APPRAISING A RELATIONSHIP BETWEEN MORPHOLOGY AND ENERGY INDEX OF OFFICE BUILDINGS IN TROPICS: A CASE OF URBAN BUILDING STOCK IN COLOMBO MUNICIPAL COUNCIL

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Declaration page of the candidate & supervisor

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ABSTRACT

In the last few years, together with the surge in new construction, the energy demand from buildings has also been influenced by current practice on energy demanding mechanically controlled buildings with artificially lit interiors. Present urban development strategy of implementing Mega polis development plan for city of Colombo expands its boundaries of the urban building stock. Thus, it's vital to explore the end use energy demand of national building stock and comprehend a relationship between building morphology and energy consumption. A walkthrough field investigation was performed in 46 Wards in Colombo Municipal Council region. The structure of the survey was organized in relation to geographical information system (GIS) data and land use maps of the CMC region. Data was collated to formulate a comprehensive database on morphology of office building stock comprising major physical parameters and energy indices. Results revealed the office building stock is primarily composed of Air-conditioned office spaces and of which 78% contains naturally ventilated common spaces. In this stock 53% and 13% of the office buildings have an annual average building energy index above 200KWhm^{-2} and 300KWhm^{-2} respectively. Linear shape dominates the plan form representing 70.2% of the stock. Other basic shapes such as square, circular and composites corresponds to 19.5%, 2.3% and 8% respectively.

. 54.55% of the office buildings have an average BEI of 150-250 kWhm-^{2}. Out of which 37.03% of the office buildings are EW oriented. Nexus between building façade configuration and building energy index were further analyzed using multiple and simple linear regression analysis. The analysis was conducted for buildings in the identified energy index categories by considering all four orientations. EW and NS oriented buildings were considered for further investigation to evaluate the effect of aspect ratio on energy index. It is evident that aspect ratio of 0.70 (1:1.43) in 100-150 kWh-^{2} energy index range was within the optimal range. The optimal aspect ratio for buildings along east west axis is within the range of 1.27:1 to 1.5:1. Further increase of aspect ratio beyond this range result in increase of energy consumption in buildings. The average aspect ratio for NS oriented buildings in 100-150 kWh-^{2} energy index range was 1.49 (1.49:1), which was within the optimal range. Nonetheless, the average aspect ratio for NS oriented buildings in Average Range is 3.22 (3.22:1), which is beyond the optimal range.

Further onsite thermal investigations in the selected representative buildings with deep and shallow plan forms revealed a clear indoor temperature difference during air conditioned and non-air-conditioned period. It is evident that deep plan form has a greater potential to control external heat gain and reduce end use energy demand. In contrary, shallow plan forms are more susceptible for external heat gain and higher temperature variation is evident periphery and core. Moreover, overheating building periphery in both shallow and deep plan forms are susceptible for overheating condition. Thus the findings of this study represent the criticality of building morphology based on plan shape, orientation and interior planning which demonstrate a significant impact on end use energy demand due to external heat loads.

Key words: Morphology, building stock, urban offices, Building energy intensity

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List of Abbreviations

Abbreviation	Description
ASHARE	American Society of Heating, Refrigerating & Air conditioning Engineering
BEI	Building Energy Index
BEND	Building ENergy Demand
BREEAM	Building Research Establishment Environmental Assessment Method
CBECS	Commercial Energy Consumption Survey
CBSL	Central Bank of Sri Lanka
CMC	Colombo Municipal Council
CO2	Carbon Dioxide
DS	Divisional Secretary's Division
ECCABS	Energy Carbon and Cost Assessment for Building Stocks
EEBC	Energy Efficient Building Code
EPBD	European Directives on the Energy Performance of Buildings
EUI	Energy Use Index
EW	East West
GEA	Global Energy Assessment
GDP	Gross Domestic Product
GHG	Green House Gas
GIS	Geographic Information System
GGBP	Greener Greater Building Plan
GN Division	Grama Niladari Division
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
IPEEC	International Partnership for Energy Efficiency Cooperation
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
NE-SW	North East-South West
NS	North South
NW-SE	North West-South East
SLSEA	Sri Lanka Sustainable Energy Authority

UN DESA	United Nations Department of Economic and Social Affairs
WWR	Window to Wall Ratio

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1 INTRODUCTION

1.1 Background of the Problem

Increasing growth in population, increasing demand for building services and comfort levels, together with people spending more time indoors than outdoors, have led to increased demand for energy consumption. Energy efficiency of the built environment in an urban setting is a crucial aspect when alleviating the challenges of wider environmental issues such as climate change due to GHG emissions and global warming. Multiple energy related emissions risen by mid-century due to factors such as enhanced availability to energy resources, enhanced use of electrical equipment and enhanced residential infrastructure used by billions of people in emerging nations. Moreover, factors such as population growth, migration to cities, increasing level of wealth along with change in life style and household size have a significant contribution to the increase demand for building energy consumption (IPCC, 2014). The large number of construction projects being carried out in emerging economies shows not only a substantial danger, but also opportunities from a mitigation perspective.

The increasing demand for electricity in Sri Lanka is growing at an annual rate of 6%, comprising of 38%, 29% and 20% of domestic industrial and commercial enterprises, while other industries such as religious organizations and street lighting use 13% of electricity (SLSEA, 2017). There are offices, hotels, shopping complexes, hospitals and others in the commercial sector that are not primarily intended for residential or industrial use. Hence, the development of the commercial sector along with factors such as diversity in lifestyles, modern construction strategies and shortage of energy saving technologies in buildings have resulted the highest demand for electricity.

Commercial buildings require energy for both lighting and air conditioning. According to Ceylon Electricity Board, air conditioning consumes 50-60% of total energy demand while lighting systems in commercial buildings use the remaining 20-30% (Emmanuel & Rogithan, 2002). Due to the rapid urbanization in Colombo, the commercial capital of Sri Lanka, it is evident that the increasing hard land cover over soft land cover has affected its bioclimatic condition (Emmanuel, 2003). Land use change related temperature building up in the urban core areas of a city is apparent compared with the non-urban areas with vegetative surroundings, which is known as the formation of urban heat islands. Based Landsat TM and ETM+ satellite images 42% of the area in the city of Colombo was under urban heat islands and forecasted an annual increase of 1.75% (Ukwattage & Dayawansa, 2012). Expansion of these urban heat islands over time may not only contribute to global warming but also affect energy crisis issues where formation of heat islands increases the cooling energy demand. Thus the upsurge demand in energy in terms of electricity is the most adverse effect of urban heat island which should be immediately addressed due to the present energy crisis in the world.

Expansion of built-up area and emergence of compact urban milieus increases energy indices of the building stock (Nikolopoulou & Steemers, 2003). This is attributed to the excessive use of air conditioning and artificial lighting of the building interiors. Construction of office buildings will increase in Colombo Municipal Council (CMC) region due to the implementation Mega Polis and western development plan. Thus it is significant to explore urban building stock and its status of energy consumption.

1.2 Research Problem

The building industry is regarded as the largest single contributor to global energy use and GHG emissions. Thus, proper understanding on the nature and structure of energy consumption in building is mandatory to establish policy measures on climate change and energy resources for future consumption (Allouhi et al., 2015). Knowledge of the energy related features of current building stock is needed to minimize GHG emission and energy use attributed to the construction industry. Even though a variety of research on energy saving technologies of buildings has been conducted, present knowledge of the energy related features of the building stock remains limited. Energy consumption in buildings varies with the primary function of the building. Therefore, these buildings can be categorized based on the primary function and these building types can be utilized in order to simplify the valuation of energy efficiency of the building stock. The building sector consists mainly of two categories of buildings. They are domestic and non-domestic buildings. Single family houses (attached and detached houses) and apartment blocks are considered under residential buildings. Non-domestic buildings are more diverse in terms of its function and generally classified by use. Non-domestic buildings consume more energy per square meter of floor area compared to residential buildings (Emmanuel & Rogithan, 2002). In addition, many studies have investigated the energy usage in domestic buildings and the Carbon dioxide emission in this sector is well understood. In contrary there is comparatively little information available on the energy use of the non-domestic building sector. No-domestic buildings are specified as buildings for manufacturing, offices, hotels, healthcare and educational institutes, transport and agriculture industries (Mortimer et al., 1999).

Non-domestic buildings therefore comprise of multiple types of buildings, with different operations having a significant impact on energy consumption and the subsequent carbon dioxide emissions. Office and commercial facilities in the non-domestic building sector are known to be the most energy intensive types. Hence this investigation is focused on the morphological characteristics of the existing office building stock to in order to implement well established energy conservation initiatives for the existing building stock.

1.3 Aim and Objectives

The main aim of the investigation is to develop a data base of the morphological characteristics of the existing office building stock and ascertain a relationship between these characteristics and energy consumption of the office building stock in CMC region.

The investigation has several objectives. They are,

- Analyze the dispersion of office buildings in CMC Region
- Identify the energy consumption patterns in office buildings based on the morphological characteristics of the office building stock in CMC region
- Formulate an evidence base building models based on energy consumption of the office building stock
- Investigate the thermal performance of the reference cases based on the energy consumption
- Derive relationships between building form, envelop and energy consumption

1.4 Scope and limitations

The study consists of four stages, where the scope and limitations were identified in each stage. The scope in Stage 1 is to map the office building dispersion of the study focus area (CMC region). This was conducted based on land use maps and walk through investigations. Key limitations in stage one was,

- No updated database of the existing building stock a

- Available Geographic Information System (GIS) data on land use maps were not up to date. Hence, 2013 land use maps were used as a base for the investigation

The scope of Stage 2 is to identify the areas with the highest dispersion of office buildings in CMC region and to develop a filtering mechanism based on morphological and operational attributes to select the sample office building stock. Key limitation in stage 2 were

- Buildings which are exclusively used for offices were taken for the investigation
- High-rise buildings and low-rise buildings were excluded from the investigation.

The scope of Stage 3 is to develop a data profile and calculate Building Energy Index (BEI) of the sample office building stock. Limitations in Stage 3 were,

- Difficulties in retrieving information on the building energy consumption, operational pattern and other related data due to security reasons.
- Difficulties in obtaining reliable data from office buildings
- Difficulties in obtaining permission to collect data
- No sub metering system to monitor the electricity consumption
- Building area and other related documents were not up to date
- Alterations and amendments have done to the originally submitted plans for approvals. Hence taking the total floor area was difficult.

The scope of Stage 04 is to identify the reference buildings which represent the office building stock. Key limitations in Stage 4 were,

- The operational hours and number of occupants were not constant in the buildings.
- Overshadowing of the buildings were not taken into account
- Thermal investigations were not carried out on the same day and same time.

1.5 Methodology

Investigation of the office building stock conducted in three sections. Section A was focused on formulating a data repository of the existing office building stock. Section A has three distinct stages. Stage 1 was to identify the dispersion of office buildings in the study focus area. This was achieved by performing walk through investigation in all the 46 Wards in City of Colombo. The structure of the survey was organized in relation to GIS data and land use maps of the CMC region. Stage two was to identify the areas with the highest concentration of office buildings in CMC region. In this study middle rise buildings (5-12 Floors) which were exclusively used for administrational purpose were selected. Stage three was to develop a data profile of the extracted office buildings.

Hence a filtering mechanism was developed based on morphological and operational attributes of the extracted buildings. Number of working hours, type of space conditioning system, type of artificial lighting system and number of lifts were recorded under operational attributes. Building height, plan form, length and width of the building, orientation of the building and glazing percentage of the building façade were considered under morphological attributes of the identified sample office buildings. Simultaneously, electricity consumption data and gross floor area were used to calculate BEI of the office buildings. Stage four was to categorize the extracted buildings according to its energy consumption. Hence three energy index categories were identified. They were Accepted Range (100-150kWhm-^{2}), Average Range (150-250 kWhm-^{2}) and Critical Range (above 250 kWhm-^{2}). Section B is to conduct a detail investigation of the selected reference cases. The reference cases were selected from each energy index category to represent the building stock. Section C was analytical investigation on building morphology and energy index. In this section different reference performance models were developed to show the nexus between building energy index and façade configuration and building form in each building orientations. The investigation structure is shown in Figure 1.

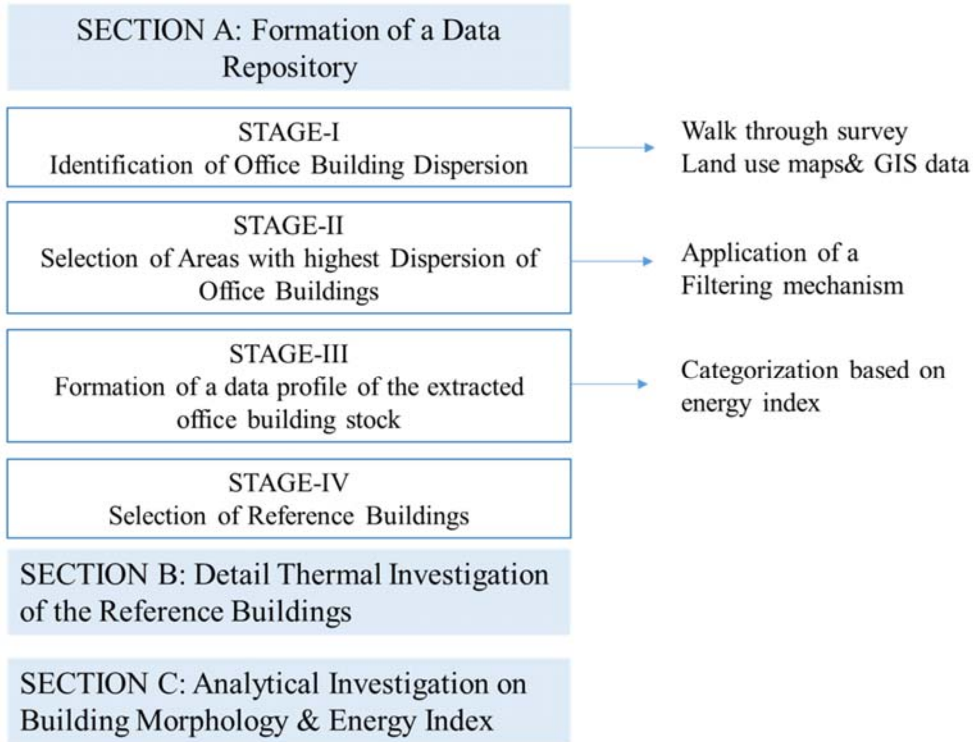


Figure 1 Structure of the Investigation

1.6 Outcome and contribution

This research will be a frame work to develop a baseline database matrix focusing on the existing office building stock in CMC region. Implementation of energy conservation methods for the building sector is hindered due to the limited knowledge on the characteristics of the existing building stock. Thus, this investigation will assist to develop a comprehensive data base of the morphological characteristics of the office building stock in CMC region, which represent the highest built density in the country. Further, analysis of the office building stock will be a foundation to construct energy efficient new buildings. The dispersion patterns of the office buildings in CMC region shall be taken as a foundation when implementing intra-urban and urban development strategies in future development plans. Further, development of a database of the existing office building stock will enable to implement and monitor energy conservation policy measures on mitigating GHG emissions.

Moreover, the existing database will enable to give a better statistical picture of the office building stock in terms of its energy consumption, type of construction, age of the building stock, type of mechanical ventilation system, type of lighting system, and what are the morphological characteristics of the buildings, the amount of energy used and etc. Thus enable to implement energy efficient retrofitting and face-lifting for the existing building stock.

In addition, proper understanding of the geometric attributes of the existing building stock will enable to configure the morphological parameters in new building constructions to minimize energy consumption and detail thermal investigations will enable to ascertain the indoor thermal behavior in deep and shallow plan forms during AC and non AC period. Thus permit to configure interior of the existing building plans and new layouts to prevent indoor overheating condition in tropical climate.

2 OVERVIEW OF THE BUILDING ENERGY SCENARIO

Preface

This chapter analyses prevailing information concerning energy consumption in buildings. The chapter consists of several sections. The first section elaborates on current world energy scenario which emphasis on the criticality of the GHG emission from buildings. The second section gives an outline of the contributing factors for building energy consumption. Generally, several aspects have been the key contributors to the ultimate energy used in buildings. They are size of the population; size of buildings sector, economic activity and building energy policy.

Apart from that, factors such as cost for energy utilities and climatic condition also have an impact towards energy use in buildings. The magnitude of each driver' input to energy consumption differs from nation to nation, within the nation and over time due to districts factors, such as the differences in social, economic and demographic and geographic factors.

The third section of this chapter analyze on the building sector emission. This section elaborates the contribution for CO2 emission from buildings in different countries from different regions. According to the IEA, the Asian region has been regarded the primary cause of CO2 emission to reach 17.4 GtCO2 in 2016 since the mid-2000s. This level of CO2 emission is twice the emission level of the Americas and three times the emission level of Europe.

The fourth section discusses the literature on climate change and its effect of energy consumption. This section highlights the probable decline of climate change, energy saving techniques and appropriate methods on energy savings to mitigate global warming condition and GHG emissions. The fifth and sixth section discuss on the energy consumption pattern of the non-domestic building stock and morphological parameters of the office building stock.

2.1 Building Energy Consumption Status

2.1.1 Energy and emissions in the buildings and construction sector

Energy consumed by buildings plays a foremost role in the global energy system. Energy used in the construction industry is composed of residential and commercial end users, contributing 20.1% of the total electricity production in the world. Buildings represent for 30% of the final energy demand globally, and 55% of world electricity usage. In addition, the construction industry accounts for more than a quarter of energy related CO2 emissions and accounts for two-thirds of halocarbon and 25-33% of Black Carbon emissions(GEA, 2012).It is evident that buildings are responsible for 28% of the worldwide energy related CO2 emission in 2018 by considering the indirect emissions from upstream power generation (IEA, 2019). Moreover, Construction and operation of buildings contributed for 36% of worldwide total energy consumption and 39% of energy associated GHG emission in 2017(UN Environment and GlobalABC, 2018).

Buildings consume a significant quantity of energy generated by direct and indirect use of fossil fuels as electricity worldwide. In addition, buildings are responsible for half of the global energy demand. Many efforts have taken to improve the energy efficiency of the buildings. But the energy usage in buildings has rapidly increased over the period of time. For an example energy usage in buildings have increased by 20% since 2000 and the global energy demand for buildings is forecasted to increase by an additional 50% by 2050 compared to 2012 level (IEA, 2015). As a result, the building sector has increasingly drawn global attention.

2.1.2 Overview of Drivers in Building Energy Consumption

Historically, several elements have been main contributing factors for energy consumption in the bluing sector. Building form, working hours, population size and amount of occupants as well as environmental circumstances are main causes of final energy consumption in the building sector. The level of which each of these contributing factors on energy consumption differs from nation to nation, within the nation and over time depending on the differences in cultural, financial, regional and population as well as the policy milieu (IEA/IPEEC, 2015). Despite energy efficiency improvements, the energy consumed in buildings highly correlated to population growth (IEA/IPEEC, 2015). Energy consumption in buildings has been decreased strategically, despite population growth in a number of developed countries which is achieved through insistent building policies. For example, demographic data reveals that population growth have increased from 8%, 13.5% and 6.5% in France, Canada and the United Kingdom between 2000 and 2012. When analyzing the energy consumption in building sector, final energy consumption has reduced by 1%, 1% and 11% over the same period.

It is evident that the growth in population effects the energy consumption of the buildings. Thus it is mandatory to mitigate the impact of population growth on energy consumption in buildings and this is a significant global issue since the world population is expected to increase by 2,5 billion by 2050 (UN DESA, 2013). Floor area of the building and economic growth go hand in hand with building energy consumption. It is evident that building energy demand increase with the floor areas in non-residential buildings. Further, residential building sector is responsible for 70% of the global final energy consumption in year 2017 and the energy consumption in this sector building sector get predominantly influenced by population and floor area (UN Environment and GlobalABC, 2018).

According to IEA, upward trend in energy consumption is evident in developing countries due to the improved access for energy resources. Further, strong correlation is evident between energy consumption and the individual wealth level, the increase in the size of the housing unit, the improvement in space conditioning and the increased procession of energy consuming appliances. Further, affordability for accessing energy resources vary with the house hold income and it is a contributing factor for energy demand. Moreover, nexus between GDP and floor area as well as energy demand is evident in national level which confirms higher GDP growth levels in developing countries (IEA/IPEEC, 2015). Urbanization and the forms of energy used are factors which affect energy consumption. In developing countries, urbanization is frequently related with enhanced access to energy resources, electricity usage, enhanced use of facilities and decreased use of biomass for water heating and cooking. In developed countries, despite large single residential units, migrating to urban centers can lead to a reduction in residential unit size, which can also decrease energy consumption as well. The number of people per house hold can be taken as another demographic factor which affects energy consumption in buildings. The decrease in house hold size results in increased number of household for a given population. The amount of residential units is a primary cause of energy consumption from equipment used for heating, lighting and space conditioning. The decoupling of energy use from these factors can be accommodated over time by implementing effective energy policies for buildings.

These government policy measures are comprised with amended building energy codes for both new and current buildings. These codes are implemented for both new and current buildings when these buildings undergo retrofitting, for building rating, for capacity building, enhanced information accessibility and performance to guide strategy development and execution (IPEEC,2014;IEA,2013). Many European countries are evident for implementing these policies over the last few years. Further, growing interest is apparent in a number of key emerging and transition economies that will eventually leads to low emission buildings.

2.1.3 Trends in buildings sector emissions

Being the dominant source of GHG emissions, Asia has achieved 17.4 GtCO2 in 2016 since the mid-2000s, which is three times that of Europe and twice the extent of America. Whereas China contributed for more than half of the CO2 emissions in Asia in 2016 followed by India with 12%. Several other regions in other countries also have increased the emission since 2000, as per the statistics Korea +36%, and Indonesia +78%. (IEA, 2019). 42% of the global CO2 emission in 2016 is attributed by electricity and heat generation (IEA, 2018).

Comparing the emissions of consumer sectors over electricity, industry was the largest emitter, with 36%, or 12 billion tons of CO2; followed by building and transport sector respectively. The building sector emission increased from 8% to 27% due to its strong dependency on electricity. Direct emissions from buildings have risen somewhat more than 3 GtCO2 in 2018, which was slightly lower than 3 GtCO2 in past few years (IEA, 2018). In addition, it was reported that in 2018 buildings are responsible for 28% of worldwide energy related CO2 pollution each year. According to the International Energy Agency, building related CO2 emissions had increased for the second year in a succession to an all-time high of 9.6GtCO2. This tendency reversal since 2013 is primarily attributed to advance in decreasing carbon intensity production of energy. The supply for building energy infrastructure (electricity for heating, equipment, other plug loads) is increasing at a faster pace compared to the carbon free power supply. Thus result in resurgence in buildings related emissions. Moreover, rapidly changing climatic condition of the world has a considerable impact towards building electricity consumption. The increased demand for energy consumption in 2018 was responsible for severe heat in many parts of the world. As a result, Extreme temperatures and continuous heat waves record the demand for air conditioning in many countries (IEA, 2019).

2.1.4 Effect of Climate Change on Building Energy Consumption

Because of the long life span and high initial costs of the buildings, designers must acknowledge the impact of climate change on buildings. According to IPCC (2018), human activities have resulted in projection of global warming from 1 C° compared to pre-industrial level and it is predicted to reach 1.5C° within 2030 and 2052 if it continues to increase at present rate. Thus highlight the importance of climatic change on building energy consumption. People spend considerable amount of time in buildings and these buildings accommodate the financial, social and cultural activities which contribute directly to climate change. The consequence of climate change in building energy consumption is widely discussed by many scholars.

A study conducted by Dirks et al.(2014) investigated the impact of climate change on annual energy consumption in the United States. This was assessed by analyzing the changes in characteristics of mean climate as well as shift in the regularity and length of severe weather occurrences. BEND (Building ENergy Demand) model was used to run the simulations for 26,000 building patterns which represent the characteristics of the building population in terms of size and features of the building stock. Wan et al.(2018) explored the effect of climate change on energy consumption in five significant architectural climatic conditions. Energy consumption in these climates were analyzed based on heating and cooling of the buildings. Through the investigation it was evident that a substantial energy saving and reduction in GHG emission could be achieved by increasing the summer indoor temperature by 1-2C°. In another investigation carried out by Wan et al. (2011) explored the impact of climate change on building cooling and heating load and its energy consumption. The investigation reveals a declining patter in heating and an increasing tendency in cooling load due to climate change in future years. The study reveals that substantial amount of energy consumption in buildings are attributed for indoor thermal comfort during winter and summer .Increasing energy consumption in buildings would continue to greater emissions, aggravating global warming and climate change (Wan et al., 2011).

The impact of climate change on building energy consumption in heating and cooling is more severe in countries with warmer climatic conditions. A study conducted in Dhaka, Bangladesh with a tropical climate, revealed that there will be an increasing energy demand for comfort cooling in the 2020s, 2025s and 2080s (Mourshed, 2011). A net reduction in total energy consumption of buildings is apparent in severe cold climate conditions. However, carbon emissions are predicted to increase despite this condition. Reducing carbon emissions could be accomplished by integrating energy efficient designs and operations to help to reduce energy demand in buildings (Wan et al., 2011). Many scholars have conducted research over reduction in Carbon emission and building energy consumption. Kneifel (2011) conducted energy simulations for 12 building types in 228 cities in the US. The study revealed that 15-20% energy reduction can achieved in average and new commercial building by implementing conventional energy efficient systems in an integrated design structure (Kneifel, 2011). Moreover Perez & Capeluto (2009) carried out a sensitivity analysis of building façade configurations including infiltration and thermal mass for school buildings in hot humid environments. Based on the investigation, it was evident that annual energy consumption could be reduced from 180 to 80 KWh/m² per year (Perez & Capeluto, 2009). Rahman et al.(2010) identified three forms of energy saving approaches known as Zero Cost, Minor Cost and Major Cost that can be implemented without affecting the occupants' thermal comfort in an institutional building located in subtropical climate in Australia. According to the investigation, Minor Cost interventions are referred as resetting heating/cooling set point temperature. Replacing single glazing to double glazing are considered under Minor Cost interventions and chiller plants with higher coefficient are considered as Major Costs interventions. The study found that energy saving up to 42% could be achieved by adopting these three energy conservation measures (Rahman et al., 2010).

