Bauhaus-Universität Weimar

Faculty of Civil Engineering

Chair of Construction Engineering and Management

Master Thesis

A numerical comparison of the impact of different climatic conditions in different geographic locations on the construction of an office building

For obtaining the academic degree

"Master of Science"

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A numerical comparison of the impact of different climatic conditions in different geographic locations on the construction of an office building

Background:

The use of energy in buildings accounts for a large share of the total end use of energy. In sectors such as residential and the commercial sector the major part of the energy consumption takes place. This includes energy used for controlling the climate in buildings and for the buildings themselves, but also energy used for appliances, lighting and other installed equipment. Energy efficiency requirements in building codes or energy standards for new buildings are among of the most important single measures for buildings' energy efficiency. This is in particular the case in times of high construction activity or in fast developing countries. However, this can only be achieved, when the operating conditions of a building suit the users' needs. Therefore, it is a research question, how much different geographic locations – and their differing climate conditions will have an impact on the optimum building structure with regard to energy consumption for heating and cooling

Project Description:

A propitious and balanced approach to represent a comparative scenario of energy efficiency of a structure is being aimed. This project is supposed to observe the variance of the efficiency of a typical multi-story office building (reinforced concrete core structure, variable façade structure) under the exposure to different climatic conditions. Building simulation (e.g. Energy Plus) has to be used to simulate the energy consumption for heating and/or cooling. The impact of the climate zones has to be considered using local weather data (e.g. Test Reference Years). This will also help to understand the effect of adverse versus moderate climatic conditions on the construction and operation of a building.

Task Description:

1. Become acquainted with the appropriate software in order to validate simulation results and comparisons.
2. Develop a representative virtual building model in accordance to the international energy code of buildings for the analysis of energy consumption for heating/cooling for a typical multi-story office building, which might be placed in different locations in the world. This model is not necessarily a complete building, but it must have the relevant functionalities of a real building.
3. Collect and process data of the climatic data of considerably different places representing different climate zones, for example namely Berlin, Delhi, Mumbai, Dubai, Montreal, Copenhagen and Lisbon.
4. Differentiate work environments in respected climate zones according to time periods without and with energy consumption.
5. Compare the different energy consumption behaviors and summations of the yearly energy consumption in each location.
6. Make suggestions for the international energy code of buildings, if there is, differentiated according to the specific locations.

Structure

see style sheet on website of Institute for Construction Engineering and Management

- title page
- original document of problem definition
- summary
- abstract *) (notice: no translation via google translate)
- preface *)
- table of contents
- list of abbreviations*)
- list of symbols*)
- text chapters
- bibliography list
- other lists (pictures, tables, charts, figures) *)
- appendix *)(if necessary: a list of contents in the appendix)
- declaration of independence

The parts marked with *) are not mandatory.

The currently applicable examination regulations of the Bauhaus-Universität Weimar, Faculty of Civil Engineering apply for the thesis procedures.

At the closing date, the following has to be submitted:

i. 2 copies of the work (including appendix) in hard copy

ii. 1 electronic copy of all the digital work (including appendices and digital list of literature via email or electronic media)

At the date of thesis defence, the following has to be submitted:

i. The final defence presentation in electronic version (via email or electronic media)

ii. 1 poster with key messages of the thesis (size DIN A1; on flame retardant paper B1 according to DIN 4102 - can be printed in the SCC)

Setting the work in the publishing Portal of the University Library (OPuS) has to be prepared.

Organizational information:

An interim advice from the Institute of Construction Engineering and Management on the intended research methodology, the structure of the work and the progress of the work is encouraged. At least a number of two consultations is mandatory.

Internet sites can be cited, if they originate from a credible source. The respective internet sites with a complete specification of links and with the date of the last call (http://www ...) have to be included in the bibliography list.

Weimar, 03.01.2017 Prof. Dr.-Ing. H.-J. Bargstädt, M.Sc.

Summary

The aim of my research is to observe the variance of energy efficiency of a typical multi-story office building under the exposure of different climatic conditions. Energy efficiency requirements in building codes or energy standards are among the most important single measures for buildings' energy efficiency. Therefore, this study can be set up for a better understanding of how energy efficiency of a building changes under the effect of adverse to moderate climatic conditions which possess a mentionable effect on the operation of a building.

This thesis is structured in three balanced and conceptual steps. Following the aim of the project, the virtual building model is to be analyzed under the effect of seven distinct climatic conditions namely work environment of New Delhi, Mumbai, Berlin, Lisbon, Copenhagen, Dubai and Montreal. Firstly, the task is to do a complete literature research based on the scope of similar researches and studying the problems in detail along with the theoritical background all the concepts which are implemented to get the numerical results. This chapter also comprises a detailed study of the climatic conditions of the above-mentioned cities. Different climatic traits like temperature variations, count of heating and cooling degree days, relative humidity, temperature range and comfort zonal charts for the specified cities are studied in detail. This study helps to understand the effect of these adverse to moderate climates on the operation of the building. On the second step, the virtual building model is prepared on a software platform named Revit Structures. This virtual building model is not necessarily a complete building, but it has the relevant functionalities of a real building. We perform the energy analysis and the heating and cooling analysis on this virtual building model to study the operational outcome of the building under different climatic conditions in detail. By the end of these above two tasks, two scenarios are observed. On one hand, we have a literature research and on the other hand we have the numerical results. Therefore, finally we present a comparative scenario based on the energy efficient performances of the building under such variant climatic conditions. This is followed by the prediction of thermal comfort level inside the building and it based on Fanger's PMV Model. Understanding the literature and the numerical values in detail helps us to predict the index thermal comfort level inside the building.

The conclusion of this master thesis focuses mainly on the scopes of improvement of energy efficiency requirements in energy codes if any, differentiated according to specific locations. The initial aim of my hypothesis which is to study the impacts of climatic variations on the energy efficient performances of a building is fulfilled but as such topics have very deep and broad roots, the scope of further improvements is always predominant.

Acknowledgement

Firstly, I want to thank my thesis advisor Prof. Dr.-Ing. Hans-Joachim Bargstädt of the "Chair of Construction Engineering and Management" at Bauhaus-Universität Weimar. It is always a very prestigious experience to work under the guidance of Prof. Bargstädt with his clarity and variety in different ideas and thoughts which always paved my way of thinking during the work process. The door to Prof. Bargstädt's office was always open whenever I ran into any trouble or had any sorts of doubts or questions regarding my thesis and writing. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it.

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I would love to share all of my privilege for being a student of Bauhaus-Universität Weimar. It had been my honor to be a part of such a wonderful university and such wonderful professors and students. I was completely an amateur when I first came to Germany as that was the first time I was away from my family for education. But the environment in my university campus is so inspiring and friendly that it took no time for me to get accustomed to be a part of such a university which is so rich in culture and heritage. Professors and their teachings, seniors and their inspiring thoughts, friends and their friendliness changed the demographics of an amateur man's life. Now I am gifted with wide stretched horizons of knowledge, eagerness to learn and also with new way of thinking and understanding different situations. Thank you.

I consider myself a very a lucky person to share the bond of friendship with my unconditional friend Ishita Ghosh. Starting from professional to personal traits, she has been my all-weather friend. She has been my continuous source of happiness and determination in all spheres of life. She motivated me every single time when I thought of giving up. I am forever indebted for her continuous support.

Whenever it comes to parents, I always fall short of words as their contribution has been limitless. My father has always been the backbone of our family and had continuously supported me even in our bad days when we were going through a period of financial crisis. My mother on the other hand has been the light of my life who encouraged and held me up every single time when I was about to bog down. Lastly my uncle who loves and takes care of me no less than my father. He has always been my father figure. I dedicate my Master Thesis and I owe my whole life to my family. Thank You.

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etc.	**ET Cetera**
IEA	International Energy Agency
GDP	Gross Domestic Product
EU	European Union
RE	Renewable Energy
GHG	Green House Gases
CHP	Combined Heat and Power Systems
AST	Active Solar Thermal
HVAC	Heating, Ventilation and Air Conditioning
PPD	Predicted percentage of dissatisfied
A, B and C classes	Thermal comfort zonal classes
BIM	Building Information Modelling
MEP	Mechanical, Electrical and Plumbing
2D	Two dimension
3D	Three Dimension
BLAST	Basic Local Alignment Search Tool
HDD	Heating Degree Days
CDD	Cooling Degree Days
OCED	The Organization for Economic Co-operation and Development
SHGC	Solar Heat Gain Co-efficient
EPS	Expanded Polystyrene Insulation
EUI	Energy Use Intensity
TR Chart	Temperature Range Chart

CZ Chart	Comfort Zonal Chart

Symbol directory

°C	Degrees in Centigrade
T_{max}	Maximum outside temperature
T_{min}	Minimum outside temperature
T_{base}	Base temperature
D_h	Heating Degree Days
D_c	Cooling Degree Days
PMV	Predicted mean vote
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
M	The metabolic rate
W	The effective mechanical power
H	The sensitive heat losses
E_c	The heat exchange by evaporation on the skin
C_{res}	Heat exchange by convection in breathing
E_{res}	The evaporative heat exchange in breathing
f_{cl}	The clothing surface area factor
t_a	The air temperature
t_{cl}	The clothing surface temperature
p_a	The water vapor partial pressure
t_r	The mean radiant temperature
Pa	Pascal
W/m^2	Watt per square meter
I_{cl}	The clothing insulation
m^2K/W	Square meters Kelvin per Watt

t_{sk}	Skin external temperature
kW	Kilo Watt
MW	Mega Watt
mm	Millimeters
kms	Kilometers
m	Meters
MJ	Mega Joule
hrs	Hours
SO,	Sulphur dioxide
NO	Nitric Oxide
CFCs	Chlorofluorocarbons
HCFCs	Hydro chlorofluorocarbon
CO_2	Carbon dioxide

Chapter 1: Introduction

1. Introduction

Our Earth will undergo a sea-change in the upcoming two or three decades. According to one of the International Programs relating to Global Population Profile: 2002 [1] of the United States Census Bureau, there would be an additional 3 billion people on this planet with an annual growth rate over 1 % [2]. By that time almost 70 % of the people will live in the urban areas which will have an adverse effect on the ecological balance of this world. The natural phenomena's like the depletion of natural resources, ozone layer depletion, emission of greenhouse gases etc. which is resulting in Global Warming has brought in great concern to humanity. The concept of energy efficiency or energy conservation were not so predominant in the past decades which resulted in the construction of many (energy wise) inefficient buildings which consume about 40 % [3] of the world's energy which is in turn responsible for almost the same amount of carbon emission. Thus, governments along with institutions have come together to take necessary measures to improve the energy consumption. And in this aspect the concept of energy efficiency has been used as a liaison to bring down the use of natural resources along with decreasing amount of annual carbon emissions [4]. Energy efficiency happens to be one of the most promising and sometimes cost-effective way to contend ecological challenges on sustainable economic growth. In the total percentage of the world energy consumption by the construction sector, almost 50 % [3] of the building energy consumption happens to be due to space heating and cooling. However, the impact of the climatic changes on the heating and cooling use of energy will vary with change of locations. This is due to the reason that different locations have different climatic conditions [5].

1.1 Background work

The use of energy in buildings accounts for a large share of the total end use of energy. In sectors such as residential and the commercial sector, the major part of the energy consumption takes place. According to the estimation of the International Energy Agency (IEA), the potential for energy improvements is supposed to be in the range of 20 % - 50 % of the total final energy consumption in five notable sectors namely buildings, equipment, lighting, transport and industry. In the construction industries, the biggest cost carrying sectors are personnel, material and energy. Controlling the cash flow in these areas leads to more profitability of an organization. Now reduction of staff can tend to increase in additional salaries for the present staff or inaccuracy of time frame and results. Savings in the material often affect the quality of the material. Thus the construction sector which happens to be the bigger consumer of the world energy have taken the correct path to work towards energy conservation in accordance with research institutes. Energy efficiency requirements in building codes or energy standards for new buildings are among of the most important single measures for buildings' energy efficiency. This is, in particular the case in times of high construction activity or in fast developing countries. However, this can only be achieved, when the operating conditions of a building suit the users' needs. Cost reductions in the energy remains is implemented through efficient planning and in accordance with rising environmental awareness. The attribute of this technique is that it prioritizes the actions to reduce the need for energy or else to consume less amount of energy for the same level of service. The second practice of consuming less energy is generally implemented in the building design. In sectors such as the residential and the commercial sectors, the maximum energy consumption takes place for purposes like space heating and cooling, lighting, appliances and also other installed equipment [6]. During the planning stage, it is easier to work on the improvement of the buildings' efficiency as compared to the stage after the initial construction is done. Some of the efficiency measures may only be possible during the construction stage or by major renovation which is likely to happen after several decades.

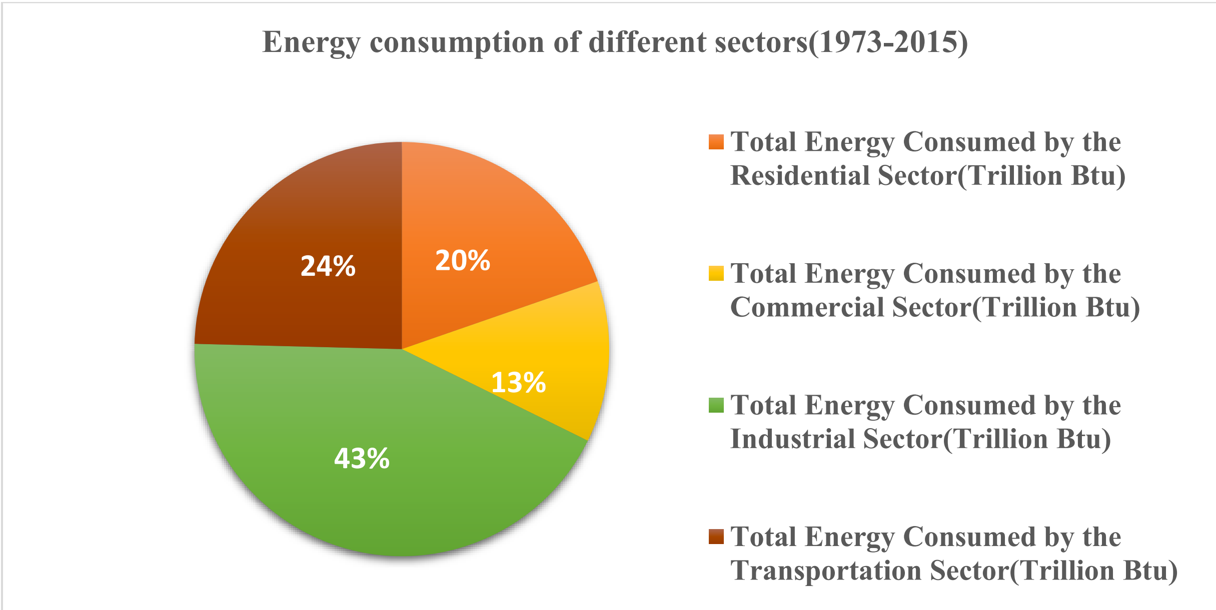

Figure 1 Energy Consumption of different sectors (1973-2015) [7]

In a building, the energy consumed gets divided into various sectors such as heating and cooling, ventilation, lighting etc. But it is fairly difficult to draw a subdivision of the energy consumed in case of individual sectors. So the energy use in buildings is generally defined by end use.

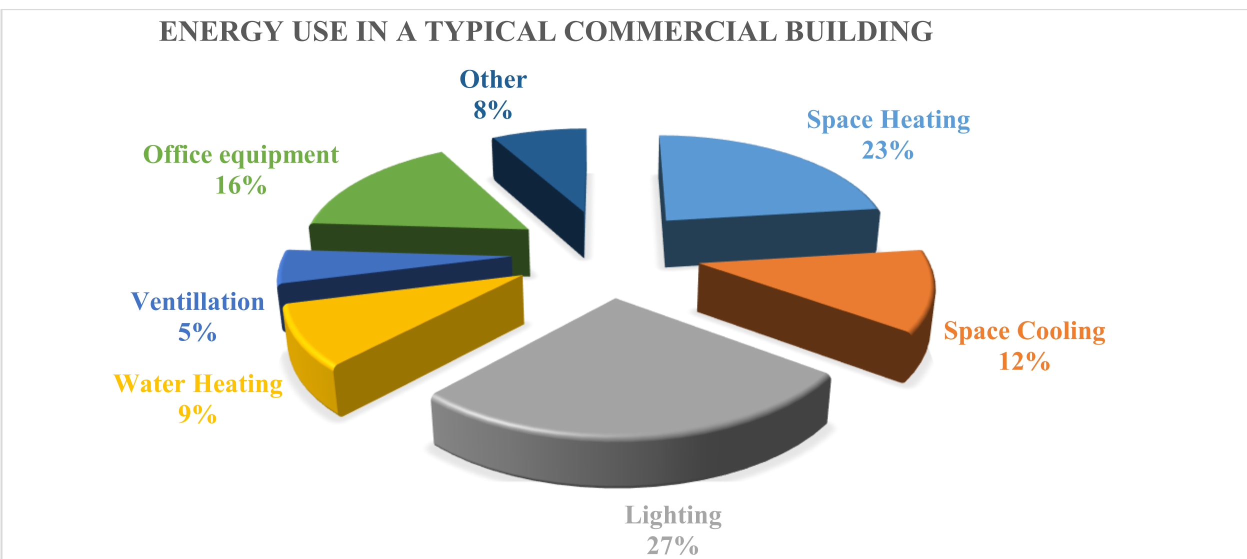

Figure 2 Energy use in a typical commercial building [8, 9]

Generally, in the construction and commercial industries, the lighting and the heating & cooling sectors consume the maximum energy annually. Thus the energy efficient techniques when applied in these sectors, a lot of energy can be conserved. With the increasing and alarming environmental conditions, many means to save building energy are being applied which in turn is also proving to be cost effective [10].

1.2 Problem statement

With the increasing population, the per capita energy consumption is also increasing at a fair rate over 1 % [11]. And most of the worlds energy needs are met through fossil fuels like coal or natural gases. So if the energy demand keeps on moving up without proper conservation, it will lead to a complete misbalance of this ecological world. Thus it is generally expected by most of the governments and the research industries that improved energy efficiency and reduced energy demand will lead to promising global ecological balance. But the inter-relation between increasing finance and increased energy demand is very strong. This factor often challenges the initiatives to reduce the energy demand. Csereklyei et al. [12] analyzed 99 countries over a span of 35 years (1971-2010) and found a pattern that energy intensity is comparatively lower in richer countries and with an average 1 % increase in per capita income, per capita energy intensity decreases by 0.3 %. This leads to long term decline in regional as well as global energy intensity which reduces the chances of creating a certain level wealth with less energy. This co relation between the per capita wealth and the per capita energy intensity enshrouds the significant variations from one country to another. Countries with similar per capita GDP can vary in an order of magnitude of their per capita energy consumption or vice versa due to differences in energy resources, climatic variations, population density, economic structure etc. For example, United States requires 50 % more energy than the European Union to produce a unit of GDP [13]. Again one of the major problem to reduce the global energy demand is the lack of internal motivation as for many global company's energy accounts for only a small percentage of the company's overall cost. Thus decreasing energy cost can fade out to other initiatives that cut proportionally larger costs. This is a common scenario despite the contribution to profitable energy efficiency. Without proper accountability for energy performance, many companies and organizations are unable to take critical measures including energy strategies, prioritizing energy saving investments etc. There are also problems with unpredictable climatic impacts which affects the continuous momentum of an energy efficiency project [14] which brings and relates to this project as it was challenging task to substitute the strategy of modeling a single virtual building under different climatic conditions. Different regions across the world have different demands of material, structural and energy properties. For example, in Europe mostly architectural and masonry structures are predominant as the whole of Europe does not fall under any serious seismic zone and experience a warm summer and a very cold winter. The choice of the material and the energy properties are also adversely affected by the level of pollution in air which is arguably low in Europe as compared to other Asian countries. Again, countries like India, China, Japan and UAE have extreme weathers and high pollution levels which drives the urge for proper energy efficient and designed structure to meet the environmental needs. So, it was difficult to fit a single building model under a common shed of all climatic variations. However, in this project, the virtual building model was based on the basic material properties relating to the U-values. So this common building model has been analyzed to understand the change in the heating and cooling energy demand under the impact of different climatic conditions.

1.3 Objective

The main objective of this thesis is to observe the variance of the efficiency of a typical multi-story office building (reinforced concrete core structure, variable façade structure) under the exposure to different climatic conditions. The impact of the climate zones must be considered using local weather data (e.g. Test Reference Years). This will also help to understand the effect of adverse versus moderate climatic conditions on the construction and the heating and cooling energy demand of the building. Following the objective, this thesis is being subdivided into 6 chapters which are mentioned under the following topic of "Outline of the Project".

1.4 Outline of Project

This thesis has been subdivided into 6 chapters with proper elaboration prioritizing the objective:

Chapter 1: Introduction

This chapter describes the background of the energy efficiency techniques in accordance with the energy data available [15]. It also describes briefly about the background of this work as if why energy efficiency is necessary in today's world, what are the problems that the governments or organizations face while implementing such techniques into reality. Lastly, this chapter also shares the outline of the project along with the methodology to achieve the objective.

Chapter 2: Literature Review

This chapter focusses on all the necessary information which is necessary to be addressed while performing the tasks. It tells all about the concept of energy efficiency, its background, its present scenario and also its future prospects. It also relates the term energy efficiency to building and talks about the impact of climate change on it. This chapter also talks about the necessity of heating & cooling in a building along with its relation to climate change. The concept of Degree Days is also illustrated with all the necessary conditions and respective formulas. It describes the various effects of the climatic changes on a structure and also on the comfort level inside a building. Lastly, it describes the software tools namely Revit Structures, Energy Plus and Climate Consultant. The importance of these tools for this thesis is also described.

Chapter 3: Development of the Building Model (Multi Storey Office Building)

This chapter describes the complete development of the virtual building model which is supposed to be analyzed for the comparison with models on variable locations. Step by step integration along with all the material properties, schedules of doors and windows and the technical details have been explained here.

Chapter 4: Differentiation of work environments in respected climate zones according to time periods without and with energy consumption

Under this chapter, the weather data of different specified locations are processed, Following the processing of weather data, the work environments of the specified locations under the effect of different climatic locations are explained in detail. Study of the temperature variations, Heating Degree Days, Cooling Degree Days, relative humidity, temperature range and comfort zone are mentionable.

Chapter 5: Comparison of the results

We develop the same virtual model for individual specified locations followed by energy analysis and heating & cooling load analysis is performed. So when we have all the analytical reports, a comparative scenario of the variable energy efficiency and heating and cooling loads are put forward for better understanding

Chapter 6: Conclusion

The final chapter concludes with suggestions for the international energy code (if any) based on the performance of the virtual model under the effect of the variable climatic conditions.

1.5 Methodology

To achieve the objective of this thesis, a four-step methodology has been adopted. This generally prioritizes the main course of action which may be taken more than once during the work period of this thesis. The weather data and the building stipulations from the international code are collected for further processing. This is followed by setting the building characteristics and development of the virtual building model. When the building model is ready, the analysis is run so that a comparative scenario of the variable energy efficiency of the building model for different climatic conditions can be put forward.

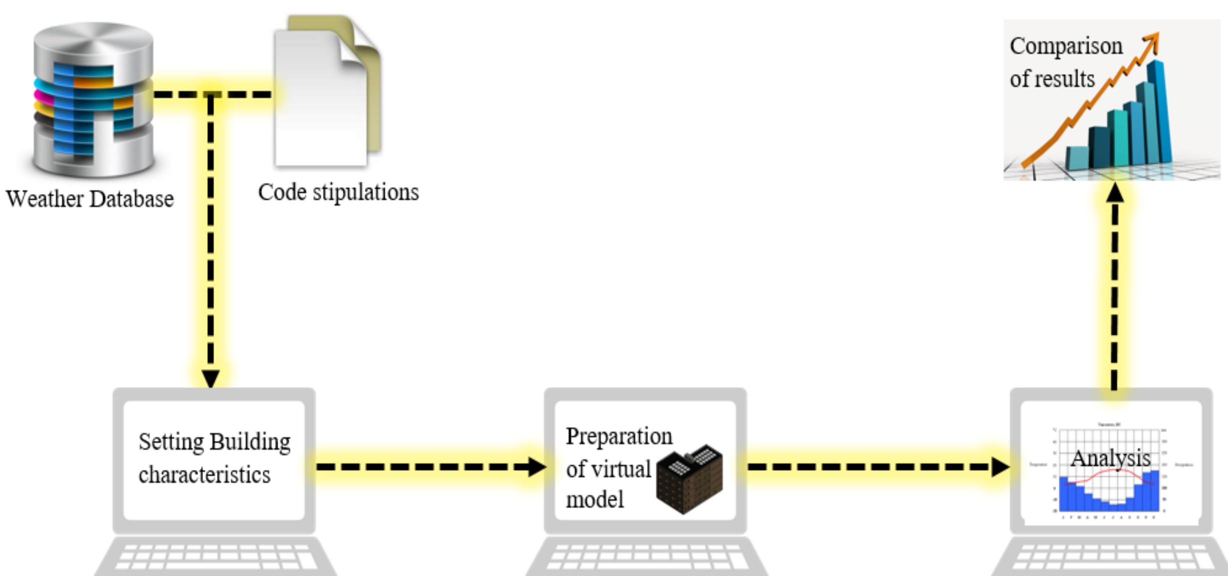

Figure 3 Methodology

Chapter 2: Literature Review

2.1 Energy efficiency

2.1.1 Introduction

Energy is a strange property of systems which can neither be created nor be destroyed but conversion and transfer from one system to another are possible. Since all forms of energy are equally not useful, exergy is more of a relevant term which is termed as the ability to perform physical work. It is a measure of both quantity and quality and also can be destroyed during the conversion process. Using the methodological and rigorous approach of exergy efficiency different energy systems can be evaluated and compared [16].

Energy efficiency refers to a situation when the same level of output in terms of both quality and quantity is provided with the use of less energy. This refers to restrain the growth in the rate of energy consumption. For example, an insulated house is more efficient in heating and cooling to maintain a thermal comfort. It can often be broadly defined by a simple ratio:

$$\frac{Useful\ output\ of\ a\ process}{Energy\ input\ into\ a\ process}$$

According to the EU Directive "Energy Performance of Building Directive", to determine the energy efficiency of a building, heating, domestic hot water, cooling, ventilation, lighting, auxiliary energy should be considered. Energy efficiency holds a very distinct place in the recent public policy agendas of most developed nations as it is considered to be the most promising, fastest, cheapest and the safest means to alleviate the climate change. The importance of energy efficiency as an objective is attached to sectors like commercial, industrial, energy security benefits as well as various environmental issues regarding reducing CO_2 emissions. But previously the attempts towards lowering the energy demand was not always successful. Nowadays the policies of energy efficiency are much more informed to various degrees by ideas of reducing the energy demand from the research institutes [17].

2.1.2 Energy Efficiency in Buildings

Buildings are responsible for about 40 % of the energy consumption in most countries and it is still rising. For countries like China, India where construction booms have accelerated as never before, it is necessary to take measures so that the construction industry can play a major role in tackling climatic awareness. But in the process of such actions several organizational and financial barriers come in way. However, these barriers can be overcome by the following approaches.

a. By adopting integrated approaches among the stake holders who guarantees a combined useful support to improve energy performance of buildings.
b. By increasing the value of energy by those involved in the development, operation and the usage of buildings.
c. By educating and motivating the associated professionals to alter their concern over improving energy efficiency in buildings.

Energy efficiency factors in buildings vary in accordance with geography, climate, building type and location. The difference between developed and developing countries is significant as it refers to the situations of retrofitting existing buildings and new constructions respectively. There are different standards of building qualities upon which energy efficiency should not depend and shall permeate all levels without being restricted to high-end properties. Energy savings up to 30 % can be achieved by raising awareness and by introducing targeted energy control and energy management policies [18].

2.1.3 Contribution of Buildings to Climate Change

In today's world, the buildings account for almost one-third of the greenhouse gas emissions. The increased rate in usage of energy in the building sector results in the potential for climate changes. The majority of the energy usage of a building is from the non-renewable finite sources which are depleting at a fair rate. By optimizing the potential for efficiency and consumption, these resources can be saved for further generations According to the report of Levine et al, 2007 [19], the estimated building-related GHG emissions was around 8.6 million metric tons CO_2 and what is more to worry is that this is increasing at a fair rate over 2.5 % for commercial buildings and 1.7 % for residential buildings every year. Apart from CO_2 emissions, buildings and construction sector is also responsible for a fair contribution rate of halocarbons, CFC's and HCFC's. This happens due to cooling and refrigeration purposes in buildings. But the good news is that the building sector comprises the capability to reduce the rate of GHG emissions significantly. With proven and commercially efficient technologies the energy consumption in both new and old buildings can be cut by an estimated 30 % to 80 % with potential net profit during the building lifespan [20].

2.1.4 CO2 emissions and global climate

The cause of the "Global Warming" is the emission of the greenhouse gases, 72 % of which constitutes CO_2, 18 % Methane, and 9 % Nitrous Oxide. CO_2 is ineluctably by burning of fossil fuels like oil, natural gas, ethanol, petrol, diesel etc. The global demand for energy has increased theatrically over the past decade and is expected to increase according to the climatic forecasts. Global CO_2 emissions are developing in accordance with the increased consumption of fossil fuels.

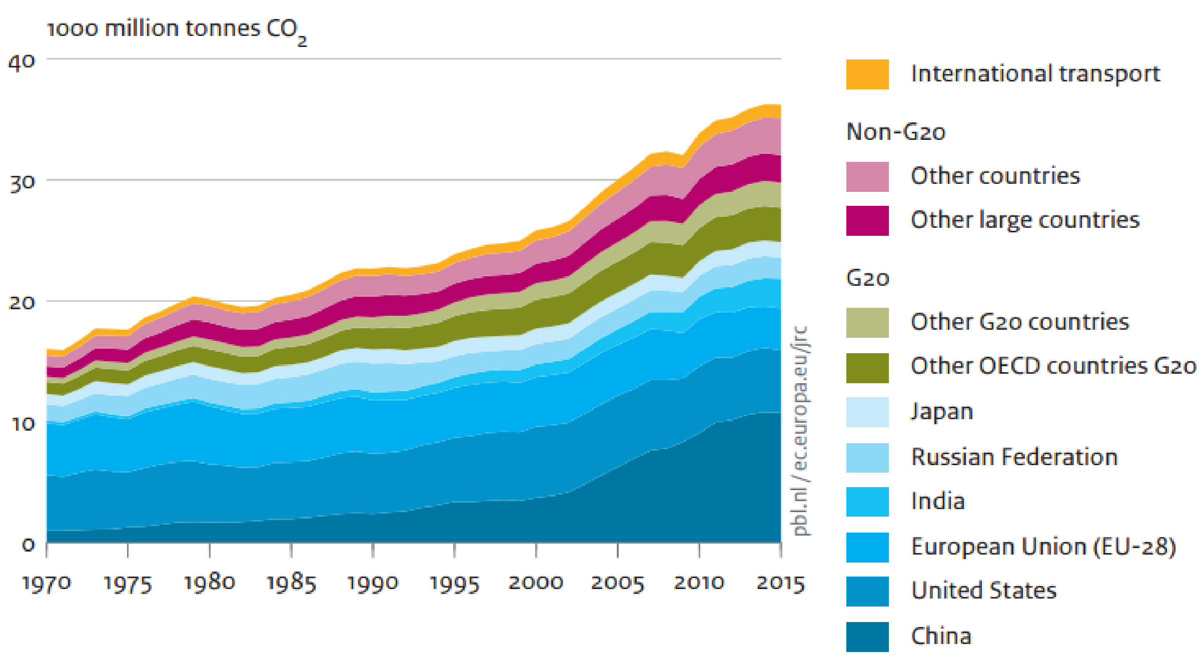

Figure 4 CO2 Emissions of the world over the past decades [21]

The impact of CO_2 emissions is very distinct. The climatic dynamics is changing drastically over the years with the temperature seeing a continuous rise.

2.1.5 Impact of the climate change on the Energy Efficiency of a building

Global warming, one of the important aspects of a climate change refers to the gradual increase of the average surface temperatures near the Earth's surface. The major cause of the climate change is the increased GHG emissions which are associated with the human activities. Therefore, it is imperative that the architects and the designers should consider the effects of climate change on long-term building performance. Aguiar et al. [22] simulated the hourly energy consumptions of Portuguese buildings from 2070 to 2099 in three different locations in the country. Under their area of research, it was found that heating load decreased for all three locations but the cooling thermal load increased. The annual heating thermal load decreased between 34 % and 60 % whereas the cooling thermal load increased massively between 130% and 525 %. The conclusion stated that overall annual energy requirements for space conditioning will increase by the end of 21st century. There are also studies on the impact of climate change on non-residential buildings. Berger et al. [23] simulated nine sample office buildings in Vienna, Austria to find out the impact of climate change on cooling and heating energy demand for the buildings. The result stated that there has been a considerable increase in cooling demand but however heating requirements have lowered. Investigation of the impact of the climate change on a number of energy efficiency measures would open up a new broader horizon of the know-how of design of energy efficient building envelopes [24]. However, this thesis investigates the impact of the climate change on a single building relating to the basic building envelopes like walls, floors, ceilings, doors, windows and roofs.

2.1.6 Strategies for reducing energy usage in new buildings

In the today's sustainable development goals, buildings need to be constructed and operated so that they have a very low environmental impact and controlled consumption of natural resources. It should be built on future-oriented low-energy standards and also should be equipped energy saving building automation and control functions. According to Pérez-Lombard et al., 2008 offices and retail outlets represents the most energy users in the non-residential buildings sector and account for more than 50 % of the energy usage [25]. Juan, Gao, & Wang, 2010 in their research mentioned that the optimal operation of a commercial or an office building is a critical component in the reduction of overall energy usage in buildings. Such optimization requires well-conditioned systems to monitor the energy usage of a building [26]. Several studies (Daly, Cooper, & Ma, 2014; Harish and Kumar, 2016a; Li and Wen, 2014) have pointed out that improving energy efficiency of a building has a considerable and positive influence on the environment. However, in one of the articles, Scott Heath [27], Managing Partner at Good Energy, LP have identified some immediate actions that can be taken to reduce the energy usage in new commercial buildings:

- **Historical Usage Data Analysis:** By analyzing the facility's energy usage patterns it is possible to understand how and where energy is consumed so as to reduce the cost and consumption.
- **Energy Procurement Solutions:** A qualified energy consultant can help commercial and industrial customers to navigate and identify the best price, product and contractual terms to meet the specific needs.

- **Power factor correction solutions:** For heavy commercial and industrial organizations motors operating 24/7 increases the potential for having a poor power factor as the motors create wasted power while idling. So by identifying the power factor requirements from beforehand and by working with an informed consultant significant power savings can be made which leads to reduce the energy consumption.
- **Efficient Lighting Solutions:** Working with lighting distributors, commercial and industrial businesses can install more efficient and affordable lighting solutions to save energy. In present scenario with new and improved LED technologies, the scope of energy savings is broader than ever.
- **Engineering Studies:** Engineering studies can be implemented to lower the energy usage and reduce the energy cost in a lot of ways. A comprehensive energy study can lead to attractive savings rebates as well as state and federal incentives.
- **Sustainable Energy products:** Attaining the sustainability initiatives is the most demanding initiative in the genre of building efficiency. Installation of sustainable energy products like solar panels or wind technologies can help a commercial building to be less reliant on the utility companies which in turn depend on the natural resources.

2.1.7 Goals of these strategies

There are many long term goals set for lowering energy use. Some of them include the cost savings from the operational energy. This can be done through a diagnostic investigation of the building energy use and its savings potential [28]. Conservation of the environment and the existing resources of the energy is of uttermost importance. Comfort was also the prime motivation for raising such requirements. With the continuous increase in population, the demand for better standard of living is also increasing accordingly. Thus the guarantee of reasonable comfort during occupancy is required.

2.2 Heating and Cooling in Buildings

2.2.1 Introduction

Temperature control in a building is important independent of the climate we live in to maintain the comfort levels for the people working or living inside. In case of both heating and cooling the heat energy should be moved from one place to another. According to the law of thermodynamics, it moves from a hotter place to a cooler place. So when some amount of hot air enters a room, the walls the furniture will try to absorb the heat from the air and increase the temperature of their own surface so that the heat can get evenly distributed all through the room. The same concept works for cooling also. There are three ways in which **heat** gets transferred from one location to another namely Conduction, Convection and Radiation.

- **Conduction in Buildings:** Building insulation is however not a good conductor. If we hold a building insulation in our hand, it would feel warm or normal as the vibration of the molecules in our hand cannot create an appreciable increase in the vibration of the molecules in the insulating material of the building. Heating or cooling through conduction generally takes place at the building envelope (exterior walls, doors, windows etc.) where such a huge volume of the warm or cold air outside causes the variations in vibrations of the molecules of the building envelope. This leads to the result of heat loss or heat gain inside the building [29].

- **Convection in Buildings:** For buildings, the process of convection is followed upon by various means. The hot water or the steam radiators utilize the process of convection to transfer the heat throughout the building spaces. The air inside the room comes in contact with these heating elements and absorbs heat from them and get warmer. The hot air then rises within the space to let the cooler air come down for absorption of heat. In this manner, it forms a circulation inside a room. In other terms, mechanical means can also be used such as forced air heating in a building where heat is generated on a furnace and then transmitted to the room through ducts by a fan which is associated with the furnace. The vents in the room are usually located near the floor levels so that the warm air from there can rise up to displace the cold air in the upper portion [29].
- **Radiation in Buildings:** For building, the system of radiant heating system can be found in bathrooms where the heat lamps are placed. In such cases, the thermal energy gets transmitted to the surface in the room which is within the sight lines of the light. The heat lamp doesn't play any role to increase the temperature of the air. Instead, the ultraviolet radiations from the lamp are directed to an object and warm up the surface [29].

Cooling in Buildings: The principle behind cooling is same as that of heating. The only difference here is warm air is being replaced with cold air. When a fluid is compressed it releases heat and when it is at low pressure it absorbs heat. Thus a refrigerant fluid at low pressure is allowed to circulate within the coils that are attached to the air conditioning equipment on the interior side of the buildings. Through the process of convection, the warm interior air transfers the heat energy into the metal which forms the coil and thus the heat energy gets transmitted to the fluid which is followed by compression of this hot air and being transferred to the outer world. This cycle continues until the comfort level is reached inside the building and the desired temperature is reached. And when it reaches the desired temperature level the building thermostat signals the air-conditioning unit to shut down. The process of cooling also brings upon an additional complexity due to the principle of condensation. When the warm air comes in contact with the surface of low temperature, the molecules of the air moves close together as it cools. Thus when the temperature drops to certain point that the water vapor molecules in the air start to attract each other and the dew point is reached. In this time liquid droplets are formed. Due to this reason, puddles of water is formed under the coils of the air-conditioning unit [30].

2.2.2 Status of heating and cooling technologies today

[31]In today's world, there are several building heating and cooling technologies which are adopted for space and water heating, heat storage, cooling and dehumidification. Some of the mentionable are:

- **Active Solar Thermal (AST):** This system can provide space and water heating as well as cooling needs. This system focuses on building integrated system though it can also be used for district heating schemes.

- **Combined Heat and Power Systems:** These systems focus on the building scale from $1kW_e$ to $1MW_e$. Traditional CHP systems are mature and useful transitional technology while micro-CHP, biomass CHP can be treated as an important option.

- **Heat pumps for cooling and space water heating:** These are very matured technologies which depends on the advantages of the principles of renewable energy.
- **Thermal Storage:** It includes sensible storage (hot water, underground storage), latent storage (ice storage) and thermos-chemical storage. It can maximize the energy savings and energy efficiency potential of other technologies and can also help in increasing the flexibility by unclogging the usage of renewables and waste heat.

