heat gains is really important, there is another important factor to take into account, since it is known that adding fixed local shading devices reduce the amount of natural light entering the zones, being translated into higher electricity consumption due to artificial lighting. Figure 85 show the performance of the building with the best option ‘1.0m Overhangs’ local shading devices in terms of electricity consumption for artificial lighting, as well as for chillers:

![Figure 85](image)

Figure 85 - Annual electricity consumption (kWh/year) in the building with 'Inside shade rolls + 1.0 overhangs' installed for Fortaleza.

Local shading was used on the main long-side façade, as well as on the two side facades because these are the ones with the largest amount of windows. It is important to mention that other zones in the building where the two options for local shading were also installed are: meeting rooms in upper floors, bathrooms in upper floors and data centers in all floors. Figure 85 shows two important facts that were the result of adding the ‘1.0 Overhangs’ as local shading: first, a 10.9% increase in terms of artificial lighting if
compared to the scenario where only ‘Inside shade rolls’ were installed which corresponds to 10 MWh/Year; second, a significant decrease of 2.88% in terms of chillers electricity that corresponds to 24.09 MWh/Year. The latter value compensates the electricity increase due to artificial lighting, since overall there is a 14.09 MWh/Year electricity consumption reduction.

4.3.3 Final Comparison between original and final building designs (Fortaleza)

The original building design is assumed to be the one where dual duct air conditioning system was installed in this city, since the un-conditioned design was far from being realistic as can be seen in the results on pages 75 and 76 due to its highly uncomfortable conditions. Figure 86 shows the operative temperature comparison between the original and final building designs, taking as reference the outdoor dry bulb temperature for Fortaleza:

![Operative temperature comparison between original and final designs in Fortaleza.](image)

Even though the operative temperature for both designs is somewhat similar, as can be seen in Figure 86, the real challenge relies on providing occupants with the best operative conditions in order to achieve a desired thermal comfort at the lowest fuel investment as possible. The constant seek of fuels usage reduction also has other beneficial aspects, such as lower environmental impact and low operative costs. The breakdown for fuels used in the original and final building designs, divided by its end use is shown in Figure 90 on an annual basis:
As it can be seen in Figure 87, ‘Room Electricity’ consumption remains constant from original to final building designs, and so it does for all cities analyzed as it has been stated before. ‘DHW (Gas)’ consumption remains constant from original to final design; nevertheless, there is a slight decrease when compared to the other two tropical cities case of study of this research due to a higher water mains supply temperature assumed of 18ºC and an unchanged value for water delivery temperature of 50ºC. Regarding ‘Chillers’ electricity consumption there was a significant reduction of approximately 21.4%, as well as for ‘Lighting’ there was a reduction of 65.2% thanks to all of the energy efficient measures taken.

The importance of fuel reduction in buildings during the design stages of a construction project can lead to saving lots of money. However, it also reduces the environmental impact, as can be seen in Figure 88:

Figure 87 - Fuel breakdown comparison between original and final designs for Fortaleza.

Figure 88 - CO2 Production comparison between original and final designs in Fortaleza.

Figure 88 shows an important reduction of CO2 emissions due to electricity of about 25.1% (37.15 Tonnes/Year). It is important to stress how low the emissions due to electricity are for this specific case.
of Fortaleza, and the reason for it is the large amount of electricity production from hydroelectric stations in Brazil, which is a similar case to Colombia, to a lower extent.

As a way to conclude the analysis for the building under Fortaleza's weather conditions, Figure 89 shows the evolution in annual specific energy consumption of the building as a result of the different measures taken to provide the occupants with thermal comfort and to reduce the energy consumption as much as possible:

![Graph showing evolution in annual specific energy consumption](image)

**Figure 89 - Specific energy consumption evolution in the building influenced by the different measures applied during the analysis for the city of Fortaleza.**
5 Discussion

5.1 Bogotá

Even though the fuel consumption for Bogotá is rather low due to the usage of natural ventilation in the majority of the building, except data centers, the energy analysis was focused towards the thermal comfort perception by the occupants given in Fanger PMV index. The combination of lighting control and orientation are by far the most effective measure when it comes to reducing the high thermal perception in about 50% as compared to the original model presented. The common scenario presented in all cities is that the building had two different behaviors: hotel part of the building is cold zones due to the low equipment and occupancy concentration during the day; and the office part of the building present really high operative temperatures due to the high concentration of people, equipment and computers.