The energy savings technologies will be influenced by climatic change in future. This was accessed by Wang & Chen, (2014) by analyzing the night time ventilation in three cities, namely Seattle, San Diego and San Francisco in the US. Natural ventilation was discovered to be no longer acceptable for San Diego but no detriment in both San Francisco and Seattle due to global warming. The study revealed naturally ventilated buildings are susceptible for overheating condition due to climate change and prevailing global warming condition. A study conducted by Lomas & Ji,

(2009) evaluated the resilience for overheating condition for naturally ventilated the buildings and its potential for overheating condition. Under severe global warming conditions, carbon emission will not be efficient in cold and temperate climate zones. These studies demonstrate the possible degradation of energy saving technologies with climate change. Further, appropriate energy saving strategies could alleviate global warming trends and GHG emission.

2.2 Energy consumption of the non-domestic building Stock

2.2.1 Overview of the Non Domestic Building Stock

The building sector is composed of domestic and non-domestic buildings. Single family houses (detached and semi-detached) and apartments are included under domestic building category. Non domestic buildings are more diverse than the buildings in domestic category in terms of space usage, energy consumption and diversity in function. Non-domestic buildings consume more energy per square meter of floor area compared to residential buildings (Emmanuel & Rogithan, 2002).

Energy consumption and related CO2 emission in domestic sector is well understood. In contrary, limited research is evident in the non-domestic sector. Bruhns et al., (2000) categorized the non-domestic buildings based on its function,

- Private Sector: Shops, commercial offices, factories, warehouses, hotels and catering, communication, social, entrainment, arts
- Public Sector: local government offices, central government offices, education, health, defense

Compared with domestic buildings, nondomestic buildings tend to have increased energy consumption per square meter of floor area (Mortimer et al., 1999). Hence, non-domestic buildings therefore comprise of multiple types of buildings, with different operations having a significant impact on energy consumption and the subsequent carbon dioxide emissions. Offices and retail spaces are among the most energy intensive typologies which represent more than 50% of the total energy usage of non-domestic buildings (Pérez-Lombard et al., 2008). Hence, proper understanding of the non-domestic building stock is vital get a better statistical picture of the building stock and its ways of energy consumption. Thus, enable to implement and monitor energy conservation policy measures on mitigating GHG emission.

Due to the diversity in built form, building envelop, size, activities and building services of the non-domestic stock, it is difficult to characterize the building stock (Bruhns & Wyatt, 2011). Hence, various methods and techniques were adopted by many countries to collect information on the energy usage of the non-domestic building sector.

2.2.2 Database of the Non Domestic Building Sector

Many scholars and international organizations have investigated the energy consumption of non-domestic building stock in many counties. Bruhns et al.(2000) and Steadman et al. (2000) developed a database of the non-domestic building stock in UK. This work was further extended by Bruhns & Wyatt (2011) developing a data frame work to measure the energy consumption of the UK's non-domestic building stock and proposed its use for energy efficiency policy formation.

In the USA, The Greener Greater Building Plan (GGBP) was introduced to upgrade and make the existing buildings more energy efficient to reduce GHG emission from building in New York. Hence, GGBP aims to minimize GHG emissions by 30% of the city wide by 2030 (*GBEE - About OneNYC Green Buildings & Energy Efficiency*, n.d.). Further, EU has established a legislative frame work which includes both European Directive on the Energy Performance of Buildings (EPBD) (2010) and Energy Efficiency Directive (2012) to boost the energy performance of the buildings. This is an example on law enactment to make the building sector more energy effective. As a part of the clean energy for all Europeans, both directives were amended in 2018 and 2019. Due the implementation of energy performance rules in national building code, buildings at present consume only half of the energy usage in an average building in 1980s (*Energy Performance of Buildings Directive*, n.d.). Moreover, voluntary ranking systems such as LEED and BREEAM also serve a part in encouraging stake holders to appreciate the environmental aspects of construction (W. L. Lee, 2012).

Jones et al.(2000) assessed the public energy bench mark values on each property type in the UK and developed Energy and Environmental Prediction Model to calculate the energy consumption of non-domestic building stock. In japan, Yamaguchi et al. (2007) developed a district clustering approach where city of Osaka in Japan was categorized into 500 × 500 m areas based on dynamic simulation of the main archetypal building in each district. A study by Coffey et al. (2009) introduced an energy consumption model which vary with time for the US commercial building stock. In addition, a study undertaken by Dascalaki et al.(2010) delivers an outline of the Hellenic building stock. The study developed a methodology to organize and process national data of the building stock. The created database consists of 225 building parameters to extract information on different characteristics of the buildings such as final energy consumption, use of solar energy collectors in the building, and characteristics of the thermal envelop. These findings were not only used to demonstrate some of the features of the Hellenic building stock but also gives a conceptual framework on how to utilize DATAMINE database as an analysis tool.

The Paris's building stock was investigated by Salat (2009) due to its numerous urban and architectural typologies where a systematic evaluation was carried out for 96,000 buildings in Paris, France where the existing thermal energy usage of the residential building stock was compared with environmental parameters such as building shape factor, daylight and passive volume of natural ventilation of urban fabric. The Study revealed how energy efficiency get affected by urban morphology and building typology in different zones in Paris by comparing the urban forms and heating energy consumption of the residential building stock.

Moreover, Salat (2009) investigated the energy efficiency and CO_2 emission linked to occupants' behavior and heating, apart from evaluating the nexus between building form and construction technology. Thus the study revealed that there is a balance perspective of the complex effect of morphologies, typologies, energy systems, and the impact of the occupants' behavior on CO_2 emissions and energy load, which make it possible to optimize the urban form with respect to density, building design configuration and building morphology.

Mata et al. (2014) introduce a methodology for aggregating national building stock through archetype institutions in four EU nations. These four EU nations, namely France, Germany, Spain and the United Kingdom, have distinct climatic conditions and account for about half of the EU-28 buildings' final energy consumption. The research includes the residential and non-residential sectors where only the residential sector is taken into consideration in Germany. Building type, year of construction, climate region and primary source of energy for heating were taken into account when identifying the number of archetypes per country. In addition, Energy, Carbon and Cost Assessment for Building Stocks (ECCABS) Model is used to verify the reliability of the description by simulating energy demand and assimilating the final energy demand. Similarly, Alves et al. (2018) created a total overview to define and analyze the energy savings potential of the current building stock categorization in Brazil. The building stock energy consumption baseline was modeled using a bottom up archetype method and the methodology comprises of six fundamental measures. This investigation illustrates the importance of the cumulative energy saving scenarios of the current high rise office building stock to reduce energy usage as well policies for new buildings. Many studies have used representative or archetype building for building stock energy modeling. Physical characteristics of the buildings such as heating system, insulation, built form, age, etc. have taken into consideration when calculating the energy consumption of the building stock and the national energy use of the built environment is assessed. In addition, the simulation results are generalized to similar buildings in a particular archetype.

This is a concern since similar buildings can vary considerably in their use of energy due to changes in their physical characteristics, disparities in management and operation, range of services delivered and effects of external conditions such as the impact of urban heat island, pollution and etc. (Choudhary, 2012). The initial step towards collecting information on energy use in non-domestic buildings is to define the types of buildings to which research should be guided and to recognize the most appropriate type of buildings. Thus helps to conduct the survey efficiently. This requires classification system for the non-domestic building stock. Mortimer et al., (1999) have principally based the activity occurring within the building as the classification system for the non-domestic buildings.

2.2.3 Formulation of a Database of the Non Domestic Building Sector

The main objective of developing a database is to give a clear statistical representation of the non-domestic building stock and its energy consumption which was not available previously. Moreover, a database of the non-domestic building stock will also help to inform government policy on mitigating greenhouse gas emission. Further, it will also help to identify the trends in the composition of the non-domestic building stock and trends in energy consumption (Steadman et al., 2000).

A salient feature of these analyses is that the energy consumption of an archetypal set of buildings in a particular region is represented as $KWhm^{-2}$ /year which referred as

BEI. This enables the gross energy usage of a large number of buildings in a region to be identified. In addition, buildings with corresponding activities in the same region produce approximately the same quantity if energy per unit area. Hence, the primary classification of non-domestic buildings therefore usually reflects their function (Choudhary, 2012).The first step in setting up a database of the energy usage of the non-domestic building stock is to collect information on the building's energy consumption pattern. It is therefore essential to define the most appropriate kind of buildings.

This needs a way of classify non-domestic building stock. Types of use and operations have an enormous effect on the performance and amount of energy services required. Quality and quantity of the required energy services greatly affected by the types of use and activities (Pérez-Lombard et al., 2008). Further, Xu et al.(2013) revealed that building energy intensity has no direct correlation with building size. Mortimer et al. (1999) state that non-domestic building stock must be able to assess the energy efficiency potential of the building stock. It must therefore show the vital characteristics such as being a representative of the current building stock, capable of generating accurate estimate of complete energy use and GHG emission, broken down by implementation, and containing appropriate details on building usage, building services, equipment and appliances, as well as building envelop. In addition, the database must be accessible in a machine readable format depending on the complexity of the necessary information. Finally, a wide range of customers must have access to the database. Therefore, the data contained in the database must be relatively self-explanatory, especially with respect to and assumption incorporated in the data collected (Mortimer et al., 1999). Defining the building based on the survey type and recognize the most suitable building types are the first stages in gathering energy related information in non-domestic building stock. A comprehensive classification system is needed to conduct the survey effectively and efficiently. Mortimer et al.(1999) have primarily classified the non-domestic buildings based on the activity taking place within building.

Moreover, Commercial Buildings Energy Consumption Survey (CBECS) is the most comprehensive and statistically significant classification system conducted in a national level to collect information on the commercial building sector (Davis & Swenson, 1998). Several countries such as Canada, Denmark, France, Sweden and Japan have started on collecting more detailed information about the energy related characteristics of non-domestic building stocks by introducing similar methods (Krackeler et al., 1998). Due to the complexity of the activities and function, this investigation is predominantly focused on analyzing the energy consumption pattern of office buildings under non-domestic building stock. The characteristics of the office building stock are further analyzed based on the morphological parameters.

2.3 Overview of the Building Morphological Parameters

2.3.1 Nexus between Building Morphology & Energy Consumption

Today's existing building stocks are a major energy consumer. This is primarily due to different factors such as construction technology, occupants' behavior, architectural archetypes and urban morphologies (Salat, 2009). Lack of data on building energy consumption makes it difficult to determine the interventions required for the existing building stock in developing countries like Sri Lanka. Morphological parameters such as building orientation, building height, building depth and width, building envelop configuration and building shape are strongly associated with building energy consumption. In order to assess the energy consumption pattern of the building stock, it is required to develop an energy consumption baseline which represent the exiting building stock (Alves et al., 2018).
Understanding the consumption pattern permits opportunities for energy efficient improvements. Hence, building stock is grouped by using bottom up archetype technique. In this method, Age, size, type and similar characteristics are taken into consideration when segregating these buildings. Such factors help to define the energy models that are representative. Additionally, these representative energy models can be scaled up to the regional or national level. Assessing energy consumption without depending on the historical energy consumption data and the ability to evaluate the impact of different technologies on energy consumption are two most distinctive advantages of using archetype models (Yamaguchi et al., 2007; Summerfield & Lowe, 2012; Swan & Ugursal, 2009;Fonseca & Schlueter, 2015). Regarding the Sri Lankan context, building stock modeling is difficult due to the lack of building energy consumption data and access to obtain building energy consumption information. Few studies have focused on highlighting energy efficiency and indoor environment quality of the office buildings in Colombo (Wijayatunga et al. 2003; Ratnaweera & Hestnes, 1996). Another study has analyzed

the building performance in terms of energy, indoor environment, environment degradation and economic aspects by using building simulations (Bandara & Attalage, 2012). A study conducted by Ukwattage & Dayawansa (2012) assessed the expansion of urban heat island effect over time with land use change and demand of energy. In this study land surface temperature was used to study the progressive distribution pattern of heat island over the city for a period of 13 years. These land surface temperature patterns were derived from remotely sensed images. Moreover, data on electricity consumption in the Colombo City area were used to identify the nexus between heat island and energy demand. According to the study, the growth of urban heat island is evident in the Sothern part of the city, which was previously limited only to northwestern areas. In this investigation, both energy consumed per land and the ratio between built up to vegetation area was considered when evaluating the land use energy demand.

In areas with higher built up to vegetation ratio, the highest energy per unit area is apparent. Nevertheless, due to the lack of information on the use of electricity and the complexity of the built up environment it is difficult to establish the correlation between the type of land cover and energy demand (Ukwattage & Dayawansa, 2012).

With the present urban development strategy of the country towards a mega-polis initiation, it is important explore urban building stock and its status of energy consumption. The city of Colombo was chosen on the basis of the socio economic importance of the city in the Sri Lankan context. Thus this study outline nexus between morphological parameters of the office building stock and its energy consumption.

2.3.2 Building Orientation

Building orientation towards the sun path is important in order to minimize solar heat gain and maximize daylight. Selecting the most suitable building orientation has an impact towards building envelop energy performance and it is the key energy efficient decision making (Al-Tamimi et al., 2011). Impact from direct solar radiation through windows, building openings as well as external opaque walls can be minimized by building orientation. The influence of orientation has affects to the building facades with higher Window to wall ratio (WWR). Adopting building configuration and orientation with local climate are considered as passive strategies

(Yeang & Powell, 2007). Moreover, solar gain can be controlled by both orientation and introducing shading devices based on the sun's position and these are widely practiced passive solar architectural concepts (Jayasinghe M.T.R., Sujeewa L.C, Fernando K.K.J.S., 1997). Availability of daylight strongly relies not only on the latitude, but also on the orientation of the building. Thus different design emphasis is required based on the orientation. Moreover, orientation of windows directly affects solar penetration through windows and other openings in the building envelop in warm climate, thus resulting increased indoor temperature (Givoni et al., 2003).

The need for artificial lighting is reduced by well orientated buildings by maximizing day lighting through building facades. Thus architectural solution is very critical for enhancing the thermal and luminous efficiency of buildings by considering elements such as orientation, envelop materials and glazing configuration (Bracarense et al., 2005). Appropriate orientation controls the solar heat gain, thus result in reducing the energy consumption. Many scholars have investigated the influence of varied orientation on building energy performance and thermal performance. Al-Tamimi et al. (2011) investigated the effect of orientation, varied WWR and ventilation on thermal performance of residential rooms in tropical climate.

According to the findings, compared to the west windows, the east windows have a more apparent effect on the increase indoor air temperature which is evident in both ventilated or non-ventilated rooms (Al-Tamimi et al., 2011). The effect of direct sunlight penetration and daylight distribution in a building was investigated by Fadzil & Sheau-Jiunn Sia (2004). The investigation was conducted in Penang which has a tropical climate and the study consisted with 12 bays with continuous orientations. Based on the results, it is evident that the best and the worst bay orientations were 0◦ and 240◦ respectively. The other orientations were 30◦, 180◦, 330◦, 60◦, 90◦, 300◦, 150◦, 120◦, 210◦ and 270◦ follows in order. According to this study, the bay that received the least direct solar radiation is considered to be the best as it receives the least heat gain, thus encourages energy saving due to reduced cooling load. Moreover, this bay also has the least glare related issues. Another study conducted by Li & Lam (2003) examined the intensity of the direct and indirect solar radiation with façade orientation. The results show that the north has the lowest solar intensity ranging from 43.6 W/m² in October to 65.5 W/m² in July, while the solar intensities on the east and west are identical. Somewhere between the north and the east/west has the mean intensity on the south surface (Li & Lam, 2003). Some scholars studied the effect of orientation on natural ventilation. For an example a study in Hong Kong evaluated the effect of window positions, window configurations and surrounding blocks with different window orientations to investigate the interaction among these variables as well as its influence towards indoor ventilation (Gao & Lee, 2011). Based on the results, it was apparent that the change in the direction of the window had the greatest effect on natural ventilation followed by window orientation and door position.

However, selecting the correct position of the window and the orientation of the building would have a positive impact on the level of natural ventilation. A Hong Kong based study by John Burnett et al. (2005) analyses how cross ventilation within a design can be given and maximized by considering the orientation and prevailing wind conditions. The study revealed that Ø = 30◦ was a building's best design and orientation to the prevailing wind. This study revealed that the front flats have the highest natural ventilation potential for any given angle (Ø). Nevertheless, it is possible to achieve sufficient cross ventilation in such front facing flat where angle (Ø) is equal to 0, 45, and 90. In contrary, for the flats located on the center, these angles are totally different, where optimal ventilation can be accomplished with angle (Ø) equal to 15◦, 30◦, 60◦ and 75◦.The identified office buildings in Colombo MC Region were categorized based on its energy consumption and these buildings were further subdivided into categories according to the orientation of the long façade of the building.

2.3.3 Building Envelop Configuration

Windows are considered as one of the most important building elements and acknowledge the positive influence of building occupants on their health and well-being. Building fenestration not only provide daylight into the buildings but also affect the energy consumption of the building (Mangkuto, Rohmah, et al., 2016). Fenestration therefore plays a vital role in terms of energy efficiency and relies heavily on the building envelop, including window sizes, as they are also responsible for energy loss of about 20% to 40% (J. W. Lee et al., 2013). The area of the exterior building envelop to the area of the window/opening is defined as WWR (Rashid et al., 2016). It is one of the principal aspects which affect the thermal performance of the building. The optimal definition of WWR has an objective to reduce solar heat gain while enhancing the building's heating, cooling, day light and ventilation.

Therefore, the Energy Efficient Building Code (EEBC) for Sri Lanka and the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHARE) has united the WWR into its standards for new building construction. In recent years, the construction of new office buildings in Sri Lanka has increased significantly with a growing trend in the installation of fully glazed facades.

In recent years, the emergence of new office buildings in Sri Lanka has improved significantly with a growing trend in the use of fully glazed facades. Commercial building consumes 28.4% of the electricity demand in Sri Lanka (SLSEA, 2017). Energy consumption in commercial buildings is predominantly related to activities such as lighting and heating and cooling of spaces (R. M. P. S Bandara & R. A Attalage, 2020). Nexus between Window configuration and energy use in office buildings for heating, cooling and lighting have been investigated in several studies. The impact of geometry, window size and orientation on energy consumption for lighting and cooling in office buildings located in different climate zones were investigated by both Susorova et al.(2013) and Ghisi & Tinker (2005). Moreover, J. W. Lee et al. (2013) attempted to develop the best window configuration for office buildings located in five typical climate zones in Asia. In this study, the window configurations were developed based on the impact of geometric factors such as WWR, orientation, g-value and visual transmittance.

Similar investigation was carried out by Motuziene & Juodis (2010) on the energy consumption in office buildings in cold climate zones in Lithuania. In this investigation energy consumption of office buildings were evaluated based on the factors such as WWR, orientation of the windows and glazing type in the office building. Further, Ko et al. (2008) explored the ways of optimize day light and potential for energy saving by using simulations to find the best amalgamations of window area and glazing properties in office buildings in six differed climate zones in the U.S. Impact of façade window design has been investigated not only in office buildings but also in residential buildings. Vanhoutteghem et al. (2015) investigated the geometric features of façade windows such as size, orientation, and glazing properties in different side-lit rooms in 'nearly zero-energy' houses in Denmark. In this investigation, large windows are introduced as a design trends as well as to maximize the daylight penetration and view. But this impact of increased solar radiation in buildings leads to an upsurge demand for energy use. Thus it is important to investigate the best window configuration which will enhance the energy performance of the building. Many scholars have researched the optimum window configuration and it evident that the optimum window to wall (WWR) ration could generate significant energy savings for heating, cooling and lighting demand in buildings (Mangkuto, Rohmah, et al., 2016). Due to the implementation of more advanced technologies, WWR have resulted lower energy performance in buildings.

It is apparent that most of the window optimization investigations are performed in or at high latitude sites (beyond 23.5°N and 23.5°S), particularly in North America and Europe (Inanici & Demirbilek, 2000; Goia et al., 2013;Ochoa et al., 2012). In the other hand, sun's position changes from northern and southern part of the sky hemisphere within a year's time mainly near the equator (10°N–10°S latitude) in tropical regions. Thus, tropical region receives longer duration of sunshine. Further, tropical region has two seasons namely, wet and dry seasons which is based on the high and low rainfall. Therefore, it is apparent that tropical climatic regions are somewhat unique and different compared to regions with high altitudes (Mangkuto, Asri, et al., 2016). But less research attention had given to regions with tropical climatic conditions with respect to day lighting system, solar radiation, sky luminance and etc. (Chirarattananon et al., 2000; Edmonds & Greenup, 2002; Darula et al., 2010; Linhart et al., 2010).

In tropical countries like Singapore and Indonesia, few studies have examined the effect of building envelopes on ventilation and thermal comfort (Liping & Hien, 2007; Paramita & Koerniawan, 2013) and in Malaysia, a study on incident solar radiation is available (Ling et al., 2007). Further innovative technologies such as semi-transparent building integrated PV systems applied in buildings and the lifetime performance was assessed in studies conducted in Singapore (Ng & Mithraratne, 2014). In addition, effect of WWR, wall reflectance and orientation were addressed in a research conducted in Indonesia on different daylight metrics and lighting energy demand for buildings located in tropical climatic zone (Mangkuto, Asri, et al., 2016). According to ASHRAE 90.2 Energy Standard, the maximum recommended value stipulated for WWR in commercial buildings is 40% for all climatic zones. According to Mangkuto, Asri, et al. (2016), WWR 30%, 0.8 wall reflectance and south orientation is the best combination in tropical climate which will help to reach utopia point. However, this optimum solution can vary during complex situations when there is additional building elements and shadings. Al-Tamimi et al.(2011) investigated the impact of orientation with varied WWR and ventilation on thermal performance of residential buildings in tropical climate. It was observed that east oriented rooms are more susceptible to solar radiation compared to the rooms with west orientation. Therefore, the use of natural ventilation and WWR of 25% could increase thermal comfort in east oriented rooms. So it is vital to apply mechanical ventilation in order to improve occupant's thermal comfort (Al-Tamimi et al., 2011).

Susorova et al. (2013) evaluated the effect of geometry factors such as WWR, orientation of the window and room width to depth ratio on building energy efficiency in office buildings. The study revealed that a substantial reduction in energy consumption in office buildings is evident by optimizing the geometric parameters of the building and fenestration design and achieve energy saving in all climate zones. According to Susorova et al.(2013) the investigation revealed that overall saving up to 14%, which is the highest energy saving can be achieved in hot climate zones by utilizing the fenestration geometry. In contrary, energy saving in temperate and cold climates are insignificant. Thus the study denotes that when designing new buildings and retrofitting old ones, articulation of building fenestration should be carefully addressed.

2.3.4 Building Geometry and physical configuration

Building form has a significant impact on both construction and energy cost of the building (Ourghi et al., 2007). The construction of low energy architecture requires a careful articulation of the building's shape and form. Evaluation of buildings based on energy efficiency is mandatory in architects' and engineers' decision making in order to achieve high performance buildings and low-energy architecture. Thus, careful articulation of building shape and form is important in designing low energy architecture. Evaluation of energy performance based on building form is vital in decision making by architects and engineers to (Hemsath & Alagheband Bandhosseini, 2015). Building geometry influence the heat loss, heat gain, infiltration and solar gain that ultimately affects the heating and cooling load. Building design is therefore a key factor to take into account from a design point of view. It is evident that more wall area with windows result in higher heating and cooling loads. Gilg & Valentine (2004) identified two zones which affects the energy consumption. They are perimeter and interior zones and the extent of these zones has an impact towards the energy consumption of the building. According to Gilg & Valentine (2004), the first 10-15 feet from the outer wall is known as the perimeter zone. The heating and cooling load in the perimeter area is susceptible for the existing weather condition through the building envelope such as walls, windows and roof as well as internal loads such as occupants, lights, equipment, etc. On the contrary, interior zone is evident for less variation in heating and cooling loads. By comparing two buildings with the same floor area, occupancy, features, operating hours, etc., buildings with large interior areas typically require less heating and cooling capacity, resulting in lower annual energy consumption.

Building geometry is a significant feature to be considered in terms of both design and energy consumption. A study conducted by Gilg & Valentine (2004) demonstrated the disparity in geometry of buildings. According to the study it was apparent that two buildings with similar square area, usage, construction and same operational hours have different EUI due to the difference in the building geometry. This is partly due to the higher exposure of the buildings to the external environmental conditions and likely to have higher EUI. Therefore, buildings with multiple floors or uncommon sophisticated buildings forms consume more energy than single floor rectangular buildings with the same floor area. Building form and orientation affect the overall energy efficiency of the building, according to the basic principles of passive solar building design. In addition, building geometry is a critical variable in determining the potential for reducing the buildings' energy consumption.