However, many criteria have to be taken into account in the process of choosing heating and cooling technologies such as:

- Annual heating and cooling profile
- Space constraints
- Emission regulations
- Utility prices for electricity
- Availability and prices of other fuels
- Relative timing of thermal and electrical loads
- Complexity of installation and operation
- Seasonal efficiency of the equipment
- Reputation of the manufacturer
- Technical knowledge of the installers

2.2.3 Impact of climate change on heating energy demand and cooling energy demand of office buildings

Commercial buildings like offices generally show high levels of internal heat loads for two reasons namely high rates of occupancy and significant density of technical equipment and lighting both of which results to much of internal heat production. The workers working inside an office building depend very strongly on the comfortable conditions so that they may be able to perform complex tasks. Thus their productivity is directly and negatively influenced by increased indoor temperatures. Seppänen et al. [32] researched on literature work in relation to performance with temperature and found out that the quality and level of work performance decreases when the temperature exceeds the thermal neutrality. The study indicates an average 2 % decrement in work performance per ℃ temperature rise above 25℃. This led to the increase in the application of mechanical cooling inside office spaces on European level since 1990 [33]. Similarly, a research by Asimakopoulos et al. [34] suggested that the heating energy demand for the building sector may decrease by almost 50% while the cooling energy demand may have a steep rise by almost 248 % until 2100. To conceive effective adaptation measures for the built environment a solid knowledge basis is required on the impacts of the climate change regarding the thermal performance of building types under different climatic areas. A research in 2008 [35] suggested the expected macroeconomic impacts of the climate change in Germany mainly focusing on heat waves, heavy precipitation and extreme winds. But no references were made to impacts upon specific building types. Most of the above-mentioned researches are based on tools of simulation in order to assess the climatic impacts on sample buildings. Therefore, the generation of suitable accurate weather data is crucial in such process. Guan [36] reviewed different methods to prepare such weather data as well as Jentsch et al. [37] also described the integration of the futuristic climatic scenarios of United Kingdom into widely used Typical Meteorological Year (TMY2) and EnergyPlus Weather (EPW) file formats. It is assumed that most of the building owners, engineers as well as the users tend to respond the increasing outdoor temperatures by increasing the energy consumption for cooling in order to maintain the thermal comfort under the effect of all weather conditions. Providing more electricity for cooling purposes can lead to big consequences of climate change [23].

Considering the average lifespan of buildings, it is evident that the present building stock must cope with the long-term impacts of climate change. Therefore, it is necessary to conceive climate proof new buildings today. This thesis research investigates the impact of the climatic variations on a single building type (commercial/office building). The building model has been kept same for different extreme climatic regions but the weather conditions of the different geographical locations and the effect from the climate over the thermal comfort inside the building have been studied in detail.

2.3 Degree Days: Theory and Application

2.3.1 Introduction

Degree days in simple terms can be termed as the measure of the degree of hotness or coldness of a particular location. It is essentially the summation of temperature difference over time. This temperature difference is between a reference temperature and the outdoor air temperature where the reference temperature is a base temperature and treated as balance point temperature for buildings. The two main uses of degree days in buildings are:

- Estimation of energy consumption and CO_2 emissions due to space heating and cooling.
- Ongoing energy monitoring and analysis of existing buildings based on historical data.

When the outdoor temperature is less than the base temperature, the heating system needs to provide heat. Since the heat loss from a building is directly proportional to the indoor to the outdoor temperature difference. Therefore, it follows that the energy consumption of a heated building over a period should be associated with the sum these temperature difference over this period of time usually which is considered to be 24hrs. The rise of atmospheric temperatures due to climatic changes will dictate how reliable the numbers should be for setting energy consumption. Degree days provide a significant edge over other simplified methods for calculation of energy demand. This is due to the fact that degree days account for the fluctuations in the outdoor temperatures and eliminate those periods when heating or cooling systems don’t need to operate. This method can capture the extreme conditions in a very significant way as compared to the other mean temperature methods [38].

2.3.2 Calculation of Degree days

[39] The calculation generally comprises of daily measurements of maximum and minimum outside temperatures ($\boldsymbol{T_{max}}$ and $\boldsymbol{T_{min}}$) and a base temperature $\boldsymbol{T_{base}}$ which is nominated by us as an estimation of the outside air temperature at which neither heating or cooling will be required.

Heating Degree Days (D_h)

Condition	Formula
$\boldsymbol{T_{min} > T_{base}}$	$D_h = 0$
$\left\{\frac{\boldsymbol{T_{max}+T_{min}}}{\boldsymbol{2}}\right\} > \boldsymbol{T_{base}}$	$D_h = (\boldsymbol{T_{base}} - \boldsymbol{T_{min}})/4$
$\boldsymbol{T_{max} >= T_{base}}$	$D_h = \{(\boldsymbol{T_{base}} - \boldsymbol{T_{min}})/2\} - \{(\boldsymbol{T_{max}} - \boldsymbol{T_{base}})/4\}$
$\boldsymbol{T_{max} < T_{base}}$	$D_h = \boldsymbol{T_{base}} - (\boldsymbol{T_{max}} + \boldsymbol{T_{min}})/2$

Table 1 Calculation of Heating Degree Days

Cooling Degree Days (D_c)

Condition	Formula
$\boldsymbol{T_{max} < T_{base}}$	$D_c = 0$
$\boldsymbol{\{(T_{max} + T_{min})/2\} < T_{base}}$	$D_c = (T_{max} - \boldsymbol{T_{base}})/4$
$\boldsymbol{T_{min} <= T_{base}}$	$D_c = \{(T_{max} - \boldsymbol{T_{base}})/2\} - \{(\boldsymbol{T_{base}} - \boldsymbol{T_{min}})/4\}$
$\boldsymbol{T_{min} > T_{base}}$	$D_c = (\boldsymbol{T_{max}} + \boldsymbol{T_{min}})/2 - \boldsymbol{T_{base}}$

Table 2 Calculation of Cooling Degree Days

2.3.3 Degree Days for Energy Estimation

The preferable method for the estimation of the expected energy consumption of a particular building is by full thermal simulation. Buildings are generally complex entities and the energy consumption of a building is determined by various influencing factors. This makes the process of simulation a long and tedious process which also requires a high degree of skill. On the other hand, degree days provide comparatively a simpler method for energy estimation which requires less data input and can be used to assess the variation in the influence of major design decisions (level of insulation, building thermal capacity etc.) on energy consumption. The accuracy of such techniques is comparatively more questionable but it is probably more helpful to talk in terms of uncertainty in rather than accuracy of the results. The calculation in this technique attempts to define this uncertainty of heat energy demand. Degree Days method do carry an advantage and that is the reduced number of inputs reduces the user input error, which is difficult to check with other simulation techniques [38].

2.4 Thermal Comfort in Buildings

2.4.1 Introduction

Thermal comfort generally is the measure of the overall satisfaction and the state of well-being. Comfort has always been an important parameter in the building design process for almost three decades. By the end of the 19th century, the development and the usage of the energy balance models came into existence [40]. And during that time, one of the most important contributor was P.O.Fanger, who created a predictive model for general or whole body thermal comfort from laboratory and the climate chamber research. With this work, he wanted to present a method which can be predicted and implemented by heating and air-conditioning for any kind of activity. There were several environment-based thermal factors which were to be considered to provide the thermal comfort to the largest possible percentage of people. This predicted mean vote (PMV) model is now the internationally accepted model for predicting the mean thermal perception of building occupants.

2.4.2 Fanger's PMV Model

[41] The PMV model comprises of four different physical variables namely air temperature, air velocity, mean radiant temperature and relative humidity and two personal variables namely clothing insulation and activity level. These variables are combined into an index which is used to predict the thermal comfort. This index provides a scale that corresponds to the ASHRAE thermal sensation scale which represents the average thermal sensation felt by a large group of people in a space.

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	**-2**	**-1**	**0**	**1**	**2**	**3**

Table 3 ASHRAE Thermal Sensation Scale [41]

Fanger's PMV model is based on thermoregulation and heat balance theories. Following these theories, a human body undergoes the physiological processes (sweating, shivering, blood flow, etc.) in order to keep a proper balance between the heat produced by metabolism and heat lost from the body. In office buildings, it is very improbable that temperatures associated with serious bodily dysfunction will occur but thermos regulation is still used to maintain a comfort heat balance as maintaining heat balance is the primary condition for achieving a neutral thermal sensation [41]. Thus he established a model of correlation between subjective human perception expressed by a scale of comfort from -3 (cold) to +3 (hot) and the difference between the heat generated and the heat released by the human body which corresponds to the following equation.

$$PMV = [(M - W) - H - E_c - C_{res} - E_{res}] * (0.303e^{-2.100*M} + 0.028)$$

Equation 1 Fanger's PMV Equation [42]

Where the different terms refer to:

M = the metabolic rate in Watt per square meter (W/m^2);
W = the effective mechanical power in Watt per square meter (W/m^2);
H = the sensitive heat losses;
E_c= the heat exchange by evaporation on the skin;
C_{res}= heat exchange by convection in breathing;
E_{res}= the evaporative heat exchange in breathing;
In the equation 1 H, E_c, C_{res}, E_{res} represents the heat exchange between the body and the surrounding environment and are calculated from the following equations.

$$H = 3.96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} * h_c * (t_{cl} - t_a)$$

Equation 2 Sensitive Heat Loss Equation [42]

$$E_c = 3.05 * 10^{-3} * [5733 - 6.99 * (M - W) - p_a] - 0.42 * [(M - W) - 58.15]$$

Equation 3 Equation for heat exchange by evaporation on the skin [42]

$$C_{res} = 0.0014 * M * (34 - t_a)$$

Equation 4 Equation for heat exchange by convection in breathing [42]

$$E_{res} = 1.7 * 10^{-5} * M * (5867 - p_a)$$

Equation 5 Equation of evaporative heat exchange in breathing [42]

where, f_{cl} is the clothing surface area factor, t_a is the air temperature in °C, t_{cl} is the clothing surface temperature in °C, p_a is the water vapor partial pressure in Pascal (Pa), t_r is the mean radiant temperature in °C. But the main problem in implementing this calculation method is the term t_{cl} is unknown. So this temperature is calculated by an iterative process from an equation resulting from an equation resulting from heat balance established for the clothing layer. It is considered that in a steady state, the heat flux which is transmitted by conduction through the same clothing from the inner layer at skin temperature until the outer layer is equal to the sum of the heat exchange by convection and by radiation with the surrounding environment, which is expressed by the following equation:

$$\frac{t_{sk} - t_{cl}}{I_{cl}} = 3.96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl} * h_c * (t_{cl} - t_a)$$

Equation 6 Heat Flux Equation [42]

Where, I_{cl} is the clothing insulation in square meters Kelvin per Watt (m^2K/W) and we can find t_{cl} as:

$$t_{cl} = t_{sk} - I_{cl} * 3.96 * 10^{-8} * f_{cl} * \left[(t_{cl} + 273)^4 - \left(t_{eq} + 273\right)^4\right] + I_{cl} * f_{cl} * h_c * (t_{cl} - t_{eq})$$

Equation 7 t_{cl} Equation [42]

t_{sk} is skin external temperature calculated from:

$$t_{sk} = 35.7 - 0.028(M - W)$$

Equation 8 t_{sk} Equation [42]

The PMV model is primarily based on Fanger's comfort equation which is the condition for optimal thermal comfort for a large number of people and for no existence of local discomfort. Based on PMV, the predicted percentage of dissatisfied (PPD) can be determined by the following formula.

$$PPD = 100 - 95 * e^{(-0.03353*PMV^4 - 0.2179*PMV^2)}$$

Equation 9 Fanger's Comfort Equation for Predicted Percentage of Dissatisfied [42]

The predicted mean vote is the average response of a large number of people and with the nature of comfort being known there will actually be a distribution of satisfaction among a large group of people. Thus Fanger concluded in his studies an empirical variation of PMV index and the percentage of people dissatisfied(PPD)

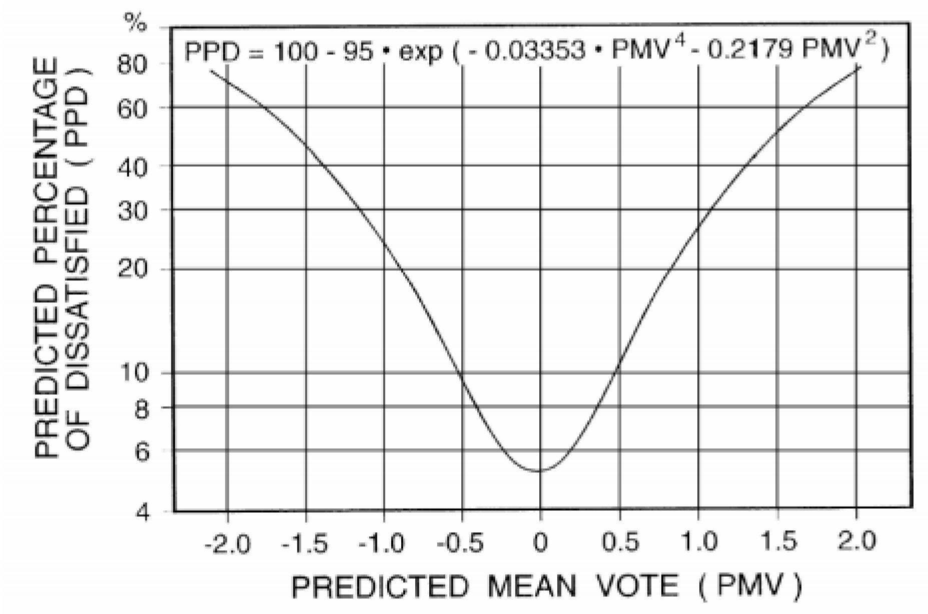

Figure 5 PPD vs PMV [43]

Thermal comfort zones (A, B and C classes) are defined by the ranges of PMV values ranging from -0.2 to 0.2, -0.5 to 0.5 and -0.7 to 0.7, which relates respectively to PPD values below 6 %, 10 % and 15 %. The graphical representation above shows that due to individual differences between people, even for the situation that is averagely considered by the population as thermal neutrality (PMV = 0), the percentage of dissatisfied is 5 % [42].

2.4.3 Conclusion

[40] Almost after 40 years of practical experience with the PMV model, its foundation and its use are growing at a very good pace. The PMV model is applied throughout every type of building all across the globe and its use is prescribed in the thermal comfort standards. Many researchers have tried to improve the PMV model and enlarge its application domain by introducing methods to increase the accuracy of the model's input parameters. The current PMV model is used for assessing and predicting thermal comfort in indoor spaces, often office buildings but however, it also holds promising interests that will surpass the original scope such as optimizing productivity.

2.5 Acquaintance with Software Platforms

Apart from the theoretical research and the literature review, certain platforms have been used to serve the purpose of various calculations, comparison of different variables, plotting graphs based on the data revived, building modelling, running analysis and also for studying the climatic conditions of the specified seven cities namely Delhi, Mumbai, Berlin, Lisbon, Oslo, Dubai, Montreal. In all there are five operational software that has been used for the purpose of this Master Thesis namely:

- **Microsoft Excel:** Microsoft Excel is a spreadsheet application developed by Microsoft Corporation for performing basic and complex mathematical computations and functions. Apart from performing arithmetic operations, it also holds the capability to create graphical displays of data, forms and pivot tables. However, for the purpose of this Master Thesis, Microsoft excel has been used for the assessment of weather data. The weather data of the seven above specified cities are to be collected and then processed. All the climatic variations starting from temperature variations to Heating and Cooling Degree Days are being collected, processed and plotted n Excel.

- **Autodesk Revit:** Autodesk Revit is a building information modeling (BIM) software developed by Autodesk for architects, structural engineers, MEP engineers, designers and contractors. This software allows user to use the intelligent model-based process to plan, design, construct and manage buildings and infrastructures.

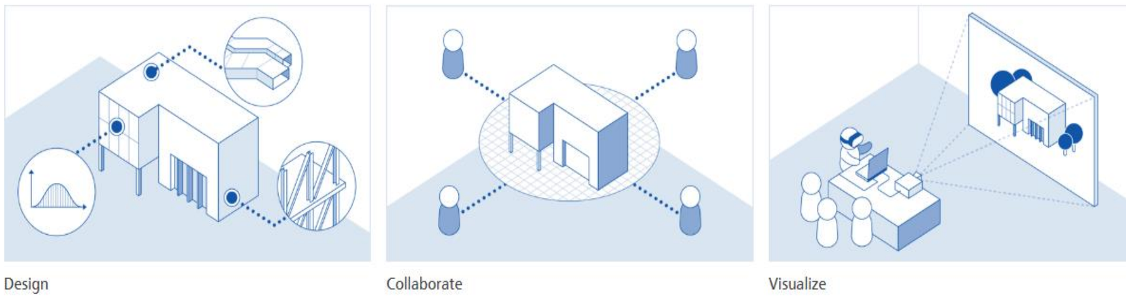

Figure 6 Work Flow and Properties of Autodesk Revit[44]

Some of the features of Revit are:

- Detailed annotation and drafting in 2D along with complete modeling of building components, analysis and simulations of systems and structures in 3D is possible in Revit.
- Complete collaboration among multiple project contributors is possible with the access of centrally shared models. This results in better coordination which in turn reduces the clashes and the reworks.
- Rendering of the created project as well as scheduling of the structural components can be showcased through Revit. For more effectiveness designers can communicate with the project owners by using models to create high impact 3D visuals.

However, for the purpose of this Thesis Revit Structures 2017 has been used to serve the purpose of modeling of the commercial office building which is to be further analyzed for the energy efficiency and heating and cooling load analysis. For the purpose of energy modeling and calculation of heating and cooling demand, the software EnergyPlus has been used as an add-in to the Revit platform. The detailed modeling along with the detail of the building components have been explained in Chapter number 3.

- **EnergyPlus:** EnergyPlus is one of the most used and reliable tool for energy analysis and thermal load simulation. It is based on the physical properties of a building and also associated with its mechanical properties. It has the ability to calculate the heating and cooling loads dynamically. These loads are necessary to maintain thermal control setpoints, conditions throughout a secondary HVAC system, coil loads, the energy consumption of primary plant equipment as well as many other simulation details. These data are necessary to verify that if the simulation is performing as the actual building is supposed to perform. Many of these simulation programs have been inherited from the legacy programs of BLAST and DOE-2.

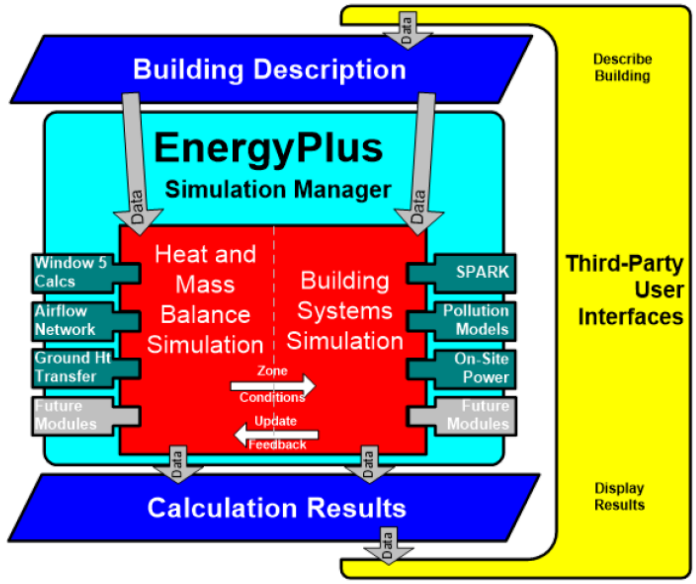

Figure 7 EnergyPlus the bigger picture [45]

However, for the purpose of this Thesis the newly launched add-in of EnergyPlus has been installed in the platform of Autodesk Revit Structures so that the heating and the cooling load analysis can be done with ease under the shed of a single tool. This analysis is done in complete accordance with the actual EnergyPlus software. This analytical process has been further described in detail under the Chapter number 3.

- **Climate Consultant:** The objective of the Climate Consultant is to show us a variety of graphical representations of hourly climate data for our chosen location so that we can characterize the different climatic zones distinctly. Designing and remodeling buildings that truly are climate responsive, depends firstly on a detailed accurate understanding of the local climate. So Climate Consultant seeks to translate outdoor conditions to indoor comfort, so as to make generalized assumptions about building design [46].
  However, for the purpose of this Thesis, Climate Consultant has been used to understand the temperature variations and comfort levels over the course of the year for the specified locations. Through the chart of temperature variations, the climate of the whole year has been studied in detail along with the comfort level maintained all through the year.

Chapter 3: Development of the Building Model (Multi Storey Office Building)

3.1 Introduction

A virtual building model has been prepared in Autodesk Revit to serve the purpose of studying the performance of that specific building under the influence of different climatic conditions. This virtual building model is not necessarily a complete building, but it has the relevant functionalities of a real building. It generally consists of the building envelope which surrounds the heated and the cooled parts of the building. It generally comprises of external walls, floors, roofs, ceilings, windows and doors. This also includes the cellar walls and the floor provided if they are heated. But if it is not heated the building shell only includes floor between the ground floor and the cellar. The generalized requirements of energy efficiency of the building envelope generally depend on the resistance to heat transparency through a unit of the construction, R-values and U-values. For example, in cold climates, low U-values and high R-values causes the prevention of heat from buildings and in hot climates, the same factors prevent the heat from entering the building [6]. Now the analysis of building envelopes has become a complicated issue due to the extreme global diversity of building materials, climates, standards and practices of building design and construction. There is a huge technology and an improvement gap in the construction practices in developing and OCED countries. With the general rise in population housing demand has also increased at a fair rate and therefore it is of real importance that new buildings use the most efficient technologies so that the process of retrofitting is not that difficult or expensive [47]. Thus the International Energy Agency has come up with some notable building envelope technologies.

Type of Economy	Climate	Technology: New Construction	Technology: Retrofit
Developed Economy	Hot Climate	Architectural shading	Exterior window shading and dynamic glass/shading
		Very low-SHGC windows (or dynamic shades/windows)	Reflective roofing materials and coatings
		Reflective walls/roofs	Reflective wall coatings
		Advanced roofs (integrated design/BIPV)	Window film with lower SHGC
		Optimized natural/mechanical ventilation.	New low-SHGC windows.
	Cold Climate	Highly insulated windows	Highly insulated windows
		Passive heating gain (architectural feature /dynamic glass/shades)	Low-e storm or interior panels
		Passivhaus-equivalent performance based on LCC limitations.	Insulated shades and other insulating attachments (Low-E films)
			Exterior insulating wall systems
			Interior high-performance insulation.

Type of Economy	Climate	Technology: New Construction	Technology: Retrofit
Developing Economy	Hot Climate	Exterior shading and architectural features	Exterior shading
		Low-SHGC windows	Reflective coatings (roof and wall)
		Reflective roofs and wall coatings	Low-cost window films
		Optimized natural/mechanical ventilation	Natural ventilation.
	Cold Climate	Highly insulated windows (possibly double-glazed with Low-E storm panel)	Low-e storm or interior panels
		Passive heating gain (architectural feature)	Insulated shades and other insulating attachments (Low-E films)
		Optimized low-cost insulation and air sealing.	Exterior insulating wall systems
			Cavity insulation, lower-cost (e.g. expanded polystyrene) interior insulation.

Table 4 Building envelope technologies according to Economy, Climate and Construction type[47]

3.2 Requirements for Energy Efficient Building Envelope according to the International Energy Agency used for the development of the virtual building model

a) **Insulation:** Generally, most of the heat is carried out from the building from roofs, walls and floors which represent most of the external area of any residential or commercial buildings. Thus proper insulation reduces heat loss in cold weather as well as reduces excess heat to enter inside during the hot weather. This helps to maintain a comfortable indoor climate without incurring maintenance cost. Now the necessity of type and insulation depends on building type. For example, due to higher density of people and a large number of electrical equipment, service sector building requires less insulation as compared to residential buildings [47]. The requirement of insulation in accordance with energy saving potential for a normal commercial building is listed below.

Name	Standard	Good	Ambitious
Roof	10-15 cm of thermal insulation	20 cm of thermal insulation	30 cm of thermal insulation
Wall	5-10 cm of thermal insulation	15 cm of thermal insulation	20 cm of thermal insulation
Base	10 cm of thermal insulation	10 cm of thermal insulation	15 cm of thermal insulation

Table 5 Requirements of insulation for a normal commercial building [48]

b) **Windows:** Windows, doors and other parts of buildings which comprise of the glass areas requires special attention beyond its role in insulation. In warm climates, the orientation of the windows and the glass areas play a major role in reducing the heat absorption from the sunlight where during the cold climate solar heat gains reduce the necessity of building's active heating. The solar heat gain coefficient (SHGC) is also affected by shading from the frame as well as the ratio of glazing and frame. The SHGC ranges for from above 80 % for the uncoated water white clear glass to less than 20 % for highly reflective coatings on tinted glass. The value of SHGC decreases with the addition of low E-coating [49].

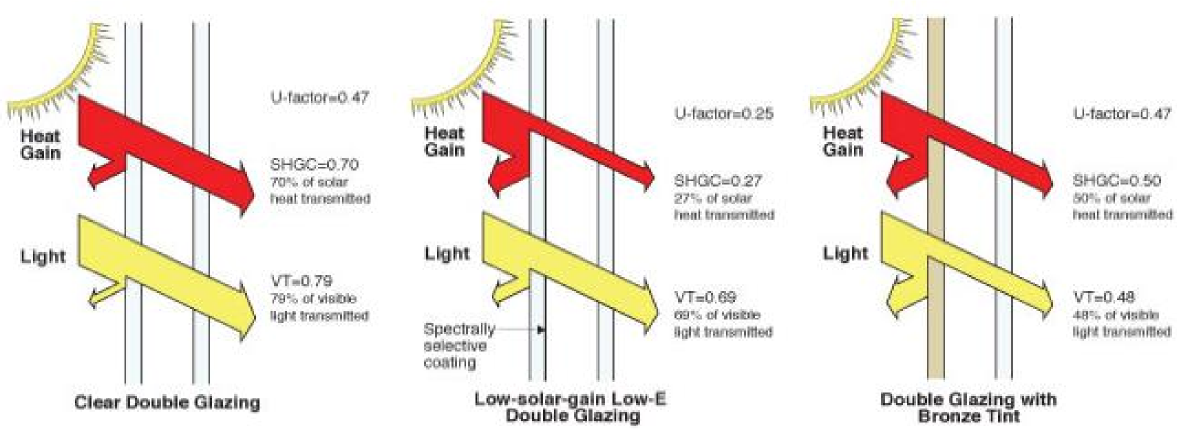

Figure 8 Solar heat gain values of double pane units [49]

c) **Hot sanitary water:** Hot sanitary water is required for hygiene, food preparation, cleaning and other commercial purposes. This water can be provided by the central heating system or heat pumps or by district heating [50].
d) **Zoning of buildings:** This means that the building gets divided into separate spaces with potentials for uniquely calculated requirements for energy efficiency and indoor climate. Energy gets transferred from one zone to another if there are differences in the indoor temperatures [50].

3.3 Resemblance of the building model with a validation building model of Berlin

While developing the virtual building model, the process was quite confusing in the first phase. This is because, following the objective of the project, a single building model is to be prepared for the energy analytical check and calculation of the heating and cooling energy demand. These numerical results are to be compared based on the impacts of different climatic conditions upon the virtual building model. So, for every distinct place the climate varies largely and depending upon the impact of the climate, a structure should be built with proper materials and energy efficient features. Now, there are not enough energy codes for every country. That makes the work a bit more difficult as without a proper energy code, choosing material properties and the energy efficient properties will just be an assumption. So, it was a challenging task to find some proper required values form a proper “International Energy Code”. Therefore, based on “Energy efficiency requirements in building codes, energy efficiency policies for new buildings” published by International Energy Agency and written by Mr. Jens Laustsen [6] and also on a validated building model situated in Berlin [51], our virtual building model is prepared. But again, due to insufficient information on the material properties, the building model is based on the specified Heat Transfer Coefficient values (U-values). In the following table, the U-values of the validation model is specified.

Ordnungsnummer	Bauteil	U-Wert(W/m^2K)
1	Außenwand	0.154
2	Bodenplatte	0.157
3	Dach	0.119
4	Innenwand	0.962
5	Fenster	0.52
6	Tür	1.93

Table 6 U-values of different Building Components [51]

This virtual building model is prepared in resemblance to the validation model of Berlin and has been used under every climatic condition to study the behavioral changes in terms of energy efficient factors and heating and cooling demand of the building.

3.4 Development of the virtual building model

The virtual building has been modeled completely in Autodesk Revit Structure 2017. The whole model has been sub-divided into the following sections.

3.4.1 Construction of Floors

For the flooring of the structure, we are trying to use the concept of radiant flooring where the floor has been divided into a few parts, namely, thick wooden or concrete layer in the bottom on top of which there is a layer of adhesive. On top of the adhesive layer we place the insulation and then over it, the heating pipes are placed which tend to keep the floor warm. These heating pipes are connected to an assembled hydronic control appliance which is supposed to take power from the solar panel placed on the roof. Then a layer of flexible adhesive covers the pipes which is followed by the final finishing of the floor comprising of Wood as it has better insulation value as compared to tiles or ceramics. However, the process of developing the floor has been described below.

1. For the bottom most layer we choose lightweight concrete as material because thermal mass is a property that enables building materials to absorb, store, and later release significant amounts of heat. Concrete and masonry have a specific energy saving capability due to their inherent thermal mass. These materials absorb energy slowly and hold it for much longer period of time as compared to other materials[52]. This delays and reduces heat transfer through a thermal mass building component resulting to three important factors:
   - There are fewer points in heating and cooling requirements as mass slows the response time and moderates indoor temperature fluctuations.
   - A massive building uses comparatively less energy as compared to a similar low mass building due to reduced heat transfer through the massive elements.
   - Thermal mass can shift the energy demand to off-peak time periods when utility rates are lower. For example, power plants are designed to provide power at peak load where shifting of the peak load can reduce the number of power plants required.

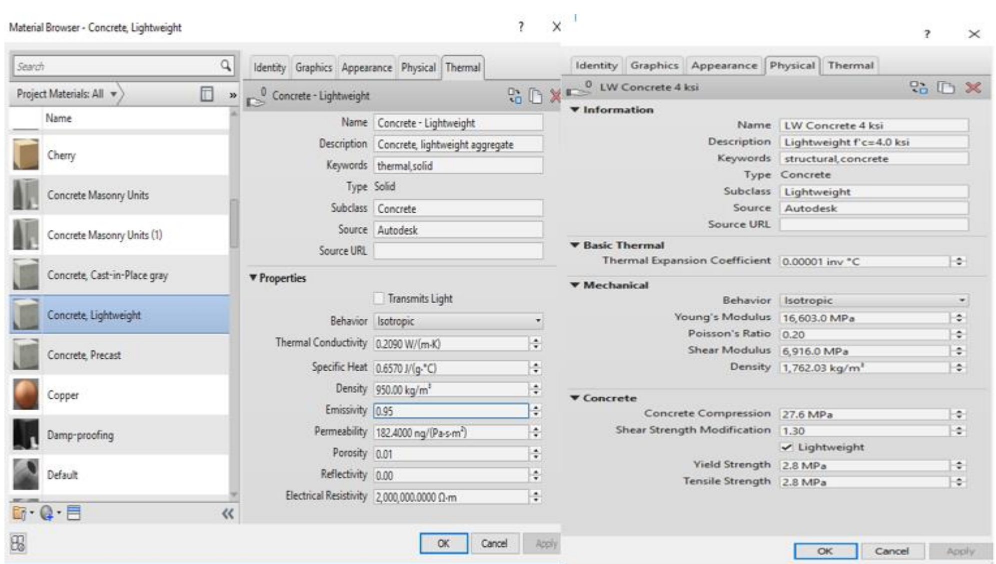

Figure 9 Thermal and Physical properties of Light Weight Concrete

2. On the top of concrete comes the layer of flexible adhesive. And the material used in this layer is **Polyurethane Based.** They are the most common flooring adhesives available in today's market. They are solid in form which doesn't evaporate into the air and instead form a solid structure between the bottom of the surface and top of the sub floor[53].

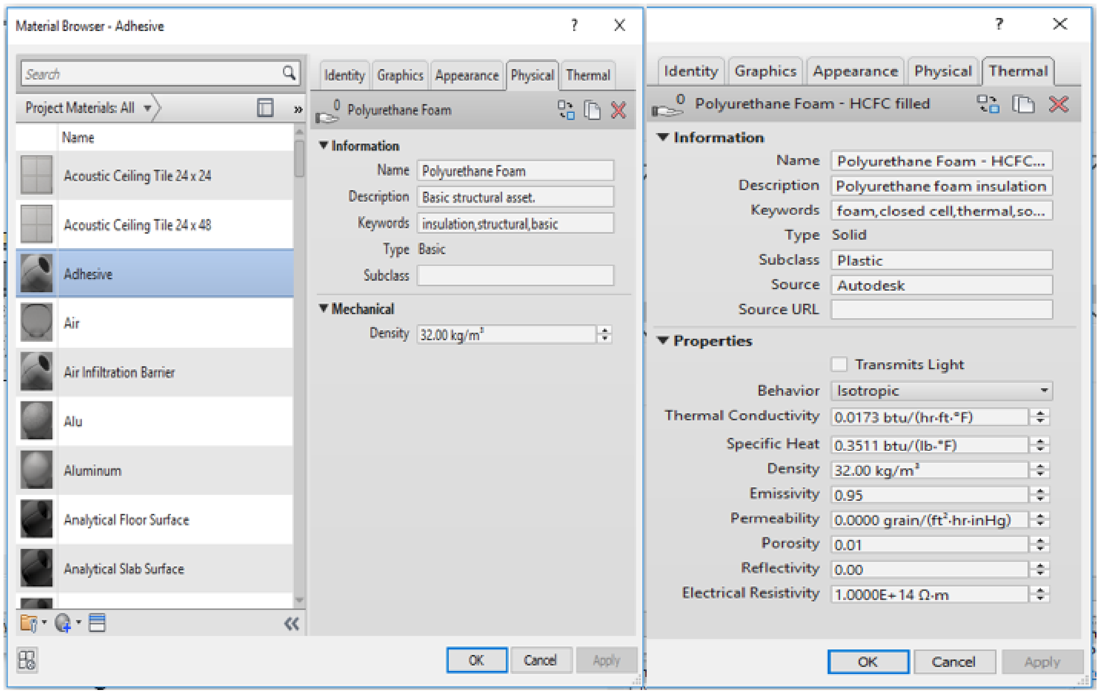

Figure 10 Physical and thermal properties of Polyurethane based adhesive

3. Then on top of the adhesive layer comes the layer of insulation. Now a wide range of insulation materials is available; however, few meet the requirements of modern construction. Selection of insulation material should be based on initial cost, effectiveness, durability, the adaptation of its form or shape to that of the installation methods available in each particular area. From an economic point of view, it may be better to choose an insulating material with a lower thermal conductivity rather than increase the thickness of the insulation in the walls. However, for the purpose of the development of this model, Polyurethane foam has been used as the insulation material. Polyurethane foam is effective as an insulator because it has a high proportion (90 percent minimum) of non-connected closed microcells, filled with inert gas. The main ways polyurethane foams can be applied and used are as rigid boards/ slabs and pre-formed pipes, which can be manufactured in various shapes and sizes [54].

4. On top of this layer comes another layer of adhesive. The material used for this layer is Polyurethane and its physical and thermal properties are mentioned above.

5. Lastly, for the finishing, we use softwood because Wood, bamboo, cork and linoleum flooring have a better insulation value than stone or ceramics or other types of tile flooring. This, in turn, can help in controlling thermal gain or loss which can be advantageous in some heating or cooling strategies [55].

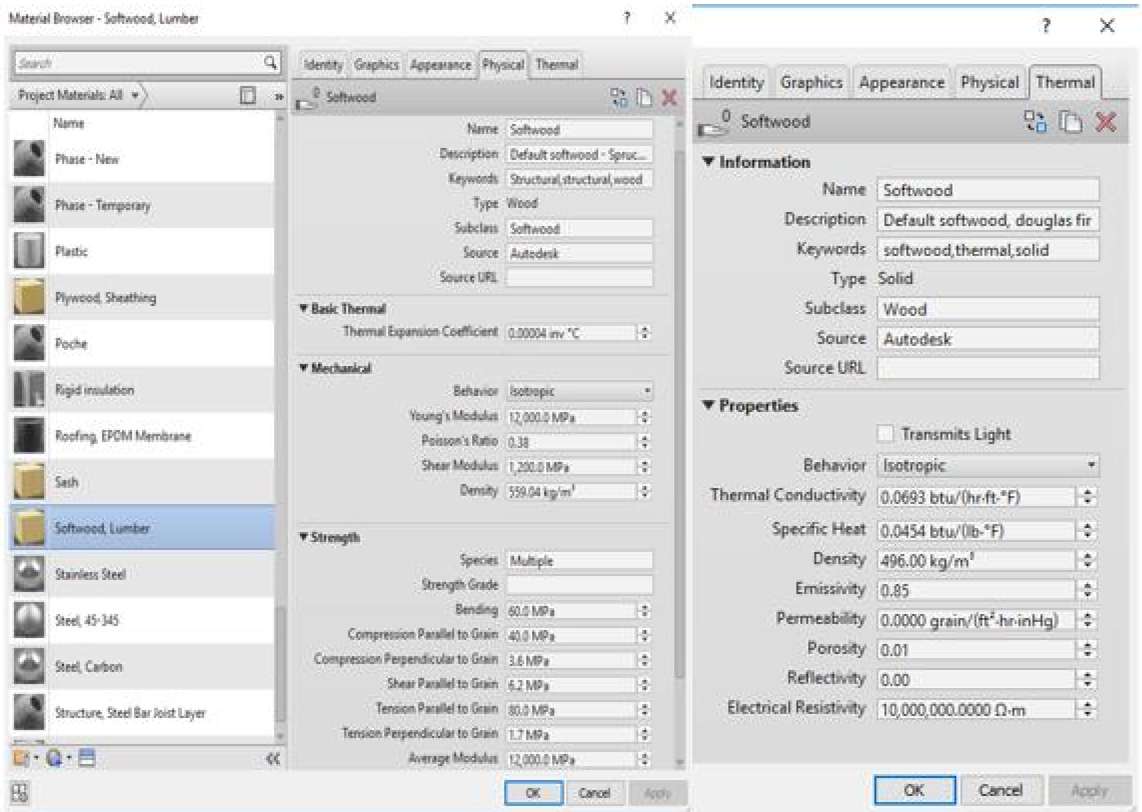

Figure 11 Physical and Thermal properties of Softwood

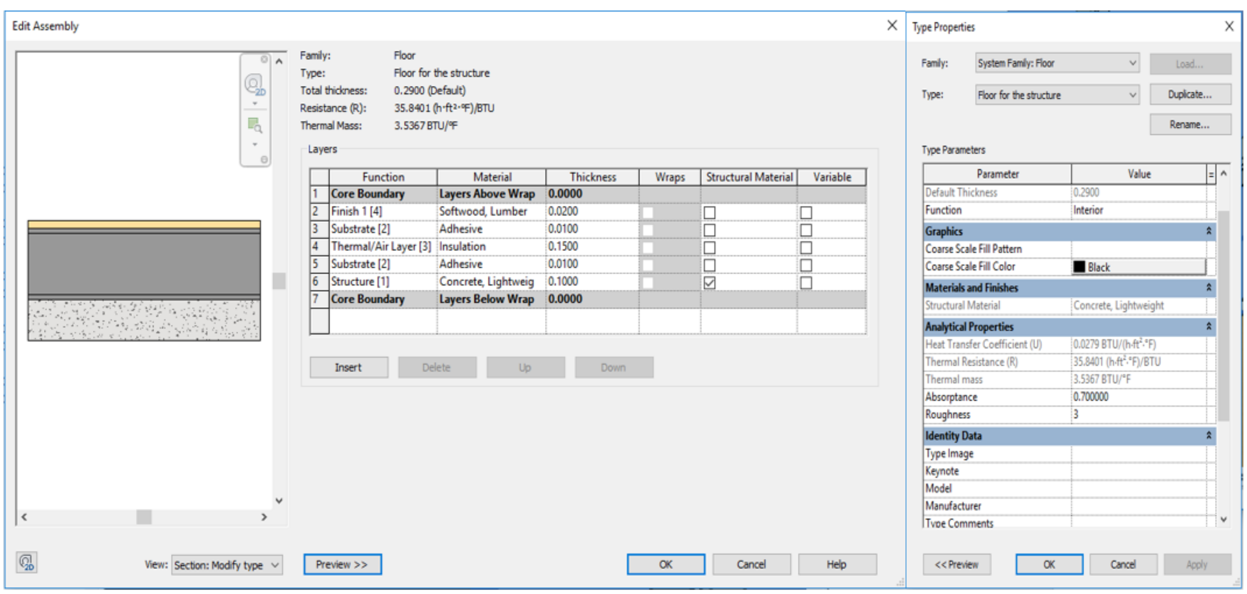

Figure 12 Detailed assembly of Flooring

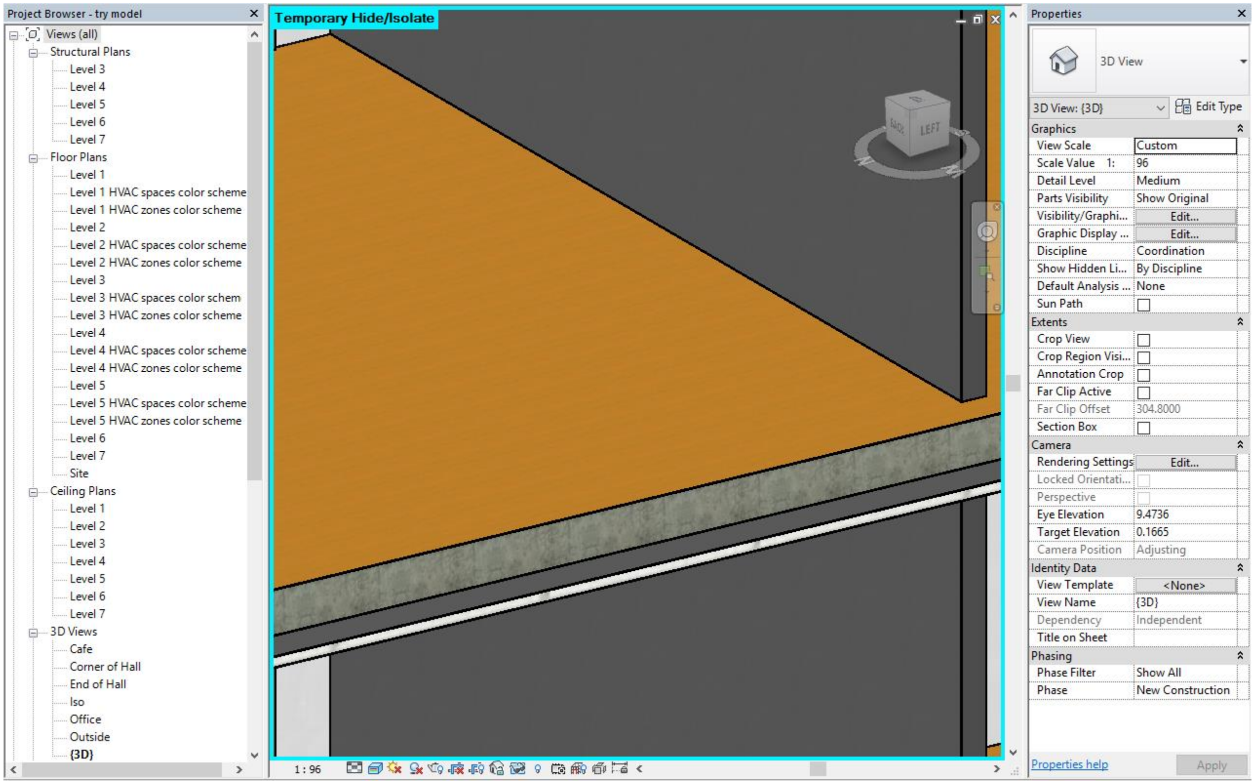

Figure 13 Floor Finish

3.4.2 Construction of Walls

The system of wall system has been divided into three parts. Three ad-joint facades are made of a thick insulated wall faced with brick slips, the east facade is made of an exterior glazing curtain wall and also comprises of the interior walls.