The idea was then to find a proper equilibrium between the two parts of the building. When choosing a lighter kind of external walls, the Fanger PMV index drops a significant amount in general in the building, however it is needed to use a layer of extruded polystyrene to reduce the heat flow outwards in hotel rooms and make the conditions warmer and therefore, more comfortable in these zones, leading to an overall annual Fanger PMV level reduction of 10% thanks to the external walls in offices that allow heat to flow outwards easily due to conduction. A high U-value (Sgl Green 6mm) type of glazing in the office part of the building in order to facilitate the heat flow outwards, and a low U-value (Dbl Clr 3mm/13mm Arg) type of glazing for the hotel to avoid the heat loss were the approaches chosen, presenting an annual overall Fanger PMV reduction of approximately 39%. Shading devices (Drapes in hotel rooms and external blinds in offices) contributed to reduce the discomfort due to solar glare, however there was a slight increase in the Fanger PMV levels of approximately 2% in the building.

On the other hand, electricity consumption due to lighting was reduced in 61% thanks to the lighting control, orientation of the building and glazing modifications. Also, changes in glazing had a direct effect on the electricity consumption in data centers of 31%. Overall, the specific energy consumption in the building presented a reduction from 96.264 kWh/m² to 75.822 kWh/m² with the different measures applied.

The environmental impact in terms of Tonnes of CO₂ emissions was reduced in 28.8%, due to the 26.36 Tonnes/CO₂ kept from being emitted to the atmosphere thanks to the significant reductions shown above due to artificial lighting and chillers electricity consumption.

5.2 Mexico City

It is important to take into account the geographical location of Mexico City is the furthest of the three cities from the Equator line, therefore, having more noticeable weather changes throughout the year due to seasonal change. The energy performance analysis for Mexico City was focused mainly on the fuel consumption for the building to operate during the year, since an AC system is needed to provide thermal comfort in the offices part of the building. In the hotel rooms the scenario was different because NV was enough to provide occupants with the required levels of thermal comfort, reducing significantly the electricity consumption due to chillers.

Lighting control and orientation measures show a significant electricity consumption reduction of 34.11% due to chillers; and 73.57% due to artificial lighting. Choosing a combination between ‘External Walls 2 + External Walls 3’ for the building (External Walls 3 for the hotel rooms) have a direct impact on the chillers electricity consumption since it is reduced in 4.6% than when ‘External Walls 1’ was the default external wall option for the building. Glazing plays an important role in the electricity consumption of the building and also, in the thermal conditions perceived in hotel rooms, since it was needed to reduce the heat flow outwards in order to maintain the temperature in these zones, which are the coldest. The improvement in glazing (Sgl LoE e2=0.2 Clr 3mm in hotel rooms; and Sgl Green 6mm in offices)
represented a slight increase in lighting electricity consumption of about 3.16% (2442.5 kWh/year); however, a 4% (23699.9 kWh/year) reduction was perceived due to chillers electricity. Finally, shading devices (Drapes in hotel rooms, Inside shade rolls and 1.0m overhangs in offices) addition has a similar outcome if compared to the one observed with glazing; there was considerable increase in artificial lighting of 39.39% (31368.2 kWh/year), but at the same time a great reduction in terms of chillers electricity consumption of 14.82% (83718.41 kWh/year).