Victor Olgyay suggests the shape is associated with orientation and aspect ratio. Further the author of The Architect's Studio Companion by Allen discuss the building orientation and optimizing natural lighting into the building (as cited in Hemsath & Alagheband Bandhosseini, 2015). Many scholars have investigated the synergy between building form and energy consumption. For example, Hachem et al. (2014) explored the possible roof areas to optimize renewable energy generation in multi-family housing projects by investigating various housing shapes that simulate total radiation (kWh/m2). Results from solar radiation simulations showed higher results related to building shape variability and energy usage. Hemsath & Alagheband Bandhosseini (2015) proposed a technique for determining building form in order to evaluate energy consumption by considering the variation in building geometry and material consideration through two methods of sensitivity analysis. This research examined the effect of geometric features such as stacking and aspect ratio on energy performance of the residential buildings in four U.S locations

The study suggested that the most efficient geometry for residential buildings is the compact form. In fact, in some situations, geometric features such as the aspect ratio and the stacking of a building have a greater impact on the energy efficiency of a building that the materials used in the building envelop. Effect of aspect ratio on energy consumption in multi residential buildings in Canadian cities was investigated by McKeen & Fung (2014). This research examined the ideal aspect ratio for buildings along east west and north south axis. It was apparent through the analysis that the optimum aspect ratio resulted in significant savings in heating and cooling.

Therefore, the optimum aspect ratio helps buildings to obtain more solar gain in winter and shade in summer, reducing heating and cooling requirements. Moreover, the optimal aspect ratio has also lowered peak loads, which can have a significant impact on capital and operational costs. Susorova et al. (2013) researched the influence of geometry aspects on the quality of fenestration energy performance in office buildings. A study revealed that in rooms with small window in hot climate and in rooms with large window areas in cold climates, room depth (W/D ratio) has a significant impact on total energy performance. Moreover, it is apparent that energy consumption in temperate climate slightly affected by width to depth ratio. The best energy performance in hot climate is evident in buildings with shallow pan forms since it required less artificial lighting. In contrary, best energy performance in cold climatic conditions are evident in deep plan forms. This is mainly due to the minimal heat transfer between interior and exterior through the building façade compared to the heat gain from internal sources such as electrical lighting and other equipment. In temperate climatic conditions, the best energy performance is apparent in rooms with medium depth. Steemers (2003) expanded Martin & March's first launched review of the building form archetypes. The main intension of the study was to define the building forms which utilize the land most. The optimal land use was therefore related to measurable parameters such as the built capacity, which refer as the ratio between the floor areas of the built form to its site extent as well as day light availability. Martin and March explored a variety of archetypal simplified forms known as courtyard and pavilion type (as cited in Ratti et al., 2003). Courts are similar to the traditional forms of construction found in many countries. Although pavilions represent more modern forms of tower construction that became popular after the Traditional Movement. The reason for using this simplified form was to restrict the complications contained in the actual urban texture and analyze and compare the effect of geometry alone. In addition to the pavilion and court, another elementary form known as street was introduced. It is possible to identify some other combinations of these three basic forms that produce the six archetypal forms and these forms were investigated by March and Trace and measured in terms of productivity and availability of built capacity and daylight (as cited in Ratti et al., 2003). Evidence indicated that the performance of land use improves as circumference increases. For an example courtyard performs better than pavilion. Building form has an impact towards energy consumption of the building. Thus careful articulation of the building form is a necessary feature to decrease energy consumption.

2.4 Summary of Chapter 02

Chapter two discuss literature related to energy consumption in buildings. This chapter consists of four sections. Section one elaborate on the world energy scenario. Energy consumption in the construction industry is comprised of residential and commercial end users, contributing 20.1% of the total electricity production in the world. Buildings represent for 30% of the final energy demand globally, and 55% of world electricity usage. Moreover, construction industry is responsible for more than a quarter of energy related CO_2 emissions and accounts for two-thirds of halocarbon and 25-33% of Black Carbon emissions. This section further deliberates the drivers which contribute towards energy consumption in buildings. It was evident that several elements have been main contributing factors for energy consumption in the bluing sector such as building form, working hours, size of the population and environmental conditions. The impact of these factors towards energy consumption differs from nation to nation, within the nation and over time depending on the differences in cultural, financial, regional and population as well as the policy background.

Further, section two elaborates on the impact of climate change on energy consumption in buildings. Due to the long life span and high initial costs of the buildings, engineers and architects must consider the impact of climate change on buildings. It was evident that human activities have resulted in projection of global warming from 1 C° compared to pre-industrial level and it is predicted to reach 1.5C° within 2030 and 2052 if it continues to increase at present rate. Thus highlight the importance of climatic change on building energy consumption.

Further, third section of this chapter analyze the GHG emission from buildings in different countries from different regions. It was evident that the Asian region has been regarded the primary cause of CO_2 emission to reach 17.4 $GtCO_2$ in 2016 since the mid-2000s. This level of CO_2 emission is twice the emission level of the Americas and three times the emission level of Europe. Fourth section gives an outline of the building energy consumption pattern of the non-domestic building stock. The energy consumption of the non-domestic building stock was further analyzed based on the morphological parameters such as building form, orientation, building envelop configuration, building geometry and physical configuration.

3 SECTION A: FORMATION OF A DATA REPOSITORY

Preface

This chapter discuss the formation of a data repository of the existing office building stock in CMC region. The investigation is composed of three sections. Section A is focussed on development of a data repository, Section B is detail thermal investigation of the reference buildings and Section C is analytical investigation of building morphology and energy index. This chapter is focus on Section A which consist of four stages. The stage 1 is to identify the dispersion of office buildings in CMC region. Dispersion of office buildings in CMC region was identified based on land use maps, GIS data and walk through investigation.

Stage 2 is focused on identifying the areas with the highest dispersion of office buildings. Further, this section describe on the development of a filtering mechanism based on building morphology to extract the sample office building stock. Stage 3 is formation of a data profile of the extracted office buildings stock. In this stage BEI is calculated based on annual electricity consumption and gross floor areas of the buildings. Further, these buildings were categorized based on the BEI. Hence, three levels of Building energy index categories are identified Based on the calculated energy indexes. These three levels are: Critical Level, Average Level and Accepted Level. Stage 4 of the investigation is to identify the reference buildings which represent each energy index category.

3.1 Structure of the Investigation

This study is primarily focussed on investigating a nexus between building morphology and energy consumption in office buildings under the non-domestic building category. The structure of the investigation is composed of three sections.

- Section A- Formation of a Data Repository
- Section B-Detail Thermal Investigation of the Reference Buildings
- Section C-Analytical Investigation on Building Morphology and Energy Index

This chapter is primarily focus on Section A which is to formulate a data repository of the existing office building stock. Formulation of a data repository was conducted in four stages. Stage I is to identify the dispersion of office buildings in CMC region. GIS data, land use maps and walk through investigations were performed to identify the dispersion of office buildings in CMC region. During the walkthrough investigation it was observed that many office buildings have multiple functions. For instant, some buildings have a combination of activities along with offices such as retail spaces, restaurants, educational institutes, residential activities and etc. Hence this investigation is focussed on buildings which are exclusively function as offices. High rise office buildings were excluded from the investigation due to the higher energy consumption for building services. Thus, intermediate and middle rise buildings (5-12 floors) were taken into consideration. Further, office buildings constructed within the last 30 years were considered since older buildings tend to consume more energy due to wear and tear.

Stage II is to identify the areas which has the highest concentration of office buildings in CMC region. These identified office buildings were further classified based on geometric and operational attributes of the office buildings. Plan form, orientation, façade configuration and physical configuration were taken under geometric attributes. Number of occupants, operational hours and system of mechanical ventilation were considered under the operational attributes. Stage III of the investigation is to develop a data profile of the sample office building stock. The energy index of these office buildings were calculated by using annual electricity consumption and gross floor areas. Three energy index categories were identified. They are Critical Level (above 250kWhm^{-2}), Average Level (150-250kWh^{-2}) and Accepted Level (100-150 kWhm^{-2}). The extracted sample office buildings were categorized based on these energy index levels. Stage IV of the investigation is to identify reference buildings which represent the energy index categories. The structure of the investigation is illustrated in Figure 02.

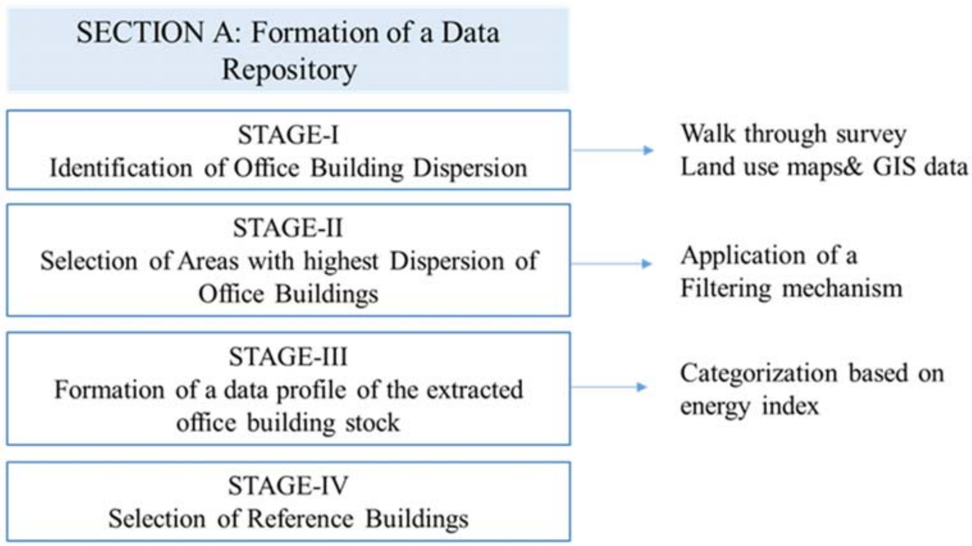


Figure 2: Structure of Section A in the investigation

3.2 Stage-I: Identification of Office Building Dispersion

3.2.1 The Administrative Structure

The study focus area is Colombo Municipal council, which is also known as the City of Colombo. It is located in Western Province, Sri Lanka. According to the administrative structuring system, Western Province is composed with three Districts. They are Gampaha, Colombo and Kaluthara Districts. A District is further divided into a number of Divisional Secretary's Divisions (commonly known as DS divisions), which are in turn subdivided into Grama Niladhari (GN) Divisions. GN Divisions are the smallest administrative unit in Sri Lanka. CMC is the largest municipality in Sri Lanka and it is comprised of 35 GN Divisions. For the ease of admiration in CMC region these 35 GN divisions are further sub divided into Wards. Thus, CMC region is comprised 47 Wards. The walk through investigation along with a photographic survey was performed in all 47 Wards based on GIS data and land use maps. Figure 03 illustrates the administrative structure of the study focus area.

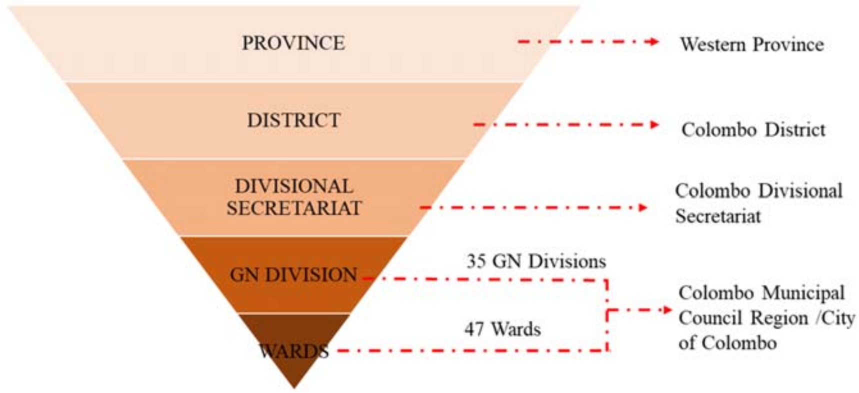


Figure 3: Administrative Structure of the Study Focus Area

3.2.2 Climate

Climatic condition in Colombo is defined as a tropical monsoon climate with high humidity and uniformly high temperature level. The average temperature through the year varies from 26°C to 29°C and the highest temperature variation is evident during March to April. Highest temperature level recorded during this period was 36°C. In addition, Colombo has a high amount of humidity, where the average amount of relative humidity differs 60%-80% throughout the year. Colombo receive lengthy hours of sunshine and mean hourly global horizontal radiation ranges between 398 and 350 W/m² per annum and the highest radiation level 1030 W/m² is evident in March.

3.2.3 The Study Area

The study area covers CMC Region which is located in Colombo District (6°55' N, 79°51' E at an altitude of 8m). CMC Region was selected for the investigation since Colombo District has the highest population density in Sri Lanka where the population density is within the range of 2000 to 4000 persons/Km2. Further, Colombo is considered as the commercial capital of Sri Lanka which is composed with residential population of 647,000 and 700,000 floating population (CBSL, 2018). According to statistical data, 50% of the floating population travel to Colombo for occupational purpose. Some of the primary features of this region are the elevated urbanization rate, density of secondary and tertiary financial activities, significant amount of vehicle population and energy consumption along with increasing synthetic surface coverage and limited vegetation coverage. A study conducted by Manawadu & Liyanage (2008) have identified some of the dominant features prevailing in this area as rapidly growing urbanization, increasing number of vehicle population along with increasing fuel consumption, secondary and tertiary economic activities, artificial surfaces and low vegetation cover (Manawadu & Liyanage, 2008). GIS Unit in Urban Development Authority (UDA) has recoded the land use activities along with the land area in each GN Divisions in CMC region which was taken as a guideline to carry out the investigation. The land use map of CMC region is illustrated in Figure 04. Some of the identified land use activities are administration, apartments, automobile parking, automobile repair and workshops, banking and allied, cinemas and amusements, community organizations, educational institutes, hotels and guesthouses, manufacturing, religious and etc. Land extent used for administrative, bank and allied activities were taken to calculate the built-up percentage of office in each Ward. Annexure A indicates the derived percentages of office building dispersion in each 47 Wards in CMC region.

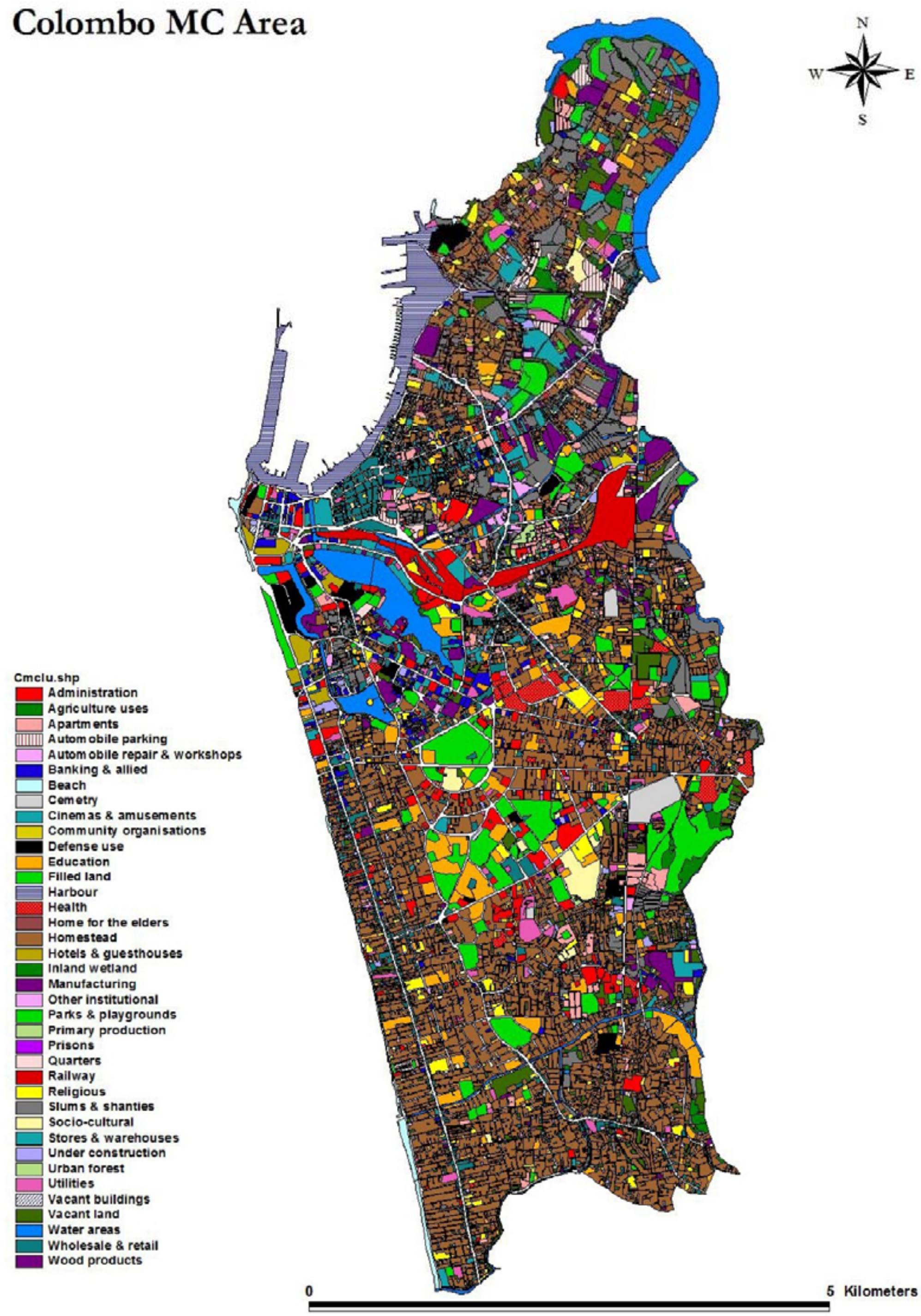
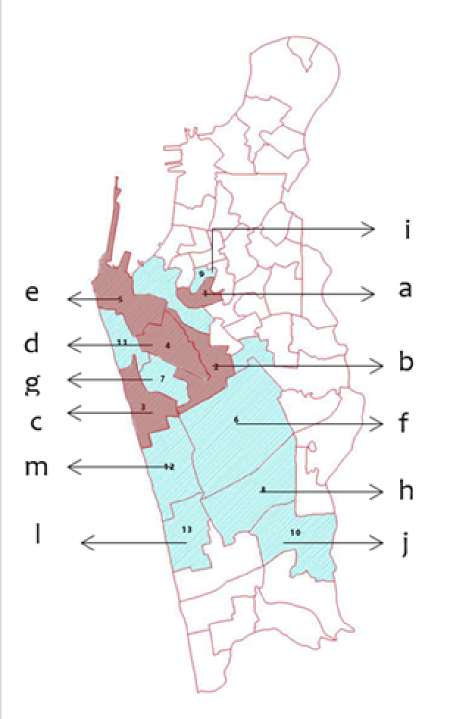


Figure 4: Land use map of CMC region (CoMTrans Urban Transport Master Plan , 2014)

3.3 Stage-II: Selection of areas with the highest office building dispersion

The calculated office building dispersion percentages of all the 47Wards were taken as a guideline to identify the Wards with the highest concentration of office buildings. The percentage of office building dispersion above 4% was taken to identify the buildings which are primarily used as office buildings. During the walk through investigation as well as the calculated office building dispersion percentages it was evident that 5 Wards had the highest dispersion of office buildings. Wards with the percentage of the office building distribution is illustrated in Figure 5. The highest concentration of office buildings in CMC region is evident in Keselwatte (18.92%), Suduwella (16.19%), Kollupitiya (15.07%), Hunupitiya (12.25%) and Fort (11.42%). Further, office buildings are located along the main traffic arteries such as Galle Road, Dharmapala Mawatha, Sagharaja Mawatha, Sir James Peris Mawatha and D.R Wijewardhane Mawatha in these Wards. More over 75% of the office buildings located in Kollubitiya Ward are East West oriented.



Ward		Percentage of Office Buildings
a	Kesellwatte	18.92
b	Suduwella	16.19
c	Kollupitiya	15.07
d	Hunupitiya	12.25
e	Fort	11.42
f	Cinnamon Gardens	9.94
g	Wekanda	9.38
h	Thibirigasyaya	7.46
i	Aluthkade West	6.92
j	Kirula	6.93
k	Kompannaweediya	5.77
l	Millagiriya	5.05
m	Bambaapitiya	4.39
n	Kuppiyawatte West	4.91

Figure 5: distribution of office building stock in the CMC region

3.3.1 Overview of the office buildings in the highest dispersion

Distinct features such as building height, orientation, age of the building, building envelop configuration are evident in the identified office buildings in the selected five Wards along with macro context. The average building height in Keselwatte Ward is within the range of 4-5 floors. Middle-rise & high-rise office buildings are evident in Suduwella, Wekanda, Kollupitiya and Fort. Further, 85% of the office buildings are east west oriented in Kollupitiya Ward. Majority of the office buildings in Fort are more than 50 years old. The office buildings constructed in Kollupitiya, Kesellwatte, Wekanda and Hunupitiya are constructed within the last 30-25 years.

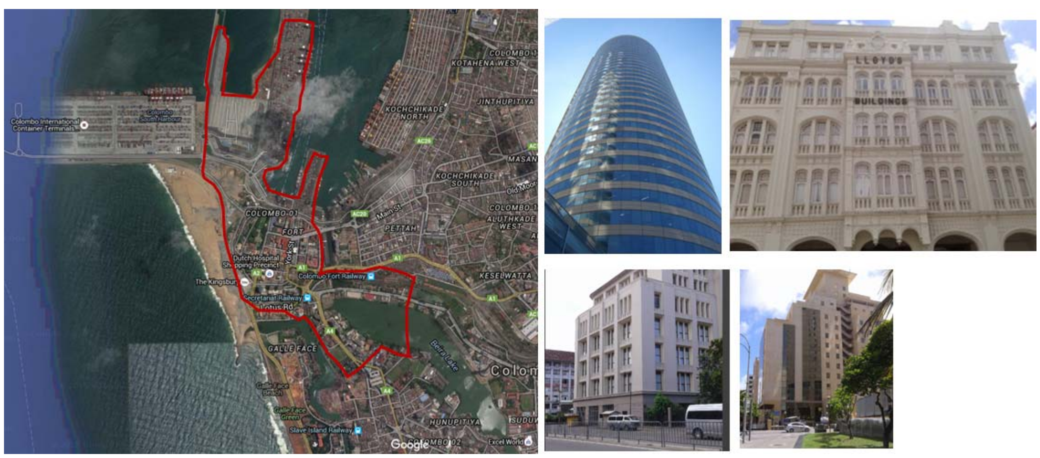
The building facades in all the Wards are with fixed glazed & Aluminium cladding. However, the office buildings in Fort have operable windows with shading devices. The macro context of each Ward has distinct features as well. Kesellwwatte Ward has limited green lungs with densely built low rise buildings. Whereas, Suduwella & Hunupitiya Wards are located in the boundary of Beira Lake and Viharamahadevi Park. Kollupitiya and Fort Wards are bordered with sea.

Name of the Ward	Kesellwatte
Percentage of office building	18.92%
Average Number of floors	4-6

Name of the Ward	Suduwella
Percentage of office building	16.19%
Average Number of floors	5-10

Name of the Ward	Kollupitiya
Percentage of office building	15.07%
Average Number of floors	4-9

Name of the Ward	Hunupitiya
Percentage of office building	12.25%
Average Number of floors	6-13



Name of the Ward	Fort
Percentage of office building	11.42%
Average Number of floors	5-12

Figure 6: Building Characteristics of the selected Wards

3.3.2 Application of a Filtering Mechanism

Characteristics of the existing office buildings in selected Wards were recorded based on building operational data, morphological data and general information. The location of the building, age of the building, activities performed inside the office buildings were recorded under general information. Façade configuration, physical configuration, building form, building height and orientation were recorded under morphological data. Numbers of occupants, working hours, number of lifts & escalators, type of air conditioning system, indoor lighting system are considered under building operational data. These parameters perform as a filtering mechanism to cluster buildings with similar features.

Six types of building plan forms were evident in the office building stock. They are square, rectangular, cylinder, trapezium, L shape and U shape. The most common plan forms were rectangular and square shapes. Orientation of the long side of the building façade was evident in all four cardinal directions. They are East-West, North-South, and Northeast-Southwest and Southeast-Northwest orientations. Three distinct façade configurations were evident in the building stock. They are operable windows, fixed glazed panels, fixed glazed panels with aluminium cladding. When considering the physical configuration of the buildings, it was observed that buildings were either free standing or attached to another structure from one side or from both sides.

When considering the operational aspect of the buildings, two distinct operational hours were observed in the building stock. They are regular working hours from 8.30am to 5pm and extended working hours during week days and week end from 8.0 am to 1.pm. Number of people occupied within a building vary during the day and it was categorized into three groups namely, buildings with less than 100 people, 100-200 people and above 200 people. All the working spaces of the office building stock were mechanically ventilated. The service areas and common lobbies such as lift lobbies and staircase lobbies in some office buildings were naturally ventilated. Further, artificially lit interiors were evident in all the office buildings even though provision for natural lighting was possible. Hence, glazed windows were covered with blinds or curtains to prevent light coming. When considering the age of the buildings in office building stock, majority of the buildings were constructed within the past 25-30 years period. Whereas few buildings were more than 50 years old and some were less than 20 years old. The summery of these operational, morphological and general parameters are illustrated in Table.1.

Table 1: Morphological Parameters of the existing building stock

	Morphological Parameters				Operational Parameters					General Information			
	Plan form	Orientation	Façade configuration	Physical configuration	Operational Hours	Number of Occupants	Mode of Ventilation	Type of Lighting	Number of Lifts	Location	Age	Number of Occupants	Activities Performed
Building Characteristics	Square	EW	Operable Windows	Normal 8.30am-5.0pm			Free Running				Above 50		
	Rectangular	NS	Fixed Glass	Extended			Mechanical				25-35		
	Cylinder	NE-SW	Operable Windows with Al. Cladding				Mix Mode				Below 25		
	Trapezium	SE-NW											
	L Shape												
	U Shape												

3.4 Stage-III: formation of a Data Profile of the Extracted Office Building Stock

The building morphological and operational attributes were recorded in single use office buildings such as buildings with administrative/professional activity, government offices, banks/other financial offices. This is mainly due to the similar type of activity and energy consumption within the building. Building energy index was calculated in all the extracted office building stock by using the annual electricity consumption and gross floor areas. These extracted office buildings were further analysed based on the morphological parameters and energy indexes.