- **Exterior Walls:** For the purpose of exterior walls, a thick coat of (EPS) external wall insulation facade system which is faced with brick slips or ceramic tiles is used. This combination offers a greater degree of impact resistance. The exterior wall is comprised of six different layers of materials which are stated below

    1. The base layer is comprised of solid concrete. As discussed above Concrete and masonry has a specific energy saving capability due to their inherent thermal mass. These materials absorb energy slowly and hold it for much longer period of time as compared to other materials.

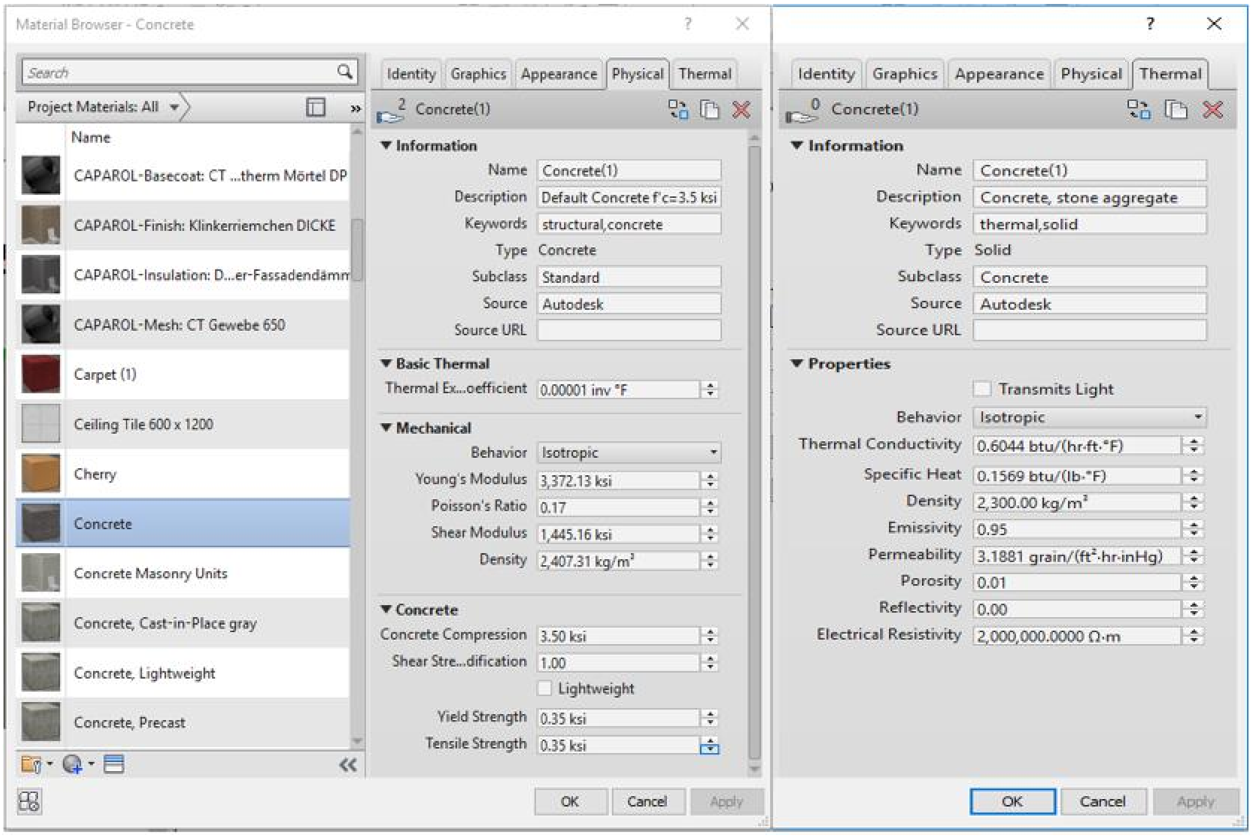

Figure 14 Physical and Thermal properties of Concrete

2. On top of the solid concrete layer comes another layer of adhesive. And as discussed above the material used in this layer is **Polyurethane Based** as they are the most common flooring adhesives available in today's market. They are solid in form which doesn't evaporate into the air. The physical and the thermal properties are stated above.

3. Then on top of the adhesive layer comes a thick layer of insulation. The thickness of this layer is 4cm. For the purpose of usage in this wall Expanded Polystyrene-based (EPS) insulation. The low stable thermal conductivity of EPS is the use for its important use in reducing CO_2 emissions from buildings. Other properties like compressive or tensile strength can be declared at a variety of levels independently of each other [56].

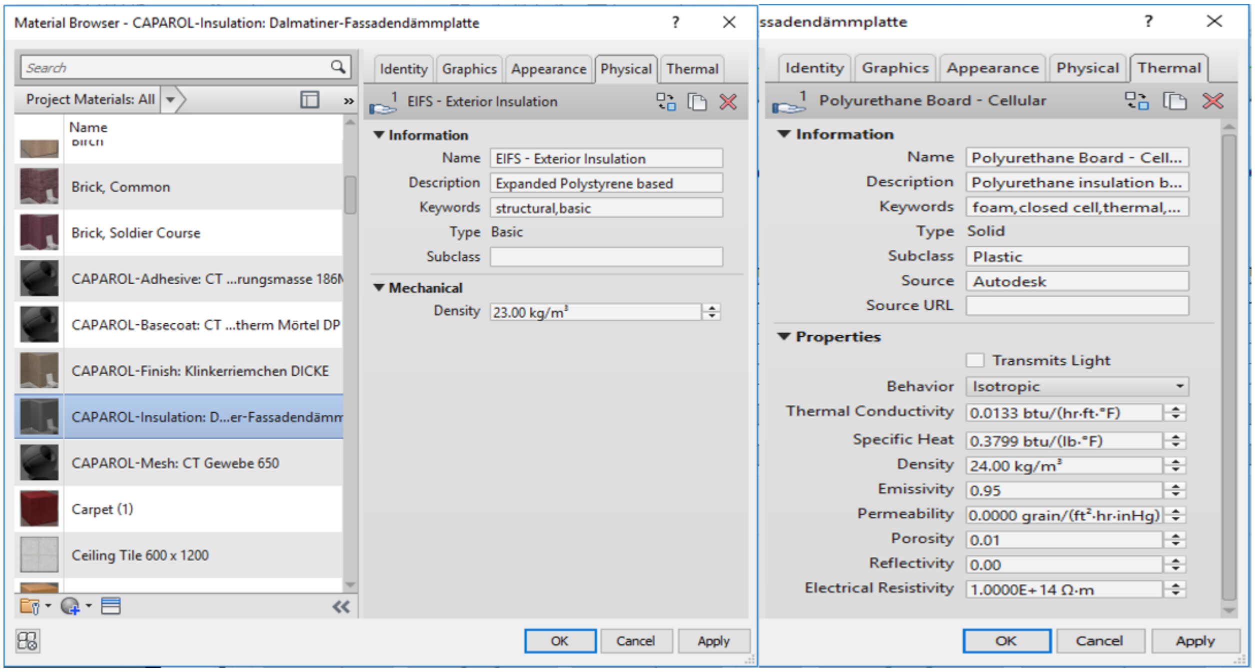

Figure 15 Physical and Thermal properties of EPS Insulation

4. Over the layer of insulation comes a very thin membrane layer of basecoat. This is a carbon filler organic base coat. It is a ready to use base coat which is highly impact resistant and also possess the property of excellent workability as well as weather proof criteria.

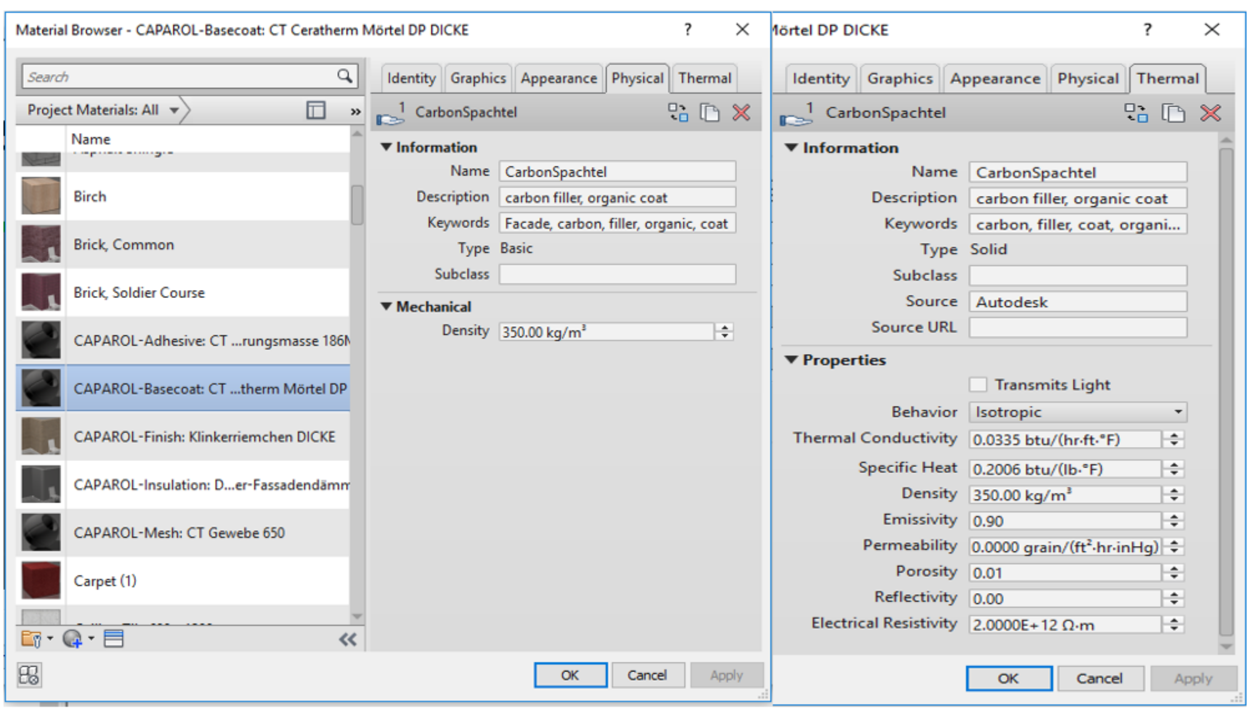

Figure 16 Physical and Thermal properties of CarbonSpachtel Basecoat

5. On top of the layer of the base coat comes the final finish of the brick layer. The physical and the thermal properties of the brick layer are shown below.

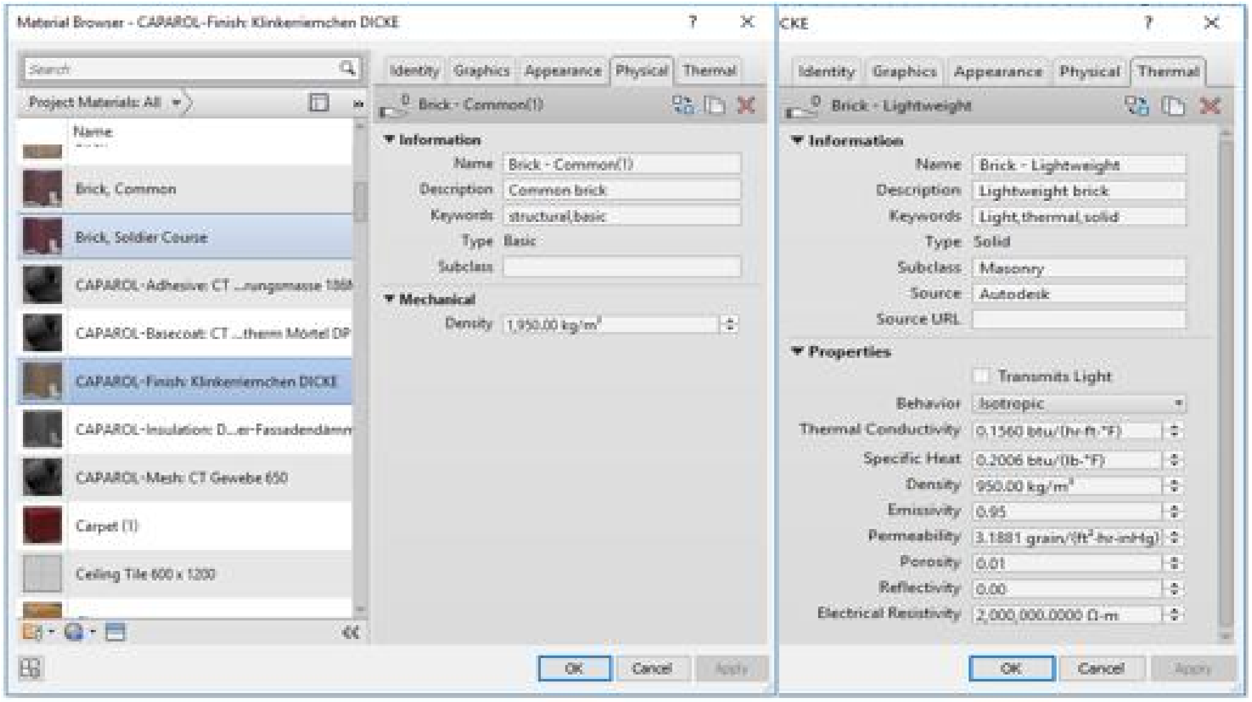

Figure 17 Physical and Thermal Properties of Brick Layer

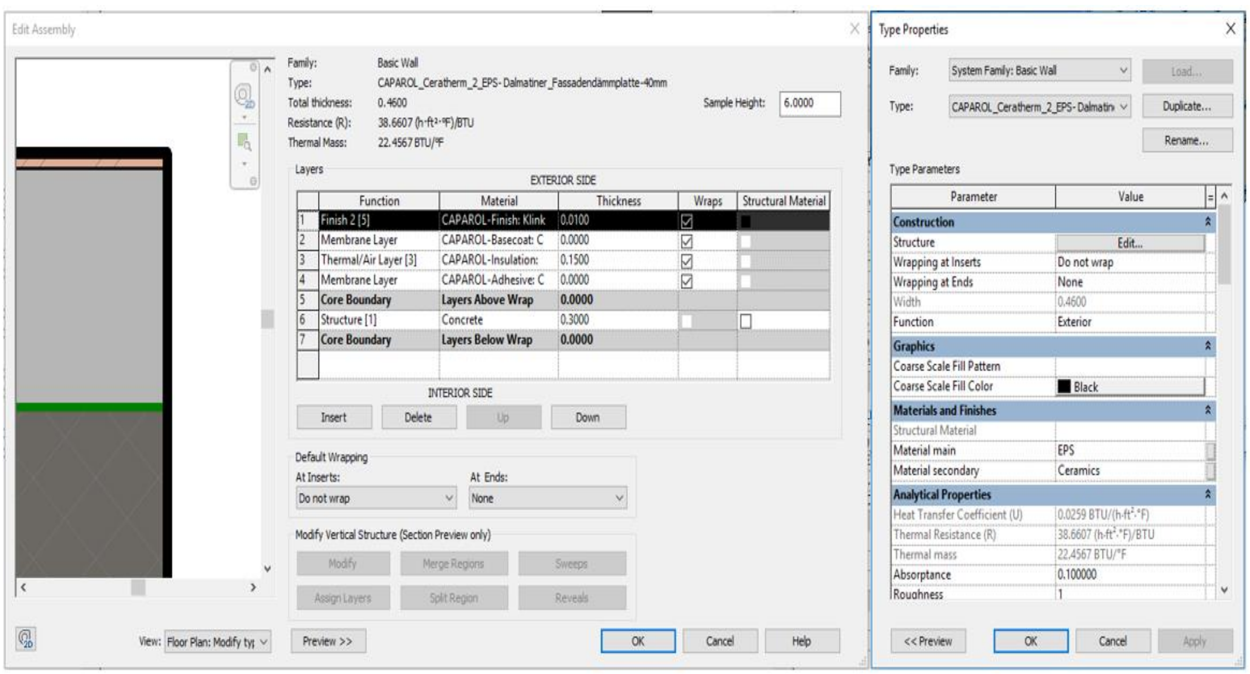

Figure 18 Exterior Wall System Layer wise

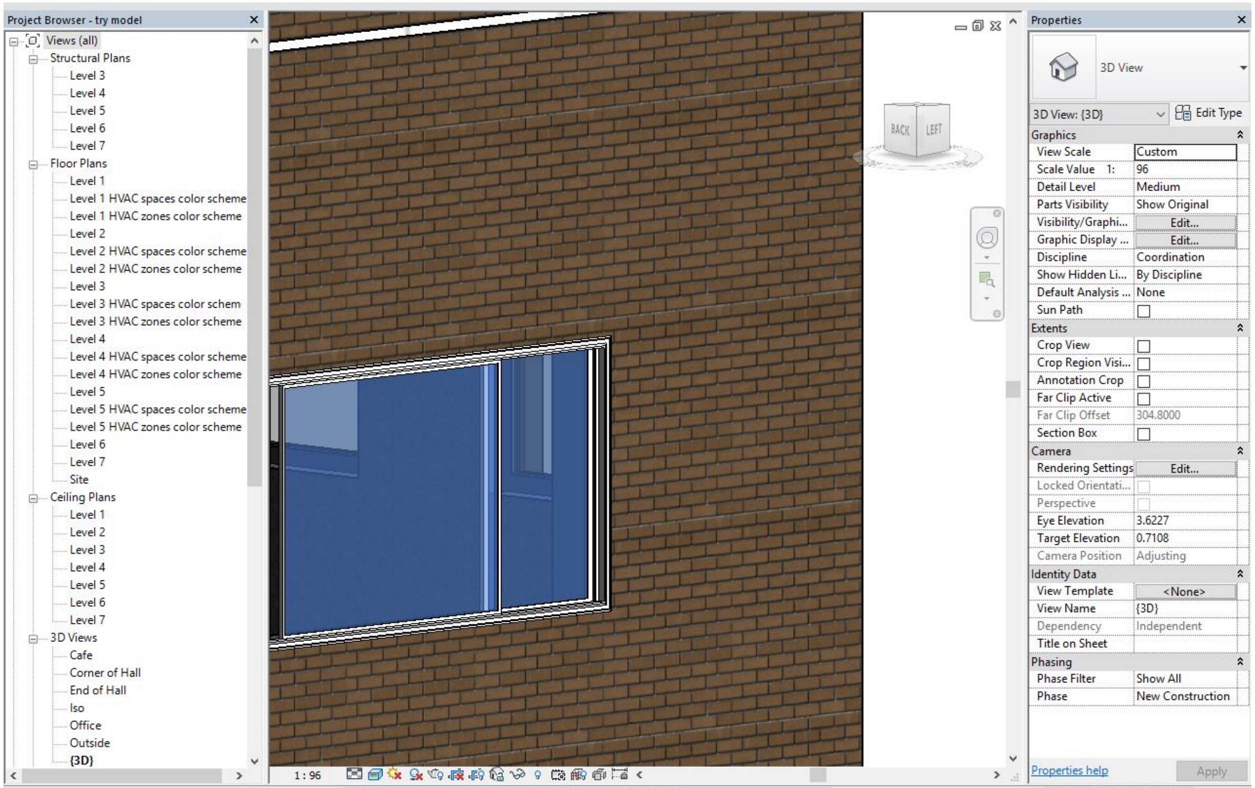

Figure 19 Exterior Wall Finish

- **Curtain Wall System:** The east facade of the building is made up of the exterior glazing curtain wall. The purpose behind the construction of the glazed curtain wall is that a part of the structure should also be capable of repelling the heat during the daytime. The exterior glazing curtain wall plays a very important role in controlling the overheating of the structure. They are glass and aluminum non-load bearing structures which offer multiple benefits to multistory buildings [57]. To name some of the benefits are:
    1. Natural light is one of the big benefits which is often a selling point for property management. The benefits to workers are that natural light is easier on eyes and shows true colors.
    2. Due to the way that the glass blocks fit their aluminum frame, they provide an air tight fit which helps to seal the building so that warm air is not lost during the winter and also during the hotter months' cool air is kept inside too.
    3. Energy efficient glass also helps to reflect the ultraviolet radiations so that the building doesn't become an oven during the summers. The energy efficiency of the curtain walls helps to keep the cost of building operations as low as possible.
    4. The sealant used during installation acts as a moisture proof barrier which offers a durable prevention from water damage. It also helps in resisting corrosion [58].

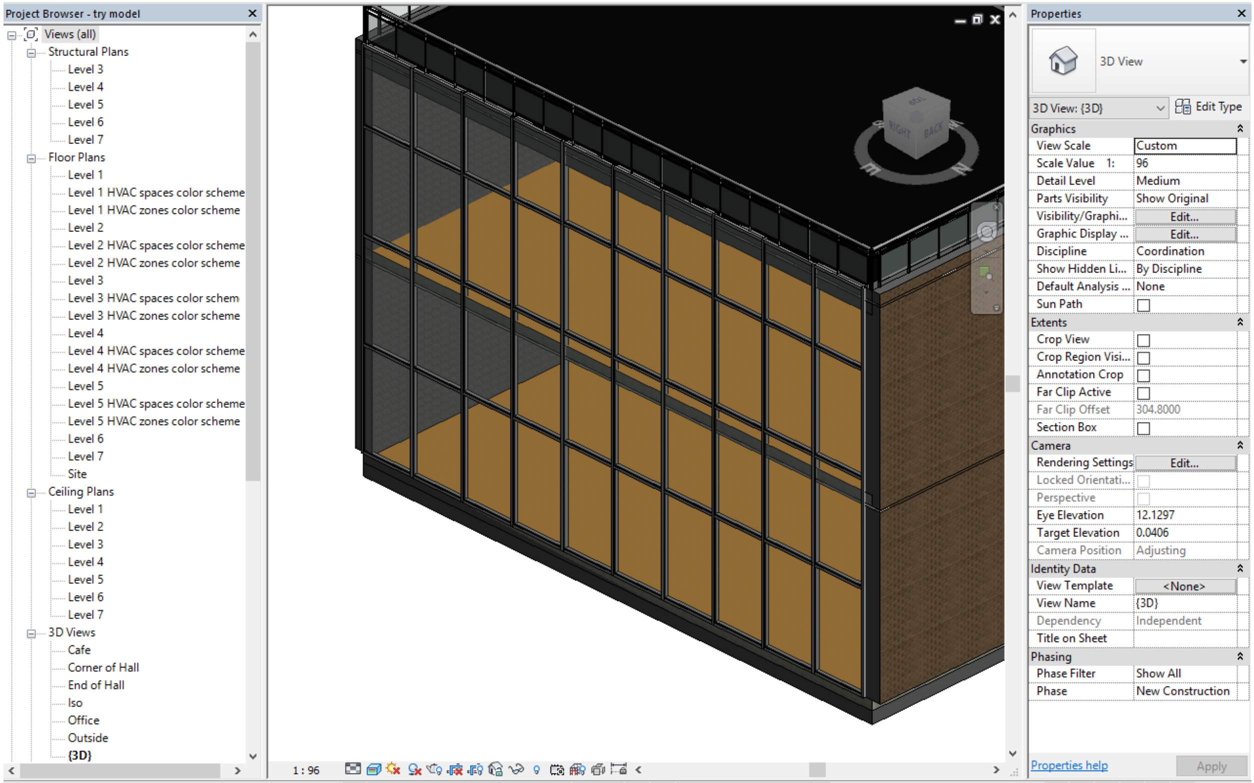

Figure 20 Curtain Wall in the East Facade

- **Internal Wall**: For the purpose of the construction of internal wall a basic partition wall system has been chosen which is comprised of metal stud layer as the core boundary and gypsum board finish on both the sides. The importance of the metal stud layer falls on the zone of internal load bearing applications it is designed to support the vertical loadings. The gypsum board finish is one of the most commonly used material in commercial and residential buildings. It provides better finish proper impact resistance as well as fire resistance. The physical and the thermal properties of the metal stud layer and the gypsum board are shown below.

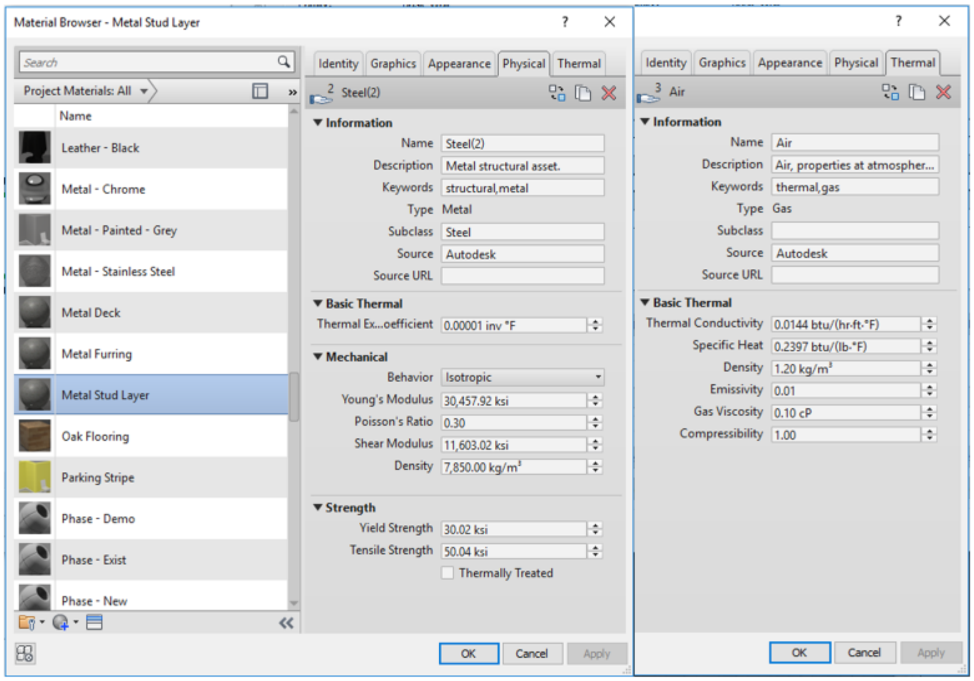

Figure 21 Physical and Thermal Properties of Metal Stud Layer

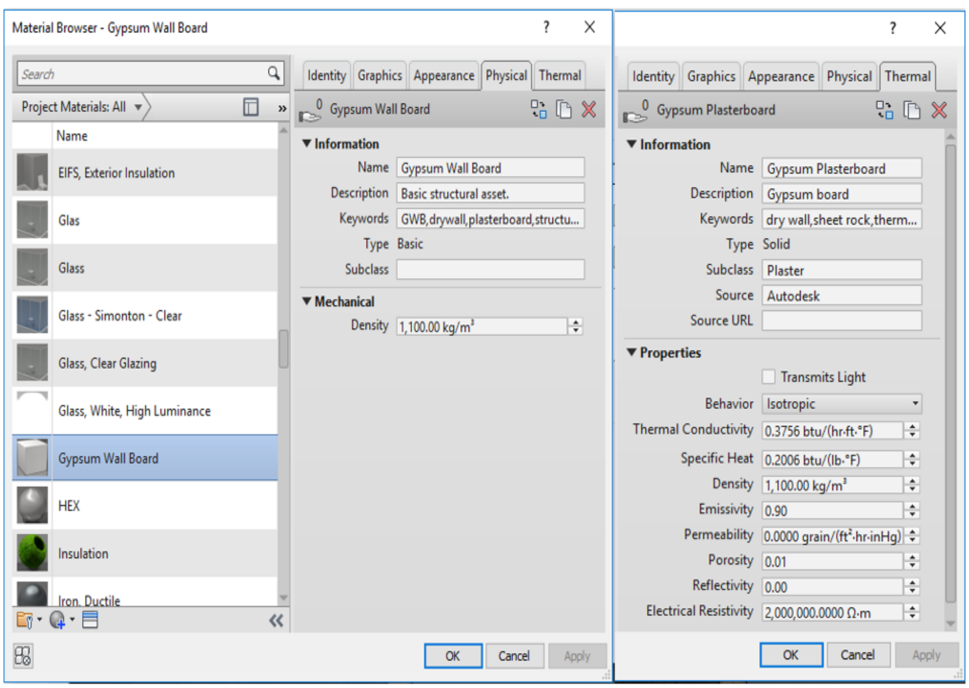

Figure 22 Physical and Thermal Properties of Gypsum Wall Board

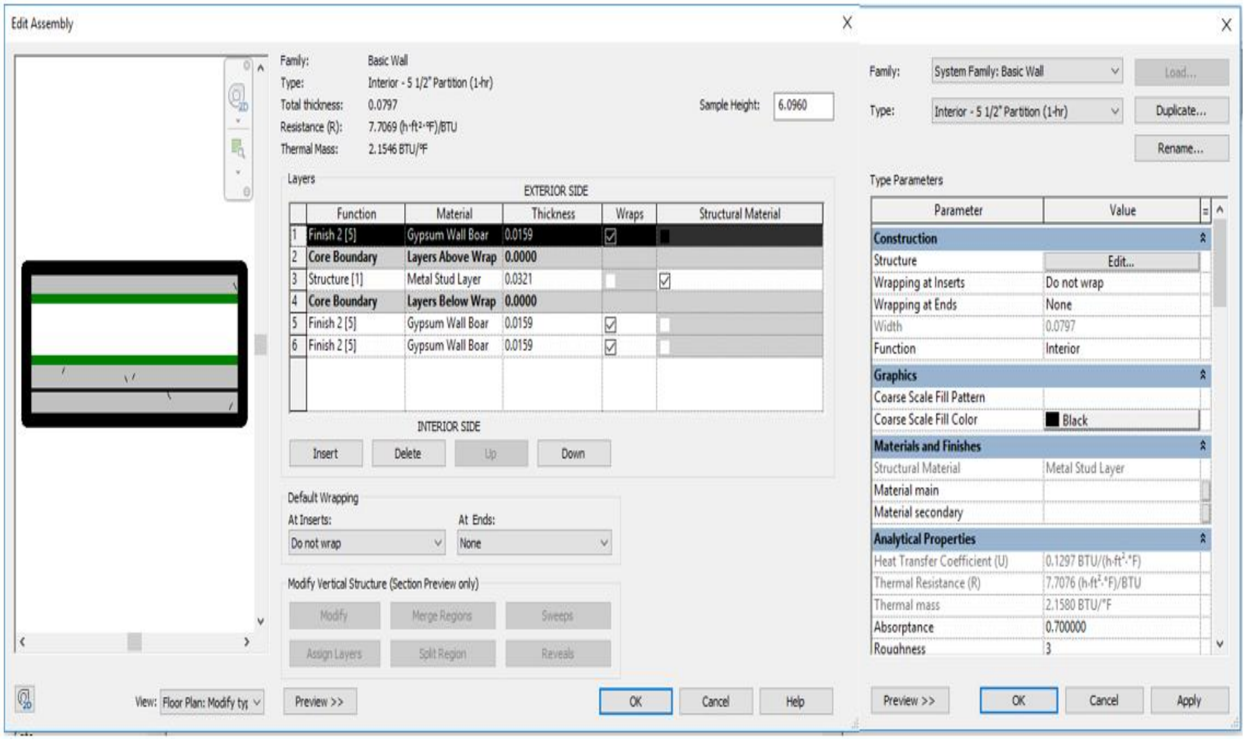

Figure 23 Internal Wall system Layerwise

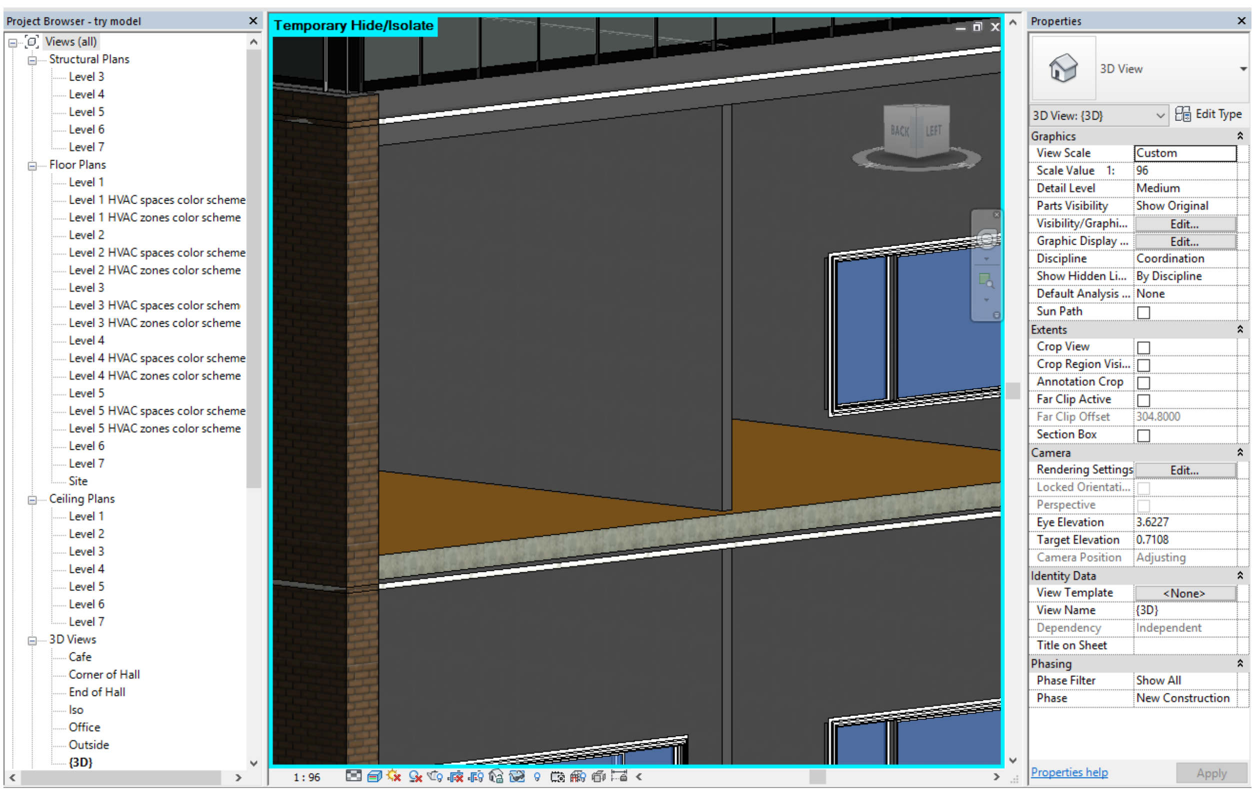

Figure 24 Internal Wall Finish

3.4.3 Construction of the Ceiling

For the purpose of the construction of ceiling, a simple ceiling system has been modeled. It is an acoustic ceiling system which is proven to be an integral factor of indoor environment quality. It enhances the functionality of any space relative to its design usage. Acoustic ceilings have a significant effect on the noise level and reverberation within a space. A combination of sound absorption, sound attenuation and background noise will combine to determine the acoustic performance of the space [59]. This system comprises a layer of gypsum wallboard as the main material and the acoustic ceiling tiles attached to the gypsum wallboard. The physical and the thermal properties of the gypsum wallboard is same as mentioned before. But the detailed physical and the thermal properties of the acoustic ceiling tile is mentioned below.