The specific energy consumption in the building was successfully reduced by 34.15%, from 185.105 kWh/m² to 122.669 kWh/m², leading to reduce significantly the environmental impact due to electricity usage in 39% by keeping 269.93 Tonnes of CO₂ from being emitted to the atmosphere. From the results and analysis presented, it can be seen that the combination between lighting control and orientation is the measure that contributed the most to reduce the fuel electricity consumption, followed by glazing and shading devices.

5.3 Fortaleza

Fortaleza showed the most extreme and fuel consuming scenario because of the high conditions with regards to dry bulb outside temperatures and relative humidity. The installed AC system provides the whole building with the thermal comfort requirements; however, the real challenge was to fulfill those requirements at the lowest fuel consumption possible. The analysis performed was focused, measured and the progress was compared with different scenarios from the fuel savings point of view.

Just as it happened with the previous two cities in the analysis, lighting control and orientation of the building have a really important contribution in reducing the electricity consumed, with 72.86% due to artificial lighting and 17.42% due to chillers. With regards to the external walls, it has been decided to keep the heavy-wall option since it reduces the heat gain due to conduction from the outside to the inside of the building, which is exactly the opposite phenomenon that took place for Bogotá and Mexico City. Even though the outside conditions are too extreme to use natural ventilation, the hotel rooms conditions become rather cool when using air conditioning in these zones, which can be explained by the low occupancy levels and brief occupancy period of time. Thus, two different options were needed for glazing: one that enabled to maintain indoor operative temperature a little higher by passive heating in hotel rooms; and other that enabled heat to flow outwards easily in the offices part of the building so that the air conditioning system loads were lower. This measure (Sgl LoE (e2=0.2) Clr 3mm in hotel rooms; and Sgl Green 6mm in the offices part of the building) increased the artificial lighting consumption in 2.66% (2114.92 kWh/year), but also a reduction in chillers electricity of 1.83% (15696.28 kWh/year). Finally, including shading devices (Drapes in hotel rooms, Inside shade rolls and 1.0m overhangs in offices) in the building design increased the artificial lighting electricity consumption in 19.79% (20081.3 kWh/year) but, at the same time, brought a reduction of 3.14% (26343.2kWh/year) in AC systems electricity consumption. It is important to clarify that the increase in artificial lighting is something that could not be avoided, since shading devices have a really important role which is prevent the solar glare discomfort.

The environmental footprint due to CO₂ emissions from electricity were reduced in 25.13% (37.15 Tonnes/year) if comparing the original and final building designs. This fact was directly linked to the specific energy consumption of the building, which was reduced from 198.001 kWh/m² in the original design to 154.449 kWh/m² in the final design.
6 Conclusions and recommendations

The geographic location of the cities and its weather characteristics influenced directly the building energy performance, therefore the thermal comfort perception and fuel consumption varied according to them. Natural ventilation was proven to be slightly troublesome when it comes to controlling the indoor conditions, as it was noted for Bogotá; nevertheless it reduces significantly the building's specific electricity consumption. On the other hand, the usage of air conditioning for the whole building was needed in the design for Fortaleza in order to provide occupants with thermal comfort, but at the same time this city was the most fuel consuming. Mexico City presented suitable weather conditions to mix natural ventilation and air conditioning, the former for hotel rooms and the latter for offices and upper floors; reducing the specific energy consumption in the building.

The most important goal in this research was to provide the needed thermal comfort for Category B buildings according to the standard ISO 7730; from there the measures to reduce the energy consumption in the building were taken. Complying with more strict thermal comfort standard would mean higher investment costs in new technologies to improve air tightness in the envelope, and its performance in general under the influence of the different weather conditions in the three cities. The Fanger PMV thermal comfort requirements were successfully met for the three cities in all zones of the building.

From the results, it can be noted how air conditioning clearly represents the most electricity consuming end-use in the building, which is when the different measures to make the building energy efficient become handy. Lighting control + orientation were greatly beneficial measures to reduce the heat loads to be removed by the AC system. Glazing was also helpful to reduce the internal gains due to solar transmittance; however glazing played a really important role in the passive heating design for hotel rooms, which were rather cool zones for the three cities. Even though the shading devices installed during the analysis reduce the chillers consumption, it increases the artificial lighting energy consumption to make up for the lack of the needed amount of lighting to perform different tasks in the building.