The considered morphological parameters are building geometry, building façade configuration, building orientation and physical configuration. Building form is represented as the aspect ratio of the office buildings which is a key morphological parameter when optimizing the building energy consumption (Timothy L Hemsatha, Kaveh Alagheband Bandhosseini, 2015). WWR was considered as the building façade configuration which resembles the amount of glazed area in the building envelop. The direction of the long side of the building façade is considered under building orientation. It was evident that the amount of energy consumption varies with building orientation and façade configuration. Physical configuration represents the buildings which are free standing or attached with another structure from one side or from both sides. Analyses of these morphological parameters are expanded under each subsection.

3.4.1.1 Building geometry

Lack of research attention is evident on the impact of building geometry on energy consumption in Sri Lanka. Factors such as building plan form, physical configuration, façade detailing and orientation aspects are discussed under building geometry. Six types of office building plan forms are identified in CMC region. These six types of plan forms fall under either basic or composite plan forms. Square, linear and circular plan forms are considered under basic plan forms. Whereas, composite plan forms are derived from a combination of these basic plan forms. Thus, L shape, U shape and trapezium plan forms are demonstrated under composite plan forms. 85.05% of the office buildings in CMC region are composed of linear and square plan forms. Out of which, 62.07% and 22.98% of the building plan forms are linear and square plan forms. L shape composite plan form is a combination of two linear plan shapes or a linear shape with a rectangular shape. Whereas U shape composite plan form is depicted by three linear plan shapes. Circular and trapezium plan forms in the office building stock have an equivalent percentage of 2.3%, where 2.29% and 8.045% of the office buildings are composed U and L shape composite plan forms. Figure 07 illustrates the basic and composite plan forms and their distribution percentages

3.4.1.2 Building façade configuration

The impact of building façade on energy consumption is widely addressed by many scholars. Construction of new office buildings have increased in Colombo during the past few years. These new office buildings are composed with fully glazed facades with Aluminum cladding. The arrangements of the doors and windows in the building facades play a prominent role in terms of energy performance (Alghoul et al., 2017). Due to less conductivity of the materials used for fenestration, less thickness and exposure to direct solar radiation make the building fenestration susceptible for heat gain to the building. Due to the increased glazed area in the building façade can lead to increase solar radiation to the buildings. This affect cooling demand and has the potential to contribute overheating condition in tropical climate. In contrary, peripheral zones of the buildings can get benefitted from the large glazed facades due to increased availability of daylight. Thus, large amount of day light can cause visual discomfort due to substantial amount of daylight entering from large glazed facades. The amount of glazing used in non-domestic building façades have rapidly changed over the period of time. At the beginning of the 20th century, glazing percentage in the building facades were less than 20% (Gakovic, 2000). The main reasons for having less glazing ratio for the buildings are mainly due to the poor characteristics of the glass and it was a quiet an expensive material back in the days. But the amount of glazing percentage increased over the period of time as a result of the improved quality of glass and reduction in cost. In addition, architects extensively used glazed in facades to create bright spaces with transparent facades which make the building controversial. CMC region is predominantly composed of glazed and Aluminum cladded building on the front façade which is the entrance to the building from the road.17% of the buildings had glazed facades in the front.

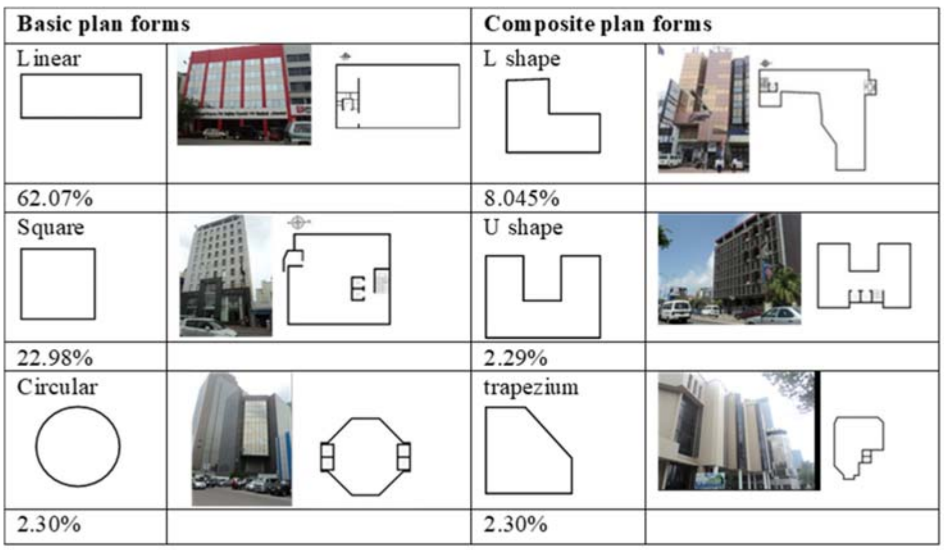


Figure 7: Percentage distribution of Basic and Composite Plan Forms

These glazed facades were assembled with a combination of fixed and operable panels. In some instances, blinds were used to control the heat gain to the building interior. Figure 08 illustrates the fenestration compositions of the east west critical facade.

Building Fenestration Detail		
57% of the buildings are cladded with Al. & Glass in the front façade	26% of the buildings are Al. Cladded throught the front façade	17% of the buildings have full length glass openings in the front façade.
		

Figure 8: Typical Fenestration Details of the Building Stock

The percentage of glazed are to wall area define as Window to Wall Ratio (WWR) of a building façade. WWR is used to evaluate the impact of fenestration on energy consumption. The WWR helps improve heating and cooling of the building by decreasing direct solar radiation to the building and enhance day lighting and ventilation. Further, WWR is one of the primary factors which affect the thermal performance of the building. Thus, WWR has integrated into new building construction standards in both EEBC for Sri Lanka and ASHARE.

As stated in ASHRAE 90.1, the maximum recommended value given for WWR in commercial buildings in all climate zones is 40%. According to Mangkuto, Rohmah, et al.,(2016) 30% of WWR with a wall reflectance of 0.8 and south orientation is most suitable for buildings in tropical climate. However this optimum solution can vary during complex situations when there are additional building elements and shadings.

A photographic survey was conducted to identify the variation in WWR in the front façade. Buildings were categorized based on the percentage of window in all four facades of the buildings. The minimum to maximum WWR was taken as 10% to 100% with 10% intervals. Figure 09 illustrated the summary of WWR variation on the building front facades.

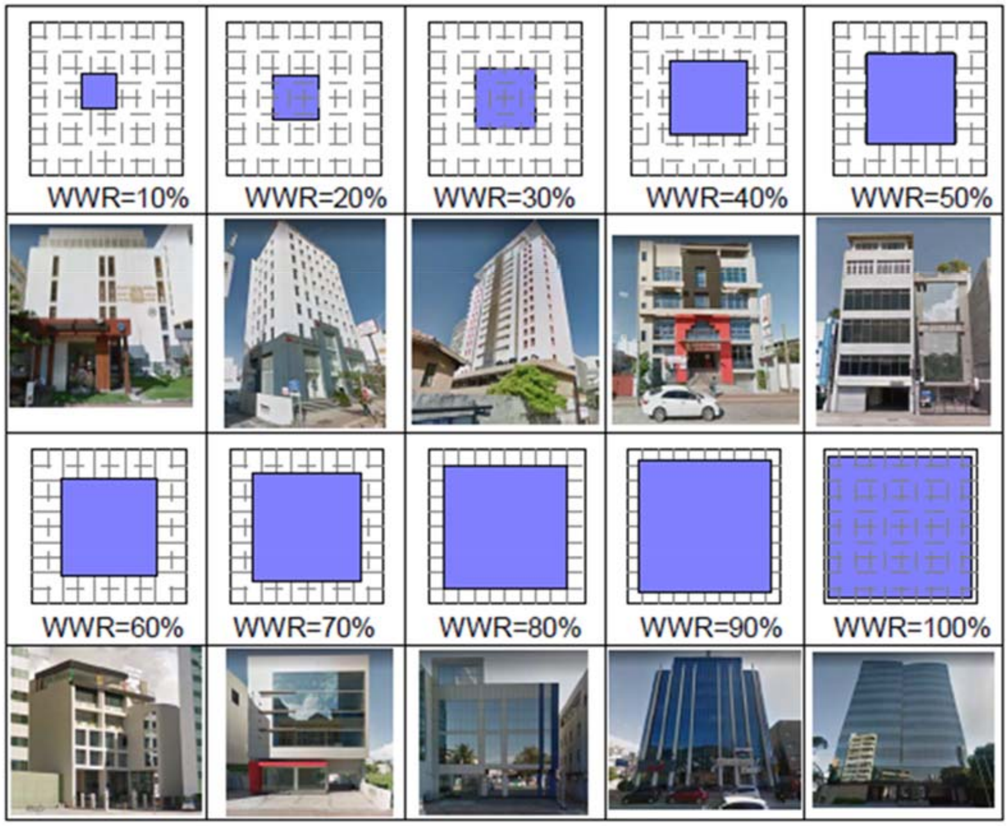


Figure 9: Elevation View of the Window Wall from 10% to 100%

3.4.1.3 Building orientation

Building orientation towards the sun path is essential to optimize daylight and minimize solar heat gain to the building. Optimum orientation is a key strategy in warm climates which means that buildings should be positioned in particular planning implications for the designer (Rajapaksha & Hyde, 2005). Further, orientation helps to increase or decrease the heat gained from the sun by either maximizing or minimizing the amount of time that the building is susceptible to direct sunlight. The short axis of the building foot print should be north south oriented with 5◦ north of east to reduce direct solar heat gain for the buildings which are located in the tropical climate zone (Yeang & Powell, 2007). Thus, east and west facades are affected by direct solar radiation in tropics which upheave solar heat gain into the building. Therefore these facades are designated as critical facades for buildings in tropical climatic conditions. It was found that 41.38% and 13. 79% of the office building stock is East West and North South oriented respectively. Of which the average BEI per annum is 211.60kWhm-² and 200.21kWhm-² respectively. It is evident that the building facing East and West facades have higher energy intensity due to the increased cooling load as a result of the direct solar gain. Building orientation and BEI of the office building stock is illustrated Table 2.

Table 2: Building Orientation and Building Energy Index

Orientation	**Percentage**	**Average BEI**
East-West	41.38%	211.60 kWhm-^{2}
North-South	13.79%	200.21kWhm-^{2}
North East-South West	25.59%	200.08kWh-^{2}
North West-South East	19.24%	205.69KWhm-^{2}

3.4.1.4 Physical configuration

When building positions are taken into account, the office building stock signifies a combination of attached and detached building forms. Of which 63.22% of the buildings are detached buildings and 36.78% of the buildings are combined with another building at least from one side. Buildings with both sides attached to another building have an average energy index of 210.04KWhm-^{2}.The average energy intensity of the buildings with one side attached to another structure is 211.07kWhm-^{2}. Thus denotes the building energy index varies with the physical configuration. Buildings with both sides are attached to another structure has limited opening where building getting overheated from direct solar radiation is limited.

3.5 Stage-IV: Selection of Reference Building

3.5.1 Calculation of BEI in the extracted office building stock

Notable amount of studies have enable to develop and analyze the energy used pattern of non-domestic building stock. A common feature of all the energy related studies is that the energy consumption of a set of similar buildings in a designated area with similar activities is expressed as kWh/m2/year. This value is referred as Building Energy Index (BEI). It is a qualitative indicator to assess a building's energy consumption with reference to its floor area within a period of year.

Monthly electricity bills were taken to analyze the energy consumption for each building. These bills were taken for a period of one year from January to December. It has been confirmed that most of the electricity consumption is due to air conditioning, ventilation and artificial lighting of the building interiors. The buildings primarily used fluorescent tubes, track lights, tungsten halogen lamps, and

LED artificial lighting. All the floor plan areas were collected during the survey and areas of the air conditioned spaces were calculated. Figure 10 illustrate the variation in Building Energy Index of this building stock. The corresponding energy indices of the building stock were derived based on the collected data.

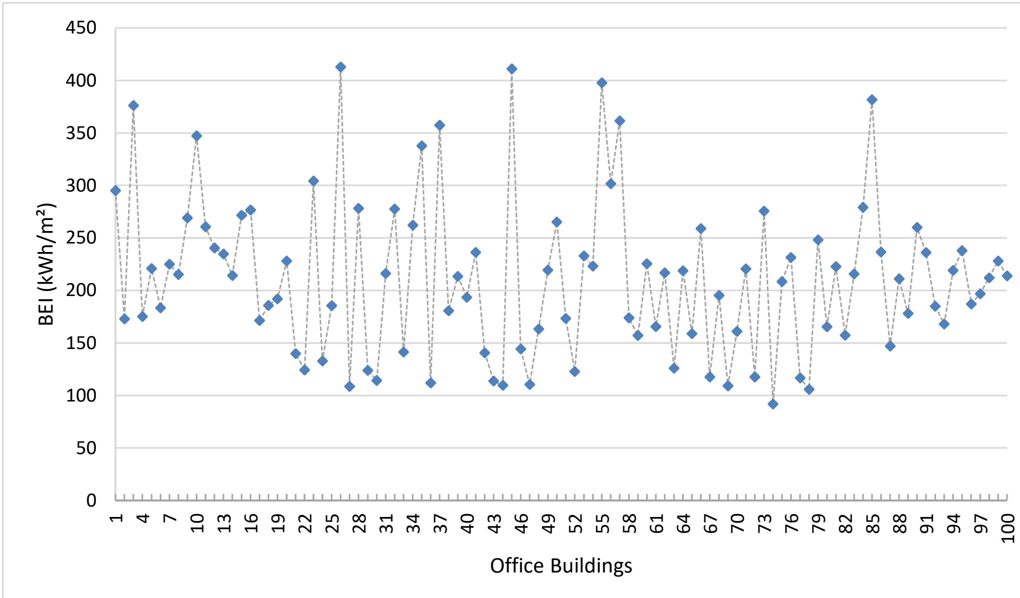


Figure 10: Building Energy Index Pattern of the Office Buildings in CMC Region

The retrieved information on the building information in order to calculate the energy indexes were robust. The graph in Figure 10 illustrates the fluctuation in energy index in the extracted building stock. It is apparent that some buildings have energy index levels more than 300kWhm-^{2} and majority of the buildings are within the range of 200-250 kWh-^{2}. 52.80% of the office buildings have annual energy use intensity more than 200KWhm^{-2} of which 12.64% of the buildings have annual energy intensity more than 300KWhm^{-2} Moreover only 25.84% of the office buildings have annual energy intensity less than 150KWm-^{2}. Further, the average Building Energy Intensity of CMC is 211.59 KWhm^{-2} per annum. Drastic fluctuation in the energy indexes are evident in Figure 10 is that the buildings are not segregated based on the energy index categories.

3.5.2 Categorization of office buildings based on Building Energy Index

Further, corresponding energy index was around 200KWh/m2/annum in 52.8% of the buildings and 12.8% of the buildings have the energy index around 300 KWh/m2/annum in 12.8% of the buildings. Number of factors affects the variation in building energy index. They are factors such as number of occupied hours, air conditioning system, amount of equipment used and etc. Office buildings with energy intensity above400 kWh/m2/annum have extended working hours. All the office buildings in CMC region have a combination of artificially ventilated working spaces with naturally ventilated common spaces such as lift lobbies, corridors and services areas.

It is significant to note that the buildings with central air conditioning system have less building energy intensity than the buildings with split type air conditioning system. Moreover, the age of the building has an impact on the building energy intensity. Older buildings have exposed more wear and tear and typically have a higher infiltration rate. In addition, frequent maintenance is typically needed for heating, ventilation and air conditioning (HVAC) equipment which are near or past the efficient period. 37.93% of the buildings in CMC region consist of office buildings more than 20 years old. Further, 34.48% and 27.59% of the buildings are below 20 years and 10 years old respectively. Wards such as Fort consist of office buildings more than 100 years old. This research considered the office buildings constructed within last 35 years.

Majority of the office building stock in CMC region is composed of rectangular and square plan forms. Of which 62.06% and 22.98% of the buildings are rectangular and square plan forms respectively. Average energy intensity of rectangular and square plan forms is 211 KWm2/annum Buildings with higher wall to floor area ratio requires larger cooling capacities (Gilg & Pe, 2004). Thus L and U shape plan forms has a higher building energy index than the basic plan forms. This is due to the increased perimeter wall area which influences heat gain to the building.

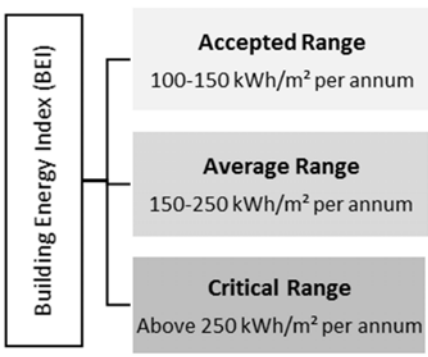
Accepted level of good practice of energy use for air – conditioned buildings is within the range of 110 – 120 kWh/m2 per year (Taylor et al., 2012). Further according to the MS 1525:2007 Standard in Malaysia indicates that any building which implements energy efficient measures can achieve the BEI of 136 kWh/m2/ year for non-residential buildings in tropics (Mohamad Kamar, 2010).

Based on the calculated Building energy indexes of the office building stock of CMC region three levels of BEI categories are identified. These three levels are: Critical Range, Accepted Range and Average Range,

- The Critical Range is one of the most energy intensive buildings to be found in Sri Lanka today BEI = above 250 kWh/m^2/yr.
- The Average Range represents the typical range of buildings and energy use characteristics that are prominent in the sector. BEI = 150-250 kWh/m^2/yr.
- The Accepted Range represents the level of energy efficiency required to achieve by building policy guidelines. BEI = 136 kWh/m^2/yr.

The identified three energy use levels of building energy index ranges are illustrated in Table. 03. All the buildings identified in the CMC region is categorized under these three energy index ranges.

Table 3: Identified Energy Index Levels



The Critical Range represents the most energy intensive buildings where BEI is above 250 kWh/m^2 per annum and 35.72% of the buildings are comprised within this range. The Average Range reflects the majority of office buildings where 54.08% of the buildings in CMR are within the BEI range between 150-250 kWh/m^2 per annum. The office buildings in this category have energy intensive features such fully glazed facades. This is a common feature in most of the existing and new office buildings in CMC region. Accepted Range consist of office buildings where BEI is within the range of 100-120 KWhm^{-2} per annum and 10.20% of the buildings represent this energy index range. This is considered as the accepted level of good practice for mechanically ventilated buildings in tropical climate. Summary of the energy index range and the percentages are illustrated in Table 04

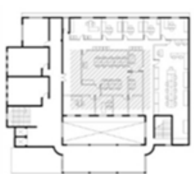
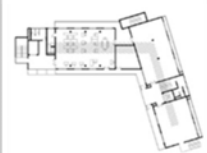
Table 4: Energy Index Range and the Percentage of Buildings in CMR

Building Energy Index Range	**Building Energy Index** (KWh/m² per Yr.)	**Building Percentage**
Accepted Range (Ac.R)	100-150	35.72%
Average Range (Av.R)	150-250	54.08%
Critical Range (C.R)	Above 250	10.20%

3.5.3 Selection of reference cases for detail investigation

Selection of reference buildings were mainly done by identifying building which represent each energy index category. Following considerations were made when selecting the cases.

Table 5: Data profile of the selected refrence cases

Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Ministry of Buddhist Affairs	Holcim	CDB	Valliant Tower	CECB
112KWhm^{-2}/yr.	270KWhm^{-2}/yr.	136KWhm^{-2}/yr.	218KWhm^{-2}/yr.	118KWhm^{-2}/yr.
				
				
Deep Plan form	Deep Plan form	Shallow Plan form	Shallow Plan form	Shallow Plan form
Mix Mode	Mechanically Ventilated	Mechanically Ventilated	Mechanically Ventilated	Mechanically Ventilated
Detached	Detached	Detached	Detached	Detached

- The building must be a free standing building. All the selected cases were not structurally attached to other building from any side. This is mainly to evaluate each building design had no thermal effect from other buildings.
- Selected one building was constructed within the past 3 years and two buildings were within the past 15 years and one building was within the past 25 years. Majority of the office buildings in CMC was constructed within the

past 25-15 years. This is to investigate the nexus between energy consumption and the age of the buildings.

- Selected buildings have a combination of shallow plan forms and deep plan forms with East- West and North-South orientation. This is to investigate the impact of orientation and plan form on building energy index
- Two of the selected buildings have operable building envelops and three office buildings have sealed building envelop. This is to investigate the impact of space conditioning on energy consumption and to investigate the impact of microclimate on indoor temperature.

Five buildings were selected which represent each energy index category to generalize the findings and to conduct thermal investigations. These reference office building morphologies were selected based its physical and operational characteristics. The selected buildings are comprised with shallow and deep plan forms with east west orientation and north south orientation. Data profiles of the selected five cases are illustrated in Table 05.

3.6 Summary of Chapter-3

Most of the office buildings consume energy in the form of electricity within the operation and maintenance stage such as running lifts, office equipment as well as HVAC system. Hence, air-conditioning and lighting consumed more energy in buildings. While the demand and cost of electricity are continuously increasing majority of the office buildings in CMC region consume more energy due to lack of energy optimization in the buildings.

Aim of this chapter is to develop a comprehensive data base of the morphology of office building stock in CMC region, which represent the highest built density in the country. Morphology of office building stock and energy intensity was based on the morphological parameters and opertaional parameters. Building orientation, physical configuration, envelop configuration and building plan form was considered under morphological parameters. Levels of occupancy, number of occupants, number of working hours, mode of lighting and mode of ventilation were discussed under operational parameter.

The building plan forms in CMC region can predominantly divide into two categories namely, basic and composite plan forms. The basic plan forms are comprising of linear, square and circular shapes. Combination of these basic plan forms demonstrate the composite plan forms namely, L shape, U shape and trapezium plan forms. During the walkthrough investigation and building analysis it was found that 85.05% of the buildings were composed with linear or square plan forms. Further, the average energy intensity of the building stock is 211.59KWh m^{-2} per year. Based on the collected data it was revealed that 41.38% of the office buildings are facing East-West orientation and 25.59%. of the buildings are NE-SW orientation. Moreover, buildings facing east west orientation have the highest average building energy intensity per annum of 211.60KWhm^{-2} which is due to the direct solar heat gain. Majority of the office building stock of CMC region consist of detached buildings. Out of which, 63.22% and 36.78 % of the buildings are attached with another structure from one side or both sides. Buildings which are attached to another structure from both sides have relatively high BEI per annum (211.07KWhm^{-2}) than the buildings attached to another structure from one side (210.04 KWhm^{-2}). This is due to the limited exposure of direct solar gain from outside. In contrary the BEI of the detached and attached from both sides are having similar energy intensity of 211 KWhm^{-2} .

Moreover, front façade of the buildings act as the most critical façade of the building due to direct solar radiation. These east and west facades have different glaze and Aluminium combinations. When analysing the building front facades, it was found that 17 % of the buildings were cladded with glass and 26% of the buildings were cladded with Aluminium. Whereas, 57% of the buildings were cladded with both Aluminum and glass. Moreover, majority of the office buildings in CMC is composed with buildings more than 20 years old. Age of the building has an impact towards the energy consumption of the building. Older buildings have been subjected to more depreciation and typically have greater frequency of infiltration. Further HVAC equipment used is usually near or past its efficient period and requires frequent sustentation and use more energy. Energy index of the office buildings were calculated by using electricity bills and gross floor area of the building. These calculated energy indexes were further categorized into three groups namely, Accepted Range, Average Range and Critical Range. Further, represntative buildings were selected from each energy index categories for further investigation.

4 SECTION-B: DETAIL THERMAL INVESTIGATION OF THE REFERENCE BUILDINGS

Preface

This chapter analyse the reference office buildings which represent each of the energy index categories. The selected five reference buildings represent the office building stock and the cases were selected based on the morphological characteristics and building energy index. These five building cases represent as Case A, B, C, D and E. out of which Case A and B are with deep plan form and C, D and E are with shallow plan form. All five buildings were thermally investigated during Non AC and AC period. All the selected case studies were free sanding buildings which were constructed within last 15 years' time.

Several limitations were observed during the investigation such as the different occupational densities, lighting conditions and equipment usage in all the five cases. Shadowing from adjacent buildings was not taken into consideration during the investigation. Even though the selected five cases were located in CMC region the micro climate of the buildings were different. And the thermal investigations were not carried out on the same day due to practical reasons. But experiments were conducted during week days and week days in all the selected cases. Since the investigation is based on assessing each building individually against its own micro context this is not a severe apprehension. All comparisons were made against ambient temperature.

The thermal investigation was carried out in these five buildings during non AC and AC period in the building periphery and core. Thermal investigation was conducted in both center and peripheral zones and temperature difference between outdoor and indoor were further analyzed to understand the cooling energy load required to condition the space. The investigation analyzed the potential for overheating in the building periphery and core in shallow and deep plan forms.

4.1 Experimental Investigation of the reference buildings

4.1.1 Structure of the investigation

The main objective of thermal investigation is to validate the energy consumption in the selected cases and to evaluate the building design in terms of operational energy use for cooling of typical office floors. Thus, the investigation was conducted by monitoring field investigations on thermal performances. The impact of building morphology on indoor air temperature behavior of these offices was investigated for a typical working day with air conditioning and a typical non-working day in the weekend without air conditioning. Recorded values were compared with ambient weather data of Colombo city. This study assumes the day without air conditioning reveals the impact of environmental load on indoor thermal behavior. Structure of the thermal investigation consists of two phases. Phase one investigate the indoor thermal performance of the selected office buildings when the air conditioners are on and off mode. Further, cooling energy load can obtain through the temperature difference of the outdoor ambient temperature and indoor temperature.