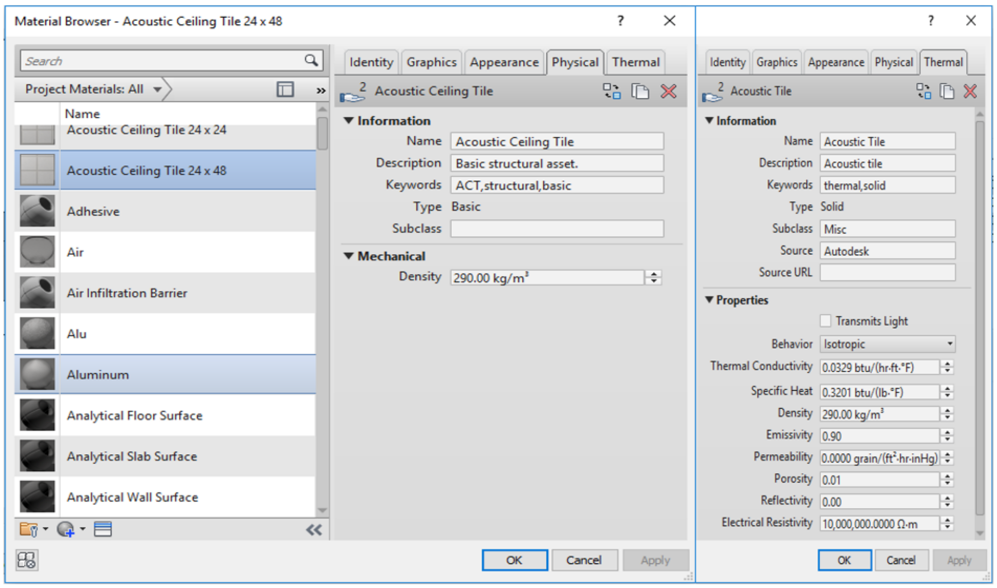

Figure 25 Physical and Thermal Properties of Acoustic Ceiling Tile

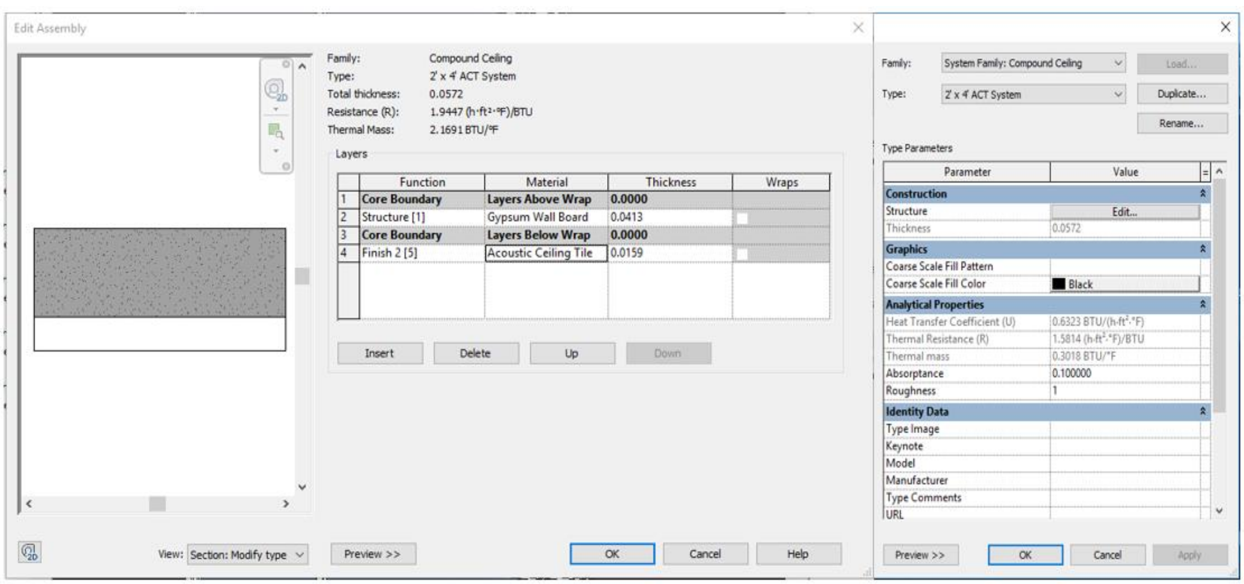

Figure 26 Acoustic Ceiling System Layer wise

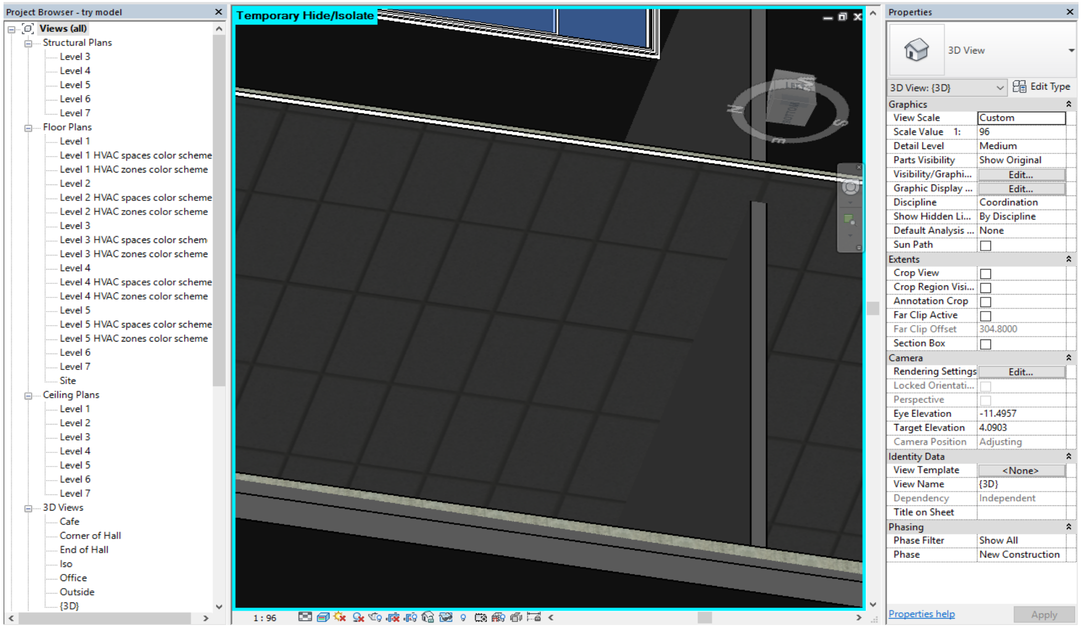

Figure 27 Finished Acoustic Ceiling

3.4.4 Construction of the Roof

For the roofing of this structure, the concept of the cool roof has been adopted and various measures have been taken to make it energy efficient. A cool roof is one that strongly reflects sunlight and also cools itself by efficiently emitting radiation to its surroundings. The roof literally stays cooler and reduces the amount of heat conducted to the building below. If a builder does not have air conditioning, this keeps the building cooler and a more constant temperature. However, it is not necessary to for a cool roof to be white as there are many cool color products which use darker colored pigments and are highly reflective. The two basic characteristics that determine the coolness of a roof are solar reflectance (SR) and thermal emittance (TE). Both properties are rated on a scale from 0 to 1 where 1 is the most reflective [60].

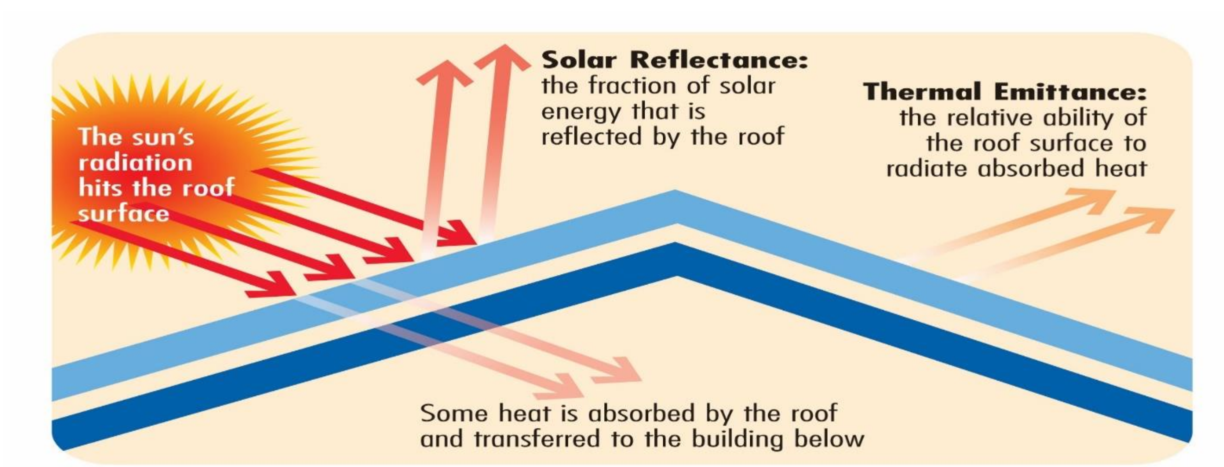

Figure 28 Roof and its Nature [61]

The roofing system used for the purpose of this project are divided into three main layers namely the rigid metal structure with an insulation layer of Polystyrene foam and topped with a finish of EPDM membrane. The physical and the thermal properties of the Polystyrene foam and EPDM membrane are shown below.

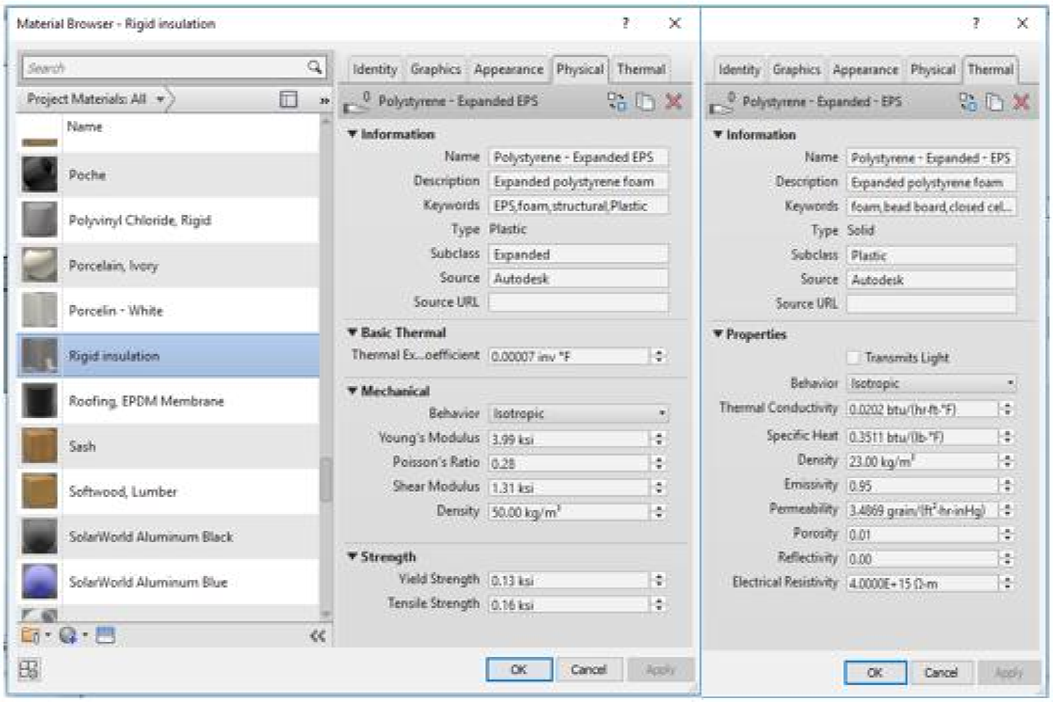

Figure 29 Physical and Thermal Properties of Polystyrene Foam

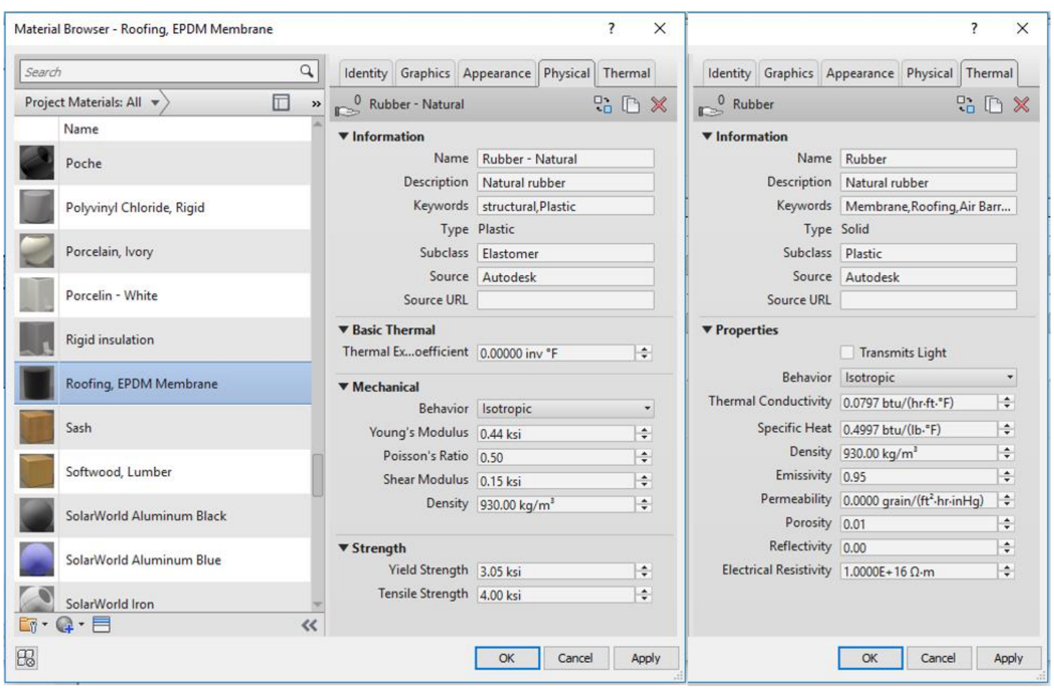

Figure 30 physical and thermal properties of EPBD Membrane

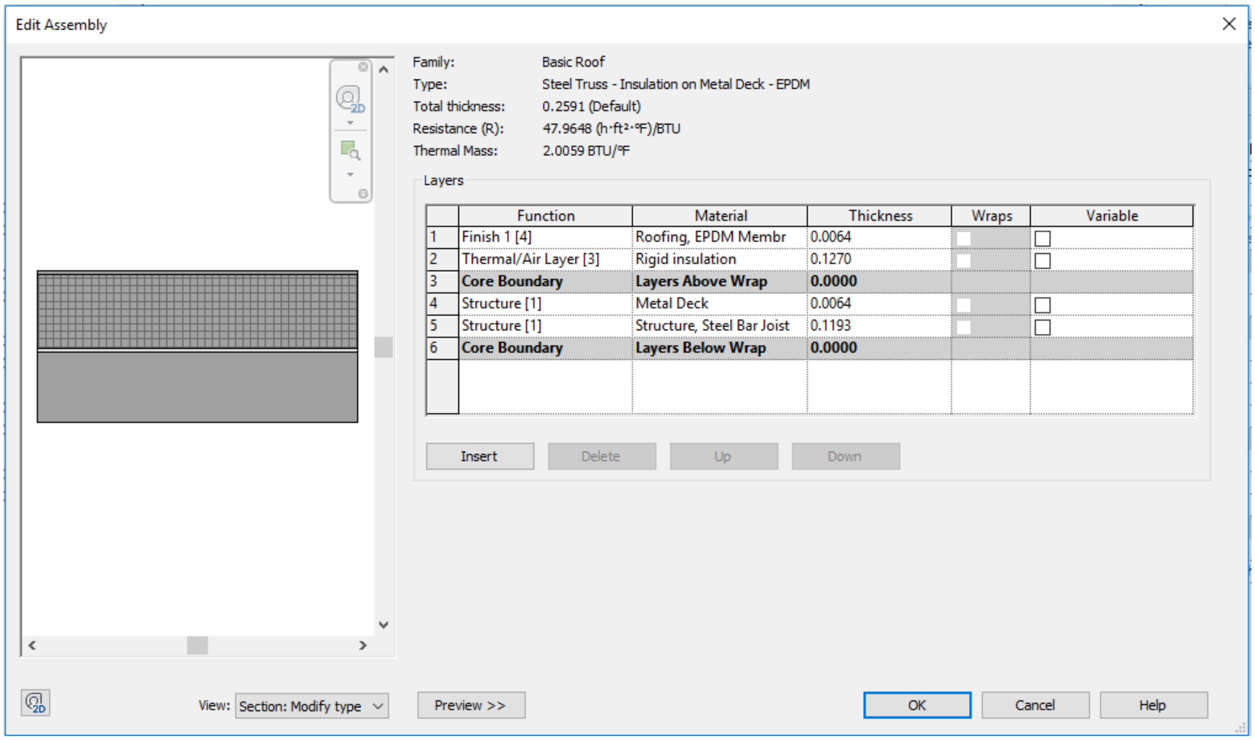

Figure 31 Roofing System Layerwise

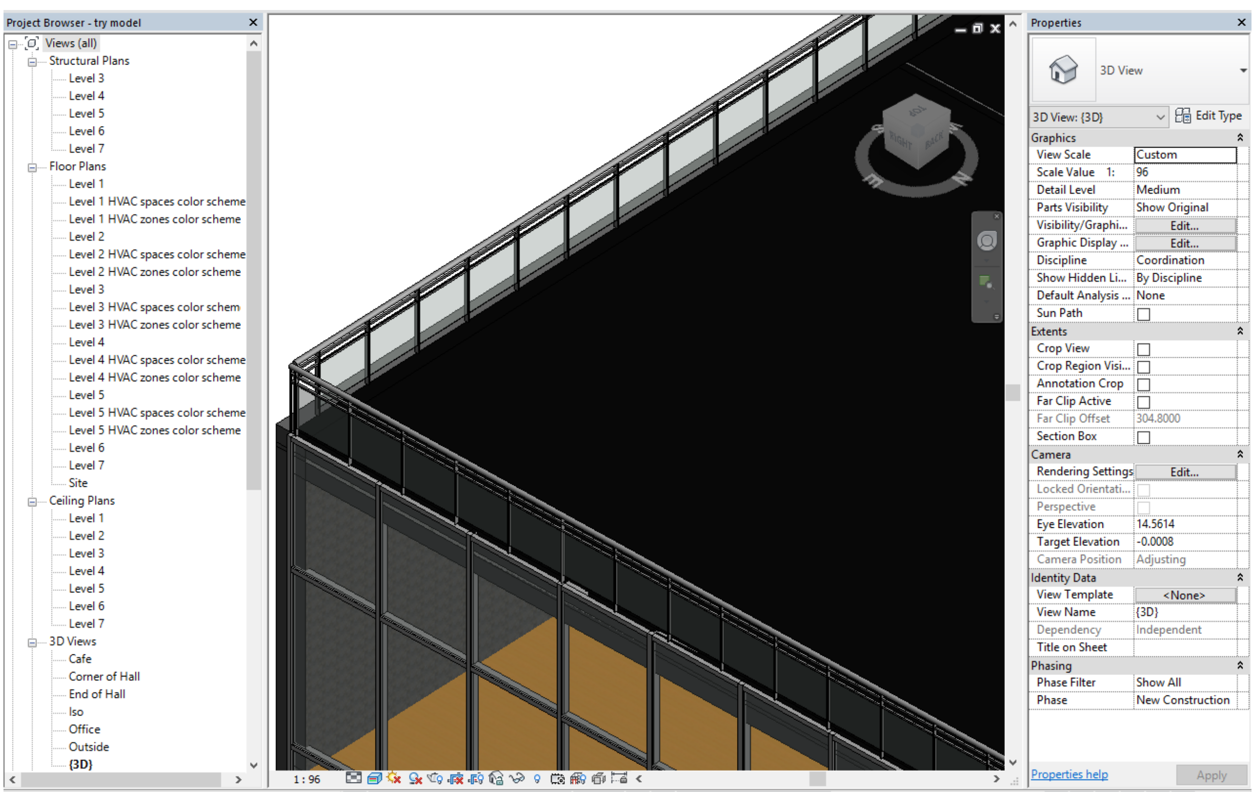

Figure 32 Roof Finish

3.4.5 Windows and Doors

Figure 34 Window System

Windows and doors provide our home with light, warmth and ventilation. But they can also negatively impact a home's energy efficiency. We can reduce the energy cost by installing the energy efficient doors and windows in our home. The energy efficiency of windows and doors are dependent upon all of its components. The frames conduct heat contributing to its overall energy efficiency particularly the U-factor. Glazing and glass technologies have become very sophisticated and designers often specify different types of glazing for different types of doors and windows based on orientation, climate, building design etc. For the purpose of our project highly thermally insulated aluminum door and window system have been chosen [62]. The analytical properties of the door and the window system are shown below.

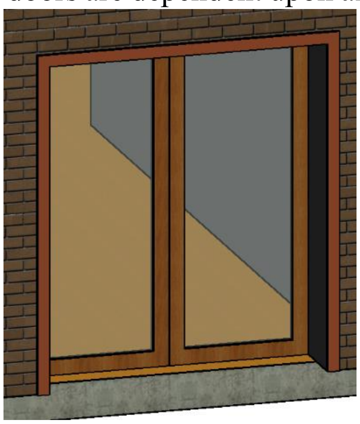

Figure 33 Door System

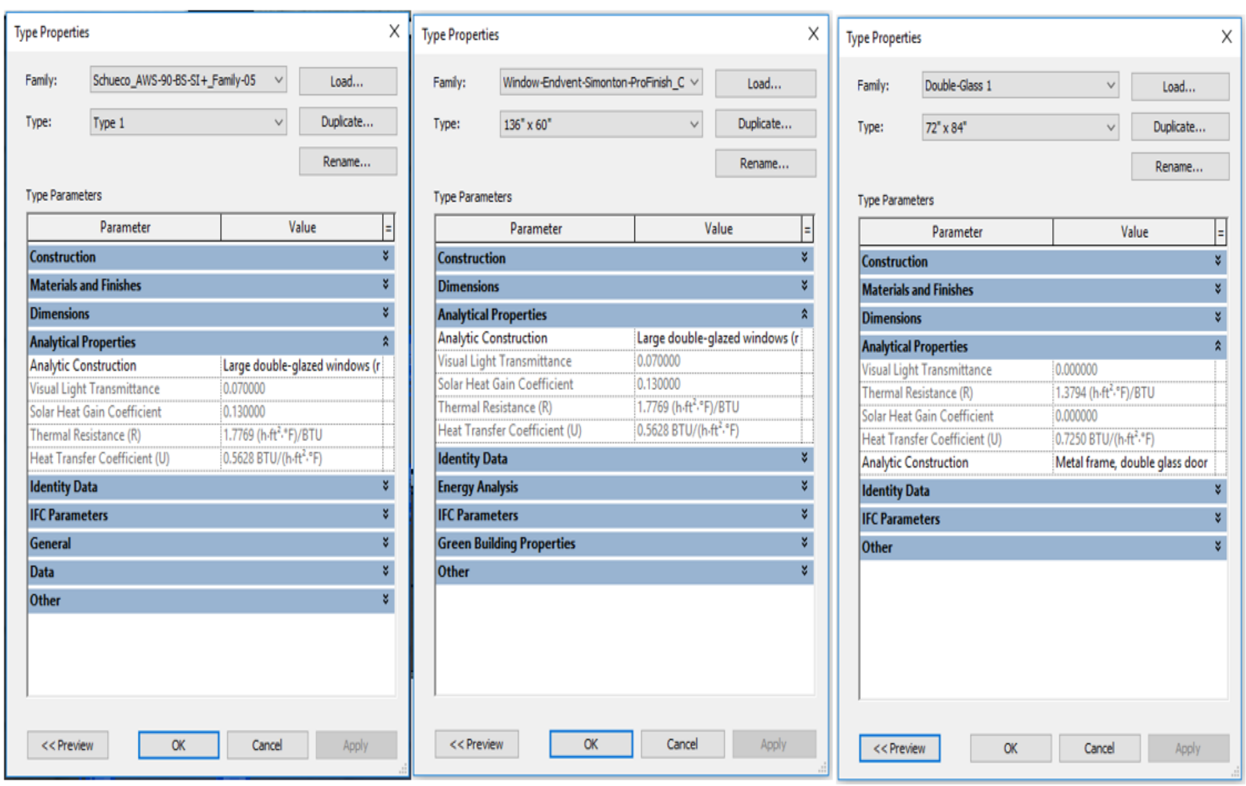

Figure 35 Analytical properties of Windows and Doors

3.4.6 Zoning of the building

When we are preparing the building model for energy analysis, thermal zoning of the building is performed to improve the accuracy of the energy simulations. It consists of groups of core zones with little or no exterior exposure. The core of a building doesn't get exposed to the variations in heat gains and losses experienced by perimeter zones. The core's heating and cooling loads differ from those for the perimeter of the building. Thermal zoning accounts for these differences in energy simulations. The zoning pattern of the building model used for this project is shown below. The zoning is performed separately for different floors [63].

Figure 36 Thermal Zones for First and Second Floor

3.4.7 Finished Building Model

This representative virtual building model is prepared in accordance with the "Energy efficiency requirements in building codes, energy efficiency policies for new buildings" published by International Energy Agency and written by Mr. Jens Laustsen [6] and also a validated building model situated in Berlin [51] for the analysis of energy consumption for heating / cooling for a typical multi-story office building, which might be placed in different locations in the world. This model is not necessarily a complete building, but it has the relevant functionalities of a real building. Lastly, a few glimpses of the finished building model are shown below.

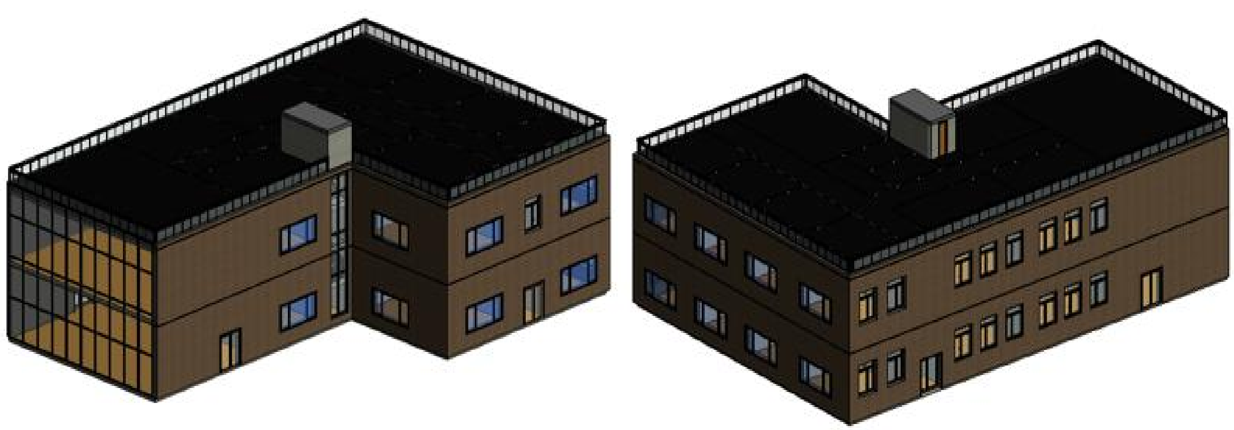

Figure 37 Outside 3D view of Building Model

Figure 38 Different views of the Building Model

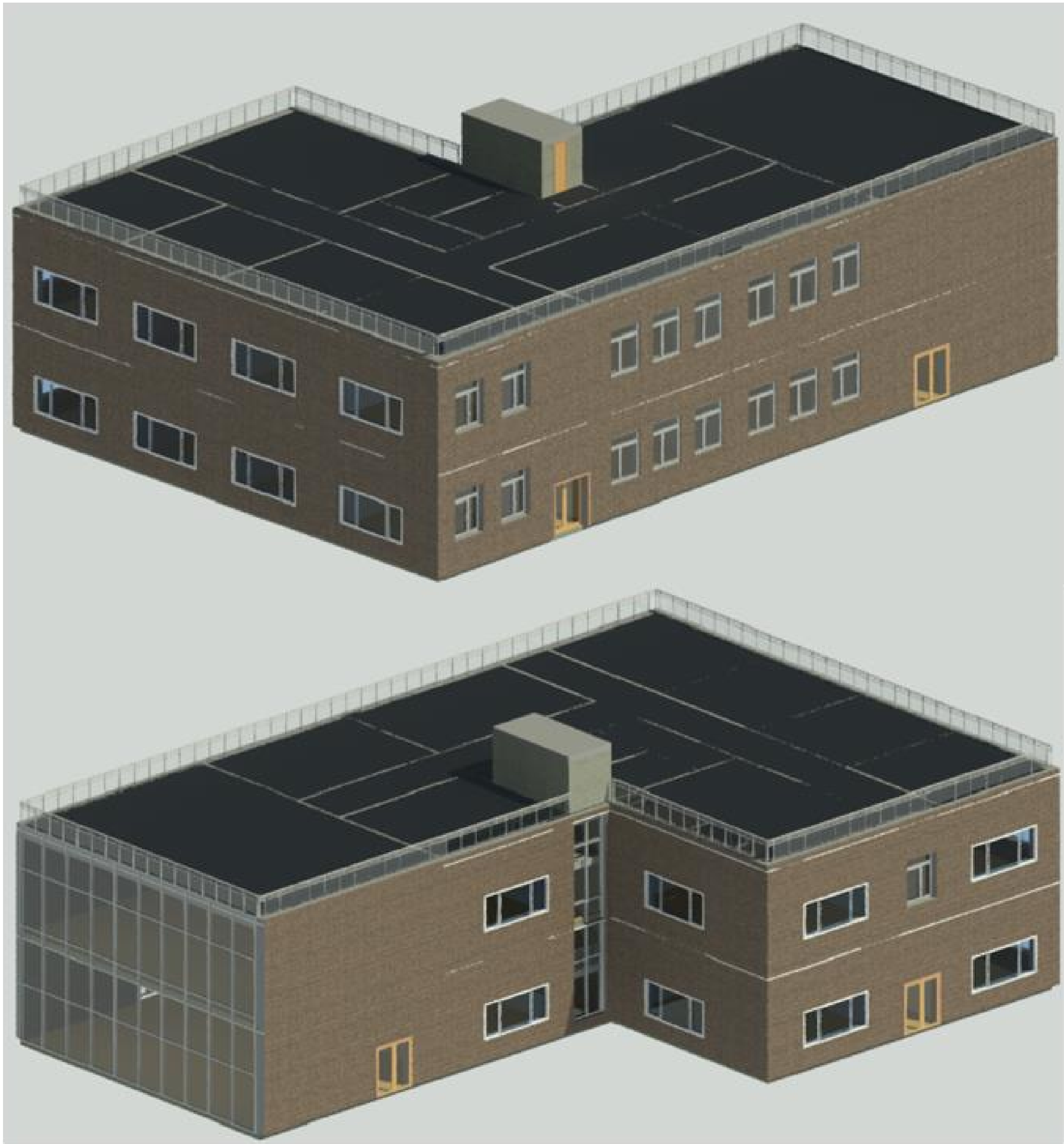

Figure 39 Rendered 3D image of the Building Model

Chapter 4: Differentiation of work environments in respected climate zones according to time periods without and with energy consumption.

4.1 Introduction

In trend with the recent development in the sphere of industrialization and modernization, the construction industry ingrained its role for the welfare and development of the society. Especially the commercial building sector has grabbed all the attention of governmental energy reduction initiatives to achieve the sustainability. A lot of researches have been performed for the evaluation of the sensitivity of the model to the buildings' technical design but very few studies related itself to the parameters relating to the energy consumption or energy modeling. Thus since the last two or three decades, the alarming situations (like depletion of natural energy resources, global warming, etc.) have brought forward the initiative to study and work towards achieving a sustainable development. This tends towards achieving more energy efficiency and lowering the energy consumption which affects the environment surrounding us [64]. The main objective of this task is to have a better insight on the work environments of some famous cities across the globe which fall under distinct climatic zones so that a proper picture of the impact of the environment on the buildings located in the specified cities can be inferred. This chapter has been divided under seven following sections namely,

1. Work Environment of Delhi.
2. Work Environment of Mumbai.
3. Work Environment of Berlin.
4. Work Environment of Lisbon.
5. Work Environment of Copenhagen.
6. Work Environment of Dubai.
7. Work Environment of Montreal.

All the cities specified above have different climatic conditions varying from extremely hot and humid to extreme cold. In this chapter the work environment of the above-specified cities has been discussed in detail. And for the purpose of this study, the weather data for the specified cities have been retrieved from the world wide web [65, 66] and then calculated and the necessary data have been plotted. All weather data are collected for the year 2015 to keep relevance with the weather data used for the office building model. The latest weather data available for the purpose of energy modeling is of the year 2015. The numbers and the plotted graphs will help us to attain a better place in understanding the impact of the environment on the buildings and vice versa so that necessary steps can be taken to help saving and consuming more energy.

4.2 Work Environments of Delhi

4.2.1 Introduction

Delhi, the capital city of India is regarded as the "Heart of the Nation". The city is popular for its enriched culture and heritage. The capital is divided into two sections namely "Old Delhi" and "New Delhi". When we talk about the climate of Delhi, it is evident that Delhi has an extreme climate. Actually, the climate of Delhi is a lapping between humid subtropical and semi-arid climate with a distinct variation between summer and winter temperatures and precipitation. Delhi's climate is greatly influenced by its contiguity to "The Himalayas" and "The Thar Desert", due to which it experiences both weather extremes. Delhi witnesses five distinct seasons namely Summer, Monsoon, Autumn, Winter and Spring [67].

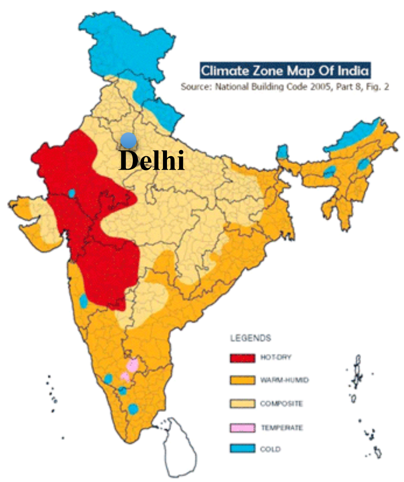

Figure 41 Climate Zonal Map of India showing Delhi

Summer in Delhi: Summer begins in early April and lasts until June. During these months the temperature reaches its scorching level. May is the hottest month. This period of time is categorized with extreme heat, low humidity, very hot winds and thunderstorms. Hot, dry continental winds called "Loo" blow across the plane during this time which makes the days feel hotter. Since the "Western Disturbance" moves eastward, there is hardly any moisture content in the air to increase the humidity. The day temperatures during this period of time vary from 35°C to 45°C whereas the temperature in nights remains in the zone of 20°C to 30°C. Thunderstorms and Dust storms get destructive when accompanied by strong winds. But however, towards the end of June, the level of humidity in the air shows a rise with the fall in temperature levels [67]

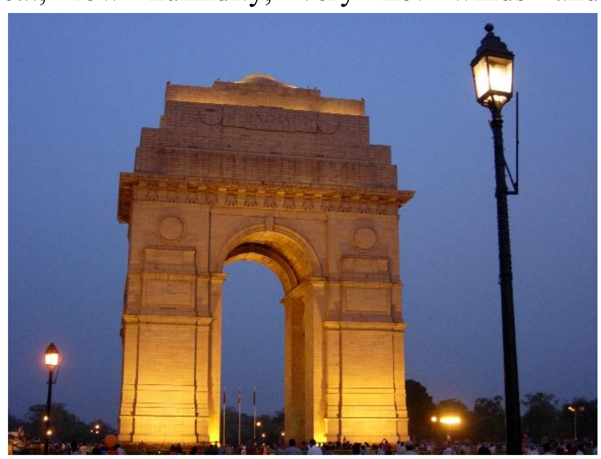

Figure 40 Gateway of India

Monsoon in Delhi: The moisture laden southwestern winds or commonly known as the "Monsoon Winds" arrive in Delhi by the beginning of July at most. This is the time when the season is attributed to high levels of humidity and heat. The temperatures in this period of time lie below 40°C whereas the humidity soars high which makes this weather particularly uncomfortable. August is the wettest month in Delhi. Dense cloudy sky with heavy rainfall is predominant during this time. By September the frequency of precipitation drops along with the humidity in the air and by the beginning of October this season comes to an end [67].

Autumn in Delhi: With the end of Monsoon, the city embraces the arrival of Autumn. It arrives by the mid of October at most. This period signifies dry ambiance, warm days and pleasant nights. The maximum temperature during this period remains below 30°C. The minimum temperature during this time drops below 15°C and the wind direction changes from South-West to North-

West. By the late Autumn or the early winter, the variation between the morning and the afternoon temperatures are considerable with the day temperatures can be more than 20℃ at times with the minimum temperature dropping below 10℃ [67].

Winter in Delhi: Winter in Delhi arrives by the beginning of December at most. The minimum temperatures during this period of time reach the single digits for the maximum number of days. Though it is not cold initially but by the late of December the temperature shows a sudden fall and it becomes chilly as the North-Western winds from the Himalayas flow across the Northern plains. The maximum temperature during this period of time remains below 10℃. By early January, the winter peaks in Delhi which bring down the temperature close to 0℃ and even goes to negative temperature rarely. During this time the city of Delhi witnesses frost but snow is an impossibility for Delhi as the winter is very dry and the northern icy winds rush from the Himalayas under a clear sky. Dense fog happens to be a common mark in the winter which cuts the sunlight and makes the days feel colder. Though by the end of January the city sees a very gradual rise in temperature, the rise is contained by cold North-Western winds which happen due to the heavy snowfall in the northern Himalayas. Due to this reason Delhi witnesses' normal rainfall along with hailstorm during the late January. The winter comes to an end by the mid-February with the maximum day temperatures crossing the limit of 20℃ and minimum temperature rising above 15℃ [67].

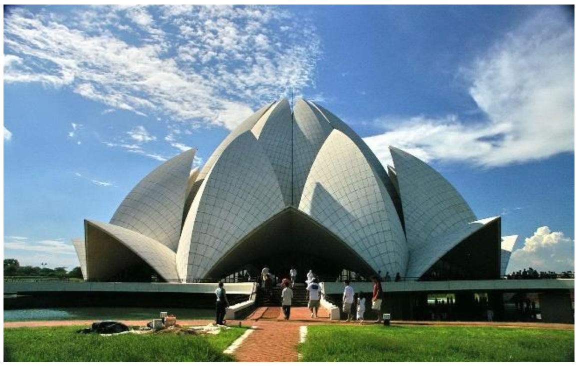

Figure 42 Lotus Temple, Delhi

Spring in Delhi: By the beginning of March the climate of Delhi sees the next transition from Winter to Summer. This time is characterized by warm days and cool nights which happens to be the most pleasant season witnessed by Delhi. On one hand, the pleasant days are marked with brilliant sunshine whereas on the other hand Spring Rains holds a distinct picture in this season. Days get warmer gradually and by the late spring or the early winter, the average day temperature goes over 30℃ whereas the minimum temperature lies under 20℃. Spring ends by the end of march when the temperature lies well above 30℃ [67].

4.2.2 Temperature variations in Delhi (2015)

The variation in the climate of Delhi shows an abrupt nature. On one hand, it experiences very hot and dry summer followed by very humid monsoon whereas on the other hand it experiences extremely chilled and dry winter under clear skies. However, following the aim of this project, the weather data of the year 2015 has been collected and worked on to study the effects of the climatic changes on the work environment concerning the operational performance of a building.

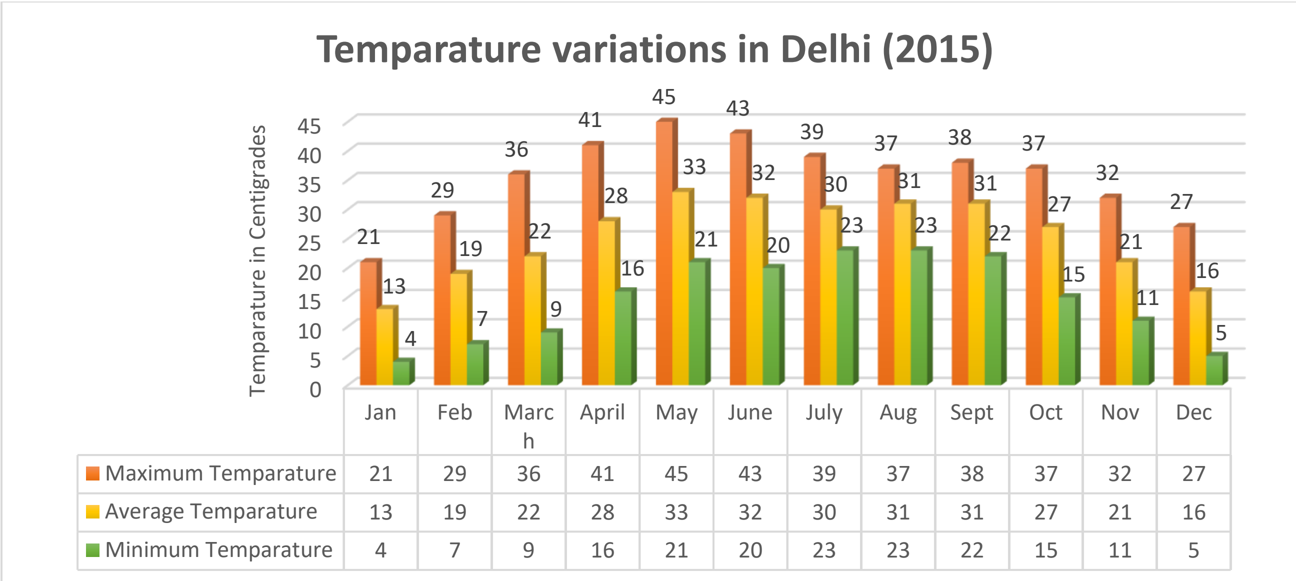

Figure 43 Temperature Variations in Delhi

From the graphical representation shown above, it is evident that extremity prevails in the nature of Delhi. These abrupt temperature fluctuations play a very prominent role on the performance of a structure. With these fluctuations, the heating and cooling of a building have to be maintained in accordance. Thus for further detail, the number of heating and cooling days have been calculated based on the weather data which can be used as a smart startup to model a structure in such conditions and as well as can be used in the comparative scenario of different work environments.