One of the most important results observed was the final results in terms of yearly specific energy consumption in the building for the three cities case of study: Bogotá (73.503 kWh/m²), Mexico City (120.35 kWh/m²) and Fortaleza (152.198 kWh/m²). These results are definitely much lower than the typical values for yearly specific energy consumption in non-residential buildings in Europe (280 kWh/m² on average) (Economidou, 2011); however, it is important to be careful when comparing these results with parts of the world where the climatic conditions are so different. Unfortunately, serious and responsible researches in this topic are mostly carried out in countries with very different climatic conditions than those in Latin America, making the comparison more complicated.

It is important to stress that even though this research did not include a life cycle cost analysis, the main idea with the different measures applied was to keep the investment as low as possible with simple but effective measures. For example, it is known the wide range of glazing available in the market with new technologies emerging everyday; however, it was demonstrated in the results and analysis that proper planning and careful design are key factors to start ambitious and energy-saving projects like office-hotel buildings. Having expressed the importance of the life cycle cost analysis for researches like the one performed in this thesis project, it is important to highlight the possibility of studying more in depth the economic factor and feasibility of energy efficient measures to reduce energy consumption in buildings in Latin America.
7 Bibliography


DesignBuilder. 2012. Retrieved October 15 from http://www.designbuilder.co.uk/content/view/6/14/
8 Appendix

8.1 Design builder features

In order to understand more in depth the different tools provided by the Design Builder software, a selection of the most characteristic features has been retrieved from the developer website (DesignBuilder, 2012):

8.1.1 Simulation and Design

- Calculate heating and cooling loads using the ASHRAE-approved 'Heat Balance' method implemented in EnergyPlus. Design weather data is included (below).
- Run simulations of your model using real hourly weather data to check how the building would behave under actual operating conditions.
- Check the effects of design alternatives on the key design parameters such as annual energy consumption, overheating hours, CO2 emissions.
- A comprehensive range of simulation data can be shown in annual, monthly, daily, hourly or sub-hourly intervals:
  - Energy consumption broken down by fuel and end-use.
  - Internal air, mean radiant and operative temperatures and humidity
  - Comfort output including underheating and overheating hours distribution curves, ASHRAE 55 comfort criteria (unmet loads), Fanger PMV, Pierce PMV ET, Pierce PMV SET, Pierce Discomfort Index (DISC), Pierce Thermal Sens. Index (TSENS), Kansas Uni TSV.
  - Site weather data
  - Heat transmission through building fabric including walls, roofs, infiltration, ventilation etc.
  - Heating and cooling loads.
  - CO2 generation.
- Environmental performance data is displayed without needing to run external modules or import data. Any simulations required to generate the data are started automatically.
- Compact HVAC systems provide an easy way into detailed analysis of commonly used heating and cooling systems. Choose from:
  - VAV with terminal reheats and options for VAV box and outside air control.
  - Constant volume.
  - Split air.
  - Fan coil units.
  - Heat recovery
  - Packaged rooftop, unitary DX.
  - Hot water radiator.
  - Underfloor heating.
  - High temperature radiant heating.
  - All air systems can have recirculation with outside air control, economiser, fan and pump modelling.
  - DHW
- Natural ventilation can be modelled with the option for windows to open based on a ventilation set point temperature; openings can be modulated by outside air temperature.
- Glazing systems including frames, dividers and reveals are modelled in detail. Electrochromic glazing, transparent insulation are possible.
- Shading by louvres, overhangs and sidefins as well as internal and mid-pane blinds.
- Model glazed cavities such as double facades and Trombe walls.
- Daylighting - models lighting control systems using one or two lighting sensors per zone and calculates savings in electric lighting. Choose from stepped or continuous dimming.
- Dynamically varying vertical temperature gradients in tall spaces such as atria and for displacement ventilation systems.
- Architectural features such as columns, awnings and complex shading devices can be treated including the effect of shading and reflection.
• Parametric analysis screens allow you to investigate the effect of variations in design parameters on a range of performance criteria.
• Generate IDF files and work with these outside DesignBuilder to access system functionality not provided by DesignBuilder.
• Choose from a range of different EnergyPlus simulators including the current DOE executable release, the current DLL release and any interim releases made available by DOE. You can even access versions of EnergyPlus you have compiled yourself.