Phase two investigate the thermal behavior of the periphery during AC and non AC time. Indoor temperature profiles of the perimeter zones of interiors close to East, West, North and South facades are assessed for the effect of thermal behavior of each façade on cooling energy demand. Internal and ambient temperature readings were recorded in HOBO data loggers and surface temperature was recorded using thermocouples. Immediate microclimatic data were recorded onsite. This chapter presents the indoor temperature profiles of the reference office buildings. These selected cases represent the morphological characteristics of the urban office building stock in CMC region.

Literature reveals that attention should be given to reduce heat gain and to promote heat loss when designing in the tropical context. Thus the building envelope and the plan form are key considerations. Moreover, it was shown that failure to integrate interactive contextual adaptability results in indoor temperature elevation and overheating, which is an indication of space cooling energy load. It was discussed that this results when indoor temperature rises above ambient temperature. Daytime temperature in Colombo Sri Lanka can reach above 33C◦ during the period from October to April. All the cases were investigated in April 2016, during this critical period. Climate of Colombo Sri Lanka (latitude, 6.9271° N and longitude, 79.8612°

E) is a warm humid, tropical climate. During the period of study, a sunlit, hot weather pattern was observed. Average maximum temperature was 36C° and min. temperature was 26C°.A high level of relative humidity was experienced with q nighttime high of approx. 80% and day time low of approx. 60%. Could cover was less than 50%. Towards the end of the month, a relatively higher cloud cover was observed. Generally, the sky was clear and there was no rain.

4.1.2 Method of Instrumentation

Air temperature readings were taken over a weekend and one working day. Measurements were recorded at 30 second intervals during air conditioned and non-air conditioned periods. Recorded data was later averaged on hourly basis using a personal computer. Ambient weather data of City of Colombo was obtained from the Met. Department. Satellite measurements of same were obtained from 'world weather online' website.

1. Selection of locations to fix hobos
2. Thermo couples
3. Immediate microclimate temperatures were taken from outside hobos.

The devices used for monitoring predominantly consisted of HOBO data logger thermometers and thermocouples. These thermocouples were used for the purpose of measuring and recording both surface and air temperature. Further, each of these thermocouples had 5m long external probe sensors connected to the devices to take the temperature reading of the surfaces. Each instrument was protected from direct solar radiation and any hazards. These devices were kept under shade over the duration of each investigation.

4.1.3 Justification of the investigation

The intension was to determine a number of comparisons, which as follow:

- Temperature variation in central and peripheral zones of a typical office floor In this way a shallow plan form and deep plan form effects on thermal behavior could be evaluated and attributed to envelope thermal performance.
- Difference between Colombo's ambient temperature and indoor temperature variations of the office floors. In this way, overheating conditions and potentials could be determined

- The day time temperature elevation within the typical office floor. In this way, the proportionate energy demand for space cooling could be determined.
- Difference between peripheral temperature variation and wall surface temperature of a typical office floor. In this way, the heat sink potential of thermal mass (concrete) walls could be determined.
- The patterns of temperature behavior between peripheral indoor temperature and outdoor micro climate temperature
  In this way the thermal behavior of the typical floors could be analyzed against effects of the urban micro context.
- The difference between micro – climate temperature variations of all these cases and Colombo's ambient temperature

4.1.4 Limitations

Even though the selected five cases were located in CMC Region the micro climate of the buildings were different. Further the selected five cases have different occupational densities, lighting conditions and equipment usage. Moreover, shadowing from adjacent building were not taken into consideration as well. Buildings were not investigated on the same day at the same time due to practical reasons. But experiments were conducted during week days and week days in all the selected cases. Since the investigation is based on assessing each building individually against its own micro context this is not a severe apprehension. All comparisons made against ambient temperature.

4.2 Profiles of the detailed investigated Cases

4.2.1 Case A: Ministry of Buddhist Affairs

4.2.1.1 Introduction

The building selected as Case A is a free standing building located Colombo 07 facing Srimath Angarika Dharamapala Mawatha overlooking Vihara Maha Devi Park. This is the main administrative building for Buddhist affairs in Sri Lanka and it was constructed 12 years ago and currently 90 employees are working in the premises.

4.2.1.2 Morphological characteristics

The selected case A is a free standing building with 7 floors. The building has a deep plan form with an aspect ratio (Length/width) of 1.39. The long side of the building façade is facing north south orientation. The average BEI of this building is 112 $KWhm^{-2}$/year which represent the Accepted Range. Façade composition of the building in east, west north and south facades are 32%, 35%, 0% and 25% respectively. All the glazed panels in the building are operable Al. Sliding windows.

The building has a mini basement which is designated for parking. The ground floor has a double height entrance lobby with a courtyard. The ground floor encompasses of a double height entrance lobby with a courtyard. The topmost floor has an auditorium and the rest of the other floors are predominantly used as office spaces. Building service areas such as toilets, stores and staircases are located in east and west periphery of the building. This internal configuration helps to prevent overheating penitential of the interior. Some office floors are partitioned with half panels and some areas are partitioned up to the ceiling level. Some of the partitioned areas only function during designated days of the week.

4.2.1.3 Operational characteristics

The building function during the weekdays from 8.0am to 4pm. but some employees tend to work till 5pm during the week days. There are two elevators in the building. The occupants tend to use the elevators more than the staircase. Interior of the working areas are mechanically ventilated with split type air conditioning units. The set point temperature of the air conditioners is 25°C. The main entrance lobby along with the service corridors lifts lobbies and staircase case areas are naturally ventilated. Air conditioning units are fully switched off during Sundays. Thus thermal investigation of the selected building was carried out on Sunday to Monday when the air conditioning units are switched off and on mode. The morphological characteristics of the buildings are summarized in Figure 11.

4.2.1.4 Thermal investigation

Thermal investigation was carried from 11th of February 2016 (Thursday) to 16th of February 2016 (Tuesday). Thermal investigation was analyzed from 14th of February 2016 (Sunday) to 15th of February 2016 (Monday). Thermal investigation during non AC and AC period was analyzed in the core and periphery. Periphery temperature readings were analyzed based on the orientation. Hobos and thermocouples were used to retrieve temperature data of the periphery and core. Temperature reading points and instrumentation of the equipment are illustrated in Figure 12. Temperature readings were averaged on hourly basis. Outdoor ambient temperature were taken from the Department of Meteorology located in Colombo 07 for the investigated dates. These temperature data were recorded on hourly basis as well.

4.2.1.5 Thermal behaviour in the core

Indoor temperature variations in the core of office interior with and without air-conditioning are shown in Figure 13. Temperature behavior of the office interior was monitored for a typical weekday and weekend with the Air-conditioner switch on and off mode respectively. Temperature profiles during Non AC time and AC time showed a clear difference in the indoor air temperature behavior. The mean temperature during Non AC and AC time in this office interior is 29.1C° and 28.7C° respectively. Temperature variation remains constant in the building core during non AC period. But the temperature difference between the outdoor ambient temperature and indoor temperature during Non AC time from 8-16h of working time is 0.2°C. Thus indicate poor thermal performances of the building envelop. According to Figure 13 indoor temperature tend to increase gradually from 9am onward and remains at a constant level till office start on the following day.

Morphological Parameters				
Micro Context				
Number of floors	Semi Basement, Ground floor and six floors			
Age of the building	12			
Orientation	North South oriented			
Plan form	Deep Planform			
Aspect Ratio (length/width)	1.39			
Physical Configuration	Detached Free Standing Building			
Typical Layout & Building Elevation	 			
WWR composition in all four facades	WWR North	WWR South	WWR East	WWR West
	32%	35%	0%	25%
Operational Parameters				
Number of employees	Nearly 110			
Number of working hours	8.30 am-4.00pm during week days			
Mode of ventilation	Majority of the working areas mechanically ventilated and some office areas are naturally ventilated. service areas and lift lobbies are naturally ventilated			
EUI	112 KWhm^{-2}/year (Within the Accepted Range)			
Thermal Investigated Period	14th of February 2016 (Non-AC)-15th of February 2016 (AC)			

Figure 11: Operational & Morphological Characteristics of Case A

Figure 12: Instrumentation of data loggers in the floor plan

This is due to the poor thermal performance of the building envelop and the high occupancy level of people in the center. Thus it can be concluded that deep plan form is suitable for mechanically ventilated building since it helps to maintain a consistent indoor temperature level in the interior. Indoor temperature in the building core gradually decrease from 8am when the air conditioners on. Mean temperature of 28.54°C during working hours of 8am to 4pm is above the AC set point temperature of 25°C.

Difference between outdoor (To) and indoor (Ti) temperature difference (ΔT) for AC and non AC days are shown in Figure 14. According to the graph it is evident for positive and negative values for temperature difference (ΔT). Positive and Negative value of ΔT represents lower and higher indoor temperature levels than the immediate outdoors respectively. Results highlight temperature difference in both non AC period and AC period is negative in the morning hours till 9am. Thus highlight overheating condition of the building interior.

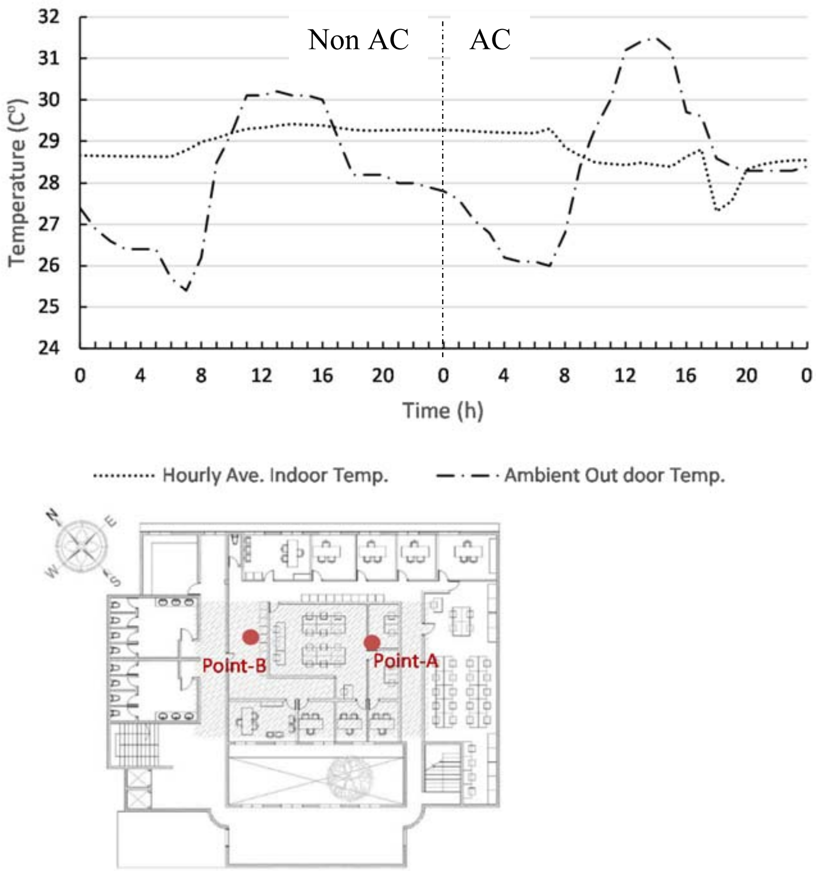


Figure 13: Thermal Behavior in the Core

Mean temperature difference in non AC period and AC period from 8am-4pm of working hours are is 0.12°C and 1.40°C respectively. Thus indicate the required cooling energy load to condition the space. Temperature difference of 1.28C° indicates the increased demand in cooling energy load due to high external heat gain of the building envelop. It is apparent that improved envelop performance can create energy efficient indoor thermal environments for mechanically conditioned deep plan forms.

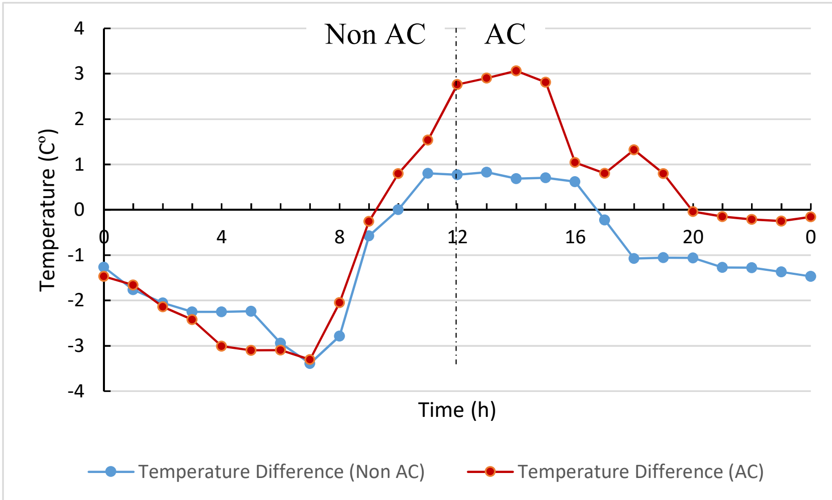


Figure 14: Temperature Difference in the indoor and outdoor during non AC period

4.2.1.6 Thermal behaviour in the periphery

Perimeter of a building is defined as 5m distance from the external building envelop. Temperature behavior of the periphery is assessed on all four cardinal directions. Figure 15 illustrates the temperature behavior in the periphery of this building during Non AC and AC period. According to the graph there is less temperature variation in north and south periphery of the building. Mean temperature in north and south periphery are 28.8°C and 28.6°C. Therefore, North and South perimeter zones are comparatively less uncomfortable than East and West facades of this building. Temperature behavior in the east periphery closely follows the ambient outdoor temperature pattern. East periphery temperature gradually increase from 6am and decrease over time. The maximum temperature reaches between 11am to 4pm with an average temperature of 30. 1°C.In contrary, the temperature behavior in west façade is at a constant temperature level of 30.4°C during non AC time, which is 2.4°C higher than the average ambient outdoor temperature.

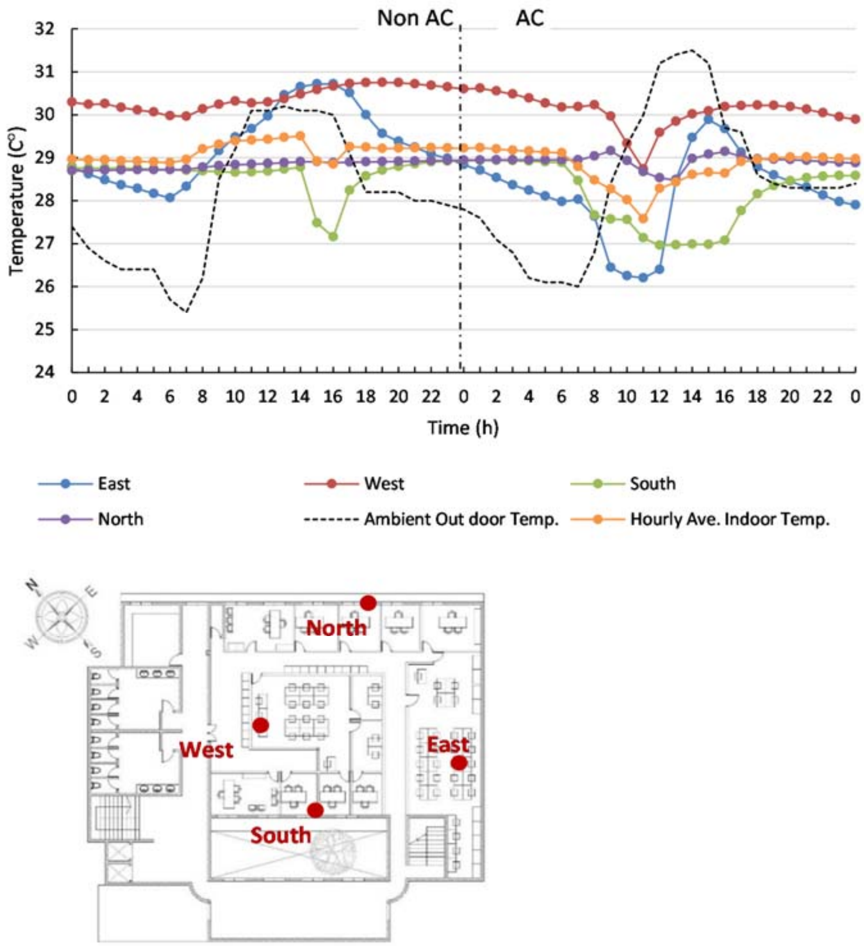


Figure 15: Temperature behavior in the building periphery during Non AC and AC period

Further, periphery temperature in all four cardinal directions and average indoor temperature exceed outdoor ambient temperature during morning and late evening hours of the day. Thus denote indoor overheating condition of the periphery of the building. It is significant to note that there is a temperature drop during Non AC period from 3pm to 4pm in South periphery which had affect the average indoor temperature as well. This indicates that the south periphery room was occupied for a few hours during the week end.

Temperature behavior during week days when the air conditioners are on mode is illustrated in Figure 15 as well. It is evident that both mean temperature in the periphery and core have not reached the set point temperature of 25°C. According to the graph less temperature variation is evident in north periphery with a mean temperature level of 28.9°C from 8am to 4pm. The mean temperature in south periphery is 27.3°C during working hours starting from 8am to 4pm. It is significant to see that it takes nearly 3 hours to reduce the periphery temperature to a constant level of 27.2°C during the working hours. This is due to the external heat gain from the building envelop due to poor thermal performance. Rapid temperature behavior is evident in east façade as a result of the flexibility in the operation of the air-conditioning unit. Temperature variation in west periphery follows a similar pattern to the temperature behavior in the core. The mean temperature in the west periphery during working hours from 8am-4pm is 29.8°C which closely follows the ambient outdoor temperature of 30°C.

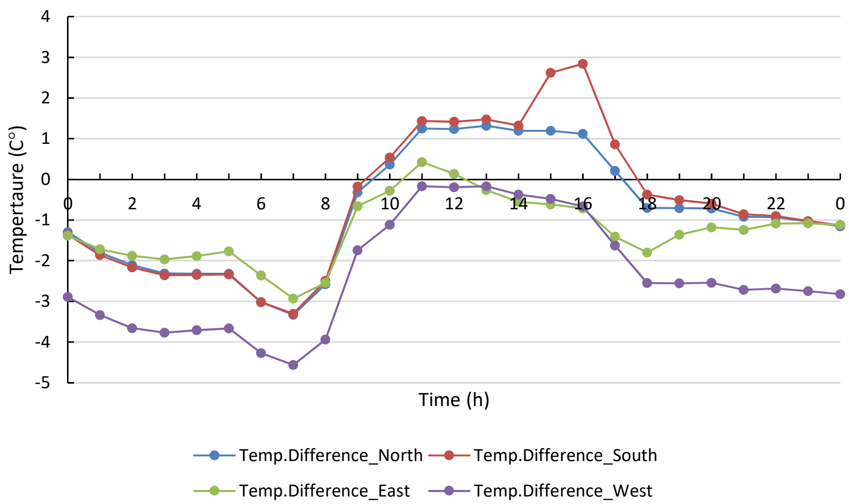


Figure 16:Outdoor and periphery temperature difference during Non AC Period

The lowest temperature reading of the west periphery is 28.74°C which has reached at 11am. It has taken 3 hours to reduce the temperature level from 1.5°C from 30.2°C to 28.7°C. This is mainly due to the direct solar radiation and poor thermal performance of the building envelop. Moreover, periphery temperature in all four cardinal directions exceeds the ambient outdoor temperature during morning and evening hours of the day. Thus highlight the overheating condition of the building periphery.

Cooling energy demand from all four zones depends on the magnitude of indoor overheating. Indoor and outdoor temperature differences indicate the cooling load required for the building. Negative and positive temperature difference in the periphery during Non AC period indicates higher and lower cooling energy load respectively. Figure 16 illustrate the temperature difference in the building periphery and outdoor ambient temperature during non-AC period. Mean temperature difference (ΔT) of north, south, east and west periphery zones during the period of

8am-4pm are -0.79°C, -0.57°C,-1.25°C and -2.36°C respectively. All the periphery facades have a negative temperature difference which represents a higher indoor periphery temperature than the ambient outdoor temperature. Thus indicate the overheating condition of the building periphery. This is evident in all four zones in the early morning and evening hours of the day. Temperature difference in north and south facades follows a similar pattern throughout the day. The mean temperature difference in north and south periphery zones during 8am to 5pm are 0.53°C and 1.0°C respectively. The positive temperature difference indicates lower cooling energy demand for these zones. In contrary mean temperature difference in east and west peripheral zones are -0.56°C and -0.98°C during the working hours from 8am-4pm respectively. The negative temperature difference indicates the higher cooling load required for east and west periphery zones. Moreover, the negative temperature difference indicates the overheating condition of these zones. Therefore, east and west periphery zones should be avoided when arranging the office working areas to create a favorable indoor thermal environment.

4.2.2 Case B: HOLCIM Building

4.2.2.1 Introduction

The building selected as Case B is a free standing building located facing Duplication Road in Colombo 03. This building serves as the main administration building for the HOLCIM Company. This building was constructed 18 years ago and currently nearly 100 employees are working in the premises.

4.2.2.2 Morphological characteristics

The selected Case B is a freestanding building with 8 floors. The long side of the building is north south oriented. The average BEI of this building is 270 $KWhm^{-2}$/year which represent the critical range. Aspect ratio (Length/width) of the building is 1.64 which represents a deep plan form. Façade composition of the building in east, west, north and south facades are 60%, 85%, 20% and 70% respectively. All the glazed panels in the building facades are sealed to prevent dust coming in from the exterior.

The building has a semi basement which is used as a car parking area for the occupants. The ground floor is comprised with mezzanine level which has created a double height entrance lobby with a reception counter and a waiting area for the visitors and a product display area. The mezzanine level is comprised with office area and meeting rooms. First floor has a gym and auditorium which is used by the employees. Second, third, fourth and fifth floors have office areas. The sixth floor has two apartment units which are used by the company guests. Moreover, the topmost terrace area is converted into an undercover dining area with a canteen. Elevators, staircases and building services are located towards easterly and westerly zones. Thus prevent direct solar radiation to the building. North side of the building façade has located for the meeting rooms and executive rooms. South side of the building has the working areas which has an open office layout.

4.2.2.3 Operational characteristics

The building operates from 8.0am to 5.0pm during the weekdays and from 8.0am to 12.20pm on Sunday. Most of the employees tend to work late till 6pm-7pm during the weekend. There are two elevators in this building. Occupants of the building tend to use the staircase as well as the lifts often. Interior of the working areas and entrance lobby is mechanically ventilated with split type air conditioning units. The services areas, corridors and lift lobbies are naturally ventilated. Air conditioning units are fully switched off during Sundays. Thus thermal investigation of the selected building was conducted on Sunday to Monday when the air conditioning units are switched off and on mode. The morphological characteristic of the building is summarized in Figure 17.

4.2.2.4 Thermal investigation

Thermal investigation was carried from 4th of March 2016 (Friday) to 8th of March 2016 (Tuesday). Out of which, thermal investigation was analyzed from 6th of March 2016 (Sunday) to 7th of March 2016 (Monday). Thermal investigation during non AC and AC period was analyzed in the core and periphery. Periphery temperature readings were analyzed based on the orientation. Hobos and thermocouples were used to retrieve temperature data of the periphery and core. Temperature reading points and instrumentation of the equipment are illustrated in Figure 18.

Obtained temperature readings were averaged on hourly basis. Outdoor ambient temperature was taken from the Department of Meteorology located in Colombo 07 for the investigated dates. These temperature data were recorded on hourly basis as well.