4.2.3 Variation in Heating Degree Days and Cooling Degree Days in Delhi (2015)

With the following chart, the number of HDD and CDD are shown for the entire year 2015 which can help us visualize the comfort period all through the year.

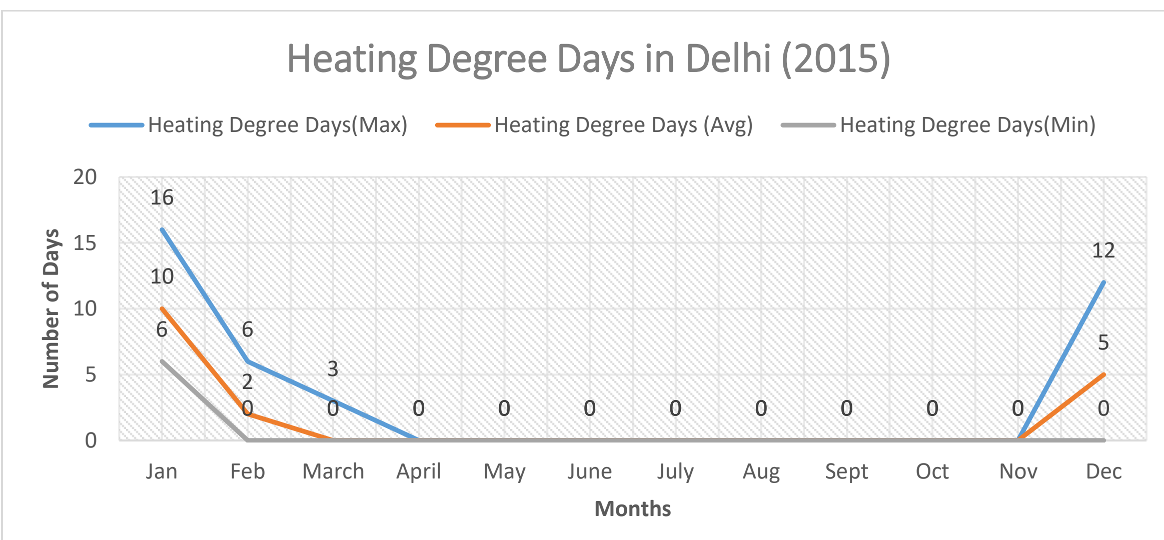

Figure 44 Heating Degree Days in Delhi

The chart above signifies that months from December to February requires proper heating. This heating can vary from thermally comfortable climate inside a building to wearing warm clothes outside. However, for this project, the thermal comfort is concentrated upon. Again it can also be inferred that from the month of May to October, a building requires no heating. This lowers energy consumption to a limit. But without the CDD, we cannot come to a conclusion, so the following chart signifies the necessity of cooling in Delhi for the year 2015.

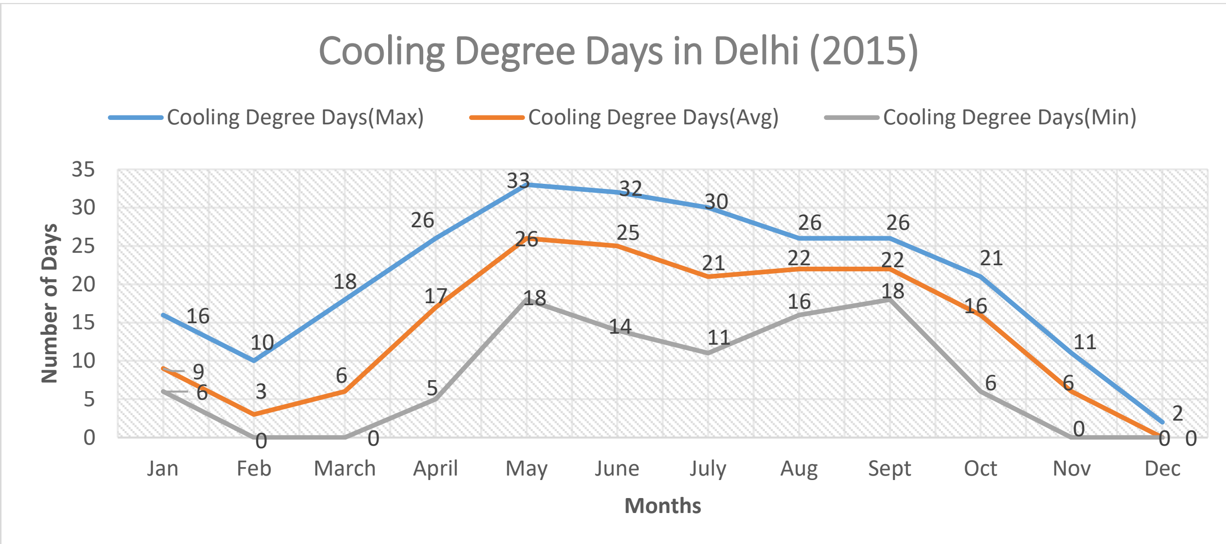

Figure 45 Cooling Degree Days in Delhi

The numbers from the chart above signify that almost for the entire year the period from March to October requires proper cooling to maintain the level of comfort in a building. High temperatures along with very high humidity are the reasons for these steps to be taken.

4.2.4 Relative Humidity Chart for Delhi (2015)

Relative Humidity refers to the ratio of the partial pressure of the water vapor in the air to the saturation pressure of water vapor at the same temperature is known to be relative humidity. The amount of water vapor in the air at any interval is usually lesser than what is require to saturate the air. The most common unit used is gm/m^3.

$$Relative\ Humidity = \frac{\textbf{actual vapour density}}{\textbf{saturation vapour density}} * 100\ \%$$

Equation 10 Equation of Relative Humidity

This is a very common factor in climatic conditions similar to that of Delhi. Delhi is usually dry but during the start of the rainy season, the weather becomes humid because small rainfall only brings out the heat of the land which increases humidity. The following table and the graphical representation will focus on the relative humidity in the climate of Delhi for the year 2015 which is further to be studied.

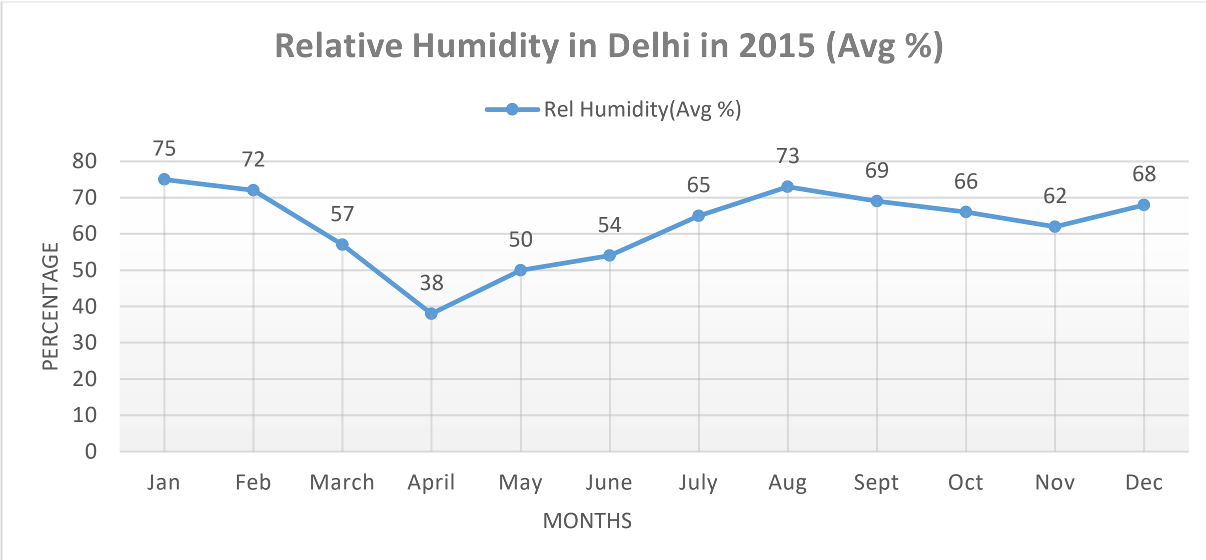

Figure 46 Relative Humidity in Delhi

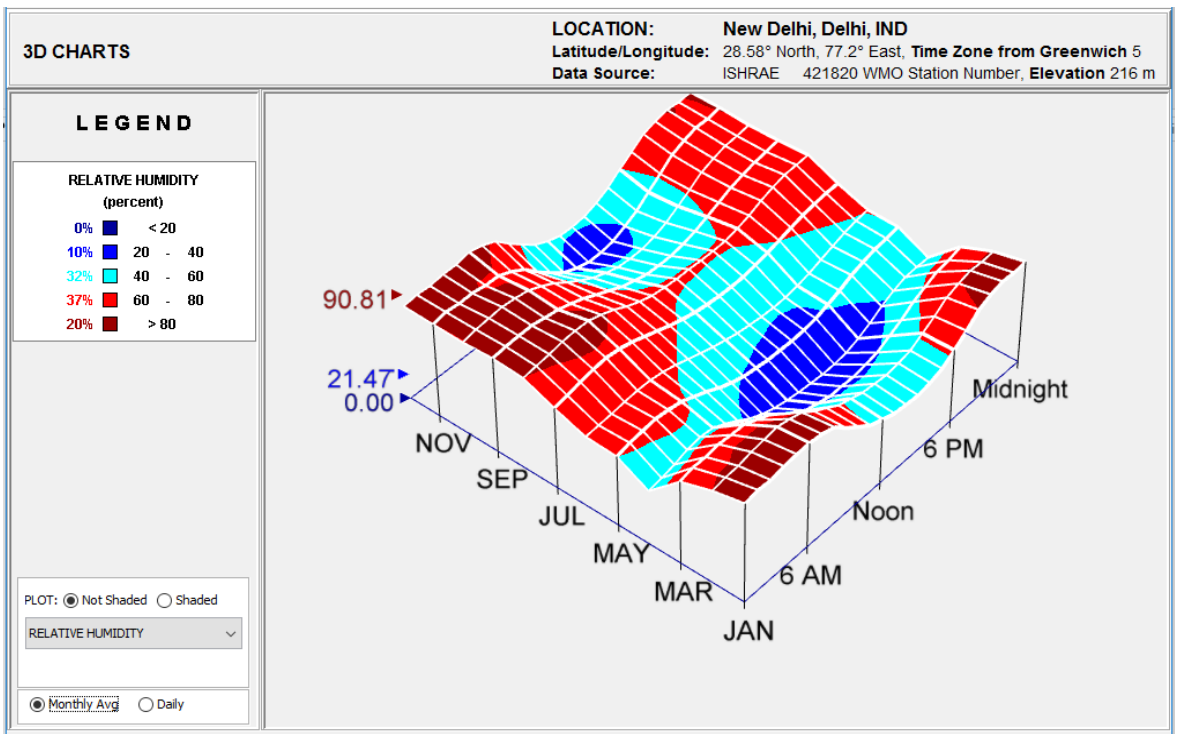

Figure 47 3D- Relative Humidity in Delhi

From the charts shown above, it is evident that the relative humidity is very high for almost the entire year except for the spring season. Therefore, in Delhi's climatic conditions cooling is a necessity for the entire year. This relative humidity plays a big role in discomfort during the Autumn or specifically the months of July August and September because of the temperature which also lies in the upper hand of the scale.

4.2.5 Temperature Range & Comfort Zonal Chart for Delhi (2015)

This following graphical representation infers the conclusion to the comfort zone of the year, in which the climate poses an acceptable condition for the building. Within this comfort zone, neither heating nor cooling should be necessary and seeing the results we can infer that heating and cooling both can be avoided during the beginning and the mid of Spring season which includes the months of March and mid-April.

(Note: In the following Temperature Range & Comfort Zonal Chart, the Record High and Low Temperatures (round dots) are the highest and lowest Dry Bulb Temperatures in each month or over the full year. The single bar on the right-hand side is showing the Annual Design High or Low Temperatures (top and bottom of green bars). This data is used to calculate the necessity of the heating and cooling in a building. Average High and Low Temperature (top and bottom of yellow bars) represents the average of the highest or lowest dry bulb temperatures for each day during the month, or annually. Mean or Average Temperature (open gap slot) is the average of all Dry Bulb temperatures in that particular month or annually.)

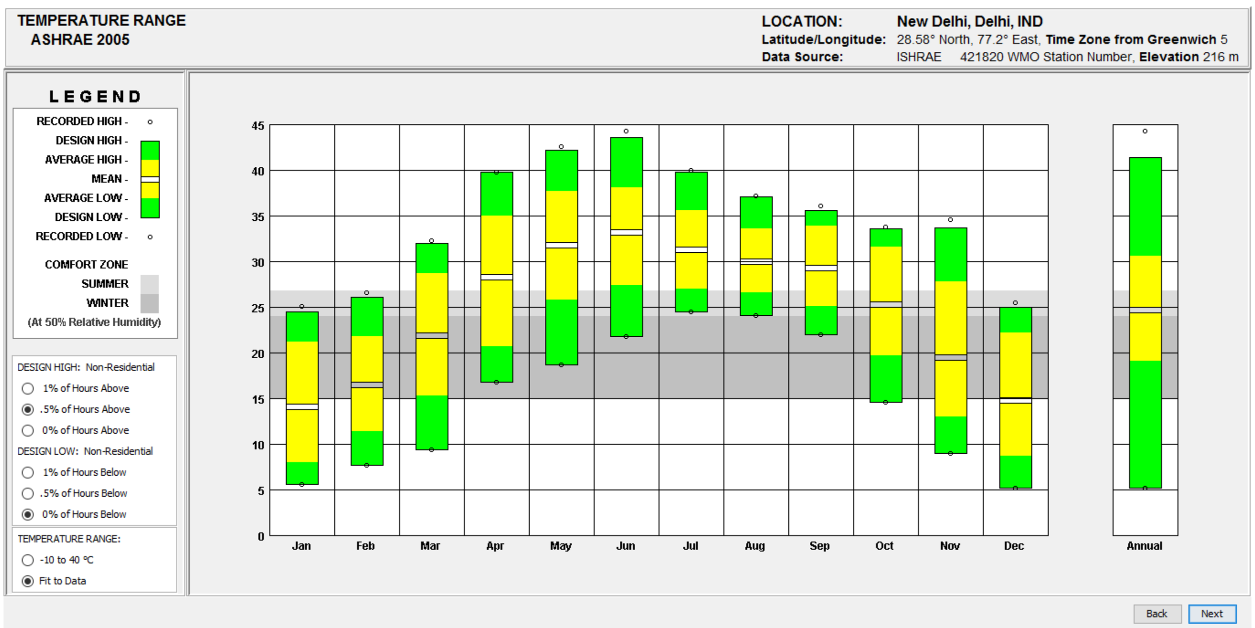

Figure 48 Temperature Range and Comfort Zonal Chart for Delhi

From this chart mentioned above, we can infer that the mean average temperature is way above the comfort zone for the period from the month of April to the month of September. Again during the winter in Delhi, the mean temperature again falls below the comfort zone which urges the requirement of heating in a building. Only the two months namely March (Spring) and October (End of Autumn) seems to be comfortable as the mean temperature falls well within the zone of comfort.

4.2.6 Summarization

With the following table, the thermal comfort level of Delhi has been shown where the levels are graded on a scale of A to E.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	December to January	5°C to 25°C	Very Cool	Heating Required
Spring	February to March	20°C to 25°C	Sunny and pleasant.	A little bit of heating or Air Conditioning is enough
Summer	April to June	25°C to 45°C	Hot	Proper Cooling is required
Monsoon	July to Mid-September	30°C to 35°C	Wet, hot and humid	Proper Cooling is required.
Autumn	September end to November	20°C to 30°C	Pleasant	A little bit of Cooling or Air Conditioning is enough

Table 7 Summarization table for Delhi

Though the temperatures during the Spring season and the Autumn season are almost the same, the characterization of Heating and Cooling is different. For Spring, Heating is necessary due to the transition stage where it changes from winter to summer and this time is marked by chilly Northern winds which happen to sweep across the city due to heavy snowfall on the Himalayas. Whereas for Autumn, Cooling is necessary as this transition stage is marked with the high level of humidity along with heat which makes the climate sweaty and uncomfortable.

4.3 Summarizations of the other cities

As for the procedure followed for the capital city of Delhi, the different aspects and margins of the climate experienced by a building in Delhi are explained in detail. Adapting the same procedure, the effect of the climatic variations of the other specified places (namely Mumbai, Berlin, Lisbon, Copenhagen, Dubai and Montreal) on a building is studied and plotted in a single table to reduce the monotony. In case of any arising questions regarding the numbers in the table, the option of comparison with the detailed information under the chapter of appendices is always open.

Name of the City	Seasons	Months	Average Temperature Variations	Average Heating Degree Days	Average Cooling Degree Days	Average Relative Humidity	TR and CZ Chart
Mumbai	Summer	March to June	32℃ - 40℃	0	85	71.00 %	Does not fit
	Monsoon	July to September	20℃ - 22℃	0	48	84 %	Does not fit
	Winter	October to February	10℃ - 25℃	0	75	63.20 %	Fit
Berlin	Spring	March to May	4℃ - 14℃	28	0	70.66 %	Fit
	Summer	June to August	20℃ - 25℃	5	10	64.00 %	Fit

	Autumn	September to November	14°C - 4°C	42	5	77.00 %	Does not fit
	Winter	December to February	(-3) °C - 3°C	80	0	82.33 %	Does not fit
Lisbon	Spring	March to May	15°C - 24°C	15	8	73.33 %	Fit
	Summer	June to August	22°C - 35°C	2	28	67.00 %	Fit
	Autumn	September to November	15°C - 25°C	12	8	75.33 %	Fit
	Winter	December to February	6°C - 15°C	40	0	80.33 %	Does not fit
Copenhagen	Spring	March to May	2°C - 10°C	50	0	72.66 %	Does not fit
	Summer	June to August	12°C - 20°C	26	10	71.66 %	Fit
	Autumn	September to November	7°C - 15°C	42	0	79.66 %	Does not fit
	Winter	December to February	(-2) °C - 5 °C	85	0	85.33 %	Does not fit
Dubai	Summer	April to October	35°C - 48°C	0	202	55.14 %	Does not fit
	Autumn	November to February	22°C - 27°C	0	40	68.00 %	Fit
	Winter	January to March	15°C - 25°C	1	26	68.00 %	Fit
Montreal	Spring	Mid-March to May	2°C - 20°C	68	8	66.00 %	Does not fit
	Summer	June to September	23°C - 28°C	12	20	73.50 %	Fit
	Autumn	October to November	13°C - 5°C	44	0	76.50 %	Does not fit
	Winter	December to beginning of March	2°C - (-15) °C	115	0	70.25 %	Does not fit

Table 8 Summarization table for all cities

Chapter 5: Comparison of the Results

5.1 Introduction

This chapter comprises of the accumulation of all the observations and results obtained from the detailed study, "A numerical comparison of the impact of different climatic conditions in different geographic locations on the construction of an office building". The energy analysis has been performed following the ASHRAE 90.1-2010 code and the results discussed and compared in this chapter must have a significant difference with the results of similar researches available online. This is due to the reason that the virtual building model prepared for this project is comprised of only conceptual building elements like wall, floor, ceiling doors, windows and roof while the building models used for similar researchs are completely optimized structures with designed and energy efficient elements like lighting, proper HVAC system etc. However, in this chapter, the comparative scenario has been subdivided under a few important factors.

1) **Carbon Footprint or CO_2 emissions**: The evaluation and management of CO_2 emissions generated by the buildings are an important factor because buildings are the main source of global CO_2 emissions [68]. The emission of CO_2 takes place both directly and indirectly throughout the lifecycle of a building which starts from the production and the construction stages to operation and end of life stages of the building [68]. So, CO_2 emissions represent tons of CO_2 which get emitted before applying the design alternatives to our project. The CO_2 emissions are based on the on-site fuel use and the fuel sources for the electricity in the region.
2) **Energy Use Intensity(EUI):** The term Energy Use Intensity can be defined as the total energy (electricity and fuel) used by the building per floor area per year. Climatic variations have a significant effect on EUI's due to the variations in heating and cooling costs across different areas of the country [69].
3) **Energy End Use of Fuel and Electricity:** While reviewing the energy analysis in Revit, the fuel end-use chart compares the estimated fuel (heating oil, natural gas etc.) use for HVAC and domestic hot water usage whereas the electricity end use chart shows the percentage of electricity use for major end uses including HVAC, lighting, and equipment. By understanding the end-use that requires the most fuel and electricity, strategies can be developed to reduce overall energy consumption for the project.
4) **Heating and Cooling Load:** Proper heating and cooling load calculations have a direct effect on the energy efficiency, occupancy comfort, indoor air quality and building durability. Therefore, while preparing the building model, with all the spaces and zones along with their respective phases specified, we can perform the heating and cooling analysis which can specify the necessity of heating and cooling in our building.
5) **Fanger's PMV Model:** Based on the complete study which involves both the literature research as well as the analytical and numerical results, the thermal comfort level inside the office building is predicted per Fanger's PMV Model. This index provides a scale that corresponds to the ASHRAE thermal sensation scale which represents the average thermal sensation felt by a large group of people in a space.

5.2 Comparison of the building in different cities based on Carbon Footprint or CO_2 emissions

The comparative scenario can be put forward by two sub-categories namely CO_2 emission by electric and onsite fuel use and condition of the onsite potentials reducing the amount of net CO_2 emission.

5.2.1 CO_2 emission by electric and onsite fuel use

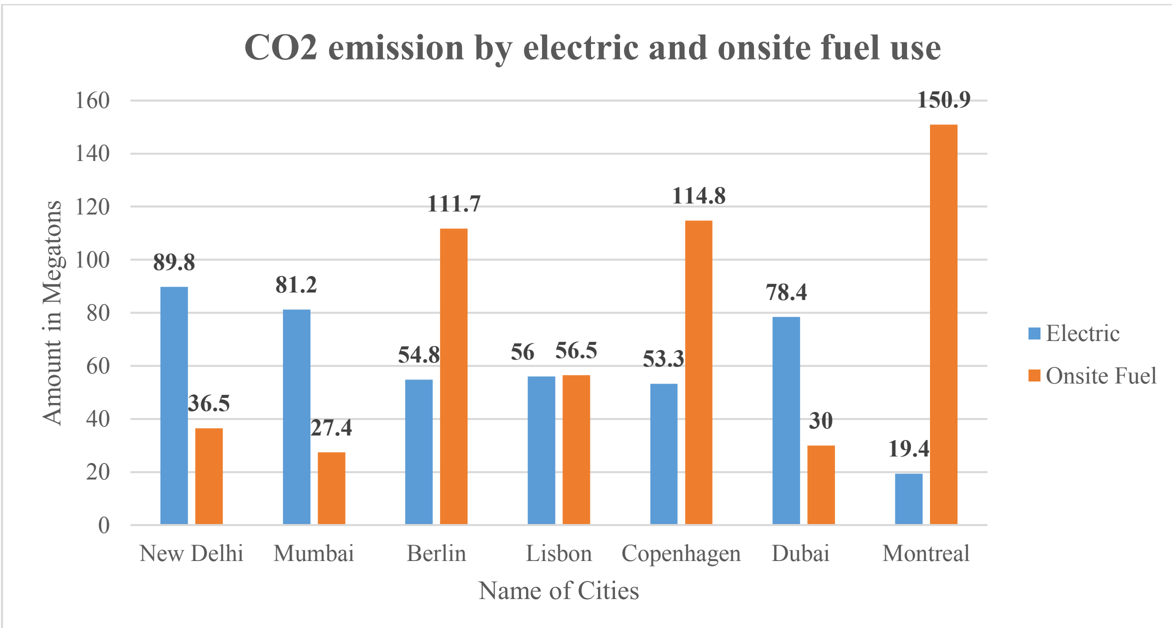

Figure 49 CO2 emission by Electric and Onsite fuel use

From the figure above, we can come up with the following derivations. The electricity consumption for the cities like New Delhi, Mumbai and Dubai are considerably higher than Berlin, Lisbon, Copenhagen and Montreal because there is a huge demand for space cooling during the summer as they experience extreme weather conditions during the summer where the temperature lies well above 40℃. The electricity demand for Montreal is very low as there is very less necessity for cooling during the summer. The temperature can be well maintained with proper natural ventilation. The energy consumption for onsite fuel use in Montreal, Copenhagen and Berlin are higher as compared to New Delhi, Mumbai, Lisbon and Dubai. This is due to the reason that cities like Montreal, Copenhagen and Berlin experiences severe winter with temperatures well below the freezing point. This results in the increase in the necessity of space heating which in turn increases the onsite fuel use. This is comparatively low for other cities as space heating is not a necessity in such tropical dry and sultry weather. So only for hot water purpose fuel is being used contributing not much to the result.

5.2.2 Onsite Potentials reducing the amount of net CO_2 emission

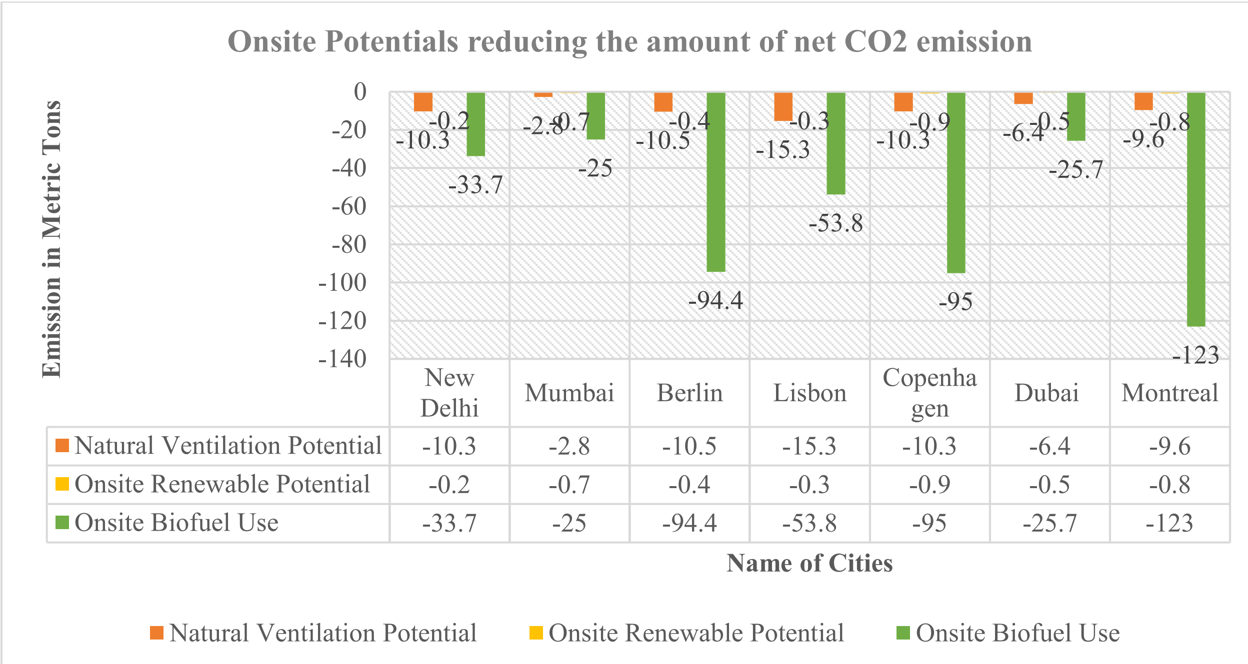

Figure 50 Onsite Potentials reducing the amount of net CO2 emission

This is followed by the potential factors available onsite which are natural ventilation potential, onsite renewable potential and onsite biofuel. Now the onsite renewable potential such as solar or wind power availability is very low as the virtual building model used for this research is composed only of conceptual building elements and not solar panels or windmills. The natural ventilation potential is very much dependent on the climatic conditions our building is associated with. It tells us about the possibility of maintaining proper thermal comfort inside the building by determining the outdoor temperature. This can potentially remove tons of carbon by avoiding the mechanical cooling systems which require electricity. In New Delhi and Lisbon, the natural ventilation potential is comparatively higher than Mumbai, Berlin, Copenhagen, Dubai and Montreal. This can be supported by finding out the total hours required for mechanical cooling and possible natural ventilation.

Places	Total Hours Mechanical Cooling Required	Possible Natural Ventilation Hours	Net hours required for Mechanical Cooling
New Delhi	4896	1048	3848
Mumbai	6022	214	5808
Berlin	1946	1199	747
Lisbon	3249	1907	1342
Copenhagen	1590	1120	470
Dubai	5521	633	4888
Montreal	2012	1098	914

Table 9 Hours of Mechanical Cooling and Natural Ventilation

The table above suggests that the necessity of mechanical cooling for the year 2015 in Copenhagen, Berlin and Montreal is very less as compared to the other mentioned cities. There is considerable availability of biofuels like natural gas, fuel oil or propane for the specified cities but for the comparison, the availability is more in Montreal, Copenhagen and Berlin as compared to Lisbon, New Delhi, Mumbai and Dubai. Based upon all these factors mentioned above, the net CO_2 emissions for has been calculated which are shown below.

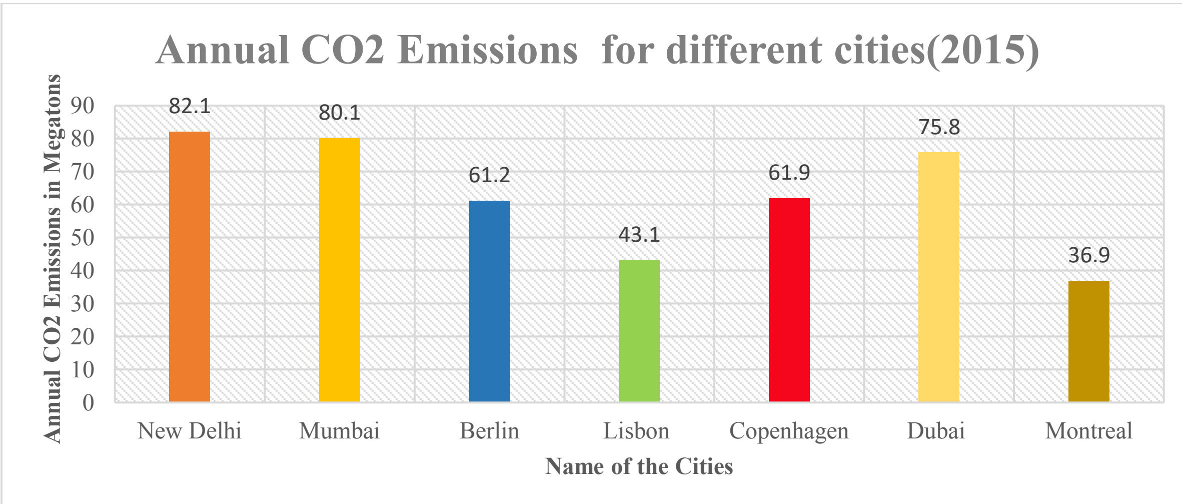

Figure 51 Annual CO2 Emissions for different cities

From the figure above we can derive that the CO_2 emission figures for Montreal and Lisbon are impressive where the emissions are below 50 metric tons. For Berlin and Copenhagen, it is slightly higher than 50 metric tons. But for the cities like New Delhi, Mumbai and Dubai it is considerably higher and alarming. Various factors including climatic conditions, the level of pollution in air and water (oceanic acidification) etc. are responsible for such high CO_2 emissions.

5.3 Comparison of the building in different cities based on Energy Use Intensity (EUI)

An important goal for the building sector is to construct buildings which have very less environmental impacts. Energy usage is one of the important issues as energy is one of the important resources used by the buildings over their lifetime. In case of this project, the virtual building model has been prepared only with conceptual masses and building elements. It is not an optimized building which can be used as an example for a low energy house. The objective is to study the variance in the numbers from the performance of the building under different climatic conditions. From the following table and graph, we can understand the behavior of the building under different climatic conditions.

Places	Electricity Consumption (kWh)	Fuel Consumption (MJ)	Total EUI (MJ / m² / year)
New Delhi	230,051 kWh	731,402 MJ	1,375 MJ / m² / year
Mumbai	272,059 kWh	549,738 MJ	1,328 MJ / m² / year
Berlin	213,238 kWh	2,239,755 MJ	2,148 MJ / m² / year

Lisbon	179,852 kWh	1,133,146 MJ	1,490 MJ / m² / year
Copenhagen	202,170 kWh	2,301,081 MJ	2,128 MJ / m² / year
Dubai	286,299 kWh	602,342 MJ	1,384 MJ / m² / year
Montreal	155,581 kWh	2,058,168 MJ	2,284 MJ / m² / year

Table 10 Table for Energy Use Intensity (EUI)

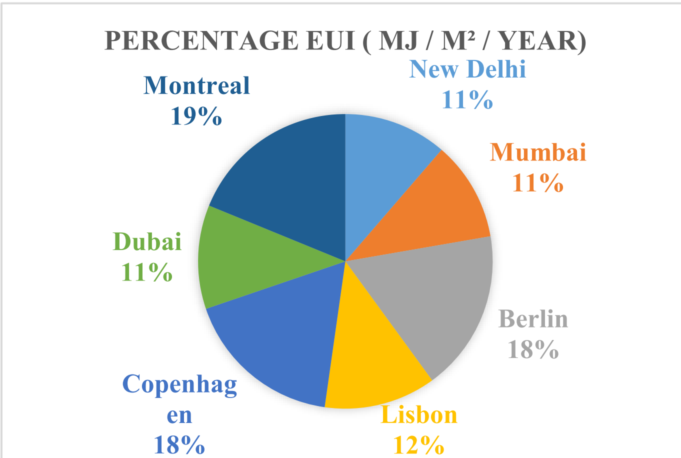

Figure 52 Percentage of EUI of the building in different cities

It can be foreseen that the building in Berlin, Copenhagen and Montreal has more Energy Use Intensity (EUI) as compared to New Delhi, Mumbai, Lisbon and Dubai. The main reasons for such results are the electricity and fuel consumption. It gets connected directly to that of heating and cooling influences in the count of the Energy Use Intensity of the building. In support of this sentence we can notify that for New Delhi, Mumbai and Dubai, the electricity consumption is comparatively higher than other cities due to the requirement of proper mechanical cooling. On the other hand, for Berlin, Lisbon, Copenhagen and Montreal, the fuel consumption is higher due to the necessity of proper space heating.

5.4 Comparison of the building based on Energy End Use of Fuel and Electricity

The results of the energy analysis give a proper picture of the building's annual electric end use and annual fuel end use. However, under this section, the performance of the building has been categorized according to Electricity and Fuel end uses of the building in different cities.

5.4.1 Annual Electric End Use

The annual electric end use of the building has been further categorized according to end uses due to Space Cooling, Fans, Lights and Misc Equipment.

1) End use of building in different cities due to Space Cooling

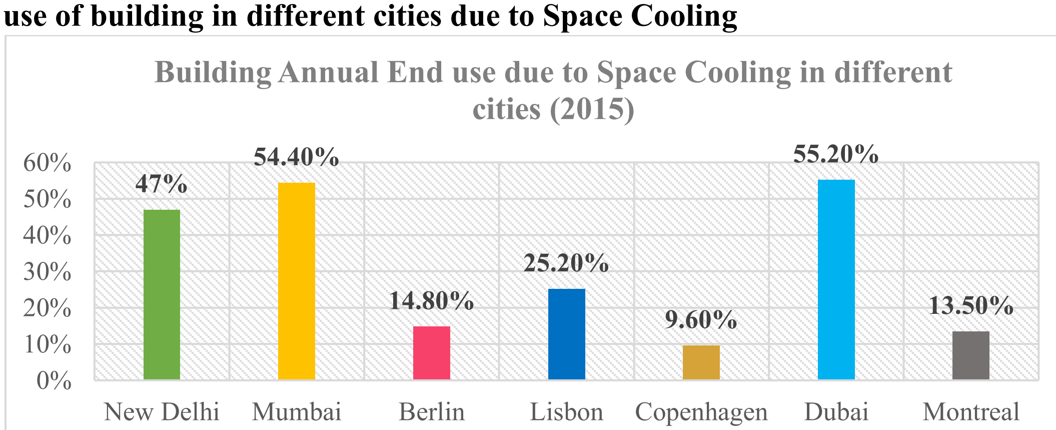

Figure 53 Building Annual End use due to Space Cooling in different cities

From the figure above we can anticipate the annual end use of the building for space cooling in cities like New Delhi, Mumbai and Dubai are much higher than in cities like Berlin, Lisbon, Copenhagen and Montreal. This is typically due to the climatic conditions which leaves a drastic effect on the performance of the building. Cities like New Delhi, Mumbai and Dubai experiences extreme climate. The summers here being very hot and sultry increases the necessity of cooling. The percentages of New Delhi and Mumbai are interesting in this case as we can easily differentiate among other cities but New Delhi and Mumbai almost experience the same weather condition but still, there is considerable difference in the space cooling percentages where Mumbai has a percentage over New Delhi. This is due to the reason that Mumbai is located on the shore of Arabian sea. This brings extreme humidity and bluntness to the weather of Mumbai which narrows down the possibility of proper natural ventilation and thus increases the percentage of the end use of space cooling. On the other hand, Delhi is located more into the northern part of India which is lapping between humid subtropical and semi-arid climate. The summers are marked with very hot and dry continental winds but with very low humidity. This increases the natural ventilation potential and decreases the percentage of space cooling. On the contrast, the European cities like Berlin, Lisbon and Copenhagen don't experience such extreme summer. So the necessity of cooling is very less in these cities. Again, Montreal though not belong to the Europe but still experience chilly winters and moderate summers where the thermal comfort can be maintained up to a certain level by natural ventilation.

2) End use of building in different cities due to Fans

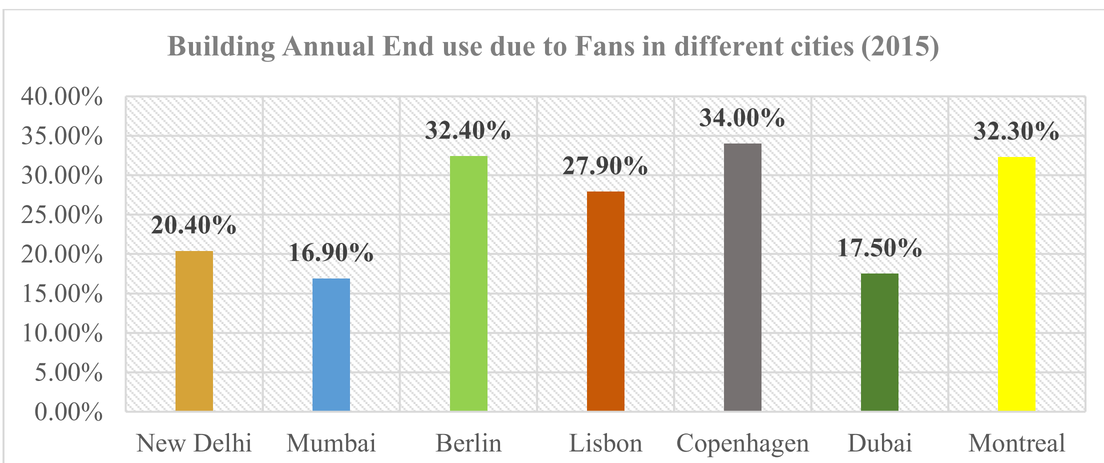

Figure 54 Building Annual End-use due to Fans in different cities

From the figure above we can anticipate the necessity of fans inside the building under the influence of different climatic conditions. By understanding this figure, we can derive that the necessity of fan will be higher in those cities where the temperature and the thermal comfort can be maintained by natural ventilation rather than consuming electricity for cooling and it is a known fact that as Berlin, Lisbon, Copenhagen and Montreal experiences moderate summer and very cold winters. The temperatures during the summers can be kept well under the uncomfortable zone by different ventilation techniques including the use of openings, ducts etc. Thus, percentage for the annual end use of the usage of fans is considerably higher in Berlin, Lisbon, Copenhagen and Montreal as compared to New Delhi, Mumbai and Dubai as the latter cities experience very humid, sultry and hot summers where the use of fans doesn't make considerable differences in the thermal comfort level inside the building.