8.1.2 Interface
• OpenGL building modeller allows building models to be assembled by positioning ‘blocks’ in 3-D space. Blocks can be cut and stretched allowing you to work with just about any geometry.
• Global changes can be made to the model at building, block or zone level.
• Control the level of detail in each building model allowing the tool to be used effectively at any stage of the design or evaluation process.
• 3-D CAD models can be imported using gbXML.
• Building geometry can be imported from 2-D CAD floor plan data and then traced over within DesignBuilder to create blocks and to partition blocks up into zones (we are also working on a new 3-D CAD import capability using gbXML).
• Generate impressive rendered images and movies of your building design including the effect of site shading.
• Extensible architecture of the internal graphics engine will allow rapid development of the new modelling features which we have planned for future versions.

8.1.3 Data
• Latest ASHRAE worldwide design weather data and locations (4429 data sets) are included with the software and over 2100 EnergyPlus hourly weather files are available free using the DesignBuilder 'Install on Demand' feature. The full list of DesignBuilder hourly weather data can be viewed on the EnergyPlus website.
• The software comes with UK NCM databases and also equivalent ASHARE construction, activity and schedule data.
• Data templates allow you to load common building constructions, activities, HVAC & lighting systems into your design by selecting from drop-down lists.
• Add your own templates if you often work on similar types of buildings.

8.1.4 Visualisation
• Realistically rendered images can be generated and exported from the model with no additional work.
• Explore the model using simple view and walk-through controls.
• Site shading analysis for any day of the year.
• AVI movies of solar shading and scene orbit automatically generated.
• Colour-coded layout images show zone activities (usage).
• Cut-away sections.
• Export your DesignBuilder model to other CAD applications such as AutoCAD, Microstation, SketchUp using 3-D DXF.
8.2 Views of the building

Figure 90 - Front view of the building.

Figure 91 - Back view of the building.

Figure 92 - Side views of the building. Parking lot car entrance façade (Left); Hotel reception entrance façade (Right).
### 8.3 Building schedules per zone

<table>
<thead>
<tr>
<th>Lighting Schedule</th>
<th>Occupancy Schedule</th>
<th>Equipment Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area</strong></td>
<td><strong>Weekdays</strong></td>
<td><strong>Weekends</strong></td>
</tr>
<tr>
<td><strong>Bathrooms</strong></td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
</tr>
<tr>
<td></td>
<td>Until 21:00, 0</td>
<td>Until 21:00, 0</td>
</tr>
<tr>
<td></td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td><strong>Elevators and Stairs</strong></td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
</tr>
<tr>
<td></td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td><strong>Offices and Meeting Rooms</strong></td>
<td>Until 07:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td></td>
<td>Until 18:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td><strong>Office Reception</strong></td>
<td>Until 07:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td></td>
<td>Until 18:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td><strong>Hotel Reception</strong></td>
<td>Until 07:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td><strong>Deposit Room</strong></td>
<td>Until 08:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
<tr>
<td></td>
<td>Until 18:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
</tbody>
</table>

Table 25 - Occupancy schedule per zone.