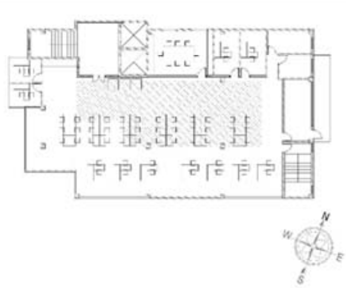
Morphological Parameters				
Micro Context				
Number of floors	Semi Basement, Ground floor and seven floors			
Age of the building	18			
Orientation	North South oriented			
Plan form	Deep Planform			
Aspect Ratio (length/width)	1.64			
Physical Configuration	Detached Free Standing Building			
Typical Layout & Building Elevation	 			
WWR composition in all four facades	WWR North	WWR South	WWR East	WWR West
	20%	70%	60%	85%
Operational Parameters				
Number of employees	Nearly 120			
Number of working hours	8.30 am-5.00pm during week days 8.30 am-1.00pm during Saturday			
Mode of ventilation	Mechanically ventilated working areas and naturally ventilated service areas and lift lobbies			
EUI	270$KWhm^{-2}$/year (Within the Critical Range)			
Thermal Investigated Period	6th of March 2016 (Non-AC)-7th of March 2016 (AC)			

Figure 17: Summery of the operational and morphological characteristics of the building

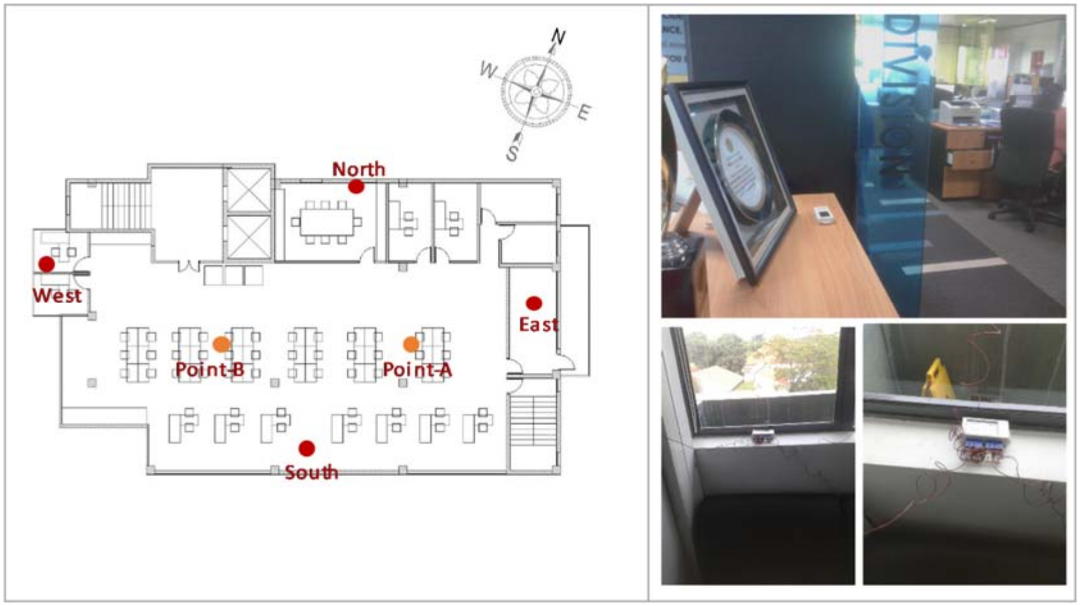


Figure 18: Location of the apparatus on the floor plan

4.2.2.5 Thermal behaviour in the core

Indoor temperature variations in the core of office interior with and without air-conditioning are shown in Figure 19. Temperature behavior of the office interior was monitored for a typical weekday and weekend with the Air-conditioner switch on and off mode respectively. Results prove a clear difference in indoor air temperature profiles of office spaces during AC and Non AC time. Mean temperature during Non AC and AC time in this office interior is 29.5C° and 27.6C°. There is less temperature variation in the interior during the weekend and interior temperature is maintained at a consistent level. But the temperature difference between indoor and outdoor is less than 1C°.This reflects the poor thermal performance of the building envelop.

Indoor temperature tends to increase gradually from 8am to 6pm from 29.20C° to 30.20C° and decrease gradually till 8.am till the office start. Indoor temperature is maintained at a consistent level of 25.7C°during the working hours of 8 am-5pm. But the given AC set point is 24C°. This due to the poor thermal performance of the building envelop as well. Thus it is apparent that deep plan form is more suitable for mechanically ventilated buildings since it helps to maintain a consistent indoor temperature and has a greater potential to control the external heat gain to the building.

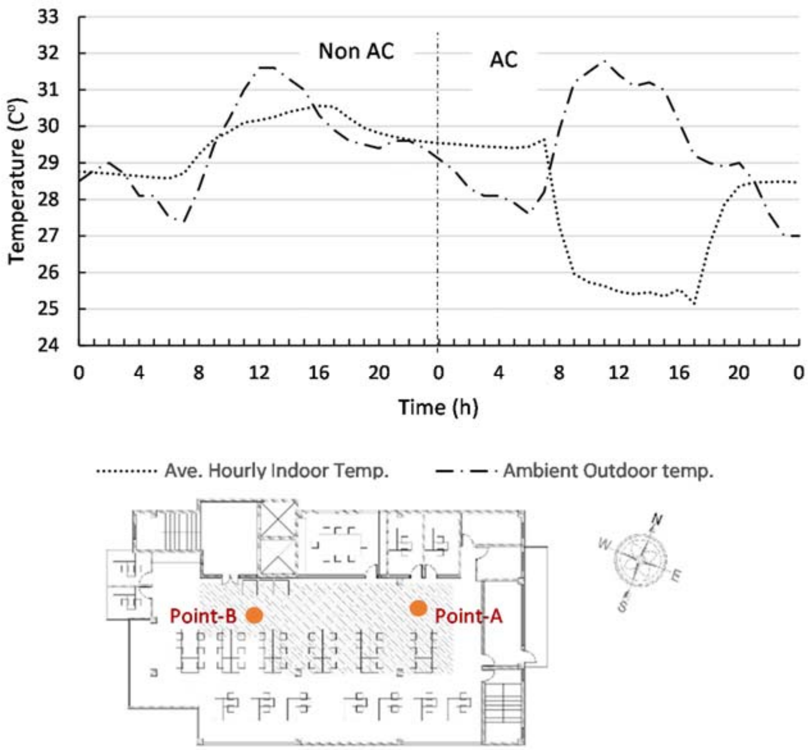


Figure 19: Indoor temperature profile in the core during with and without air conditioning for Case-B Building

Difference between outdoor (To) and indoor (Ti) temperature (ΔT) for AC and non AC days are shown in Figure 20. Positive and Negative value of ΔT represents lower and higher indoor temperature levels than the immediate outdoors respectively. Results highlight office maintains lower indoor temperature in Non AC day. According to the graph it is apparent that the indoor temperature exceeds outdoor temperature in both Non AC and AC period during early morning hours and late evening hours of the day which is known as indoor overheating. Mean ΔT during 8 hours of working period (8-17h) of Non AC and AC period is 0.35C° and 5.05°C respectively. Thus indicate the required cooling energy load to condition the space. Temperature difference of 4.7C° indicates the increased demand in cooling energy load due to high external heat gain of the building envelop.

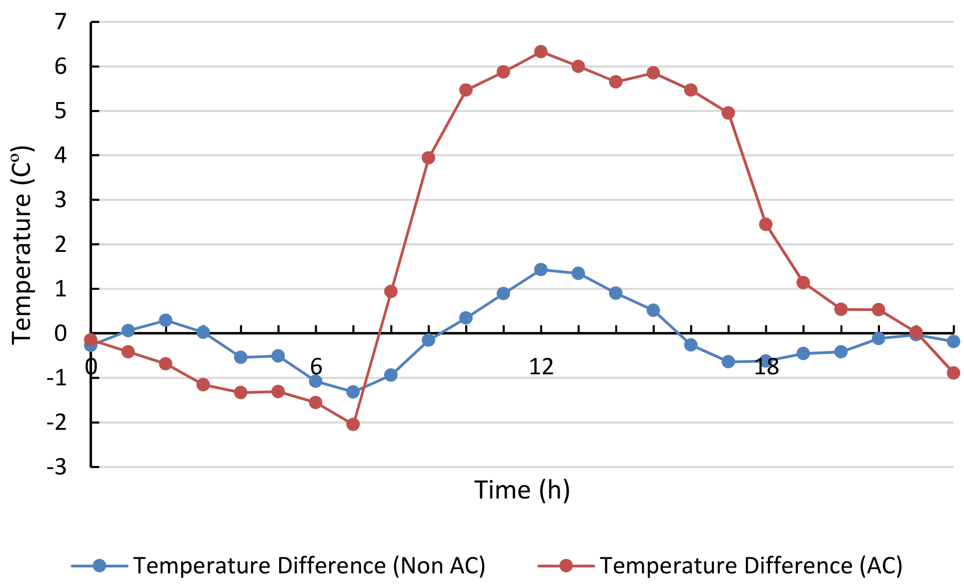


Figure 20: Temperature Difference in the indoor and outdoor during non AC period

4.2.2.6 Thermal behaviour in the periphery

The perimeter is defined as a space within 5m distance from the façade. The temperature profiles of the periphery are assessed for the effect of thermal behavior on cooling energy demand in all four cardinal directions. Figure 21 indicates the relationship of the indoor temperature profiles of four perimeters zones with the ambient temperature for deep plan offices with and without Air conditioning. Average indoor temperature profile closely follows the ambient outdoor temperature and remains at a constant temperature level of 30C°. Temperature behavior in the periphery exceeds the average indoor temperature and the lowest indoor temperature profile is apparent in the zone of North perimeter followed by the perimeter of South. The periphery temperature profile in north façade is lower than the average indoor temperature throughout the day. Therefore, North and South perimeter zones are comparatively less uncomfortable than East and West facades of Deep plan buildings.

Temperature profile in east west and south façade have exceeded the ambient outdoor temperature. Thus denote the overheating condition of the building periphery. Temperature behavior in east façade had reached up to the highest temperature level of 44C° in 8h of the day and gradually decreases over time. Temperature behavior in west façade reach to a maximum temperature level of 35C° during 16h of the day with an average temperature of 33°C during 12h to 18h of the day which decrease over time. This is primarily due to direct sunlight from the east and west facades.

Thermal mass of the walls in these critical facades does not work as a heat sink due to poor insulation. Moreover, a temperature behavior in south façade is above the average indoor temperature from 2C° from 7h-18h of the day during non AC period and gradually decreases over time. South façade of the building has the highest WWR of 85%. This temperature elevation in south façade is due to the radiation reflecting from the adjoining building.

Temperature behavior during air conditioned period in Figure 21 demonstrates that the temperature in west perimeter zone is below the indoor average temperature of 25.8°C. However, it is apparent that the indoor temperature close to AC set point temperature of 24°C is remained only in the West perimeter zone with a mean temperature of 24.5°C all through the working hours. Meeting room and building service rooms are located in the north and east periphery zone. Thus air conditioners are not used throughout the working hours. Therefore, similar temperature profiles can be identified in east and north periphery zones. Further, mean temperature in north and east periphery zones are 28.20C° and 36.20C° respectively, which is higher than the average indoor temperature of 25.8C°. The mean temperature in south periphery zone is 28.6°C which is above the average indoor temperature level. This temperature variation in the periphery and core is mainly due to the different level of heat gain from the facades have affected the optimum performance of air conditioning system. Thus the thermal comfort levels of the office workers vary in relation to the variations in heat gain from facades and also the internal heat gains. These findings inform the importance of interior planning of the working spaces to minimize the impact of external heat on occupants.

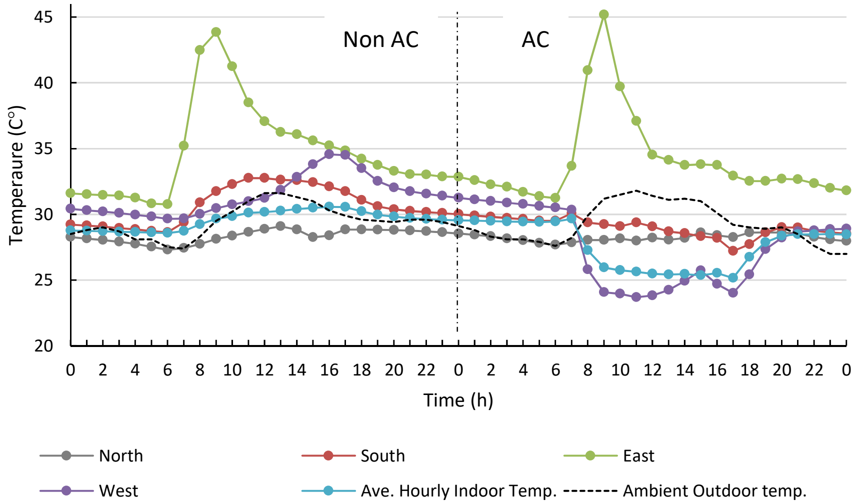


Figure 21: Temperature behavior of the periphery of the building during Non AC and AC period

Cooling energy demand from all four zones is depended on the magnitude of indoor overheating. Effect of building facades in overheating of each zone was assessed from the temperature differences (ΔT) of indoor and outdoor temperature of non-air conditioned period. Figure 22 shows the temperature difference of all zones during the working hours of non-air conditioned interiors of this office. Mean ΔT of north, south, east and west periphery zones are 1.85C°, -1.70°C, -7.36°C and -1.83°C respectively. All the periphery facades have a negative temperature value except north façade. Negative temperature difference represents a higher indoor temperature that the ambient outdoor temperature. Thus indicate the overheating condition of the building interior. It is evident that all the periphery façades except north façade are getting overheated during 8-18h of working time in non-air condition period. North zone represent the lowest temperature followed by West and South zones. Interior arrangement of working spaces with an open plan office in the North zone highlights the most occupied zone of this office is not affected from indoor overheating. Thus shows the highest ΔT minimizes the demand on cooling energy. Moreover, the overheated East zone is composed of service core and less occupied. Thus the interior planning of the deep plan office is favorable in reducing the end use energy demand of this office

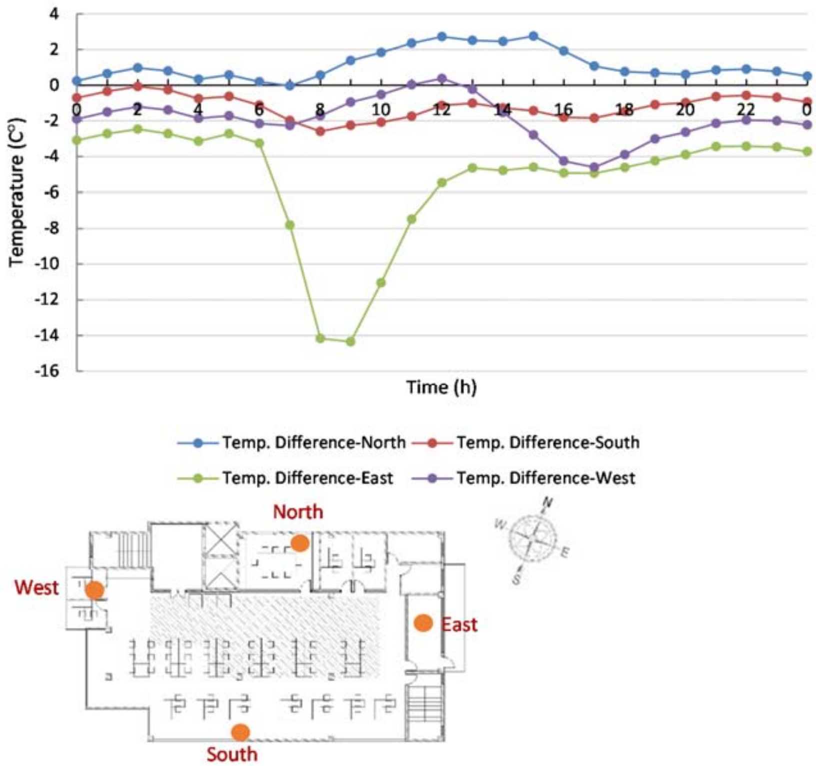


Figure 22 Temperature difference in the building periphery during Non AC period

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4.2.3 Case C: Citizen Development Business Head Office Building

4.2.3.1 Introduction

The building selected as Case C is a free standing building located in Maradana intersection in Colombo 10. It is also in proximity to the Technical Junction which is an important traffic flow intersection of Colombo City. This building is the main administration building for the Citizen Development Bank. This building has incorporated building management system to manage air conditioning and lighting controls. This system records measurements of energy use and indoor air quality (CO_2) levels. The building was constructed 5 years ago and currently 130 employees are working in the premises.

4.2.3.2 Morphological characteristics

The selected Case C is a freestanding building with 8 floors. The long side of the building is east west oriented. The average BEI of this building is 165 $KWhm^{-2}$/year which represent the Average range. Therefore, the BEI is not critical, but shows potential for improvements. Aspect ratio (Length/width) of the building is 2.67 which represent a shallow plan form. Façade composition of the building in east, west, north and south facades are 60%, 70%, 30% and 40% respectively. All the glazed panels in the building facades operable but does not function to prevent dust coming in from the exterior. The glazed panels in these facades increase direct solar radiation to the building interior.

The building has a lower ground basement which is designated for parking. The ground floor has the customer service area located. The first floor is a mezzanine floor which is connected to the ground floor with a landscaped courtyard. As a result of the courtyard it has reduced the effect of direct solar radiation and glare. 3rd floor up to 5th floors are typical office floors. The 6th floor has a higher ceiling height and this floor is dedicated as the executive office level. The 7th floor is the roof top level. This houses the lunch area and a small gathering space for staff functions. The roof top itself has a landscaped area. The service core is located on the east side corner of the building and it project put from the main building. Thus gives a certain amount of shading to the main building during morning hours. The structure of the building is concrete column beam structure with masonry walls for the building envelop.

4.2.3.3 Operational characteristics

The building function during the week days from 8.0am to 5pm and Saturday from 8.0 am-12.30pm. Most of the employees tend to work late till 6pm-7pm during the weekdays and the building does not function on Sunday. There are two elevators in this building. Interior of the working areas and entrance lobby is mechanically ventilated with central air conditioning system. The services areas, corridors and lift lobbies are naturally ventilated. Air conditioning units are fully switched off during Sundays. Thus thermal analysis of the selected building was carried out on Sunday to Monday when the air conditioning system is switched off and on mode. The morphological characteristic of the building is summarized in Figure 24.

4.2.3.4 Thermal investigation

The 3rd and 5th floors of the building were measured for thermal performance from 8th of April 2016 (Friday) to 12th of April 2016 (Tuesday). Out of which, thermal investigation was analyzed from 10th of April 2016 (Sunday) to 11th of April 2016 (Monday). Thermal investigation during non AC and AC period was analyzed in the core and periphery. Periphery temperature readings were analyzed based on the orientation. Hobos and thermocouples were used to retrieve temperature data of the periphery and core. Temperature reading points and instrumentation of the equipment are illustrated in Figure 23. Obtained temperature readings were averaged on hourly basis. Outdoor ambient temperature was taken from the Department of Meteorology located in Colombo 07 for the investigated dates. These temperature data were recorded on hourly basis as well.

4.2.3.5 Thermal behaviour in the core

Temperature behavior in the core of the building was investigated using hobos positioned in A and B points of the office layout during AC and non AC period. The temperature readings in Point A and B were averaged to take the indoor temperature. Figure 25 illustrated the indoor temperature behavior and outdoor ambient temperature behavior in the selected office floor level. The graph illustrate that the average internal temperature during the non-AC area is a consistent rate of 30.3C° The average indoor temperature exceeds the outdoor temperature during morning and evening hours of the day. Thus create indoor overheating condition of the building interior. The mean temperature in the interior during Non AC and AC period is 30.3ºC and 28.2°C respectively. The temperature difference of 2.1°C during Non AC period indicates the poor thermal performance of the building envelop. Mean indoor temperature during Non AC period is 30.4°C during working hours of 8am-5pm and the average outdoor temperature is 32°C with the highest temperature level of 33°C at 10am in the morning. It is evident that the indoor temperature during Non AC period closely follows the ambient outdoor temperature. Thus create uncomfortable thermal environment in the building interior. This is mainly due to the direct heat gain from the easterly and westerly facades which has higher WWR values of 60% and 70% respectively. The mean temperature during AC period is 26.24°C during working hours starting from 8am to 5pm where AC set point temperature is 25ºC. It is evident that temperature difference of 1.24°C between mean temperature and set point temperature level is due to the external heat gain from the building envelop.

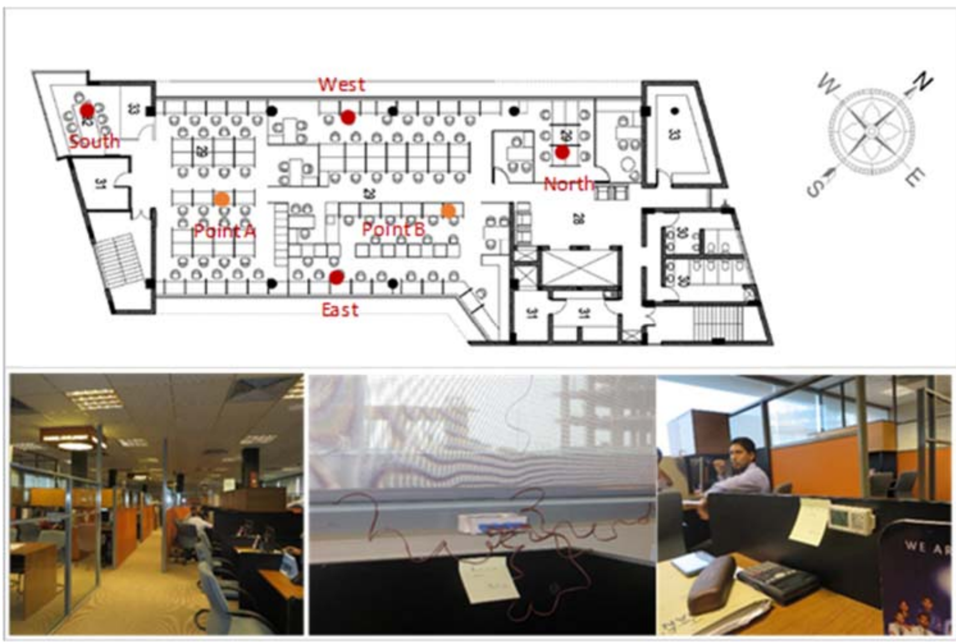


Figure 23: Temperature reading points and instrumentation of the equipment

Morphological Parameters				
Micro Context				
Number of floors	Semi Basement, Ground floor and seven floors			
Age of the building	5			
Orientation	East west oriented			
Plan form	Shallow Planform			
Aspect Ratio (length/width)	2.67			
Physical Configuration	Detached Free Standing Building			
Typical Layout & Building Elevation	 			
WWR composition in all four facades	WWR North	WWR South	WWR East	WWR West
	30%	40%	60%	70%
Operational Parameters				
Number of employees	Nearly 130			
Number of working hours	8.30 am-5.00pm during week days 8.30 am-12.00pm during Saturday			
Mode of ventilation	The building is mechanically ventilated except service areas and service corridors			
EUI	165KWhm^{-2}/year (Within the Average Range)			
Thermal Investigated Period	10th of April 2016 (Non-AC)-11th of April 2016 (AC)			

Figure 24: summary of the Morphological and operational characterizes of CBD Building

Moreover, it is significant to note that it had taken nearly two hours to reach the set point temperature of 25°C once the AC is on by 8am when the office start. Thus reflect the poor thermal performance of the building envelop and external heat gain.

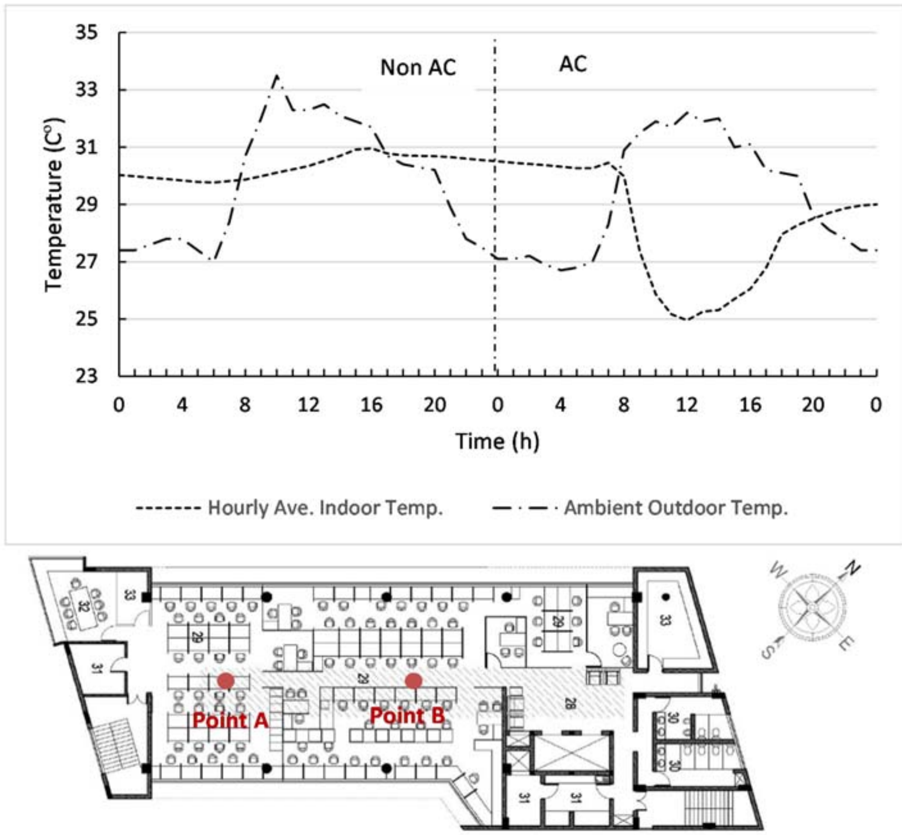


Figure 25: the indoor temperature behavior and outdoor ambient temperature behavior in the Core

Difference between outdoor (To) and indoor (Ti) temperature (ΔT) for AC and non AC days are shown in Figure 26. Positive and negative value of ΔT represents lower and higher indoor temperature levels than the immediate outdoors respectively. Temperature difference indicates the cooling energy load required to condition the space. Results highlight office maintains lower indoor temperature in Non AC day. According to the graph it is apparent that the indoor temperature exceeds outdoor temperature in both Non AC and AC period during early morning hours and late evening hours of the day result in indoor overheating condition. Mean temperature difference during non AC and AC period during 8am to 5pm of working hours are 1.53°C and 5.20°C respectively. Temperature difference of 3.67°C indicates the increase demand in cooling energy load due to high external heat gain from the building envelop.