3) End use of building in different cities due to Lights and Misc Equipment

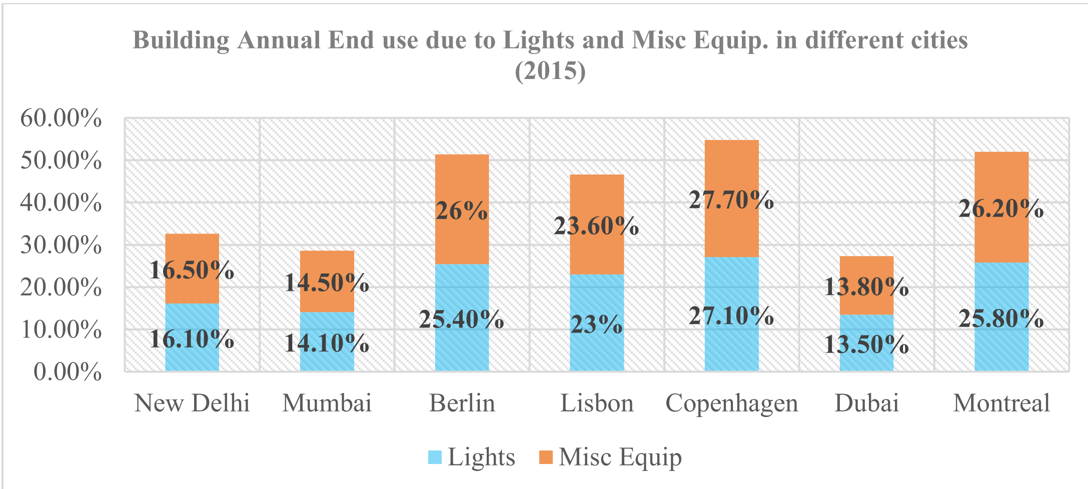

Figure 55 Building Annual End-use due to Lights and Misc Equip. in different cities

From the figure mentioned above, it can be derived that percentages of building annual end use for lights and misc equipment in Berlin, Lisbon, Copenhagen and Montreal is comparatively higher than the other cities. One of the main reasons behind such result is that countries like Germany, Portugal, Denmark and Canada contribute much of their attention to the environmental sustainability which is directly affected by the energy usage in buildings. Thus, they strive towards taking all necessary measures to bring down the energy consumption of a building. Energy efficient lights and equipment are commonly used in almost every building in such countries. But in countries like India, there are numerous old structures with no proper energy efficient properties attached to the structure. Though India is moving at a very high pace in developing the energy efficient features in new as well as old buildings, there is still much work left to be done. Therefore, the lights and equipment are generally not so energy efficient here which results ultimately to absorb low-end use of energy.

5.4.2 Annual Fuel End Use

Buildings annual fuel end-use depends mainly on two factors namely space heating and hot water. The necessity of space heating and hot water should be more where the climate brings cold winters.

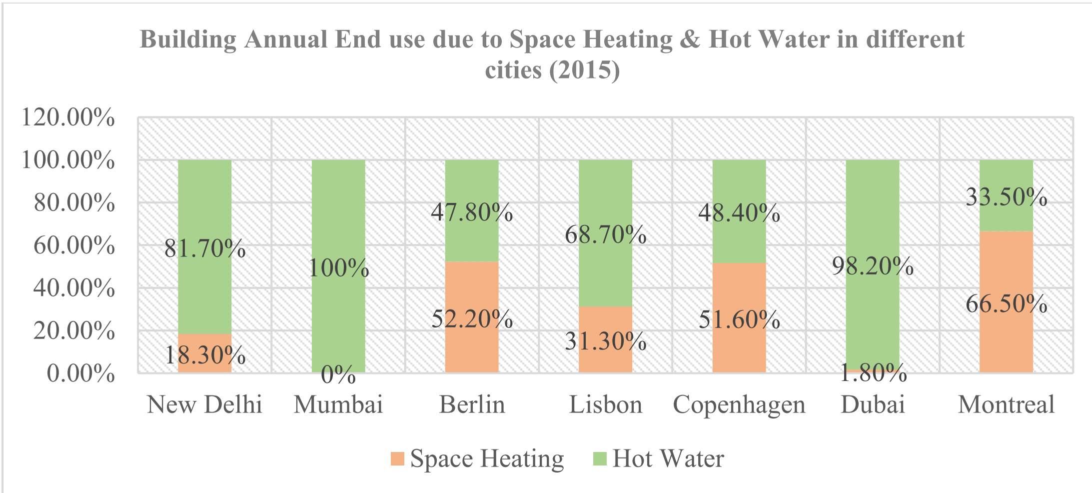

Figure 56 Building Annual End-use due to Space Heating & Hot Water in different cities

From the figure above it can be it can be inferred that percentages of energy end use for space heating are comparatively much higher in cities like Berlin, Copenhagen and Montreal. This is because these place experience very chilled winters where the temperatures fall well below the freezing zone. In case of Lisbon, the end use percentage of space heating is comparatively less because the winters are not son chilly and it hardly snows in Lisbon. Therefore, proper comfort can be maintained by energy efficient doors and windows which can help in restoring heat from escaping out into the environment from the building. This scenario is completely opposite in the case of Dubai and Mumbai where there is no necessity of space heating as they hardly experience cold winters. The percentage is 0 for Mumbai due to extreme hot summer and decent winter with high humidity where there is no necessity of space heating. But New Delhi due to the North-Western winds from the Himalayas experiences moderately cold winter when the temperature lies well below 10°C. The necessity of hot water is an important factor for all places but however, it varies with places having different climatic conditions.

5.5 Comparison of the building based on Heating and cooling loads

Heating and Cooling loads are the measures of the energy required to be added or removed from a space by the HVAC system to maintain the thermal comfort inside a building. The values obtained from the heating and cooling load calculations will help in the equipment selection and duct design to deliver conditioned air to the rooms inside the building. These results also have a drastic impact on the construction costs along with the operating energy efficiency, occupant comfort, indoor air quality and building durability. In case of this project, the virtual building model is analyzed under climatic variations of different cities in this world. This comparison of the building is studied with its performance in different cities. We consider the Peak Cooling load and the Peak Heating Load for understanding the condition inside the building.

1. **Building Performance under climatic conditions in New Delhi**
   The load report for the building in New Delhi states that the Peak Cooling Load is calculated to be 750,720.40 Btu/h whereas the Peak Heating Load is -167,122.40 Btu/h. This Peak Cooling Load figure suggest that due to very hot and dry continental winds that flow over the city, the necessity of proper mechanical cooling is the most important factor during this time. Therefore, 750,420.40 Btu of heat is gained inside the building per hour which needs

to be removed by the mechanical cooling system. But again, the winters in New Delhi are cold. The temperatures remain well below 10℃ but hardly touches the freezing point. So, Peak Heating load figure suggest that 167,122.40 Btu of the heating load is to be made up per hour inside the building to maintain the occupational comfort.

2. **Building Performance under climatic conditions in Mumbai**
   For Mumbai, the situations are different as compared to New Delhi. The Peak Cooling Load inside the building is calculated to be 670,963.80 Btu/h which states that this amount of heat is being gained during the summer season per hour which is really hot, sultry and humid. This load of heat is to be displaced from the building by HVAC equipment to maintain the level of comfort. Again, the Peak Heating Load in this building is calculated to be -51,713.30 Btu/h. This helps us to understand that this amount of heat is lost from the building and is to be made up. But studying the weather conditions of Mumbai we can infer that it has no necessity of space heating as heat can be gained by energy efficient doors, windows and walls which will not allow the heat to escape into the environment.
3. **Building Performance under climatic conditions in Berlin**
   The weather conditions are completely different as compared to the south-east Asian countries. The European countries experience moreover a colder climate with moderate summers and very cold winter. In Berlin, the Peak Cooling Load for the building is 405,627.69 Btu/h which infers that this amount of heat is gained per hour inside the building during the summer and must be removed. But climatic conditions in which Berlin falls suggests that comfort can be maintained inside the building by proper natural ventilation and there is very less necessity of space cooling. Again, the Peak Heating Load is calculated to be -137,109.19 Btu/h which means that this amount of heat has been dispersed to the atmosphere from the building creating a deficit of occupational comfort inside the building which is required to be made up by proper space heating.
4. **Building Performance under climatic conditions in Lisbon**
   Lisbon though falling in the European Zone experiences a comparatively higher temperature than other European countries. The summers here are warmer and winters are not so chilly. However, the performance of the building under this climatic zone tells us that the Peak Cooling Load is 413,757.00 Btu/h. This implies that this amount of heat is to be removed from the building to maintain the occupational comfort. But for this purpose, a proper natural ventilation potential is more helpful over mechanical cooling. Again, the Peak Heating Load figure -81,478.19 Btu/h infers that very less amount of heat escapes from the building per hour which needs to be made up. This can be achieved by energy efficient doors and windows which obstruct the heat to escape.
5. **Building performance under climatic condition in Copenhagen**
   Copenhagen experiences a cold winter with a moderate summer somewhat like Berlin. The peak Cooling load for the building situated here is 389,824.88 Btu/h which infers that this amount of has been gained over a period in summer which needs to be removed by proper ventilation techniques. The Peak Heating Load is -124,710.09 Btu/h which helps us to understand that it has a cold but not freezing winter and this amount of heat is to be gained inside the building by proper space heating to maintain the occupational comfort.
6. **Building performance under climatic condition in Dubai**
   Dubai experiences extreme weather with very hot summers and pleasant winters which last for a month utmost. The Peak Cooling Load for the building here is 434,978.53 Btu/h which infers that such huge quantity of heat is gained inside the building per hour from the

atmosphere. This heat needs to be removed with the help of proper space cooling equipment in order to maintain occupational comfort inside the building. Again, the Peak Heating load here is -46,678.14 which is very less and it infers that this amount of heat is to be gained inside the building to maintain the comfort level. However, for this purpose there is hardly any necessity of space heating as the weather during the winter is quite pleasant as rainfall is common during this time.

7. **Building Performance under climatic condition in Montreal**
   Montreal experiences a very cold and chilly winter where the temperatures remain well below the freezing point and a warm summer. The Peak Cooling Load of the building here is calculated to be 395,846.00 Btu/h which infers that this amount of heat should be removed gained during summer and this can be achieved by proper ventilation as the necessity of space cooling is comparatively less than other cities. Again, the Peak Heating Load is -194,909.86 Btu/h which states that proper space heating is very necessary to fill in this amount of heat which the building is losing per hour.

5.6 Comparison of the building based on Fanger's PMV Model

On the basis of the literature research and the analytical (numerical) results, the comfort level inside the building is being predicted. It is predicted based on Fanger's PMV Model. This index provides a scale that corresponds to the ASHRAE thermal sensation scale which represents the average thermal sensation felt by a large group of people in a space. Therefore, the following table suggests the comfort level season wise for the building situated in different cities.

Season	New Delhi	Mumbai	Berlin	Lisbon	Copenhagen	Dubai	Montreal
Winter	(-2)	0 or (-1)	(-2)	(-1)	(-2)	(+1) or (+2)	(-3)
Spring	0 or (-1)	N/A	0 or (-1)	0	0 or (-1)	N/A	(-1) or (-2)
Summer	(+2) or (+3)	(+2) or (+3)	0	(+1) or (+2)	0 or (+1)	(+3)	0 or (+1)
Monsoon	(+2)	(+1) or (+2)	N/A	N/A	N/A	(+2)	N/A
Autumn	0 or (+1)	N/A	(-1)	0 or (-1)	(-1)	N/A	(-1) or (-2)

Table 11 Comfort Index of Fanger's PMV Model

From the table above we can understand that for the European cities like Berlin, Lisbon and Copenhagen, the period from the end of Spring to the beginning of Autumn is considered to be the comfortable period of the year when the temperature is not so high and there is sufficient occupational comfort inside a building. This is the period when both space heating and space cooling can be avoided. Again for cities like Mumbai, winter is the time when we can avoid both space heating and space cooling as that is the most pleasant time of the year. New Delhi holds a contrast to Mumbai as it experiences a colder winter than Mumbai where the temperature lies well below 10°C and heating may be necessary. However, instead of space heating, people prefer warm clothes to maintain the comfort level. For New Delhi mid-Spring is the pleasant period of the year. Again Dubai and Montreal bears a contrast between each other. In Dubai, there is no period in a year when space cooling can be avoided as even during the period of winter temperatures remain well above 30°C. On the other hand Montreal experiences, extremely cold winter and moderately hot summer. But during the summer season space cooling can be avoided by proper ventilation. So the summer can be considered as to the pleasant period of the year.

Chapter 6. Conclusion

6.1 End Notes

Following the aim of my research which was to observe the variance in the performance of an office building under the effect of climatic variations, varying from extreme to moderate weather, I have attempted to establish a proper bridge between my literature work and my numerical results. This research firstly describes the background of such a topic. The past and the present scenarios of the awareness on construction and maintenance of energy efficient structures have been discussed in detail. This is followed by the main literature work which reflects topics like impacts of climate change on the energy efficiency of a building, all about heating and cooling technologies in buildings and how does climate change bring down an effect to it etc. Fanger's PMV model is a very common and specific model to predict the thermal comfort inside a building, which also has been used in my research to predict the comfort level of my virtual building model, has been described in detail. Then the virtual building model had been prepared in software platforms like Revit Structures 2017 with all proper material, physical and thermal properties which have been described in depth. This is followed by the collection of weather data for the specified cities which have been further processed to analyze the building in software platforms like EnergyPLUS, Climate Consultant and study about the comparative performances under different climatic conditions. The numerical results have been discussed in detail by dividing into various categories like comparison based on CO_2 emissions, energy end use, energy use intensity, heating and cooling loads and finally predicting the thermal comfort by following the guidelines of Fanger's PMV model.

The comparison of building performances shows that though the climate has a big effect on the performance of buildings, similarly buildings also play a major role in climate change. Reducing buildings energy consumption should be the core of all ideas of makers and users as if not controlled, it can lead to severe depletion of natural resources. Today's building energy performance simulation tools represent data at a variety of time slices like hourly, daily, weekly, monthly (used for this thesis) and annually for all components, spaces and zones inside a building. This research potentially presents only a small fraction of the present scenario of building performance under climatic variations as it is not focused on optimizations of buildings according to impacts of climate.

6.2 Suggestions for further improvements in Building Energy Codes

Only a few countries namely the United States of America, Canada, United Kingdom, Germany, France, the United Arab Emirates etc. have marked proficient progress in the field of energy efficiency and climate control. Presently climate change is the biggest threat that is faced by human race and buildings play a major role in it. Therefore, it is of utmost importance that all of the other countries take all necessary actions to contribute more to this journey of climate control. Countries like India, China are densely populated and highly populated. Though these countries have been trying to cope up with the necessary changes but still a lot should be done. There are no proper energy codes for every country. This is one of the big problems that I faced while my research work. There should be proper energy codes for every country based on their economic and climatic conditions. The next problem is that the available energy codes are generally oversimplified or generalized. For example, the international building energy code predicts the construction requirements based on other similar building performances in different countries. Now every country has a specific economic system and climatic conditions which should not be generalized. Again there are several researchs on how well a performance-based energy code predict the actual building energy use [70]. The modeling results are only good as the data input which at several intervals have been proven to deviate from the actual scenario. These are a few suggestions which can be implemented in the building energy codes to save our natural resources and controlling the climate.

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A. Appendices

A.1 Work Environment of Mumbai

A.1.1 Introduction

Mumbai located on the west coast of India is the modern financial hub of South Asia. The climate of Mumbai can be best described in the zone being moderately hot with high level of humidity. This is due to the influence of the Arabian Sea which is just by the city. The main three seasons i.e. Summer, Monsoon and Winter prevails in Mumbai [71].

A.1.2 Temperature variations in Mumbai (2015)

The temperature of Mumbai varies not so severely during the year. But due to the presence of the Arabian sea, moisture content in the air is predominant. However, the weather data of Mumbai has been collected for the year 2015 as this project aims to study the effect of the climatic conditions over the operational performance of a building. And to achieve the goal generalized local weather data has been collected through which firstly the temperature variations are shown for the complete year of 2015.

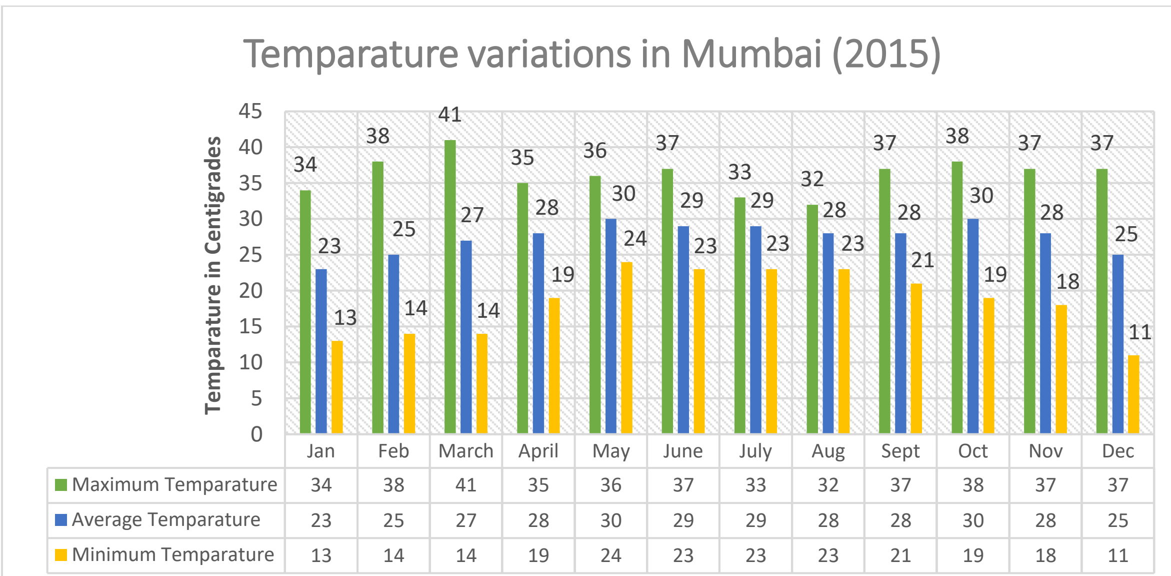


Figure 57 Temperature Variations in Mumbai

From the above graphical representation, we can infer that Mumbai has a tropical wet and dry climate. These climatic conditions have got a prominent impact on the operational performance of a structure. A lot of effects get involved with the temperature fluctuations. To get into detail a few more representations have been shown to which we can have a better insight on the climate of Mumbai and its role in the work environment.

A.1.3 Variation in Heating Degree Days and Cooling Degree Days in Mumbai (2015)

The following graphical representations signify the requirement of heating and cooling in a building based on the climate of Mumbai.

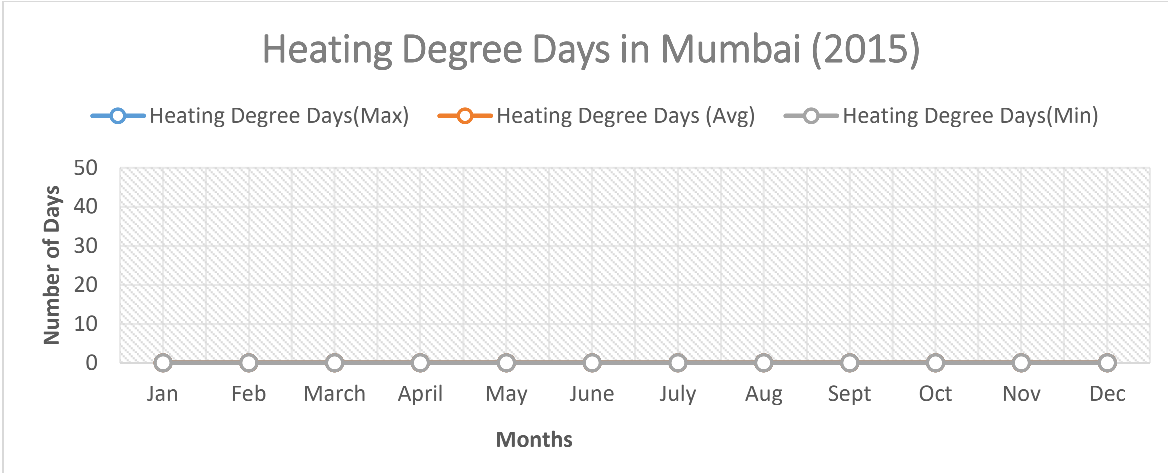


Figure 58 Heating Degree Days in Mumbai

Thus from the plot above we can understand that heating in the climate of Mumbai is not at all a necessity due to the nature of the climate which is very hot and humid. With the following graph, the number of Cooling Degree Days can be foreseen to understand the necessity of cooling in Mumbai.

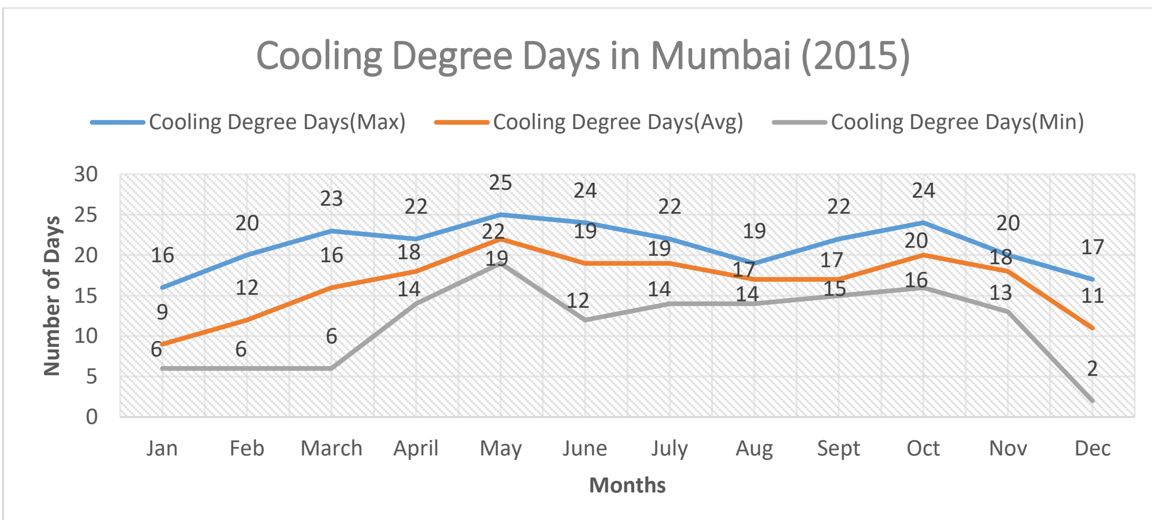


Figure 59 Cooling Degree Days in Mumbai

From the above graphical representations, it can be understood that in such a tropical wet and dry climate such as in Mumbai, a building necessarily does not require any heating during the year. This is due to the influence of the high temperature and humidity which remains the same for almost the whole year. However, it is also evident from the above graph that a building in Mumbai requires proper Air-conditioning to maintain thermal comfort and acceptable indoor air quality for the entire year. Henceforth the maximum, minimum and average number of cooling days for every month is shown above. Based on the last two inferences above, the comfort zonal graph can be brought in.

A.1.4 Relative Humidity chart for Mumbai (2015)

If the geography of Mumbai is checked, it can be understood that in the western and the southern side it is having the Arabian Sea. On the eastern side, 30 % of it is surrounded by Arabian sea, 60 % by creeks. Then on the northern side it is surrounded by various hills which include Sahyadri mountain range located just 80-90 kms away. All of these terrain situations results in water vapors from the sea to evaporate and blend with the climate surrounding Mumbai instead of drifting away. This results in high humidity and relative humidity in the air. With the following table and graphical representations, the relative humidity of Mumbai for the year 2015 has been found out.

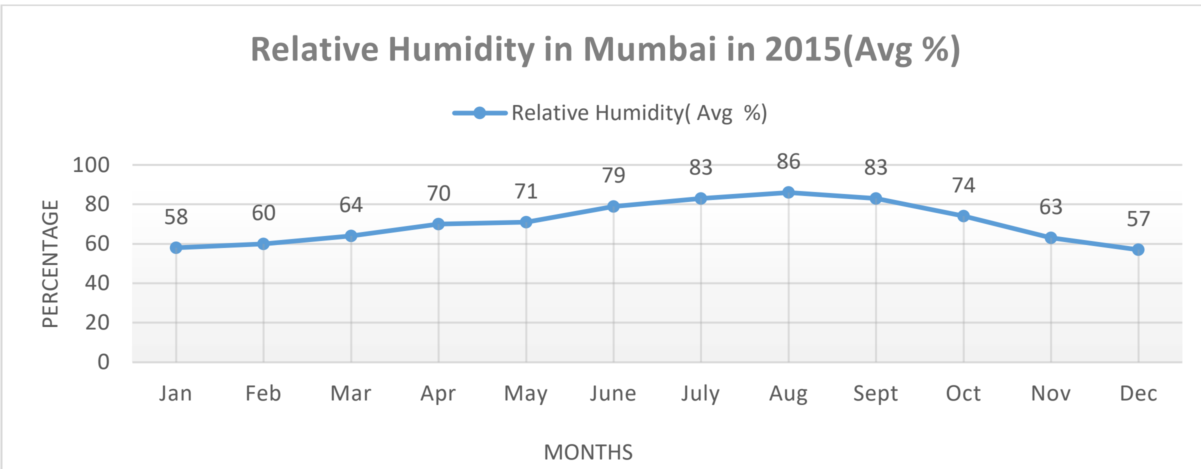


Figure 60 Relative Humidity in Mumbai

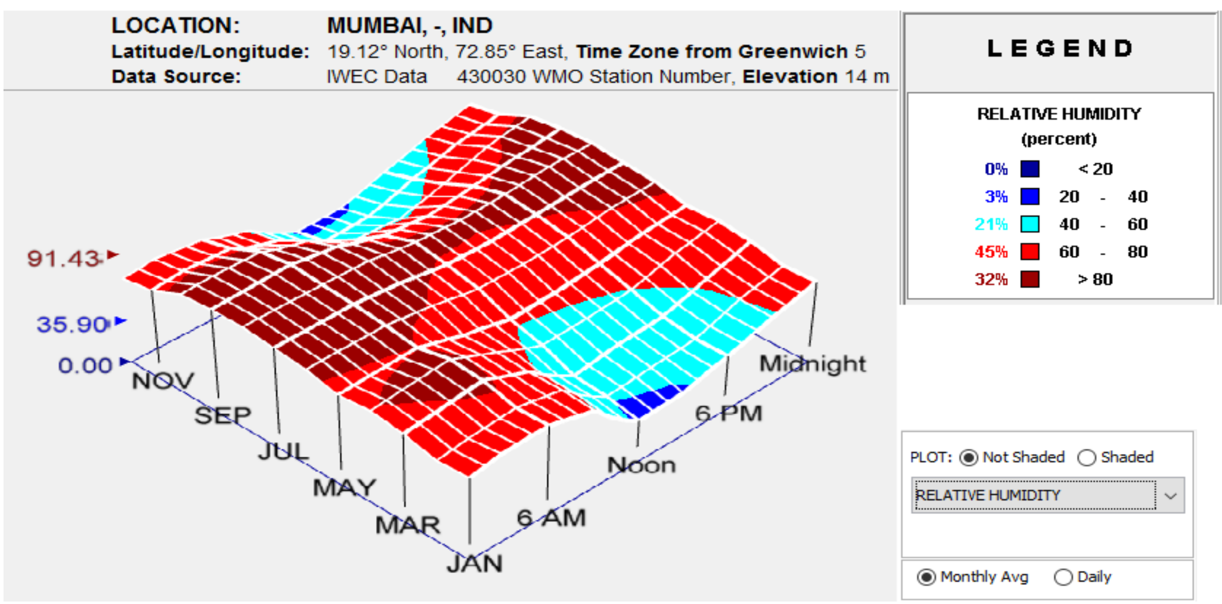


Figure 61 3D-Relative Humidity in Mumbai

Due to the presence of the Arabian sea, the weather of Mumbai carries a lot of humidity in it. On an average, the month of July is the most humid and similarly on the average February is the least humid. The following Relative humidity chart signifies the range of percentages of relative humidity that varied all through the year.

A.1.5 Temperature Range & Comfort Zonal Chart for Mumbai (2015)

This following graphical representation infers the conclusion to the comfort zone of the year, in which the climate poses an acceptable condition for the building. Within this comfort zone, neither heating nor cooling should be necessary but however, a proper ventilation is maintained almost in all buildings located in a region having climatic features similar to Mumbai. This ventilation can be defined with concepts of Air-conditioning in the official and important building to natural ventilation in the residential building.

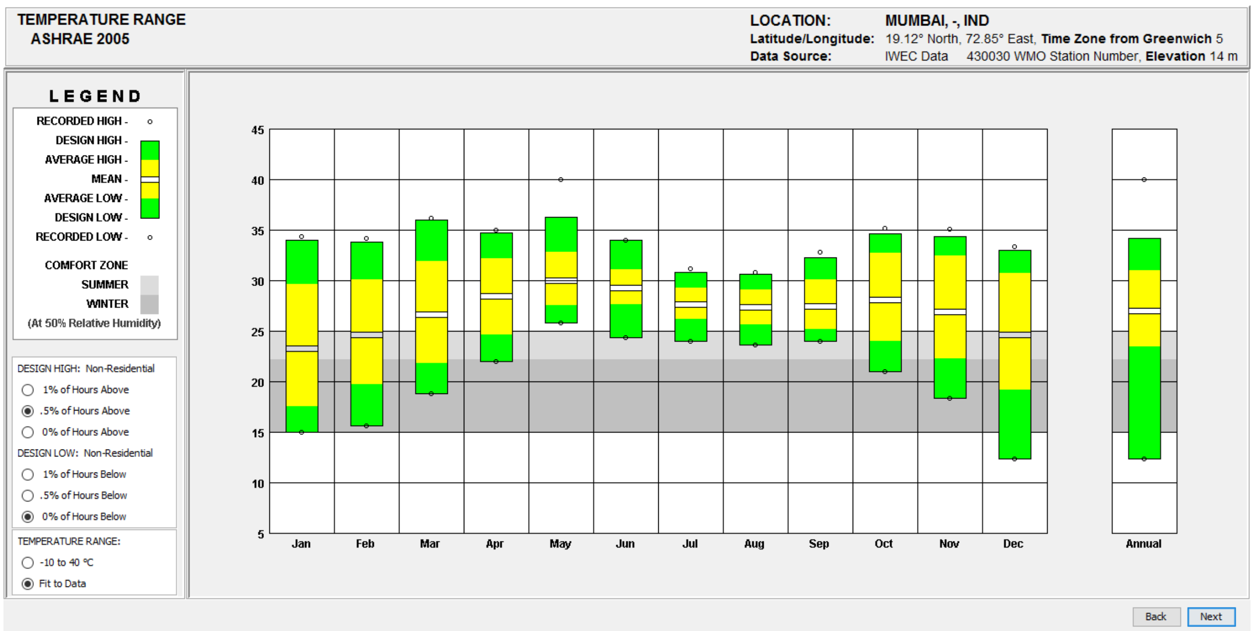


Figure 62 Temperature Range and Comfort Zonal chart for Mumbai

From the chart above it is clear that only the winter months brings fair comfort to Mumbai. However, with the following table the thermal comfort level for Mumbai is specified.

A.1.6 Summarization

The conclusion to all the mentioned weather numerical data can be bet visualized with the following table which signifies the necessity of Heating or Cooling and comfort level in Mumbai.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	October to February	10°C to 25°C	Most Pleasant	Proper Air Conditioning is required
Summer	March to May	32°C to 40°C	Very Hot and Humid	Proper Cooling is required

Monsoon	July to September	20°C to 22°C	Warm in the beginning but turns pleasant by mid-September	Cooling or proper Air Conditioning may be required.

Table 12 Summarization table for Mumbai

From the above-mentioned data, we can come to a conclusion that during the months of October to March the climate of Mumbai attains a stable condition. The operational performance of a building in Mumbai to be at its optimum level is a difficult situation because though the temperature during these months' fall to a low but still due to high humidity in the air, the necessity of cooling is to be maintained. Thus efficiency is being affected by much of energy consumption due to all year long cooling.

A.2 Work Environment of Berlin

A.2.1 Introduction

Berlin, the capital and the largest city of Germany is the second most populous city and the seventh most populous urban area in the European Union. Located in the north-eastern Germany by the banks of river Spree and Havel, Berlin is the center of Berlin-Brandenburg Metropolitan Region which gives shelter to more than 6 million residents from over 180 nations. Berlin is moreover covered with a continental climate. It is marked with cold winters, hot summers and mild autumns and springs. On an average, the wettest months are June and August, and the driest months on are October and February [72].

A.2.2 Temperature variations in Berlin (2015)

Over the course of many years, the temperature in Berlin generally varies from -3°C to 26°C and is rarely below -10°C or above 31°C. Berlin has a humid continental climate. June to September are the best months when the weather is at its best. However, with the following chart, we can get a better insight of how the temperature varied in Berlin for the year 2015.

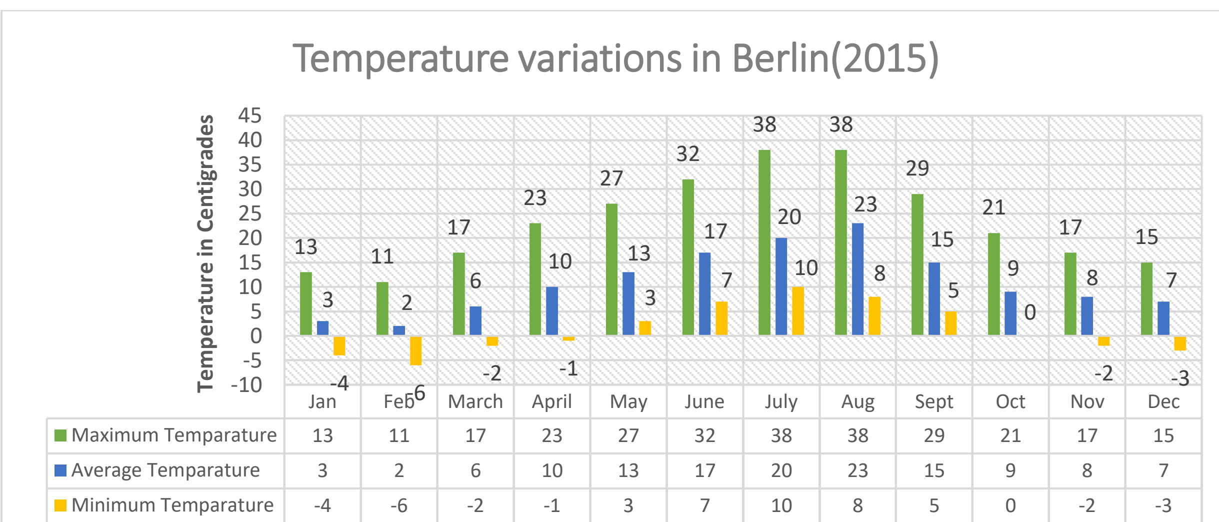


Figure 63 Temperature Variations in Berlin

From the chart shown above, it can be inferred that that Berlin has fairly a pleasant climate from March to June or sometimes can extend to the beginning of July. After this, the climate of Berlin sees a slight rise in temperature along with humidity. But however, the temperature rarely surpasses 35°C. This is followed by the winter which is chilly and frosty at times, especially by the end of the year. But we can get into detail and understand better if we have the number of calculated days which require heating or cooling.

A.2.3 Variation in Heating Degree Days and Cooling Degree Days in Berlin (2015):
With the following charts we can have a better insight into the basis of understanding the necessity of heating and cooling in Mumbai for the year 2015.

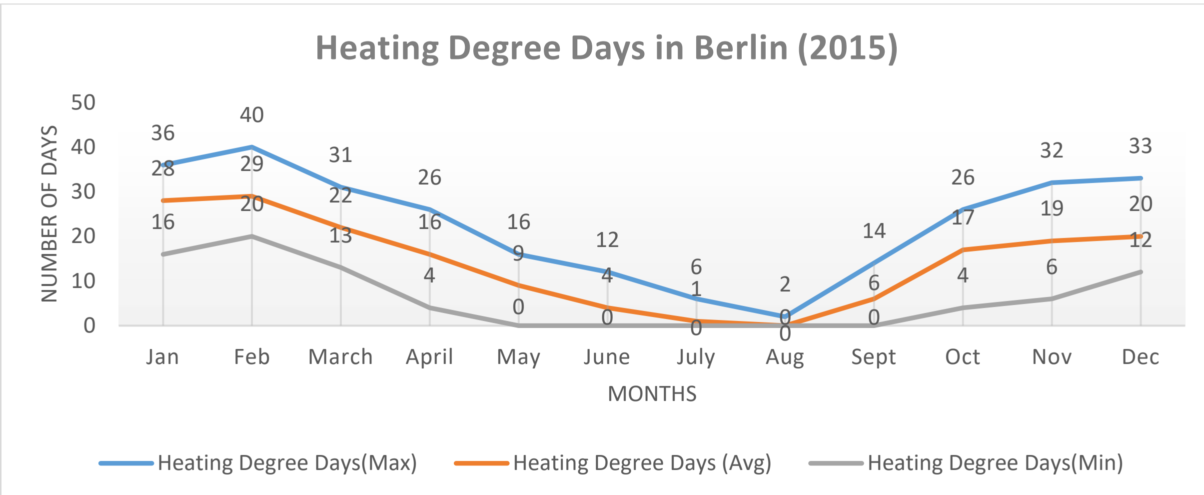


Figure 64 Heating Degree Days in Berlin

From the chart above, we can infer that proper heating is a necessity for winter until the beginning of spring. Again from mid-spring to the end of summer or mid-autumn at most, heating is not at all necessary. Now the number of Cooling Degree Days shall also be checked to actually come to the aim of this task and that is to find out the number of comfortable days during which neither heating nor cooling is necessary.

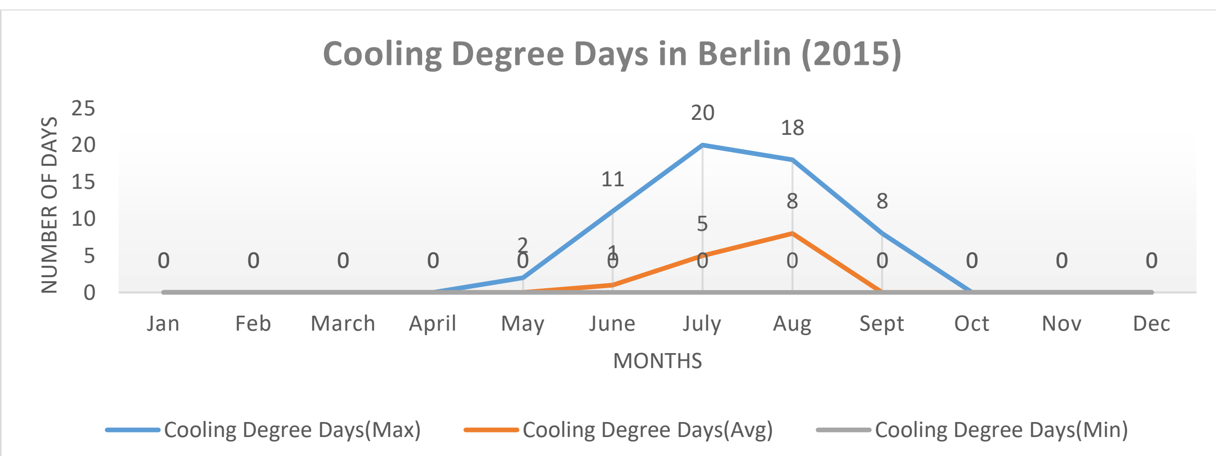


Figure 65 Cooling Degree Days in Berlin

From the table and chart shown above, it can be concluded that on an average during the month of April to the month of August both heating and cooling can be avoided. This is the most pleasant time when the temperature lies in the range of 20°C to 25°C. However, a better picture to understand the comfort level will be mentioned in the following section of Summarization.