<table>
<thead>
<tr>
<th><strong>Hotel Rooms</strong></th>
<th><strong>Weekdays</strong></th>
<th><strong>Weekends</strong></th>
<th><strong>Holydays</strong></th>
<th><strong>Weekdays</strong></th>
<th><strong>Weekends</strong></th>
<th><strong>Holydays</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Until 07:00, 0</strong></td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
<td>Until 07:00, 0</td>
</tr>
<tr>
<td><strong>0.573142857</strong></td>
<td>Until 08:00, 0</td>
<td>Until 08:00, 0</td>
<td>Until 08:00, 0</td>
<td>Until 08:00, 0</td>
<td>Until 08:00, 0</td>
<td>Until 08:00, 0</td>
</tr>
<tr>
<td><strong>Until 19:00, 0</strong></td>
<td>Until 19:00, 0</td>
<td>Until 19:00, 0</td>
<td>Until 19:00, 0</td>
<td>Until 19:00, 0</td>
<td>Until 19:00, 0</td>
<td>Until 19:00, 0</td>
</tr>
<tr>
<td><strong>0.171428571</strong></td>
<td>Until 23:00, 0</td>
<td>Until 23:00, 0</td>
<td>Until 23:00, 0</td>
<td>Until 23:00, 0</td>
<td>Until 23:00, 0</td>
<td>Until 23:00, 0</td>
</tr>
<tr>
<td><strong>Until 24:00, 0</strong></td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
<td>Until 24:00, 0</td>
</tr>
</tbody>
</table>

Table 26 - Occupancy schedule per zone (Continuation 1).
Table 27 - Occupancy schedule per zone (Continuation 2).
8.4 Building area, volume and occupancy by zone