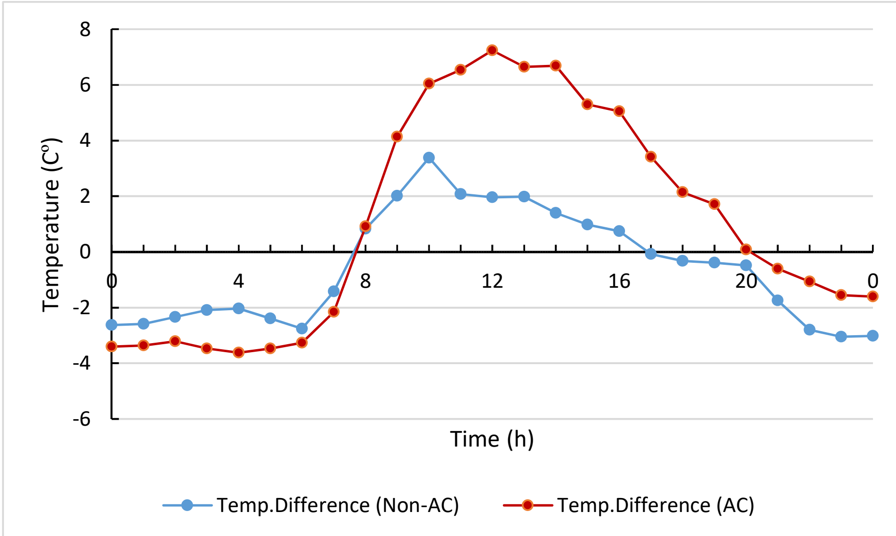


Figure 26: Temperature Difference between Outdoor temperature and Indoor Temperature during Non AC and AC Period

4.2.3.6 Thermal behaviour in the periphery

Temperature behavior in the periphery is assed based on temperature readings retrieved from all four cardinal directions. The perimeter of the building is defined as the space within 5m distance from the building façade. Figure 27 illustrate the temperature readings from all four cardinal directions along with the indoor average temperature and outdoor ambient temperature is analyzed during Non AC and AC period. Similar temperature pattern is evident in east, west and south peripheral zones which closely follows the ambient outdoor temperature pattern. West and south peripheral zone temperature increase up to a maximum temperature level of 32.6°C and 32.4°C during 2pm to 5pm and 3pm to 6pm respectively. The east peripheral zone reaches to a maximum temperature level of 32°C for a period of two hours from 11am to 12pm which closely follow the ambient outdoor temperature of 32.5°C. It is evident that the west and south peripheral zone temperature exceed the ambient outdoor temperature resulting overheating condition in the building interior. This temperature behavior is attributed due to the orientation of the building and higher WWR percentage in these peripheral zones. Thus result in direct solar radiation to the building. Further it is significant to note that peripheral temperature variation in east and west zones follows the sun path pattern. Moreover, all peripheral temperature zones exceed the ambient outdoor temperature during morning and late evening hours of the day resulting indoor overheating condition.

According to the graph northern peripheral zone temperature levels are at a fairly consistent level of 29.61°C throughout the day and lower than the average indoor temperature of 30.5°C. This is mainly because all the building services are located in the northern peripheral zone of the building, which prevent direct solar radiation to the building. In contrary, temperature behavior in westerly peripheral zone is greater than the average indoor temperature during the week end. This can be attributed to direct solar radiation exposure due to poor envelop performance and higher WWR in the building façade. Moreover, peripheral temperature variation at easterly, westerly and southern peripheral zones are far above the average indoor temperature in the center which maintained at a fairly consistent level between 30.5°C. Thus indicate a negative envelop impact. Average indoor temperature follows the outdoor ambient temperature pattern which has the highest temperature value of 33.5°C at 9.am. Hence, the indoor temperature elevation is 4°C during the weekend when the air conditioners are off mode.

The Figure 27 demonstrates the indoor temperature behavior on Monday, when the air conditioners are on mode. It can be seen that the temperature builds up during the weekend has reached a significant level of 31°C, which is 1°C more than the indoor temperature recorded at sunrise on Saturday. Indoor temperature follows the similar temperature pattern of outdoor ambient temperature until the air conditioners on at 6am and takes an average period of three hours to reach set point temperature level. The mean temperature level during the working hours (8am-5pm) in east, west, north and south peripheral zones are 27.2°C, 27.8°C, 25.8°C and 26.2°C respectively. It is evident that north and south perimeter zones are comparatively less uncomfortable than East and West facades of this building. The level of thermal performance has direct impact towards the façade configuration. Thus it can be concluded that WWR is a critical parameter in building thermal behavior. Moreover, uneven temperature distribution in a building during AC hours is a critical concern.

Cooling energy demand from all four zones is depended on the magnitude of indoor overheating. Effect of building facades in overheating of each zone was assessed from the temperature differences (ΔT) of indoor and outdoor temperature of non-air conditioned period. Figure 28 shows the temperature difference of all zones during the working hours of non-air conditioned interiors of this office. Mean temperature difference (ΔT) of north, south, east and west periphery zones are 0.09C°, -1.72°C, -1.10°C and -1.22°C respectively. All the periphery facades have a negative temperature difference except north. Thus indicate indoor overheating condition during non AC period. Moreover, indoor over heating condition is evident in all four peripheral zones during morning and evening hours of the day.

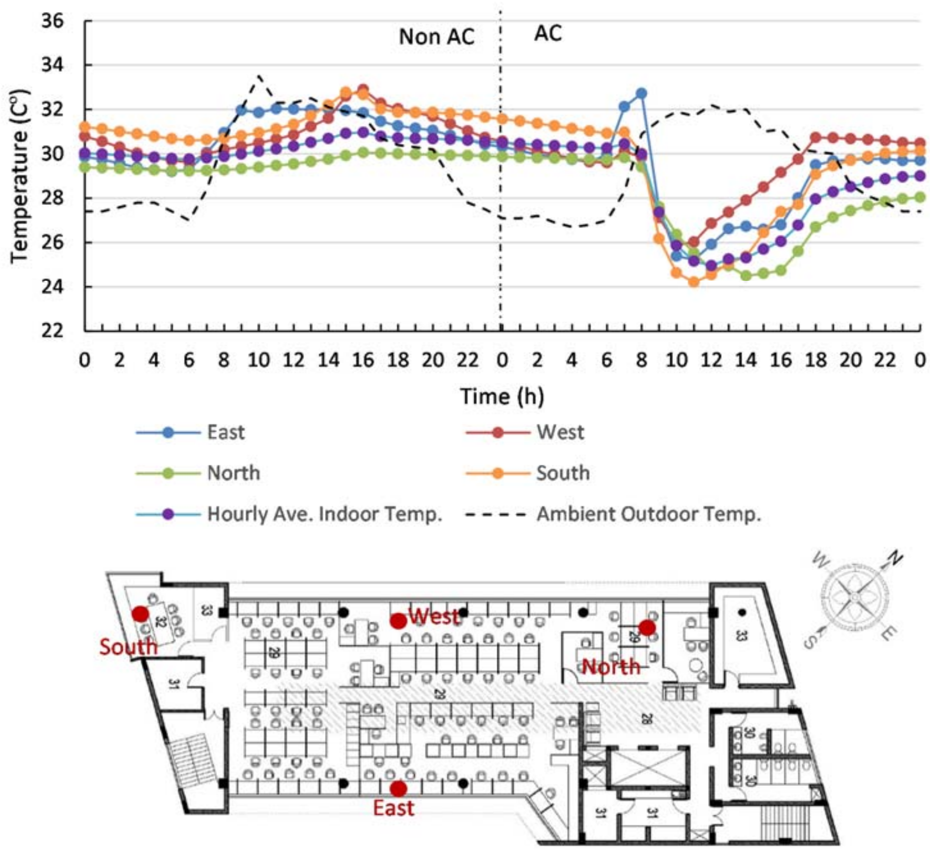


Figure 27 : Temperature variation in the peripheral zone and ambient outdoor temperature

The highest temperature difference of 2.33°C is evident in north peripheral zone during the working hours of 8am to 5pm. thus denote less cooling energy demand to condition the space. Temperature difference in east, west and south peripheral zones follow a similar pattern. Temperature difference during the working hours from 8am -5pm in east, west and south zones are 0.16°C, 0.66°C and 0.34°C respectively. Lower temperature difference during non AC period indicates a higher cooling energy demand. Thus east and south facades require higher cooling energy demand than the west periphery. Due to the adjacent tall building, the western façade of this building is not vulnerable to direct solar radiation.

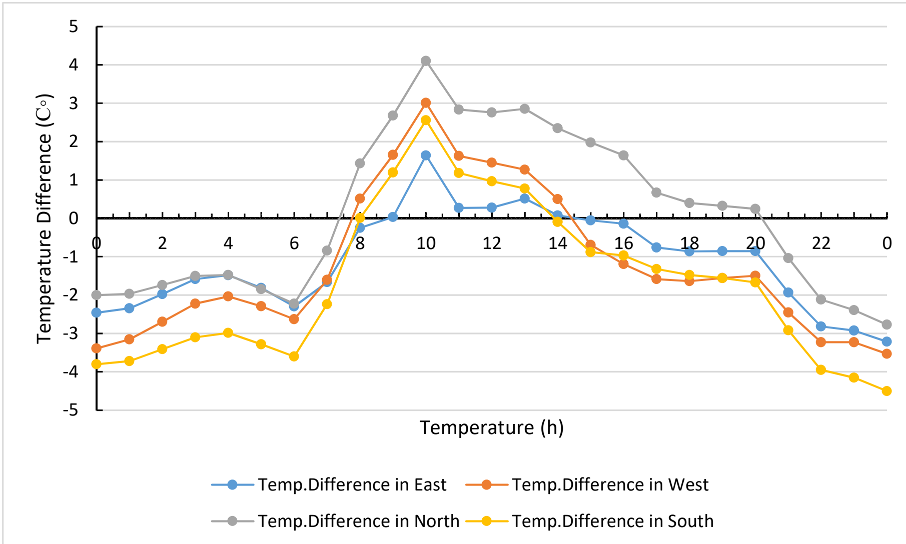


Figure 28: Temperature difference in the peripheral zones during Non AC Period

Direct solar radiation which receive to the easterly and southern peripheral zones of the building interiors are reliant on the building orientation. Nevertheless, it is significant to note that none of the peripheral zones have a negative temperature difference during the working hours. Thus denote overheating condition does not occur during the working hours which help to create thermally comfortable thermal environment.

4.2.4 Case D: Valliant Tower

4.2.4.1 Introduction

The building selected as Case D is a free standing building located in Nawam Mawatha overlooking a canal which connects with Gangaramaya Lake. Each floor of the building is occupied by different tenants for their administrative work. This building was constructed 18 years ago and currently 130 people are working within the premises.

4.2.4.2 Morphological characteristics

The selected Case D building is a free standing building with east west orientation. The building consists of 8 floors with a basement which is used for parking. The BEI of the building is 230KWh^{-2} per annum which is within the Average Range. East and west facades are comprised with fixed and operable glazed panels. Thus these facades get direct solar radiation. WWR of the east, west, north and south facades are 85%, 70%, 75% and 75%. Aspect ratio (Length/width) of the building is 3.42 which represent a shallow plan form. The ground floor comprised with a reception area and office area. All the 8 floors are predominantly function as administrative spaces. The internal floor spaces are segregated into meeting rooms, executive rooms and working areas by temporary partitioning system. Building service areas such as toilets, stores and staircases are located in north and south periphery of the building.

4.2.4.3 Operational characteristics

The building activity during the week days from 8.0am to 5pm and Saturday from 8.0 am-12.30pm. Most of the employees tend to work late till 6pm-7pm during the weekdays and the building does not function on Sunday. There are two elevators in this building. Interior of the working areas and entrance lobby is mechanically ventilated with central air conditioning system except ground floor. The set point temperature is 24°C. The services areas, corridors and lift lobbies are naturally ventilated. Air conditioning system is fully switched off during Sundays. Thus thermal investigation of the selected building was carried out on Sunday to Monday when the air conditioning units are switched off and on mode. The morphological characteristic of the building is summarized in Figure 29.

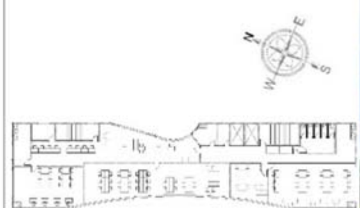
Morphological Parameters				
Micro Context				
Number of floors	Semi Basement, Ground floor and seven floors			
Age of the building	18			
Orientation	East west oriented			
Plan form	Shallow Planform			
Aspect Ratio (length/width)	3.42			
Physical Configuration	Detached Free Standing Building			
Typical Layout & Building Elevation	 			
WWR composition in all four facades	WWR North	WWR South	WWR East	WWR West
	65%	65%	85%	70%
Operational Parameters				
Number of employees	Nearly 130			
Number of working hours	8.30 am-5.00pm during week days 8.30 am-1.00pm during Saturday			
Mode of ventilation	Mechanically ventilated working areas and naturally ventilated service areas and lift lobbies			
EUI	230KWhm^{-2}/year (Within the Average Range)			
Thermal Investigated Period	31st of January 2016 (Non-AC)-2nd of February 2016 (AC)			

Figure 29: morphological and operational characteristics of Valliant Tower Building

4.2.4.4 Thermal investigation

The building was investigated for thermal performance from 29th January 2016, Friday to 2nd February 2016, Tuesday. Data was recorded for Sunday, 31st January 2016 and Monday, 1st of February 2016 to evaluate the thermal condition during non-air conditioned and air conditioned period in the core and periphery. Periphery temperature readings were analyzed based on the orientation. Hobos and thermocouples were used to retrieve temperature data of the periphery and core.

Figure 30: Instrumentation arrangement of the apparatus on the floor plan

Temperature reading points and instrumentation of the equipment are illustrated in Figure 30. Obtained temperature readings were averaged on hourly basis. Outdoor ambient temperature was obtained from the Department of Meteorology located in Colombo 07 for the investigated dates and these readings were recorded on hourly basis as well. All the working areas were mechanically ventilated using central air conditioning system and the set point temperature was 24°C.

4.2.4.5 Thermal behaviour in the core

Temperature behavior in the core of the building was investigated using hobos positioned in A, B and C points of the office layout during AC and non AC period. The temperature readings in Point A, B and C were averaged to take the indoor temperature. Figure 31 illustrated the indoor temperature behavior along with the outdoor ambient temperature behavior during AC and Non AC period.

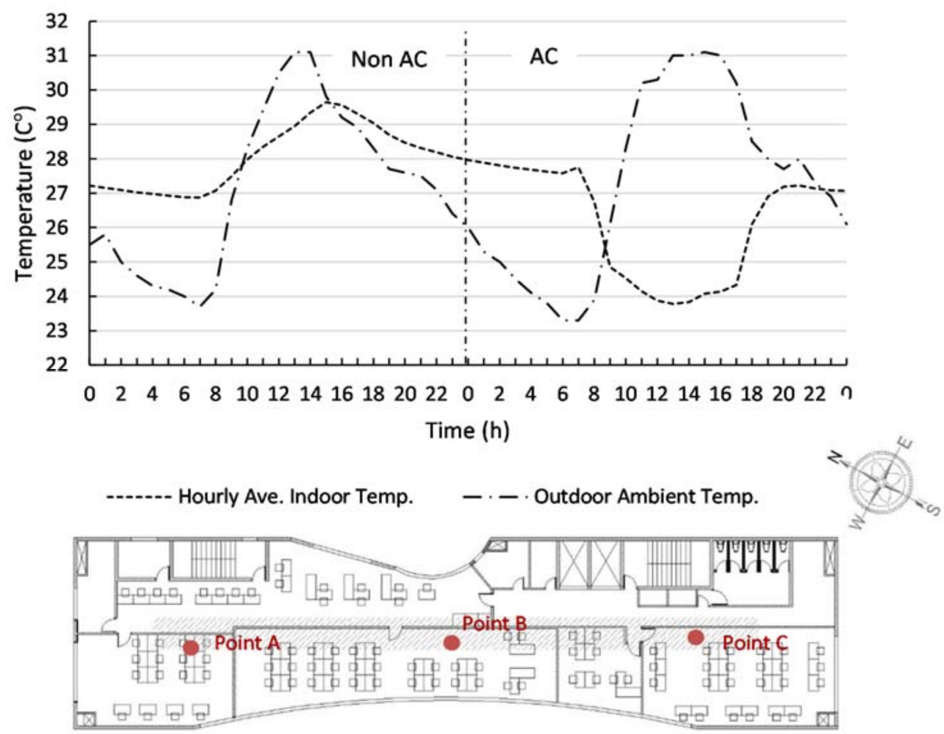


Figure 31: Temperature Behavior in the Core of the Building

According to the graph it is evident that the average indoor temperature follows the outdoor temperature pattern during Non AC Period. Further, indoor temperature tends to increase by 7am and gradually reach the highest temperature level of 29.64°C at 3.pm and remains at a consistent level for a period of 4 hours and decrease over time. The average outdoor temperature during 7am to 6pm is 28.4°C with the highest temperature level of 31.1°C reached at 2pm to 3pm. The average indoor and outdoor temperature during Non AC period is 28.0°C and 27.08°C respectively. Thus indicate average indoor temperature is higher than the average outdoor temperature during Non AC period resulting thermally uncomfortable building environment. Moreover, it is evident that overheating condition occurs during the morning and evening hours of the day. Thus highlight the poor thermal performance of the building envelop and building plan form.

Indoor temperature decrease during the working hours starting from 8am to 5pm when the air-conditioners are on mode. The average indoor and outdoor temperature during the working hours is 24.4°C and 29.3°C respectively. The temperature difference of 4.9°C indicate the cooling energy load required to maintain the average indoor temperature level closer to the AC set point. Indoor temperature level reduce below the AC set point for a period of two hours during 1pm-2pm. The uneven distribution of internal temperature with air-conditioning informs that the dissimilarity in heat gain from different facades have affected the optimum performance of the air conditioning system. Thus affect the thermal comfort of the occupants as well.

Difference between outdoor (To) and indoor (Ti) temperature (ΔT) for AC and non AC days of this office is shown in Figure 32.

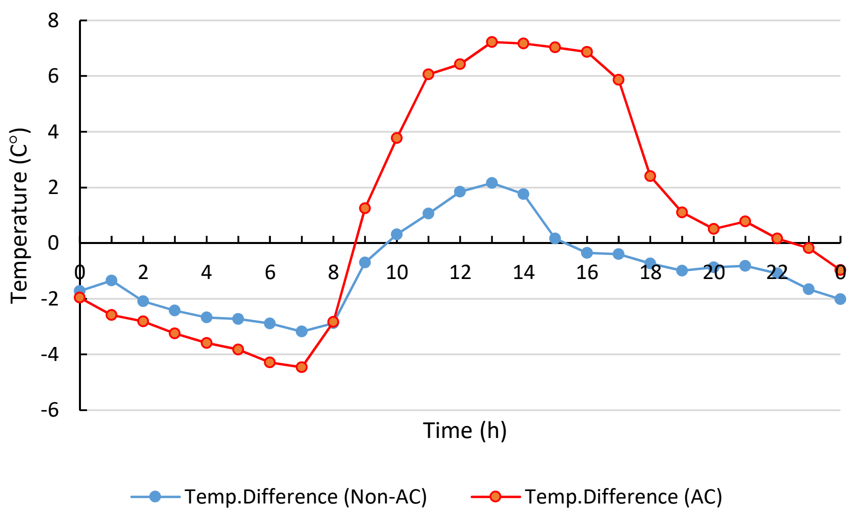


Figure 32: Temperature difference between Outdoor Ambient Temperature and Indoor Temperature during Non Ac and AC Period

Positive and Negative value of ΔT represents lower and higher indoor temperature levels than the immediate outdoors respectively. Results highlight the indoor temperature in this building predominantly a warm office interior on non AC day. In this office indoor temperature remains above outdoor ambient temperature during early morning hours and late evening hours of the day for a period of 18 hours. Mean ΔT during 8 hours of working period (8-17h) of Non AC and AC period is 1°C and 8.0°C respectively. Considerably high temperature difference of 7.0°C between Non AC and AC interior demonstrate the increased demand on cooling energy due to high external gains of the building envelope.

4.2.4.6 Thermal behaviour in the periphery

Temperature behavior in the periphery which is defined as the space within 5m distance from the building façade is illustrated in Figure 33. The graph demonstrates the peripheral temperature behavior of all four cardinal directions in both non AC and AC period.

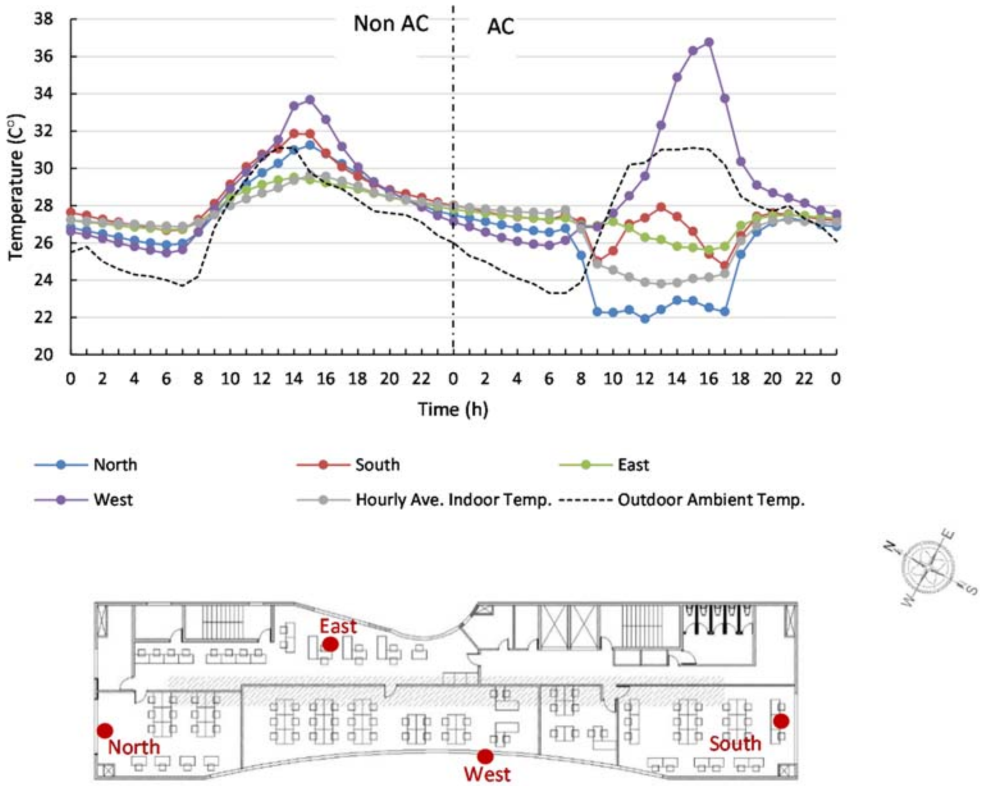


Figure 33: Temperature Behavior of the peripheral zones during Non AC and AC Period

It is evident that temperature behavior in all the peripheral zones follows the ambient outdoor temperature pattern in Non AC period. East peripheral temperature closely follows the average indoor temperature of the core. North, south and west peripheral temperature marginally exceed the average indoor temperature. Thus denote there is no significant temperature difference between the core and the periphery of the building due to the external heat gain from the building envelops and the shallow plan form. The peripheral temperature levels and the average indoor temperature in the core is below the outdoor ambient temperature for a period of 6 hours from 9am to 3pm in the afternoon during non AC period. Remain 18 hours of the time indoor temperature exceed the ambient temperature resulting indoor overheating condition.

The highest temperature elevation of 33.7°C is evident in west peripheral zone followed by south, north and east peripheral zones. The Figure 33 illustrates the temperature behavior in the peripheral zones during AC period as well.

According to the graph it is evident that temperature behavior in north peripheral zone is below the average indoor temperature in the center. The average temperature during 8am to 5pm of working hours is 22.3°C which is below the set point temperature of 24°C. Thus create thermally uncomfortable working environment for the occupants. The average temperature in east, west and south peripheral zones are 26.3 °C, 31.3°C and 26.4°C respectively. Thus indicate the mean temperature level of 31.3°C in west peripheral zone exceed the ambient outdoor temperature of 29.3°C during the working hours of 8am to 5pm. Thus denote west peripheral zone is susceptible for overheating condition. This is mainly due to the external heat gain as a result of higher WWR in east and west facades.

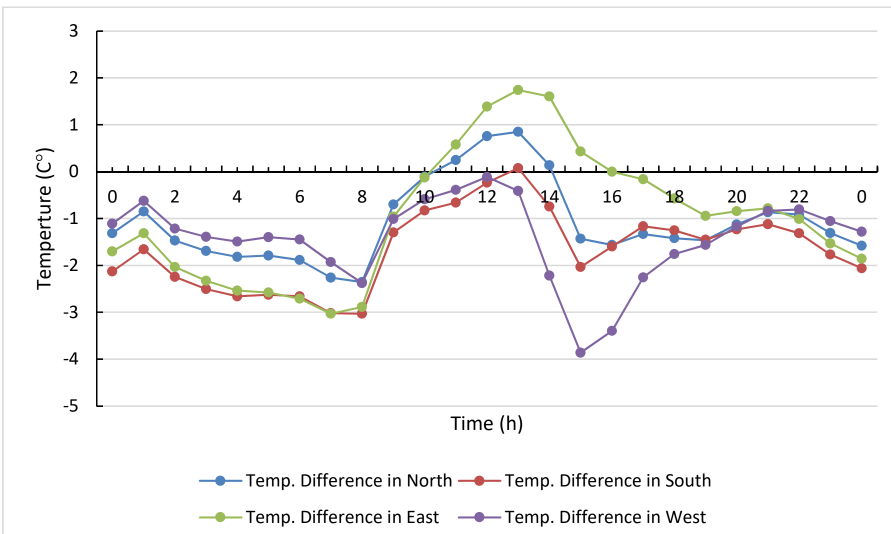


Figure 34: Temperature Difference between Ambient Outdoor Temperature and Peripheral Temperature Zones during Non AC Period

Temperature difference of the outdoor temperature and indoor temperature during non AC period indicate the cooling energy load required to condition the space. A negative temperature difference indicates higher indoor temperature than the ambient outdoor temperature which result higher cooling energy load. Whereas, positive temperature difference indicates lower indoor temperature than the ambient outdoor temperature which result in lower cooling energy load during non AC period. Figure 34 indicate the temperature difference between outdoor ambient temperature and peripheral temperature in all cardinal directions. It is evident that north and east cardinal directions have a negative temperature difference for a period of 20 hours and 16 hours respectively. South and west peripheral temperature zones have a negative temperature difference throughout the day. The mean temperature difference in east, west, north and south peripheral zones are -0.97°C, -1.43°C, -1.09°C and -1.65°C respectively. Thus indicate indoor temperature in all the peripheral zones are higher than the ambient outdoor temperature level creating less comfortable thermal environment in the peripheral zone.