A.2.4 Relative Humidity Chart for Berlin (2015)

The following table and charts signify the relative humidity in Berlin for the year 2015.

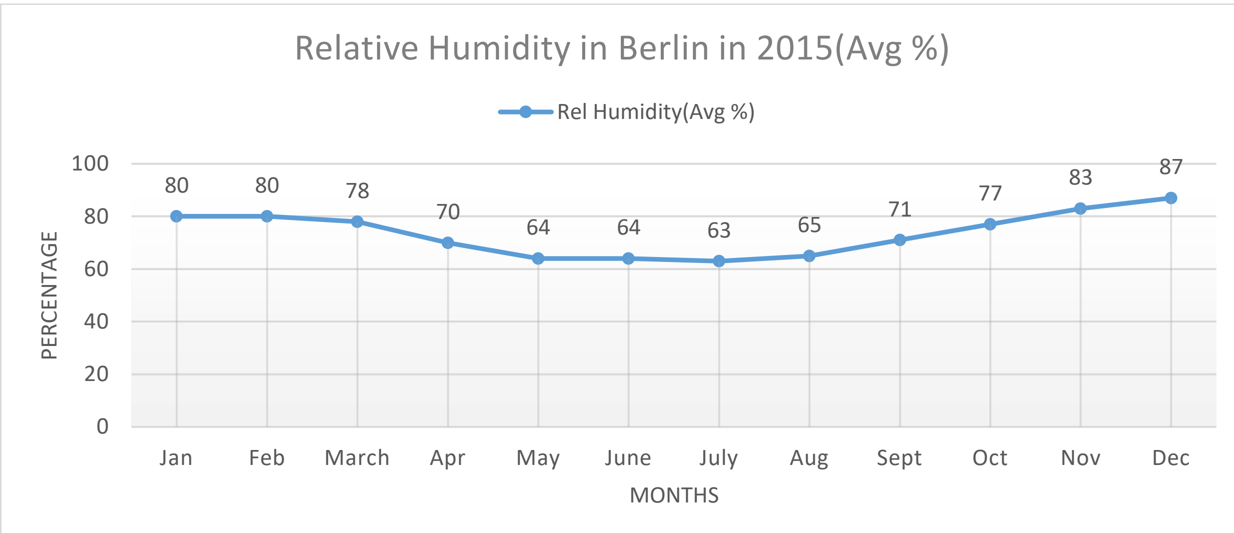


Figure 66 Relative Humidity in Berlin

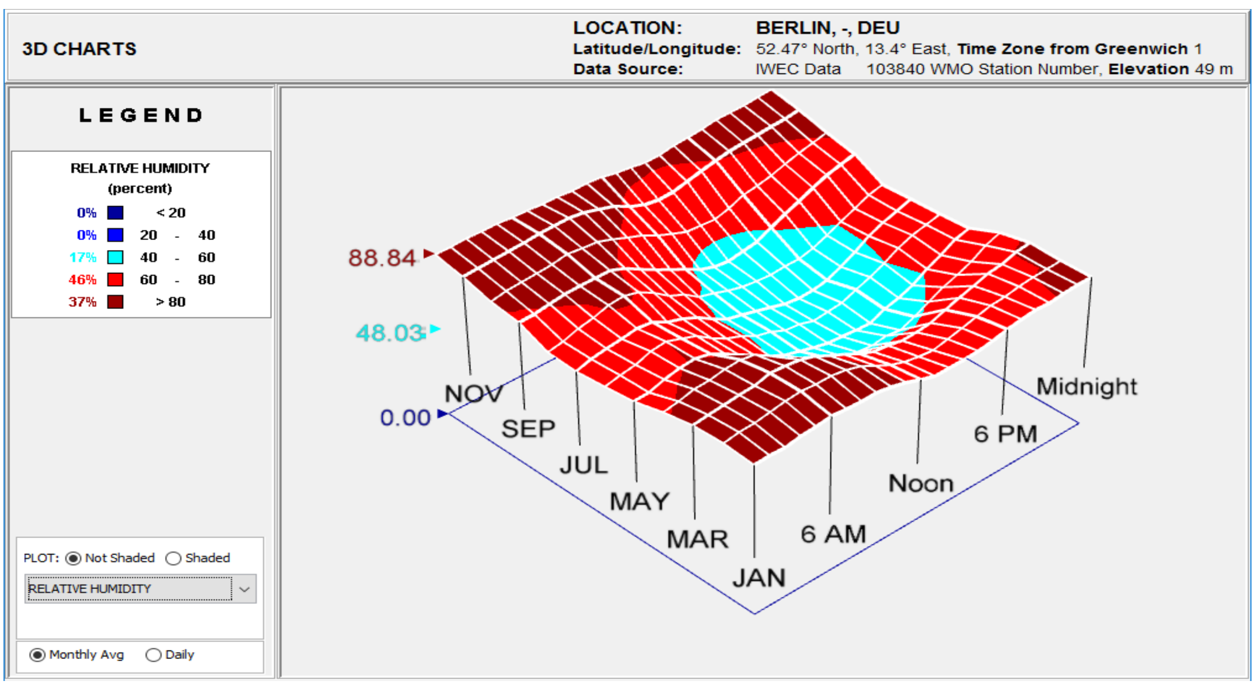


Figure 67 3D-Relative Humidity in Berlin

Over the course of a year, the relative in Berlin generally varies from 40 % which is comfortable to 99 % which is very humid. Altogether the vapor pressure differences across the area of the city is a bit low so that the relative humidity remains inversely proportional to the air temperature.

A.2.5 Temperature Range & Comfort Zonal Chart for Berlin (2015):

With the following chart, the comfort zone in accordance with the temperature variations has been shown for Berlin for the year 2015. According to the aim of this task, the period of comfort where neither cooling nor heating is required has to be found out. Now this chart can be seen as a comparison to the manual data plotting.

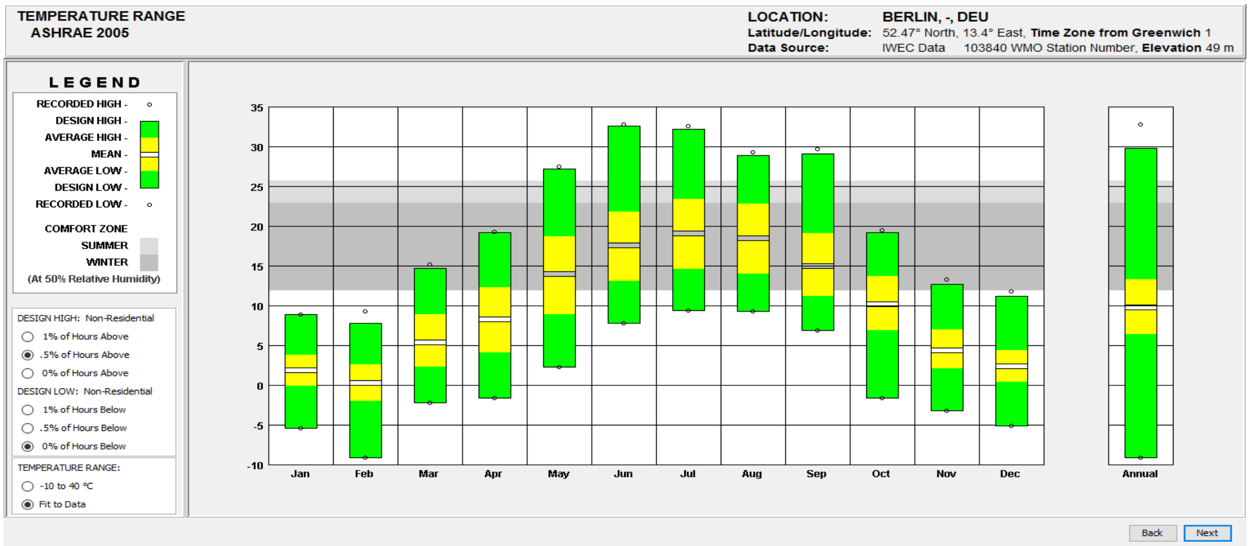


Figure 68 Temperature Range and Comfort Zonal Chart for Berlin

From the chart above it is evident that from the month of May to September, the climate remains pleasant and neither heating nor cooling is required during this course of time. And lastly, we can summarize all the above factors under the next topic of Summarization.

A.2.6 Summarization

The conclusion to all the mentioned weather numerical data can be visualized with the following table which signifies the necessity of Heating or Cooling and comfort level in Berlin for the year 2015.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	December to February	-3°C to 3°C	Very Cool	Heating Required
Spring	March to May	4°C to 14°C	Pleasant.	Very little heating is required only during the beginning of spring

Summer	June to August	20°C to 25°C	Very pleasant	No heating or cooling is required
Autumn	September to November	14°C to 4°C	Pleasant but gets a bit cold by the beginning of November	No heating or cooling is required in the beginning but by the month of November, the temperature starts to get low. So heating provides comfort at that time.

Table 13 Summarization table for Berlin

Lastly, for the summarization, we can understand that on an average, the period from the month of April to the month of August is the most comfortable period of the year. And on an average during the months of June and August, neither heating nor cooling is necessary which helps saving energy, in turn, increasing the efficiency. Due to the climatic variations which are getting bigger and bigger every year, there may be some different figures for the climate of Berlin but the above data has been based on the weather data of the year 2015.

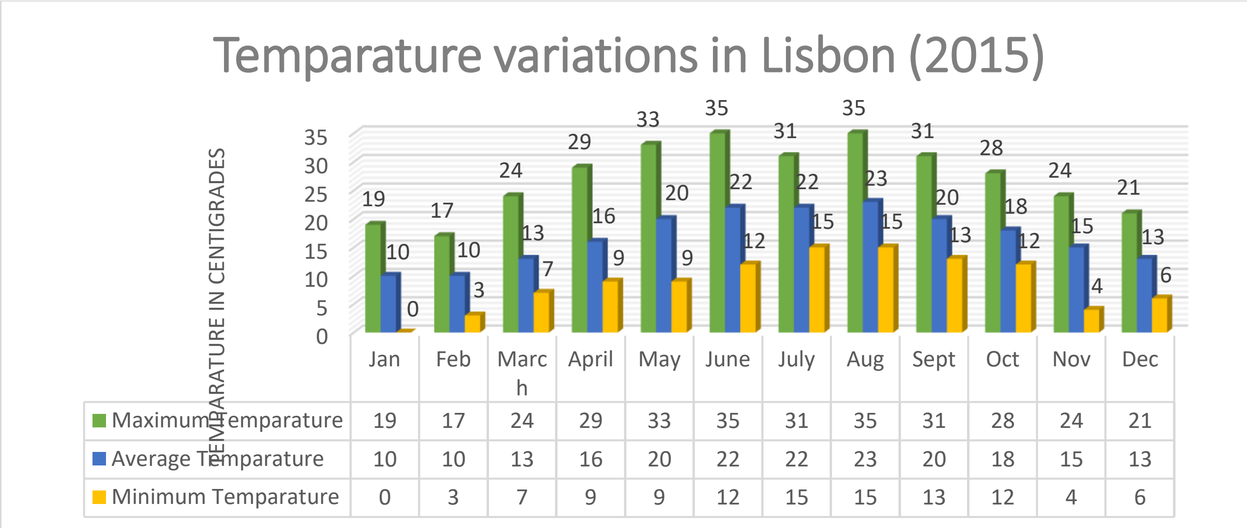
A.3 Work Environment of Lisbon

A.3.1 Introduction

Lisbon, the capital of Portugal is also the largest city in the country. It is located along the Atlantic coast where the Tagus river meets the sea. Lisbon comprises of a warm Mediterranean climate with plenty of clear, bright and sunny days. Lisbon's climate is greatly influenced by the warm gulf stream currents that flow across the Atlantic from North America. Lisbon is gifted with the four seasons namely Spring, Summer, Fall(Autumn) and Winter[73].

A.3.2 Temperature variations in Lisbon in 2015

In accordance with the geographical location, Lisbon is one of the warmest European capitals. It comprises of a Mediterranean climate with sub-tropical properties. The warm ocean currents contribute to Lisbon's advantage of enjoying warm winters. Again the sea breeze also plays a big role during the summer in treating the scorching heat, especially in the evening or at night. However, following the aim of the task, the temperature variations in Lisbon in the year 2015 are to be shown. With the help of these varying numbers, the next step can be followed on, which is the necessity of heating and cooling. So the insight on the temperature variations is necessary in this regard and thus it is represented by the following chart.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Maximum Temparature	19	17	24	29	33	35	31	35	31	28	24	21
Average Temparature	10	10	13	16	20	22	22	23	20	18	15	13
Minimum Temparature	0	3	7	9	9	12	15	15	13	12	4	6

Figure 69 Temperature Variations in Lisbon

From the graphical representation shown above it can be inferred that air temperatures tend to stabilize around 15℃ in winter during the days, without dropping below some 8℃ during the night. Thus snowfalls are rare in Lisbon, but the amount of rainfall is quite notable during the winter with precipitation levels close to 4inches. On the other hand, summers are fairly hot and dry, with temperatures rolling over 30℃. Springs and autumns remain the mildest of all seasons in Lisbon, with average temperatures stabilizing around 20℃. However, this data can be studied further to understand the necessity of heating and cooling for the whole year 2015.

A.3.3 Variation in Heating Degree Days and Cooling Degree Days in Lisbon in 2015

The following charts signify the necessity of heating and cooling if necessary and ultimately shows a graphical picture (if any) when there is no requirement for heating and cooling.

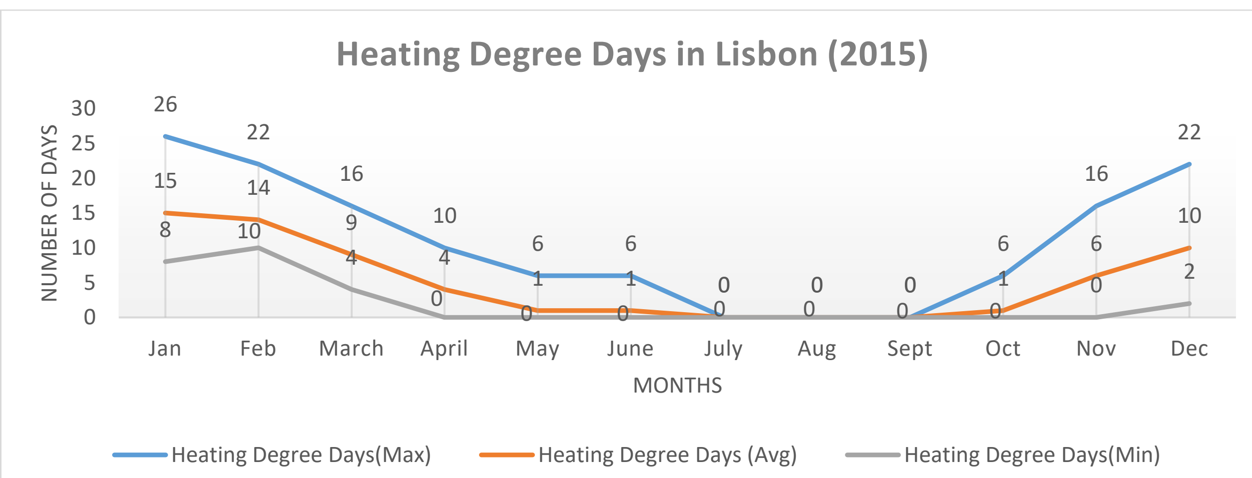


Figure 70 Heating Degree Days in Lisbon

From the chart above it is evident that a building in Lisbon requires a fair amount of heating during the winters to the period of the early spring, while the necessity of heating decreases during the period from late spring to the beginning of Autumn. It is necessary also to have a proper insight in the cooling number of days which is further shown with the help of a graph.

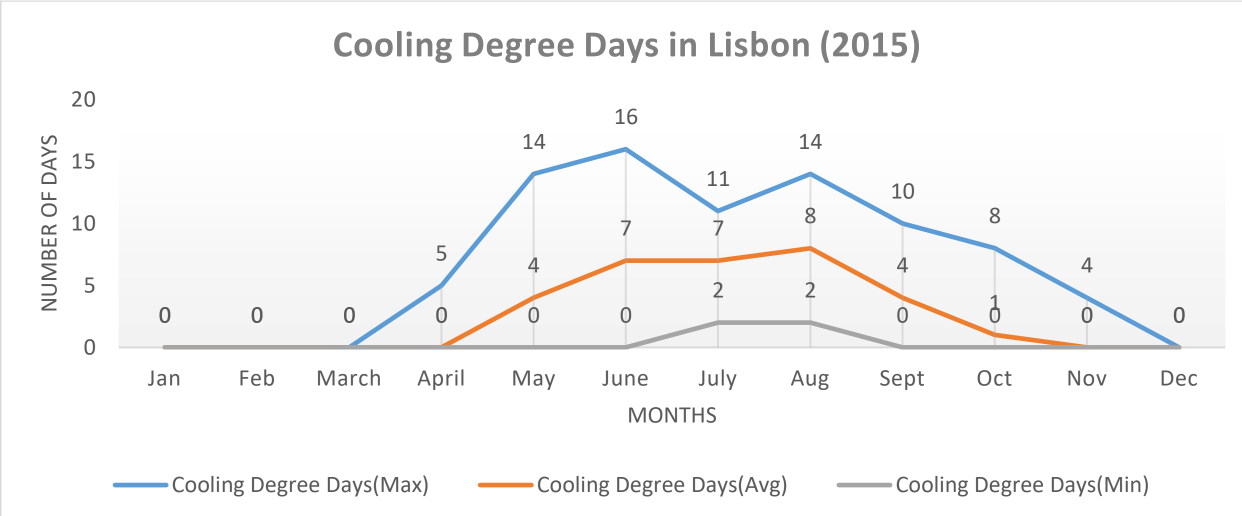


Figure 71 Cooling Degree Days in Lisbon

From the numbers above it can be inferred that by the end of spring, the necessity of cooling increases all across Lisbon. This is due to the fair rise in temperature due to the ocean currents. By the beginning of summer, the temperature soars over 30°C. So cooling it is a necessity by that time. But studying the two graphs (Heating Degree Days and Cooling Degree Days) it can be inferred that on an average between the months of March to the month of June, heating or cooling can be avoided. But however, there are exceptions and the numbers can be different over the course of years. This is just an average calculated assumption.

A.3.4 Relative Humidity Chart for Lisbon in 2015

The following chart exhibit the figures of relative humidity in Lisbon for the year 2015.

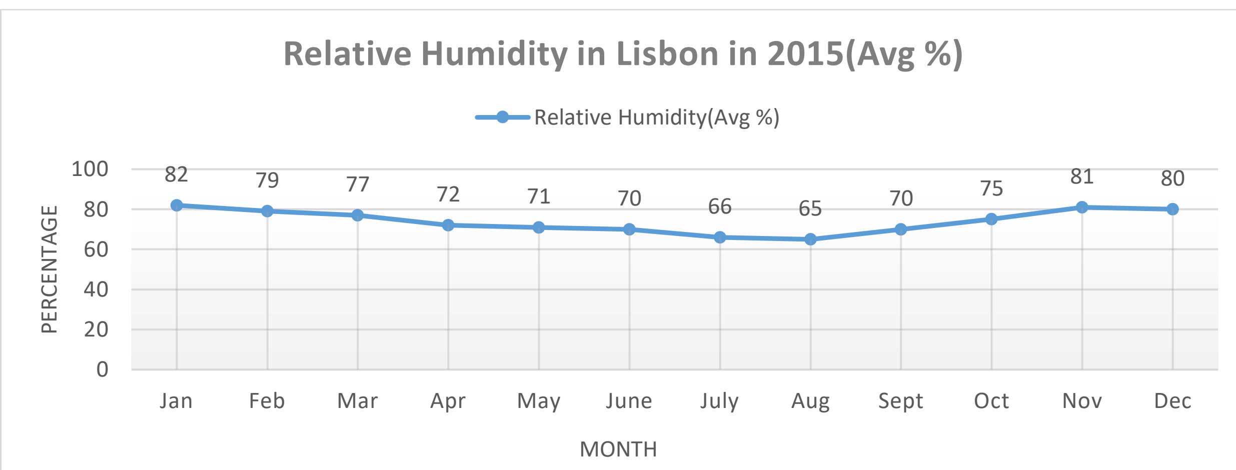


Figure 72 Relative Humidity in Lisbon

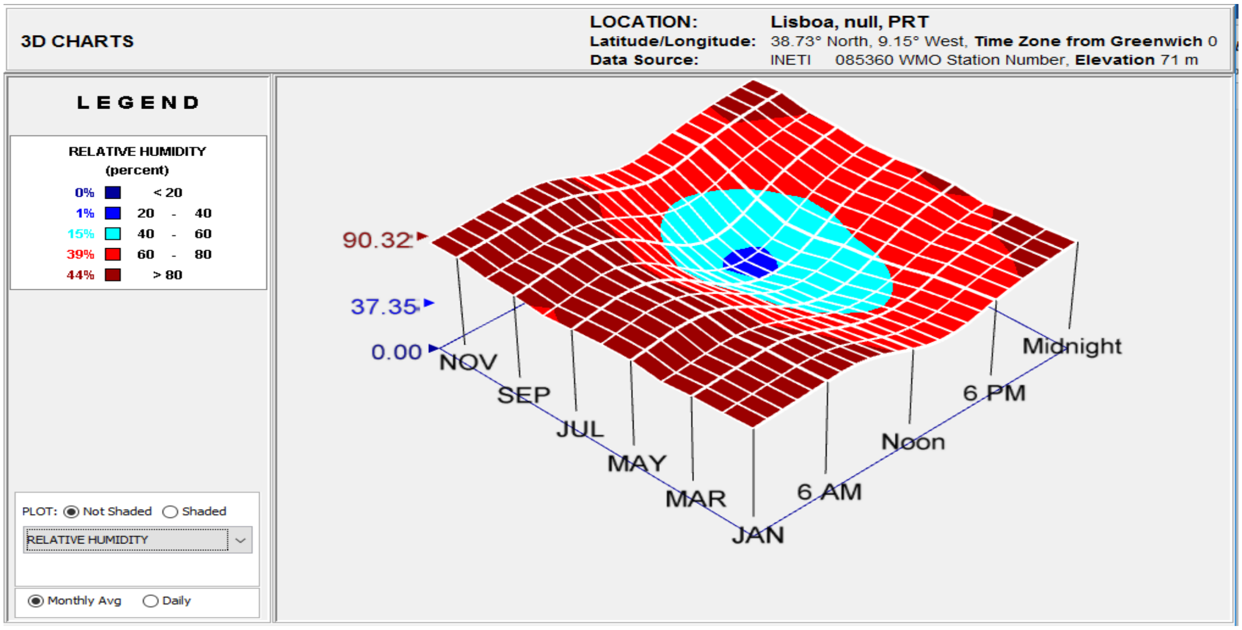


Figure 73 3D-Relative Humidity in Lisbon

The average annual relative humidity is 70.8 %. the relative humidity typically varies from 42 % which is comfortable to 96 % which is very humid. August is the driest month during which the relative humidity remains below 50 %

A.3.5 Temperature Range & Comfort Zonal Chart for Lisbon in 2015

With the following chart, the comfort zone in accordance with the temperature variations has been shown for Lisbon for the year 2015. According to the aim of this task, the period of comfort where neither cooling nor heating is to be shown. The following chart can also be seen as a comparison to the manual data plotting.

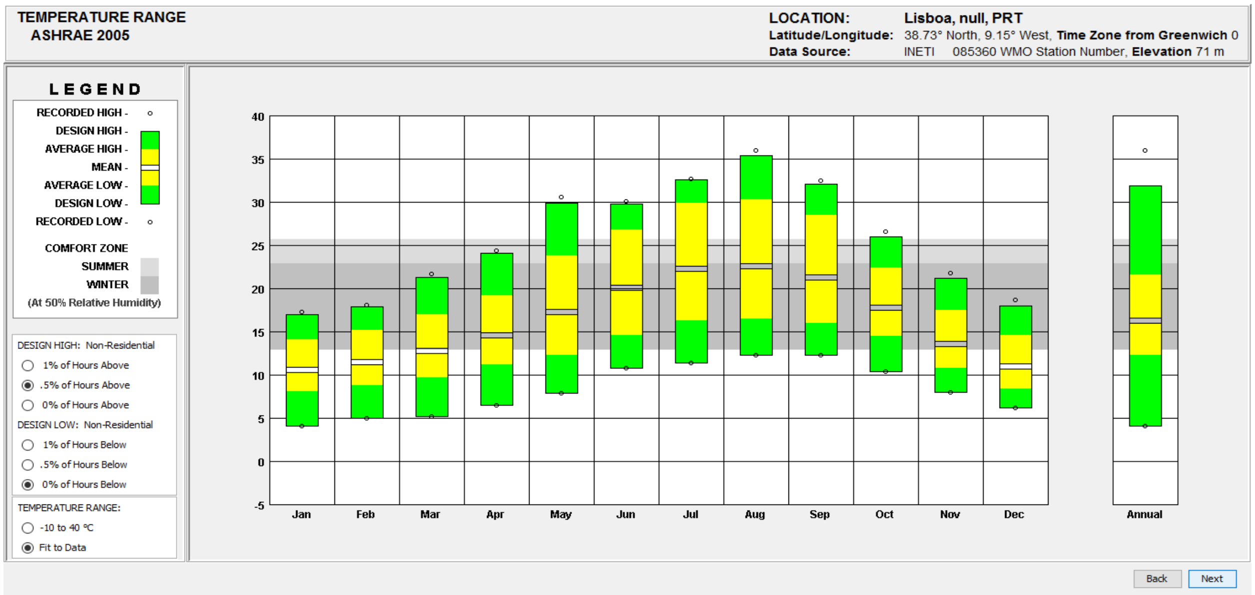


Figure 74 Temperature Range and Comfort Zonal Chart for Lisbon

From the chart above it is clear that from the period of mid-spring (March) till almost to the mid-summer Lisbon enjoys a pleasant and comfortable climate. Lisbon is also blessed with a pleasant Autumn (September, October and November) during which the temperature remains well inside the comfort zone.

A.3.6 Summarization

The conclusion to all the above-mentioned weather numerical data can be visualized with the following table which signifies the necessity of Heating or Cooling and comfort level in Lisbon for the year 2015.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	December to February	6°C to 15°C	Very Cool	Heating Required
Spring	March to May	15°C to 24°C	Pleasant.	Neither Heating or Cooling is necessary
Summer	June to August	22°C to 35°C	Fairly hot	Cooling is necessary
Autumn	September to November	15°C to 25°C	Pleasant but gets a bit cold by the beginning of November	No heating or cooling is required in the beginning but by the month of November, the temperature starts to get low. So heating provides comfort at that time.

Table 14 Summarization table for Lisbon

Lastly, for the summarization, we can understand that on an average, the period from the month of March to the month of May and along with it the beginning of Autumn are the most comfortable periods of the year. Due to the climatic variations, which is getting bigger and bigger every year, there may be some different figures for the climate of Lisbon but the above data has been based on the weather data of the year 2015.

A.4 Work Environment of Copenhagen:

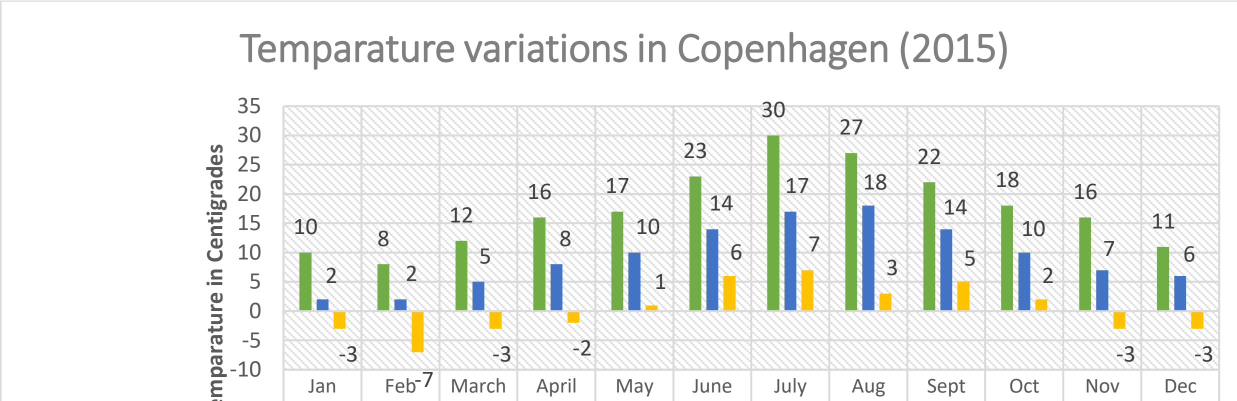
A.4.1 Introduction:

Copenhagen has a mild and temperate climate with cool winters and mild summers that are brought by the west winds hitting the city and influencing the gulf stream current system. The city experiences four distinct seasons namely spring, summer, autumn and winter. July and August tend to be the warmest months in the year whereas February seems to be the coldest. Rainfall can be expected all-round the year except during the summers [74].

A.4.2 Temperature variations in Copenhagen in 2015

Having a mild temperate climate Copenhagen is marked with mild summers and very cold winters. However, following the aim of this task, the temperature variations for Copenhagen in the year

2015 has been plotted out. This following chart can further be used as an approach to find out the days when Heating or Cooling could be necessary.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Maximum Temparature	10	8	12	16	17	23	30	27	22	18	16	11
Average Temparature	2	2	5	8	10	14	17	18	14	10	7	6
Minimum Temparature	-3	-7	-3	-2	1	6	7	3	5	2	-3	-3

Figure 75 Temperature Variations in Copenhagen

From the chart above it can be understood that the winter gets extremely chilly with average temperatures falling below freezing point and the minimum temperature is even below -5℃. Again as the spring progresses towards summer the temperature starts to rise and stays just above 22℃. The period of mid-spring till the end of summer is the most pleasant and comfortable climate in Copenhagen. Again, the temperature starts to fall from the mid-autumn towards the beginning of winter. Overall Copenhagen enjoys a mild summer and a cold winter. However, by the following heating and cooling chart, we will be able to signify the number of days required for heating and cooling.

A.4.3 Variation in Heating Degree Days and Cooling Degree Days in Copenhagen in 2015

From the following plotted graph, we are to get a better understanding about the necessity of heating and cooling in Copenhagen. The following plot is based on the weather data collected for Copenhagen for the year 2015.

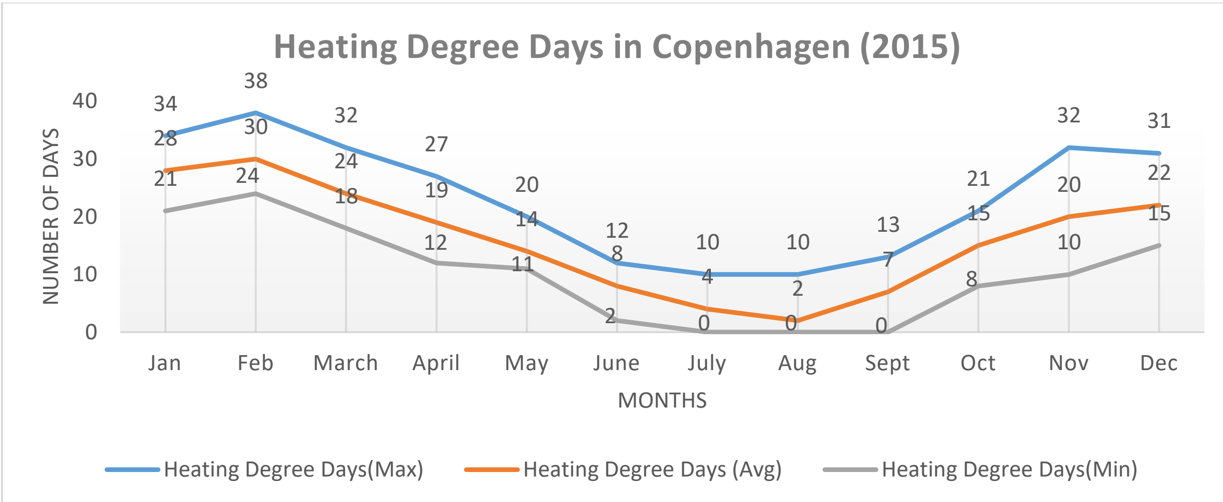


Figure 76 Heating Degree Days in Copenhagen

From this above-mentioned chart, Copenhagen requires heating from mid-autumn to the mod of spring and also even sometimes during the summers. Maybe only during the summer the necessity of heating decreases and to maintain proper thermal comfort inside a building, heating is maintained in accordance with the weather outside. Now by seeing the number of Cooling Degree Days, we will have a clear picture of the whole heating and the cooling system.

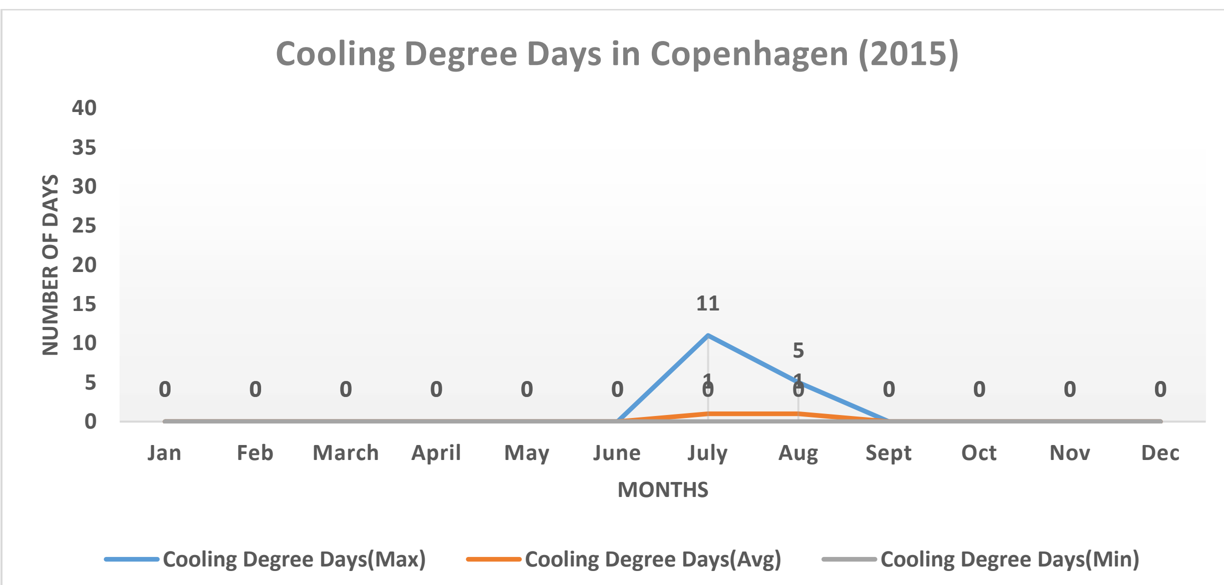


Figure 77 Cooling Degree Days in Copenhagen

So from the table and the plotted graph above it can be inferred that cooling is not a necessity in Copenhagen. Maybe during the summer, a bit of cooling can be implemented for a few days but due to a pleasantly warm temperature in summer cooling can be avoided. Except for summer, the temperature for the rest of the year remains just below 10℃ for which cooling is not required. But in today's world, the temperature is rising due to varying climatic reasons. So the numbers may vary for the near future but all the above tables and the plots are based on the weather data collected for the year 2015.

A.4.4 Relative Humidity Chart for Copenhagen in 2015

The average annual relative humidity for Copenhagen is 73.4 %. The monthly average relative varies from 70 % in May to 85 % in January. However, the relative humidity in Copenhagen for the year 2015 has been plotted out.

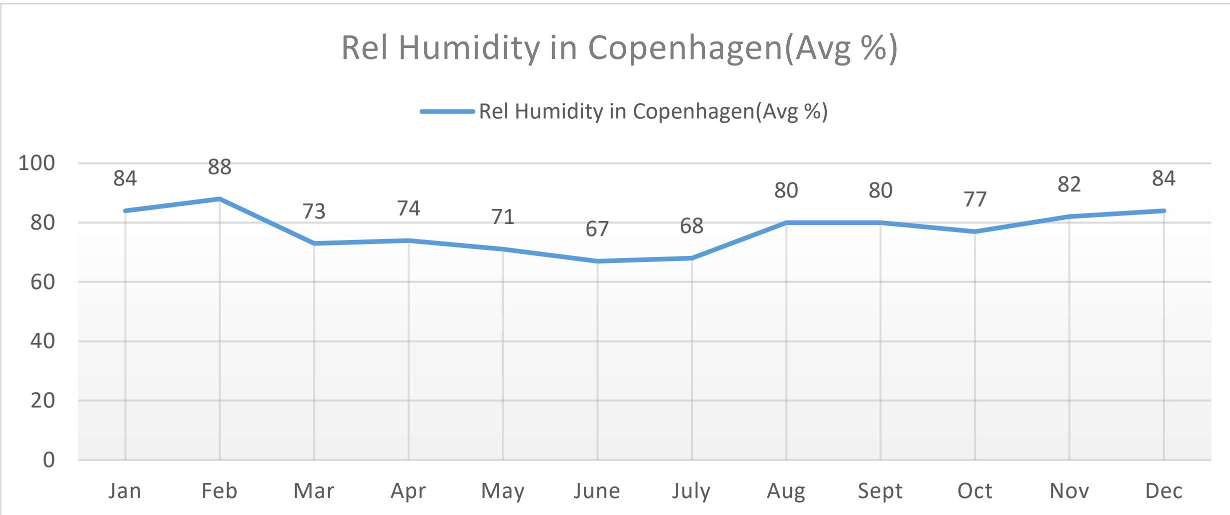


Figure 78 Relative Humidity in Copenhagen

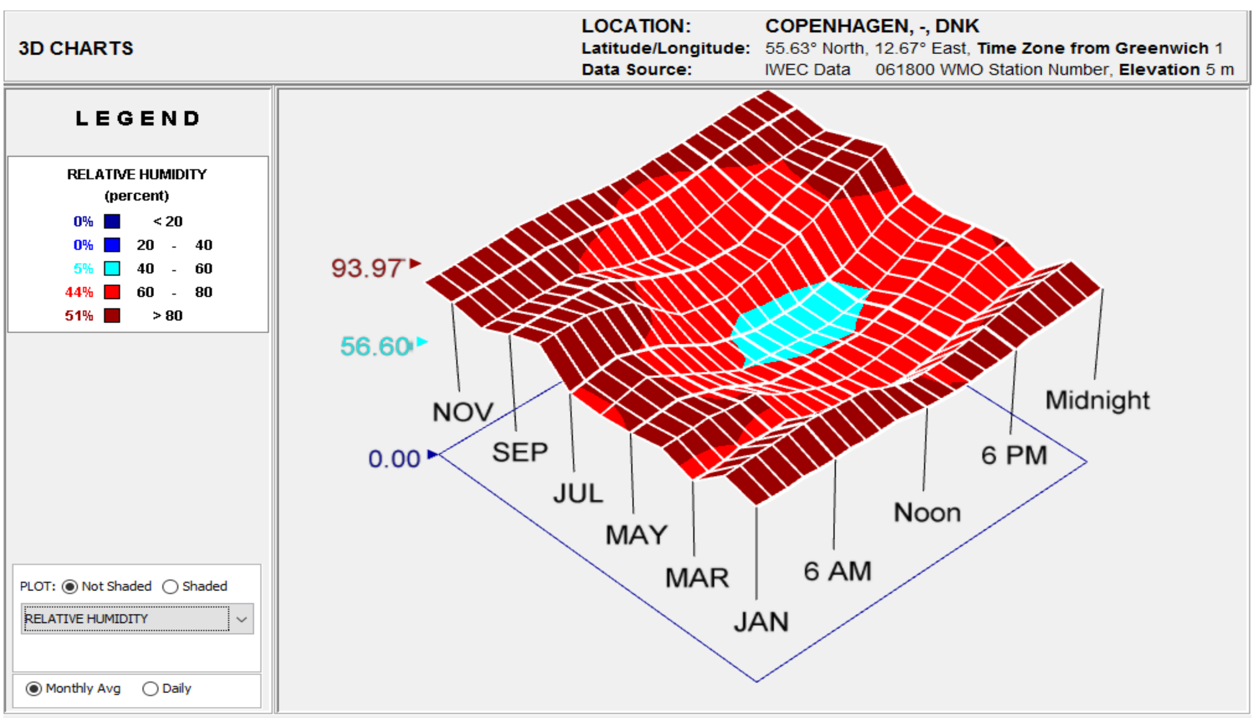


Figure 79 3D-Relative Humidity in Copenhagen

From the table and the plots above we can understand that the relative humidity generally decreases during the mid of the year from mid-spring to the mid-autumn. But again by the end of the autumn, the humidity starts to increases and lasts for the entire winter. The relative humidity during the year 2015 is highest in the month of February which is 88 % and lowest in the month of June which is just over 65 %.