<table>
<thead>
<tr>
<th>Zone</th>
<th>Area (m²)</th>
<th>Volume (m³)</th>
<th>Average Occupancy (# People)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room 201 - 301</td>
<td>53.44</td>
<td>157.65</td>
<td>4</td>
</tr>
<tr>
<td>Room 202 - 302</td>
<td>30.47</td>
<td>89.89</td>
<td>2</td>
</tr>
<tr>
<td>Room 203 - 303</td>
<td>62.05</td>
<td>183.05</td>
<td>5</td>
</tr>
<tr>
<td>Room 204 - 304</td>
<td>31.83</td>
<td>93.90</td>
<td>3</td>
</tr>
<tr>
<td>Room 205 - 305</td>
<td>29.37</td>
<td>86.64</td>
<td>2</td>
</tr>
<tr>
<td>Room 206 - 306</td>
<td>63.17</td>
<td>186.35</td>
<td>5</td>
</tr>
<tr>
<td>Room 207 - 307</td>
<td>30.89</td>
<td>91.13</td>
<td>2</td>
</tr>
<tr>
<td>Room 208 - 308</td>
<td>30.89</td>
<td>91.13</td>
<td>2</td>
</tr>
<tr>
<td>Room 209 - 309</td>
<td>63.13</td>
<td>186.23</td>
<td>5</td>
</tr>
<tr>
<td>Room 210 - 310</td>
<td>28.31</td>
<td>83.51</td>
<td>2</td>
</tr>
<tr>
<td>Room 211 - 311</td>
<td>31.86</td>
<td>93.99</td>
<td>3</td>
</tr>
<tr>
<td>Room 212 - 312</td>
<td>60.66</td>
<td>178.95</td>
<td>5</td>
</tr>
<tr>
<td>Room 213 - 313</td>
<td>29.46</td>
<td>86.91</td>
<td>2</td>
</tr>
<tr>
<td>Room 214 - 314</td>
<td>51.64</td>
<td>152.34</td>
<td>4</td>
</tr>
<tr>
<td>Room 215 - 315</td>
<td>34.51</td>
<td>101.80</td>
<td>3</td>
</tr>
<tr>
<td>Room 216 - 316</td>
<td>34.51</td>
<td>101.80</td>
<td>3</td>
</tr>
<tr>
<td>Room 217 - 317</td>
<td>33.04</td>
<td>97.47</td>
<td>3</td>
</tr>
<tr>
<td>Room 218 - 318</td>
<td>66.7</td>
<td>196.77</td>
<td>5</td>
</tr>
<tr>
<td>Room 219 - 319</td>
<td>33.33</td>
<td>98.32</td>
<td>3</td>
</tr>
<tr>
<td>Hallways 2nd and 3rd Floors</td>
<td>493.57</td>
<td>1456.03</td>
<td>24</td>
</tr>
<tr>
<td>Data Centers</td>
<td>8.24</td>
<td>24.31</td>
<td>1</td>
</tr>
<tr>
<td>Deposits</td>
<td>4.09</td>
<td>12.07</td>
<td>0</td>
</tr>
<tr>
<td>Meeting Rooms 4th, 5th, 6th and 7th</td>
<td>30.63</td>
<td>90.36</td>
<td>5</td>
</tr>
<tr>
<td>Bathrooms 4th, 5th, 6th and 7th</td>
<td>32.96</td>
<td>97.23</td>
<td>3</td>
</tr>
<tr>
<td>Office 401 - 501 - 601 - 701</td>
<td>236.61</td>
<td>698.00</td>
<td>18</td>
</tr>
<tr>
<td>Office 402 - 502 - 602 - 702</td>
<td>257.72</td>
<td>760.27</td>
<td>19</td>
</tr>
<tr>
<td>Office 403 - 503 - 603 - 703</td>
<td>297.43</td>
<td>877.42</td>
<td>22</td>
</tr>
<tr>
<td>Office 404 - 504 - 604 - 704</td>
<td>338.6</td>
<td>998.87</td>
<td>25</td>
</tr>
<tr>
<td>Elevators 1</td>
<td>19.21</td>
<td>56.87</td>
<td>9</td>
</tr>
<tr>
<td>Elevators 2</td>
<td>9.77</td>
<td>28.82</td>
<td>3</td>
</tr>
<tr>
<td>Stairs</td>
<td>232.56</td>
<td>686.05</td>
<td>26</td>
</tr>
<tr>
<td>Restaurant</td>
<td>200.95</td>
<td>592.80</td>
<td>81</td>
</tr>
<tr>
<td>Kitchen</td>
<td>49.4</td>
<td>145.73</td>
<td>4</td>
</tr>
<tr>
<td>Offices Reception</td>
<td>128.35</td>
<td>378.63</td>
<td>10</td>
</tr>
<tr>
<td>Hotel Reception</td>
<td>181.37</td>
<td>535.04</td>
<td>18</td>
</tr>
<tr>
<td>Lobby Bathroom</td>
<td>17.89</td>
<td>52.78</td>
<td>2</td>
</tr>
<tr>
<td>Meeting Room 1st Floor</td>
<td>52.71</td>
<td>155.49</td>
<td>8</td>
</tr>
<tr>
<td>Parking Lot</td>
<td>596.83</td>
<td>1760.65</td>
<td>-</td>
</tr>
<tr>
<td>Roof Equipment Room</td>
<td>75.36</td>
<td>222.31</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 28 - Area, volume and occupancy by zone.
8.5 Chillers nominal capacity (kW) for Mexico City and Fortaleza

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Chiller Nominal Capacity (kW)</th>
<th>Mexico City</th>
<th>Fortaleza</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation</td>
<td>509.247</td>
<td>982.306</td>
<td></td>
</tr>
<tr>
<td>LC + Orientation</td>
<td>346.148</td>
<td>831.063</td>
<td></td>
</tr>
<tr>
<td>External Walls</td>
<td>341.437</td>
<td>831.063</td>
<td></td>
</tr>
<tr>
<td>Glazing</td>
<td>340.657</td>
<td>822.71</td>
<td></td>
</tr>
<tr>
<td>Shading</td>
<td>316.752</td>
<td>802.596</td>
<td></td>
</tr>
</tbody>
</table>

Table 29 - Chillers nominal capacity for Mexico City and Fortaleza.