A.4.5 Temperature Range and Comfort Zonal Chart for Copenhagen in 2015

After collecting all the necessary raw data and comparison of the above plots the comfort zonal chart is being plotted so that we can get a better insight into the comfort zone where there should be no heating or cooling necessary. But for Copenhagen as from the heating and the cooling chart, we can see that on one hand there is almost no cooling implemented for the whole year whereas on the other hand heating is a necessity for almost the entire year. In spite of this, there still prevails a comfort zone and that is during the summer season. However, a combined chart of Temperature Range and Comfort Zones is shown below.

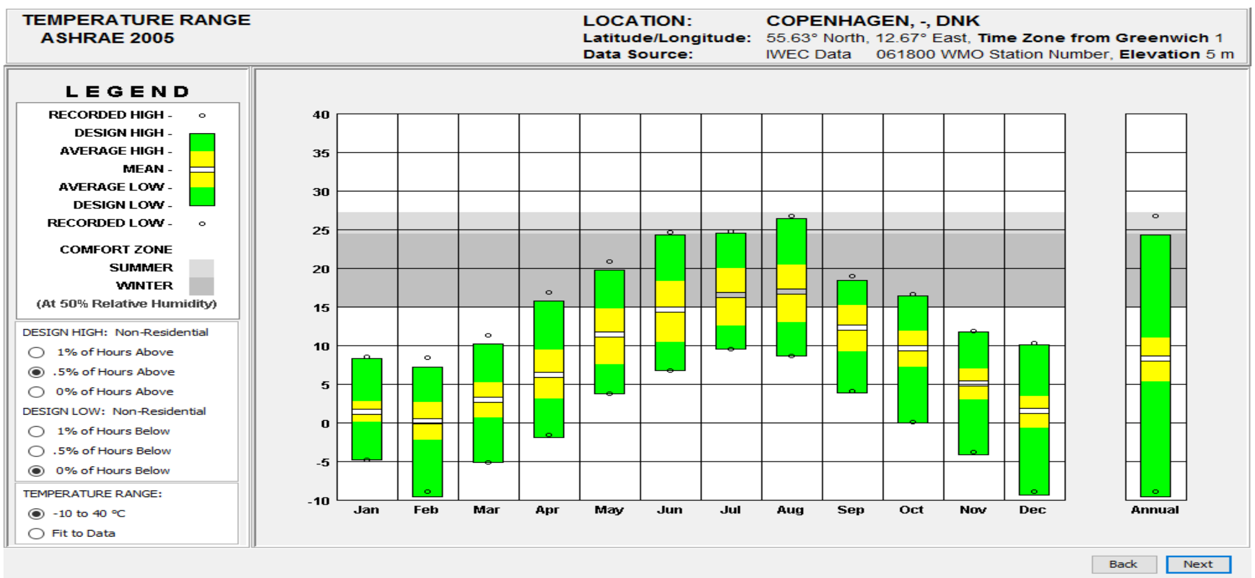


Figure 80 Temperature Range and Comfort Zonal Chart for Copenhagen

Thus from the plot above it can be inferred that the months of June, July and August are really comfortable and pleasant, though the comfort level in the climate starts to take its color from the beginning of summer only.

A.4.6 Summarization

The conclusion to all the above data for Copenhagen is summarized by this following table which signifies the thermal comfort level for each season in Oslo.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	December to March	-1°C to -5°C	Very cold	Heating is a necessity

Spring	March to May	2℃ to 10℃	Slightly cold	Heating is required
Summer	June to August	12℃ to 20℃	Warm	Little heating may be required
Autumn	September to November	15℃ in Sept to 7℃ in Nov	Mild but gets a bit cold by the beginning of November	Heating is required

Table 15 Summarization table for Copenhagen

From the chart above it can be understood that comfort prevails during the time of spring and summer. But seeing the comfort levels, there is no exact or completely comfortable season that prevails in Copenhagen during which neither heating or cooling is necessary.

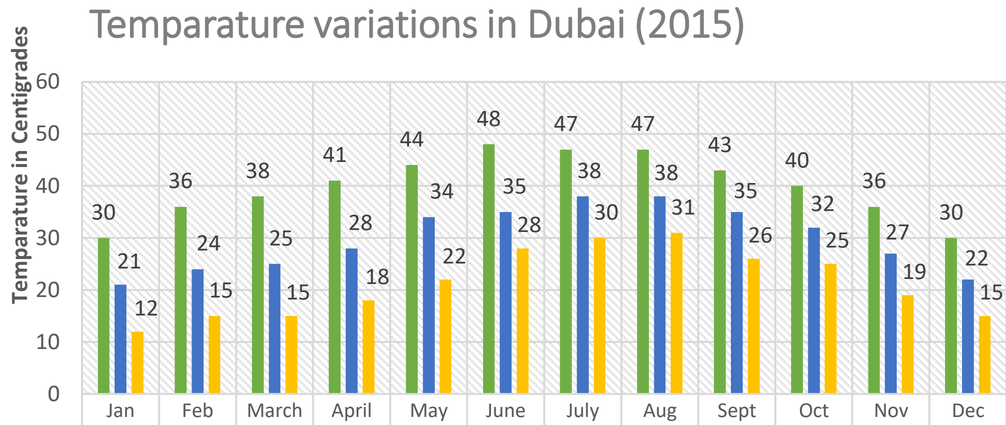
A.5 Work Environment of Dubai

A.5.1 Introduction

Dubai is the largest city in the United Arab Emirates and also the capital city of Emirate of Dubai. It is located on the eastern coast of the Arabian Peninsula and in the south-west corner of the Arabian Gulf. It is divided by a Dubai Creek, a 100-1300 m wide and 14 km long bay of the Persian Gulf. Dubai is marked with an arid subtropical climate and the weather usually remains hot and humid with a high daily average of sun hours. This is due to its position which is very near to the Tropic of Cancer. Generally, the skies in Dubai remain completely blue with some partial cloud cover at times. This attracts many astronomers from all over the world. Short and irregular rainfall is very much evident in the Middle East and for Dubai mostly the rainfall occurs during the months of December and March. Dubai generally enjoys three seasons namely Summer, Rainy and Winter [75].

A.5.2 Temperature variations in Dubai in 2015

Dubai has an arid subtropical climate which is very hot and humid during the summers and fairly warm and pleasant at times during the winter. The summer temperatures soar over 45℃ along with very high humidity whereas the winter temperatures remain pleasant at around 25℃ due to sufficient rainfall in the region. February gets maximum rainfall. Following the objective of this task the temperature variation for the year 2015 has been found out and plotted which is shown below and this can also be used as an insight to understand the necessity of heating and cooling.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Maximum Temparature	30	36	38	41	44	48	47	47	43	40	36	30
Average Temparature	21	24	25	28	34	35	38	38	35	32	27	22
Minimum Temparature	12	15	15	18	22	28	30	31	26	25	19	15

Figure 81 Temperature Variations in Dubai

From the chart above it can be foreseen that the temperatures of 2015 soar very high with maximum temperature over 40°C during the months from April to October. During this time the average temperatures also lie well above 35°C. Months of July, August and October are very hot and along with that the relative humidity also remains very high. However, as November approaches sufficient amount of rainfall happens across the city which increases till the month of February. Overall Dubai experiences a pleasant Winter with a couple of showers which brings down the temperature during this course of time.

A.5.3 Variation in Heating Degree Days and Cooling Degree Days for Dubai in 2015

With the following graphical plots, we can understand the variation in HDD and CDD to further have a better insight into the necessity of heating and cooling in Dubai in 2015.

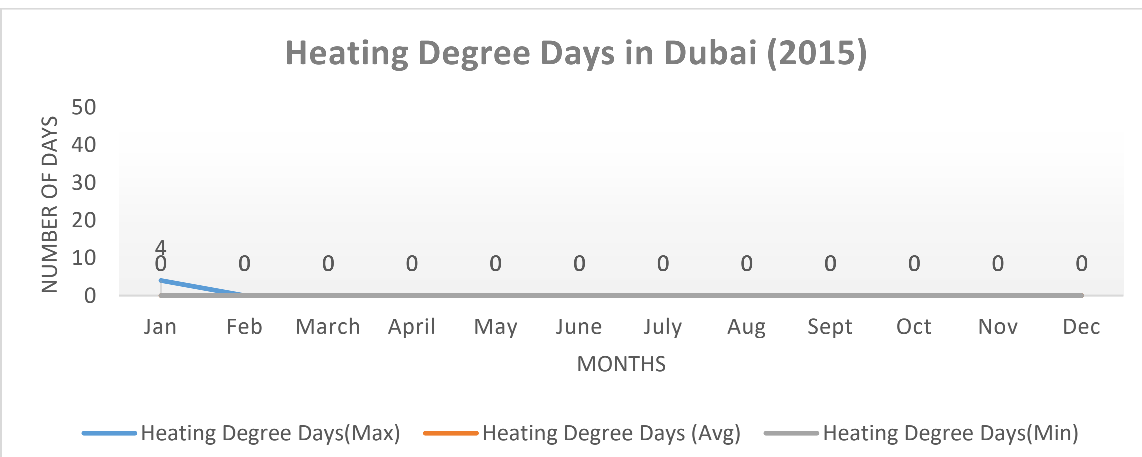


Figure 82 Heating Degree Days in Dubai

From the plot above it can be well understood that there no necessity of heating in Dubai as it is very near to Tropic of Cancer and it enjoys an arid subtropical climate due to which the weather for the entire year remains very hot and humid. Now with the following plot, we can judge the necessity of cooling in Dubai for the year 2015.

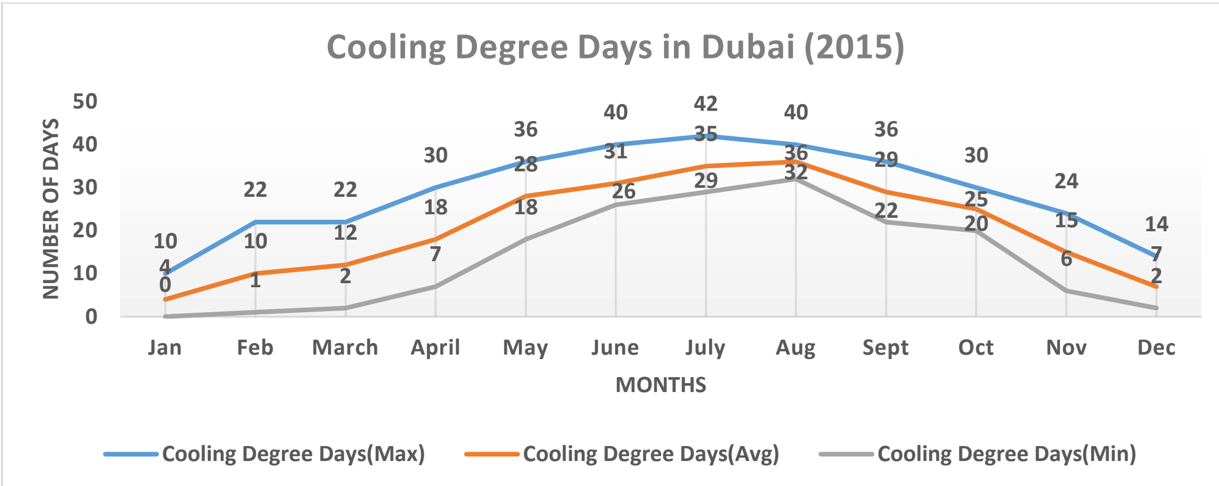


Figure 83 Cooling Degree Days in Dubai

From the numbers and plot above it is very much evident that due to the extreme climate in Dubai, it is an absolute necessity for proper cooling. And on an average during the summer season that is from April to October, the Cooling Degree Days are more as compared to the winter season. This implies that this course of time requires more cooling as compared to other periods of the year. However, there is no perfect comfort zone in the seasons of Dubai but it exhibits a fairly pleasant climate during winter when the average temperatures remain below 25℃.

A.5.4 Relative Humidity Chart for Dubai in 2015

The relative humidity in Dubai generally varies from 26% which is very dry to 92% which is very humid over the course of the year. However, as the relative humidity plays an important role in understanding the necessity of maintaining the thermal comfort in a building, the weather data for the year 2015 has been further studied to plot the relative humidity of Dubai in 2015.

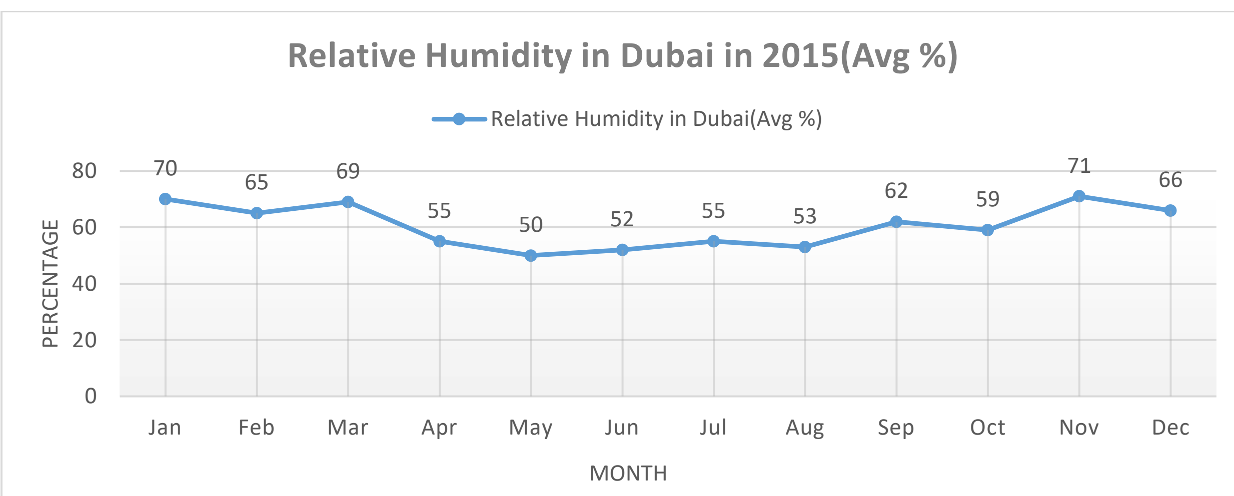


Figure 84 Relative Humidity in Dubai

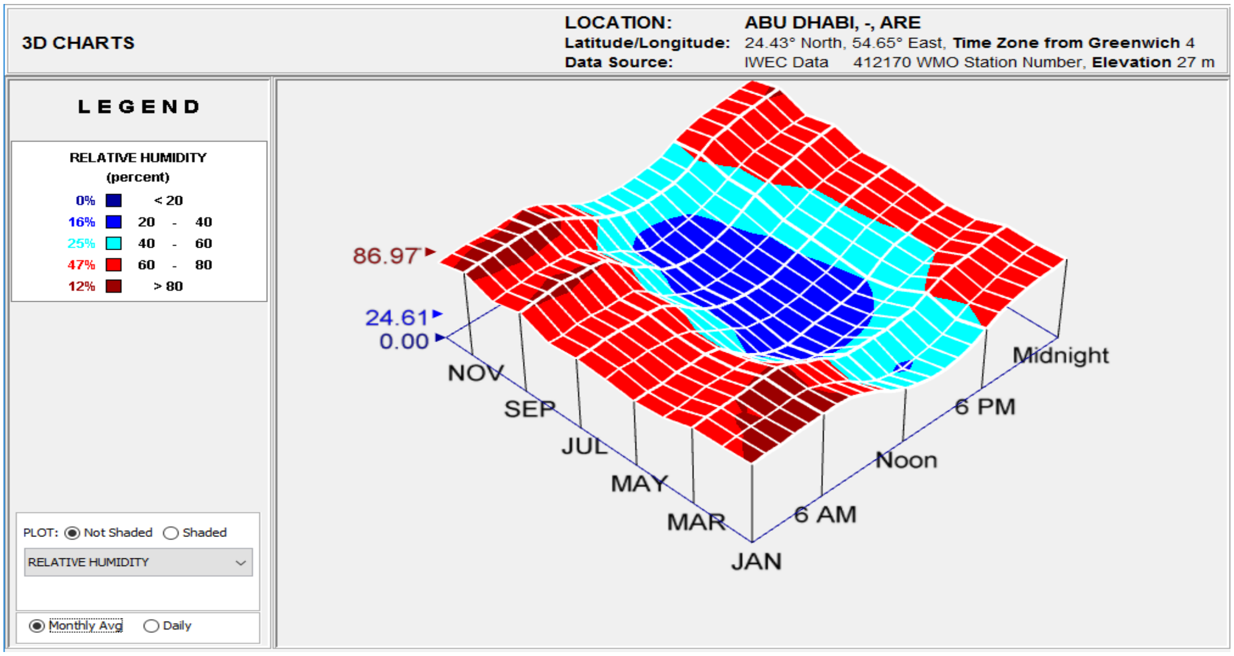


Figure 85 3D-Relative Humidity in Dubai

From the above table and the plots, it is clear that the relative humidity in Dubai in the year 2015 was generally high during the rainy and the winter season as compared to the summer season. The relative humidity in Dubai for the year 2015 was highest in the month of November (71 %) and lowest in the month of May (50 %).

A.5.5 Temperature Range and Comfort Zonal Chart for Dubai in 2015

The following chart can be treated as an abbreviation to all the above weather data tables and graphical representations. The significance of this chart is that it exhibits a comfort zone with maximum and minimum comfortable temperature scales. And then it shows us the actual weather data on the basis of that comfort zone so that we can understand that which time during the year falls under the comfort zone.

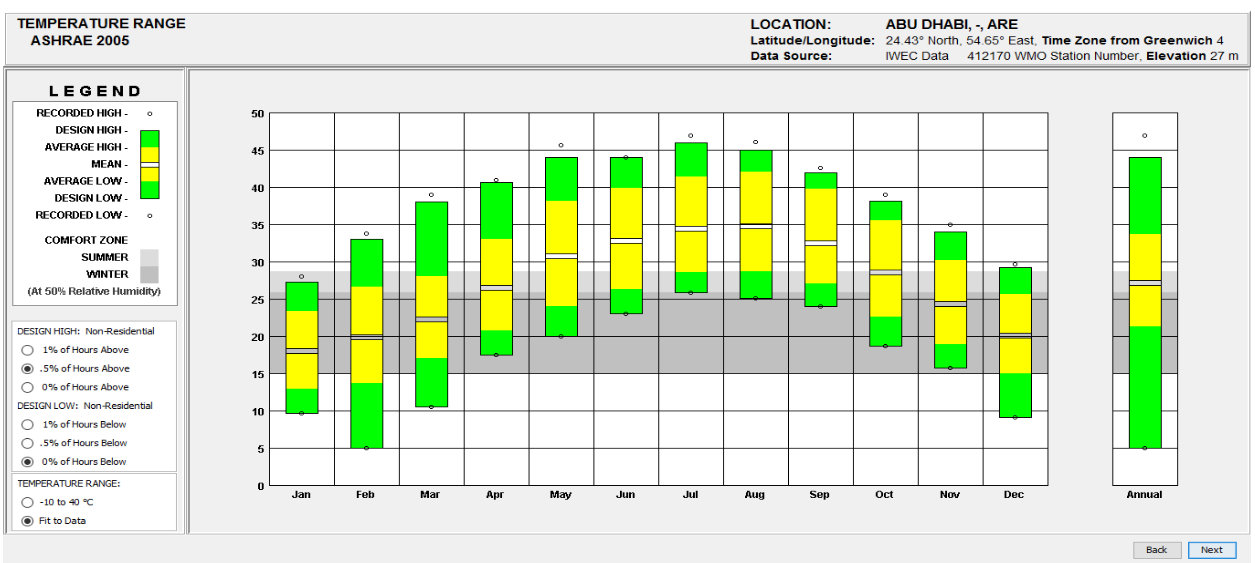


Figure 86 Temperature range and Comfort Zonal Chart for Dubai

So from the plot above, we can infer that the rainy and the winter season comes somewhat under the comfort zone when the temperatures lie just above 20℃. But from the HDD chart and CDD chart it should not be forgotten that even these months comes under the comfort zone, this is not the perfect comfort zone or the ideal weather condition where there is no necessity of heating and cooling. This comfort zone is comparably pleasant as compared to the extreme weather conditions for the rest of the year.

A.5.6 Summarization:

The conclusion to all the above weather data for Dubai in the year 2015 is being summarized on the basis of thermal comfort level for each season in Dubai.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	January to March	15℃ to 25℃	Pleasant	Cooling is necessary
Summer	April to October	35℃ to 48℃	Extremely hot	Cooling is a must
Rainy	November to February	22℃ to 27℃	Pleasant	Cooling is necessary

Figure 87 Summarization table for Dubai

Lastly from the chart above it is inferred that the climate is pleasant during the rainy and winter compared to the extreme summer. As during this time, high humidity enforces the cooling to be necessary.

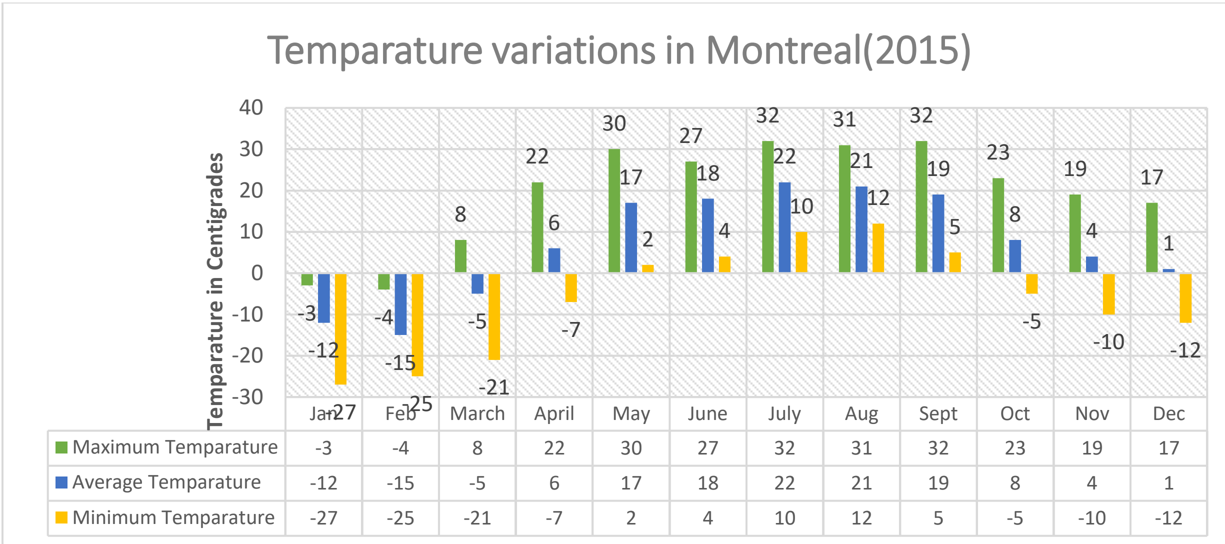
A.6 Work Environment of Montreal

A.6.1 Introduction

Montreal, a metropolis in Canada is situated in the southwestern province of Quebec on the Island of Montreal. It gives shelter to around 4 million residents. Out of this 1.7 million people speak French which makes it the second largest French-speaking city in the world after Paris[76]. When we talk about the climate of Montreal, it has a semi-continental climate which is marked with a warm humid summer and an extremely chilly winter. However, Montreal enjoys four seasons namely Spring, Summer, Autumn and Winter [77].

A.6.2 Temperature variations in Montreal in 2015

Enjoying a semi-continental climate, Montreal experiences very warm and humid summer to extremely cold winter. But however, during the course of this time, the average summer temperatures remains close to 30℃. Sometimes it can also be just over 30℃. The overnight temperatures during this time remain close to 15℃. Whereas during the period of Winter the temperatures remain well below the freezing point and sometimes it can be as cold as -30℃. However, following the aim of this task, the weather data of Montreal for the year 2015 has been worked on to show the temperature variations in Montreal throughout the year.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Maximum Temparature	-3	-4	8	22	30	27	32	31	32	23	19	17
Average Temparature	-12	-15	-5	6	17	18	22	21	19	8	4	1
Minimum Temparature	-27	-25	-21	-7	2	4	10	12	5	-5	-10	-12

Figure 88 Temperature Variations in Montreal

From the chart above it is evident that Montreal experiences fairly warm and high temperatures during the summer whereas on the other hand during the winter the average temperature remains well below the freezing point. These temperature variations can help in understanding the necessity of heating and cooling in Montreal during these months.

A.6.3 Variation in Heating Degree Days and Cooling Degree Days in Montreal in 2015

With the following graphical plots the necessity of heating and cooling in Montreal can be identified and thus accordingly measures can be taken.

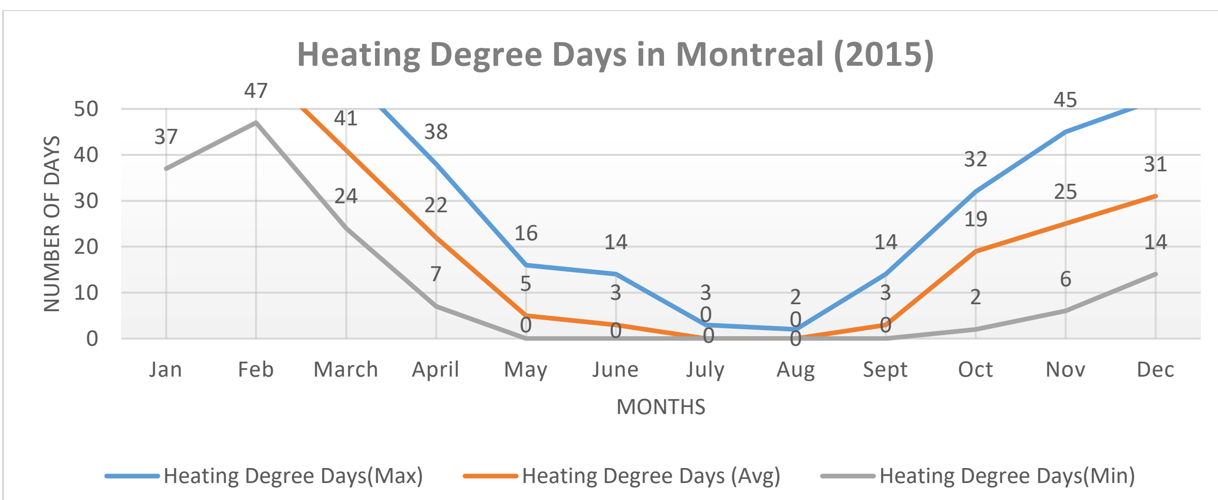


Figure 89 Heating Degree Days in Montreal

From the chart and the table above it can be inferred that except one or two months in the summer, Montreal requires proper heating during the other months as the temperature remains just above the freezing level in the beginning of Spring and Autumn whereas it falls well below the freezing level in the winter. Now when we look into the plot of Cooling Degree Days, the picture should get clear and vivid about the time (if any) when we may avoid both heating and cooling.

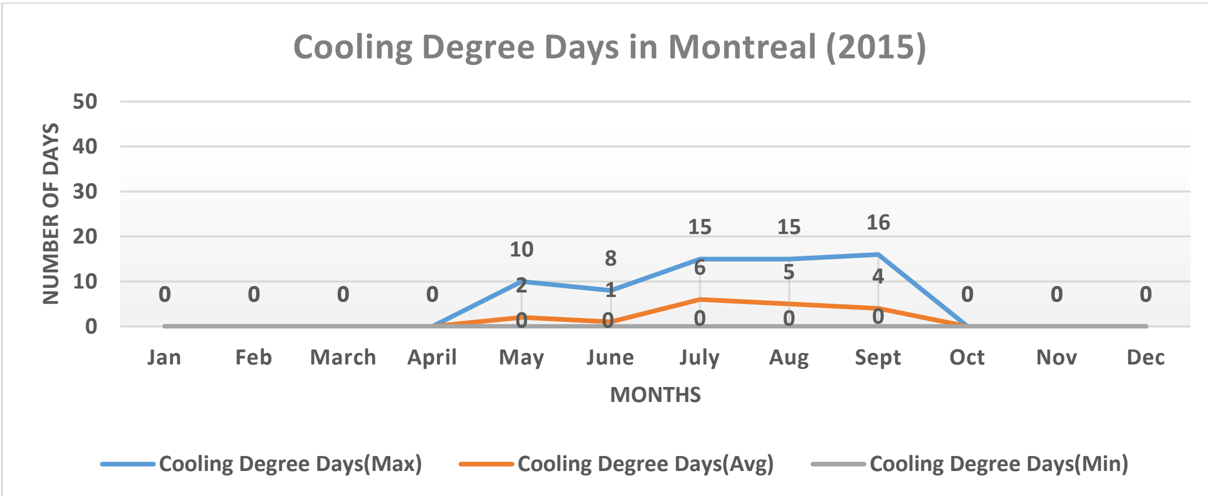


Figure 90 Cooling Degree Days in Montreal

So from the table and the chart above it can be understood that only during the months of May, June, July, August and September, cooling may be implemented also depending upon the level of humidity in the air. But however, if the humidity is also less, even though the days are warm, the cooling can be avoided at times. The thermal comfort level during the year 2015 is explained later under summarization.

A.6.4 Relative Humidity Chart for Montreal

The relative humidity in Montreal generally varies from 37 % which is comfortable to 89 % which is very humid. However, for the weather data of Montreal for the year 2015, the relative humidity during the specified year has been calculated.

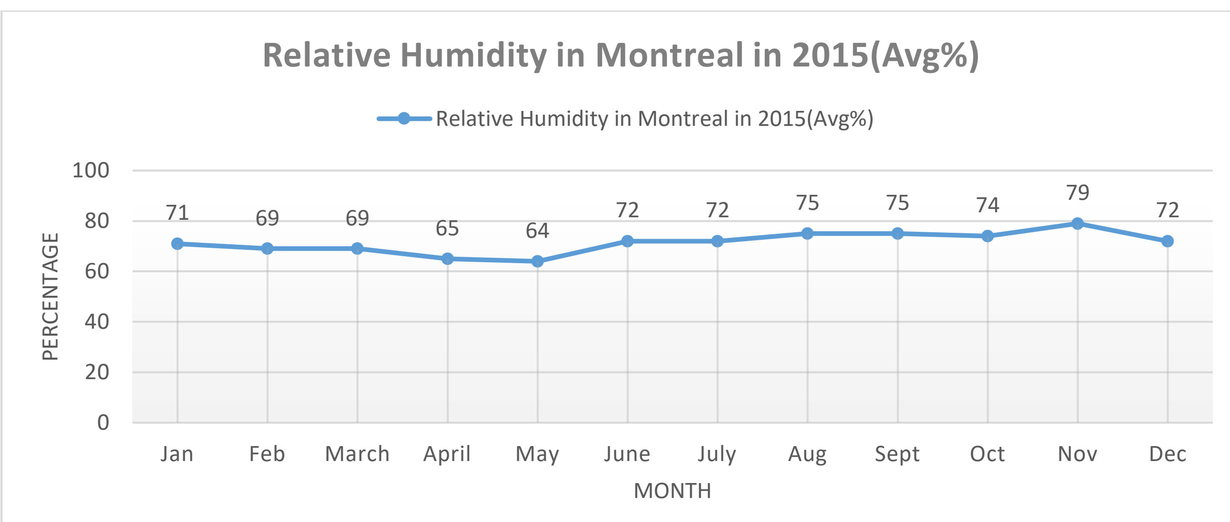


Figure 91 Relative Humidity in Montreal

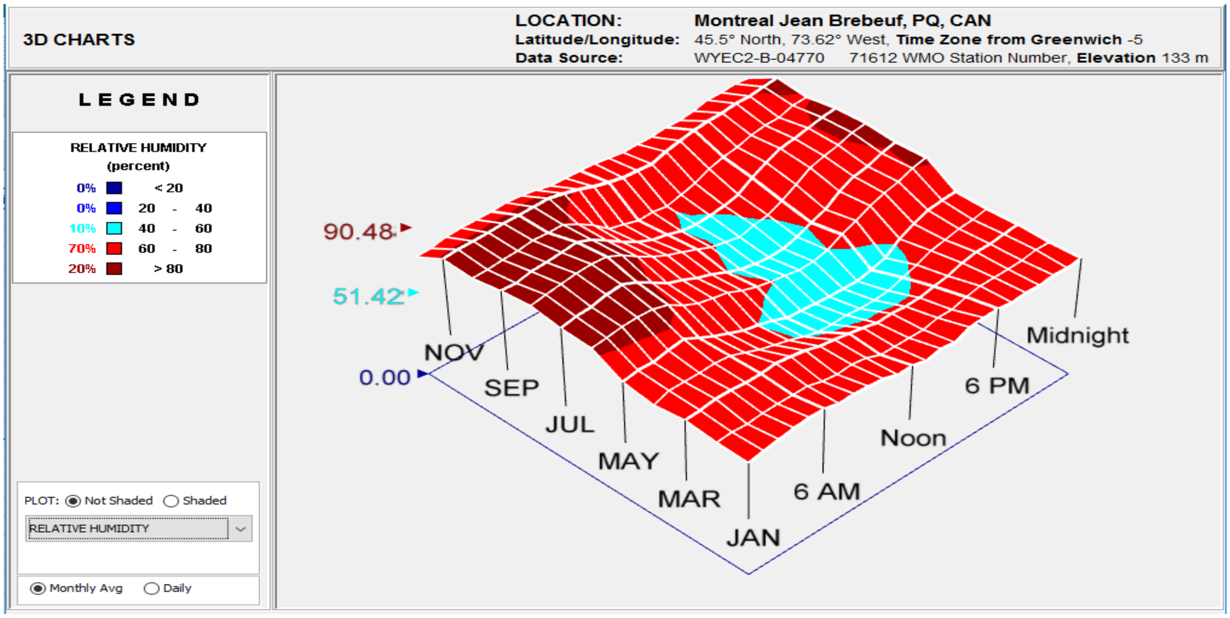


Figure 92 3D-Relative Humidity in Montreal

Therefore, from the plots and the table above the relative humidity in Montreal for the year 2015 is shown. The relative humidity just rose with the winter transition. April and May were the driest months and the relative humidity was maximum during the month of November, which lies just below 80 %.

A.6.5 Temperature Range and Comfort Zonal Chart for Montreal in 2015

The following chart signifies the comfort zone in the climatic conditions exhibited by Montreal for the year 2015. And accordingly the maximum, minimum and the average temperatures are plotted so that we can have a better insight on the matter that how many days or months falls under the comfort zone. This would help us to understand the necessity of heating and cooling and also the thermal comfort level inside a building.

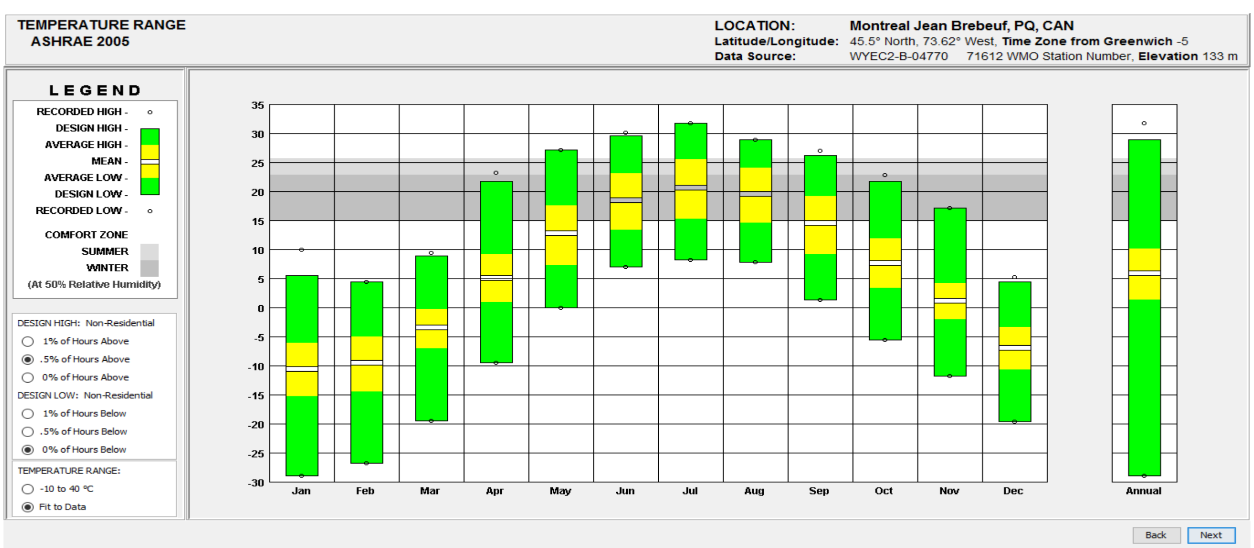


Figure 93 Temperature Range and Comfort Zonal Chart for Montreal

From the plot above we can understand that the months of May, June, July, August and September falls under the comfort zone. This is the summer period and more or less fairly pleasant. If the temperature is not too high and the relative humidity is not too high, heating as well as cooling can be avoided which will help in less energy consumption thereby increasing the efficiency of a building.

A.6.6 Summarization

This brings down the conclusion of all the above-mentioned weather data oriented tables and plots under the shade of different comfort levels.

Seasons	Month	Av. Temp (Min-Max)	Climate	Heating/Cooling
Winter	December to beginning of March	2°C to -15°C	Very chilly	Heating is a necessity
Spring	Mid-March to May	2°C to 20°C	Cold to Pleasant.	Heating is required
Summer	June to September	23°C to 28°C	Warm	Cooling may be required or may be avoided
Autumn	October to November	13°C in Oct to 5°C in Nov	Mild but gets a bit cold by the beginning of November	Heating is required

Table 16 Summarization table for Montreal

From the table above, it can be understood that during the summer months the temperature generally remains warm and pleasant except a few days. If required, the heating and cooling can be avoided during this time. The thermal comfort level remains in a fair zone during the summer season.

A.7 Schedules of the Virtual Building Model

A.7.1 Door schedule of the Virtual Building Model

Door Schedule					
Height	Width	Level	Family and Type	Heat Transfer Coefficient (U)	Thermal Resistance (R)
2	2	Level 1	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	2	Level 1	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	2	Level 1	Double-Glass 1: 72" x 82"	0.6496 BTU/(h·ft²·°F)	1.5394 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU

2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	2	Level 1	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Glass 1: 34" x 84"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	2	Level 2	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	2	Level 1	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	2	Level 1	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 34" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 34" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU

2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 1	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	2	Level 2	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	2	Level 2	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 34" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 34" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	1	Level 2	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU
2	2	Level 1	Double-Glass 1: 72" x 84"	0.7250 BTU/(h·ft²·°F)	1.3794 (h·ft²·°F)/BTU
2	1	Level 3	Single-Flush: 30" x 80"	0.6520 BTU/(h·ft²·°F)	1.5338 (h·ft²·°F)/BTU

Table 17 Door Schedule of the Virtual Building Model

A.7.2 Window schedule of the Virtual Building Model

Window Schedule					
Height	Width	Level	Family and Type	Heat Transfer Coefficient (U)	Thermal Resistance (R)
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU

2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 1	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	2	Level 2	Schueco_AWS-90-BS-SI+_Family-05: Type 1	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU

2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 1	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU
2	3	Level 2	Window-Endvent-Simonton-ProFinish_Contractor: 136" x 60"	0.5628 BTU/(h·ft²·°F)	1.7769 (h·ft²·°F)/BTU

Table 18 Window schedule of the Virtual Building Model

Declaration of Independence

I hereby declare that this master thesis is my own work based on the sources and literature listed appended bibliography. This thesis is submitted with 127 manuscript pages.

Nilangshu Mukherjee

Matriculation Number.- 115355

Weimar, 10.05.2017

Signature

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