The lowest temperature difference of -1.66°C is evident in west periphery followed by south and north peripheral zones with a temperature difference of -1.66°C and -0.55°C during 8am to 5pm respectively. Lower temperature difference during non AC period indicate higher cooling energy load. But, north peripheral zone has a positive temperature difference of 0.5°C for a period of four hours from 11am to 3pm. In contrary east peripheral zone has a higher temperature difference of 0.16°C indicate lower cooling load. This is mainly because direct solar radiation from the east façade was prevented from the adjacent tall building. It can be concluded that peripheral zones in shallow plan form is very susceptible for indoor overheating condition.

4.2.5 Case E: Central Engineering Consultancy Bureau (CECB)

4.2.5.1 Introduction

The selected Case E building is a free standing building located in Baudhaloka Mawatha, Colombo 7. This building is a leading engineering consultancy services provider in Sri Lanka. This administrative building was constructed 12 years ago and has been adhered to green building concepts. CECB use building management system to manage air conditioning and lighting controls. This system also records measurements of energy use and indoor air quality levels. Currently there are nearly 115 people working in the premises.

4.2.5.2 Morphological characteristics

The building selected as the Case E is a free standing building with 8 floors. The building is east west oriented. The BEI of this building is 135 $KWhm^{-2}$/year which is within the Accepted Range. Aspect ratio (Length/width) of the building is 2.86 which represent a shallow plan form. Façade composition of the building in east, west, north and south facades are 75%, 60%, 0% and 20% respectively. All the glazed panels in the building facades operable and function during Saturdays when the central air conditioning system is off. The ground floor has a lobby area with parking space for occupants of the building. The mezzanine level has the control rooms and IT department. Typical floors are consisting with administrative areas designated for engineering department, design department and quantity surveying department. The top most level has a conference room. Staircases and other service areas are allocated in North and south direction. East and west facades of the building have glaze windows with a corridor space. These windows are operable windows with a sill height of 1000mm. Al. Shading devices have introduced in the corridors to prevent direct solar radiation to the building. Interior office areas have not physically portioned into rooms. The structure of the building is concrete column beam structure with masonry walls for the building envelop.

4.2.5.3 Operational characteristics

The building operates from 8.0am to 5.0pm during the weekdays and from 8.0am to 12.20pm on Sunday. Interior of the working areas and entrance lobby is mechanically ventilated with central air conditioning system. The services areas, corridors and lift lobbies are naturally ventilated. Air conditioning units are fully switched off during Saturdays and Sundays. Thus thermal analysis of the selected building was carried out on Sunday to Monday when the air conditioning system is switched off and on mode. The morphological characteristic of the building is summarized in Figure 35.

4.2.5.4 Thermal investigation

Thermal performance from 29th of April 2016 (Friday) to 3rd of May 2016 (Tuesday). Out of which, thermal investigation was analyzed from 1st of May 2016 (Sunday) to 2nd of May 2016 (Monday). Thermal investigation during non AC and AC period was analyzed in the core and periphery. Periphery temperature readings were analyzed in all four cardinal directions. Hobos and thermocouples were used to retrieve temperature data of the periphery and core. Temperature point A and B in the center were averaged to take the core temperature. Temperature reading points and instrumentation of the equipment are illustrated in Figure 36. Obtained temperature readings were averaged on hourly basis. Outdoor ambient temperature was taken from the Department of Meteorology located in Colombo 07 for the investigated dates and these temperature data were recorded on hourly basis as well.

Morphological Parameters				
Micro Context				
Number of floors	Semi Basement, Ground floor and seven floors			
Age of the building	12			
Orientation	East west oriented			
Plan form	Shallow Plan form			
Aspect Ratio (length/width)	2.86			
Physical Configuration	Detached Free Standing Building			
Typical Layout & Building Elevation	 			
WWR composition in all four facades	WWR North	WWR South	WWR East	WWR West
	0%	20%	75%	60%
Operational Parameters				
Number of employees	Nearly 115			
Number of working hours	8.30 am-5.00pm during week days 8.30am-12.0pm during Saturday			
Mode of ventilation	The building is mechanically ventilated except service areas and service corridors and lift lobbies			
EUI	135KWhm^{-2}/year (Within the Average Range)			
Thermal Investigated Period	1th of May 2016 (Non-AC)-2nd of May 2016 (AC)			

Figure 35: Morphological and Operational Characteristics of the building

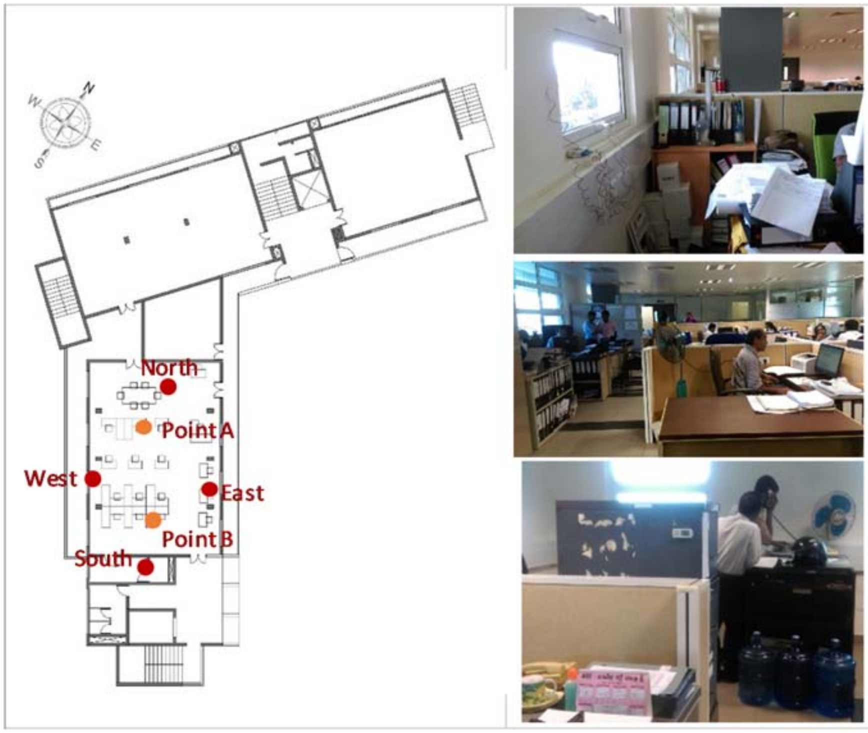


Figure 36: Positions of the Instrumentation of apparatus on the floor plan

4.2.5.5 Thermal behaviour in the core

Temperature behavior in the core of the building was investigated using hobos positioned in A and B points of the office layout during AC and non AC period. The temperature readings in Point A and B were averaged to take the indoor temperature. Figure 37 illustrated the indoor temperature behavior and outdoor ambient temperature behavior in the selected office floor level. According to the graph it is evident that the average indoor temperature during Non AC period remains at a constant level of 29.3°C. The average indoor temperature exceeds the outdoor temperature for a period of 15 hours in the morning and evening time of the day. The average indoor and outdoor temperature during working hours of 8am to 5pm is 29.5°C and 31.7°C respectively. Thus denote indoor temperature is 2.2°C lower than the outdoor temperature during non AC period. In addition, indoor temperature level does not fluctuate with the outdoor temperature and remains at a constant level throughout the day. The main reason is that building interior does not receive direct solar radiation due to the passage along the periphery. The temperature behavior of the core during AC period is also illustrated in Figure 37.

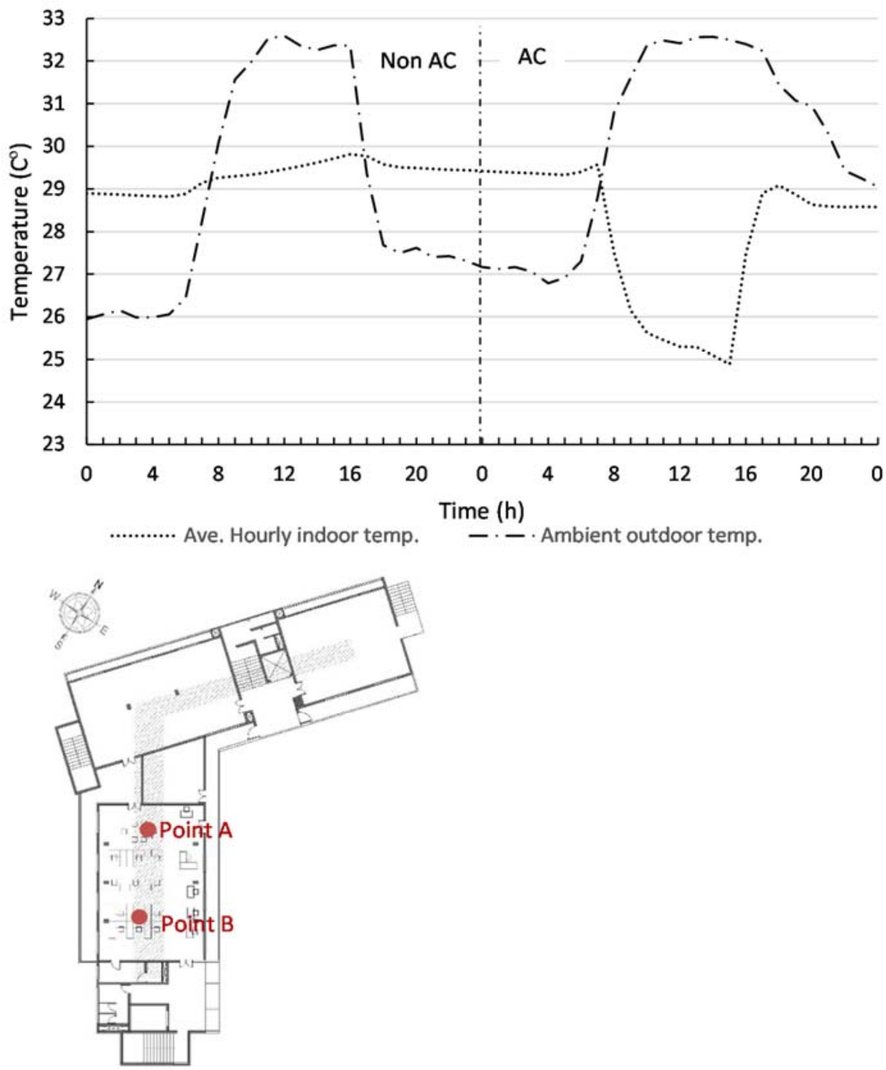


Figure 37: The Temperature Behavior in the Core of the Building during Non AC and AC Period

According to the graph is evident that indoor temperature tends to decrease from 8am when the office starts and reaches to a fairly constant temperature level of 26.1°C throughout the working hours of 8am to 5pm. moreover, indoor temperature achieve the set point temperature within a period of 2hours though the AC system is switched on in the morning by 8am. Thus the findings highlight shallow plan shapes makes the office interiors warmer than deep plan shapes and interiors of these forms closely follows its immediate hot microclimates. Teperature difference (ΔT) between outdoor ambient temperature ($T_{\circ}$) and Indoor temperature (Ti) during Non AC and AC period is illustrated in Figure 38.

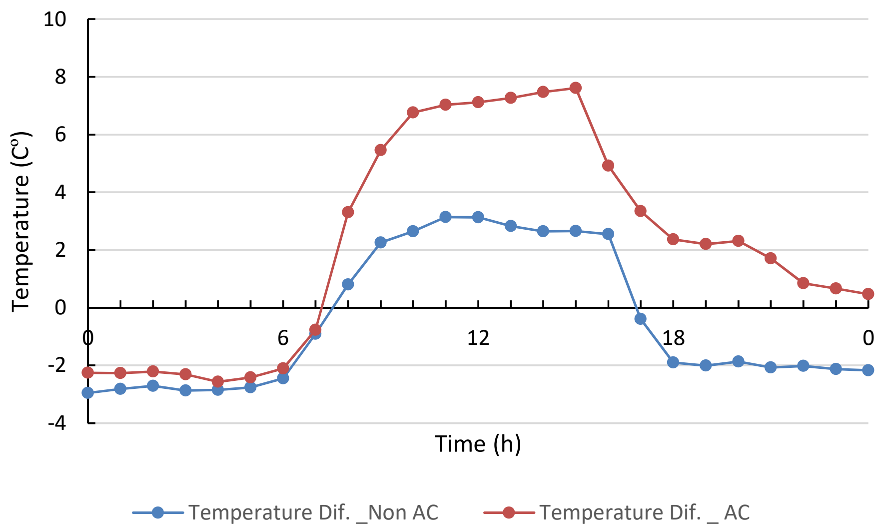


Figure 38: Temperature Difference between Ambient Outdoor Temperature and Indoor Temperature in the Core during Non AC and AC Period

Tepertaure difference indicate the requited cooling energy load to condidtion the space. A negative temperature difference is achedved when the indoor temperature exceed the outdoor temperature creating themally uncomfortable indoor environments. In contrary positive temperature difference denote lesser cooling load to condition the space. According to the graph in Figure 38, 15 hours of the day in Non AC period has a negative temperature difference which is evident in both morning and evening hours of the day. 7 hours of negative temperature difference is evident in AC period during the morning hours till 7am in the morning. Thus indicate a warmer indoor environment than the outdoor environment in both Non AC and AC period. Positive temperature difference is evident in both Non AC and AC period which remains at a constant level from 7am to 6pm and 7am to 17pm respectively. Mean temperature difference in Non AC and AC period during 8am to 5pm of working hours are 2.23C° and 6.03C° respectively. Temperature difference of 3.8C° indicates the increase demand in cooling energy load due to high external heat gain from the building envelop.

4.2.5.6 Thermal behaviour in the periphery

Periphery of the building receive direct solar radiation and susceptible for external heat gain. Thus it is important to analyses the temperature behavior of the periphery in terms of orientation. Figure 39 illustrate the temperature behavior of the building exterior in all four cardinal directions during Non AC and AC period.

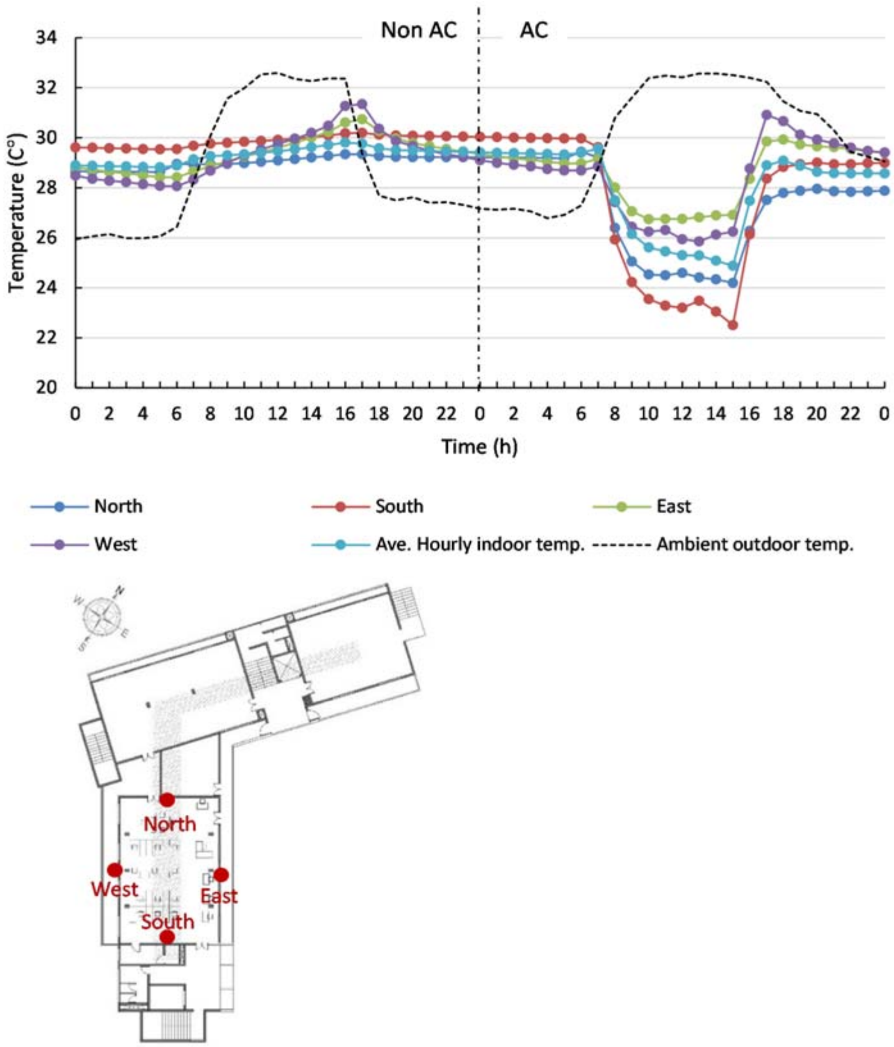


Figure 39: Temperature Behavior of the periphery during Non AC and AC Period

Outdoor ambient temperature gradually increases from 6am in the morning to 6pm in the evening reaching the highest temperature level of 32.6°C during 11am to 12pm. It is significant to note that temperature levels in all the peripheral zones remains at a fairly consistent level throughout the period of 6am-6pm during Non AC period. Slight temperature elevation is evident in east and west peripheral zones which are marginally higher than the average indoor temperature in the center. Moreover, mean temperature in north and south peripheral zones are lower than the average indoor temperature of 29.3C° in the core during non AC period. Indoor temperature exceeds the outdoor temperature for a period of 12 to 15 hours of the day in the morning and evening during non AC period resulting overheated building interiors in the periphery.

Temperature behavior during AC period is illustrated in the same graph in Figure 39 It is evident all the peripheral temperature reduces over time when the AC system is on by 7am and reaches the set point temperature during a period two hours. The mean temperature in east, west, north and south peripheral zones are 27.4C°, 27C°, 25.2C° and 24.4C° with an average indoor temperature of 26.2C° in the core during 8am to 5pm of working hours. Thus denote north and south peripheral zones are lower than the average indoor temperature from 1C° and 1.8C°. In contrary East and west peripheral zones are higher than the average indoor temperature level from 1.2C° and 0.8C° respectively. Temperature levels of each peripheral zones remains at a consistent level for a period of 6hours. Though shallow plan form is susceptible for external heat gain, it is significant to note that peripheral temperature zones have not drastically affected from the increased outdoor temperature of 32.2C° during the working hours from 8am to 5pm. this is mainly due to the external buffer zone created in east and west facades by introducing a covered balcony space.

Indoor(Ti) and outdoor(To) temeprature difference (ΔT) duirng non AC peiod indicate the required cooling energy load to condidtion the space. Higher tempertaure diffrence indicate lesser cooling energy load. In contrrary, lower temperature diffrenec indicate heigher cooling energy load during Non AC Period. Moreover, negative and positive temperature differences indicate higher and lower indoor temperature than the out door temperature. The temperature diffrenece in the periphary in all cardinal directions are illustrtaed in Figure 40 during non AC period.

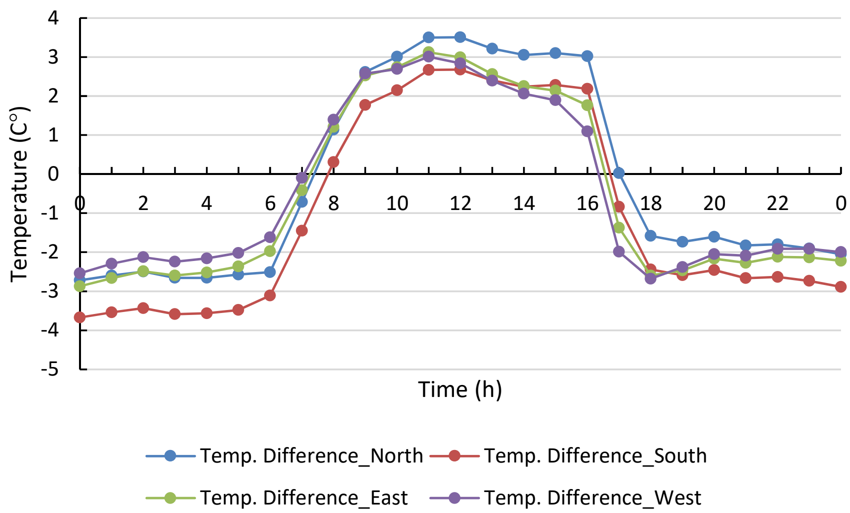


Figure 40: Temperature Difference between the outdoor ambient temperature and peripheral temperature during Non AC Period

According to the graph it is evident that all peripharl temperature differences are negative during the morining and evening hours of the day for a period of 15 hours. thus indicate indoor temperature in the peripheral zones are heigher than the outdoor ambient temeperature. The mean temperature difference in east , west, north and south peripheral zones during the working hours of 8am to 5pm are 2.0C°, 1.8C°, 2.6C° and 1.8C° respectively. It is evident that all the temperature zones have a positive temerature difference during non AC period which indicate a lower indoor peripharal temperature than the outdoor ambient tempertaure. Lowest temperature diffrence is evident in west peripheral zone follwed by south and east zones. heigher concentration of occupants working towards south periphary had an influence towards lower temperature diffrenec. In contraty, the heighest temperature difference is identifed in north peripheral zone. Which indicate lower cooling energy demand to condidtion the space.

4.3 Summary

The thermal investigation was carried out in five buildings. These five buildings represent the office building stock and the cases were selected based on the morphological characteristics and building energy index. The selected five cases represent each of the building energy index categories as well. The selected five building cases represent as Case A, B, C, D and E. out of which Case A and B are with deep plan form and C, D and E are with shallow plan form. All five buildings were thermally investigated during Non AC and AC period. Thermal investigation was conducted in both center and peripheral zones and temperature difference between outdoor and indoor were further analyzed to understand the cooling energy load required to condition the space.

When analyzing the peripheral temperature behavior of Case A and B with deep plan form has a similar temperature behavior in the core and periphery. BEI in Case A and B are 112KMhm^{-2} per annum and 270 KMhm^{-2} per annum which repent Accepted and Critical Range of BEI. Temperature behavior in the core of both the buildings had a similar pattern during Non AC and AC period. The mean temperature behavior in the center had a fairly constant temperature variation. But in both Case A and B mean temperature level in the center was slightly lower than the ambient outdoor temperature level. Thus indicate buildings with deep plan form can maintain a consistent indoor temperature level. Therefore Office A and B with deep plan form have a greater potential to control external heat gain and reduce the end use energy demand during non AC period.

Temperature behavior in the periphery closely follow the outdoor temperature pattern during non AC period and Similar pattern was evident in the peripheral temperature behavior of both Case A and Case B. east and west peripheral zones had the highest temperature elevation in both cases and exceeded the ambient outdoor temperature which result overheating condition during 8am to 5pm of working hours. Temperature difference between outdoor and indoor temperature in the peripheral zones during Non AC period in both Case A and B had a similar pattern as well. North and south peripheral zones had the highest temperature difference during Non AC period which indicate lower cooling energy demand to condition the space.

Investigated Case C, D and E buildings have a shallow plan form with a BEI of 165KWhm^{-2}, 230 KWhm^{-2} and 135KWhm^{-2} which falls under lower and upper limit of Average Range and Accepted Range respectively. Case C and E has a similar indoor temperature behavior in the core during non AC Period where temperature remains at a consistent level throughout the day. In contrary, temperature behavior in the core in Case D closely follows the outdoor ambient temperature and varies throughout the day. Further, mean temperature in the core in Case D is above the ambient outdoor temperature which results in indoor overheating condition during the Non AC period. During working hours from 8.0am to 5.pm, the mean temperature in the building core in Case C and E has slightly lower temperature level than the ambient outdoor.

Temperature difference in the core in shallow plan form indicates the potential for overheating of the building interior. The mean temperature difference in Type C and D during 8am to 5pm of working hours during non AC period is 1.5C° and 1C° respectively. Uneven temperature fluctuation is evident in both Type C and D which informs the susceptibility of external heat gain to the building due to poor thermal performance. Further it is evident for a positive temperature difference for a period of 8 hours and five hours throughout the day in Type C and D which indicate lower indoor temperature than the ambient outdoor temperature. In contrary, consistent positive temperature difference in the core is evident in Case E. This positive temperature difference remains for a period of 10 hours throughout the day which indicate a lower indoor temperature level than the ambient outdoor temperature during non AC period. Temperature difference between the AC and Non AC period indicate the required cooling energy load. In all three shallow building plan forms, Case D is evident for the highest temperature difference of 7C° followed by Case C and E which has a temperature difference of 3.7C° and 3.8C° respectively.

Case C and D are evident for similar temperature behavior in the periphery. Temperature behavior in all the periphery zones follows the outdoor ambient temperature pattern. Case D has the highest potential for overheating condition in the peripheral zones. Temperature elevation in west façade exceeds the ambient outdoor temperature during Non AC and AC period. This indicates the large amount of heat gain to the building from the external environment. The uneven distribution of temperature levels in the periphery and core create uncomfortable thermal environment in the building. Temperature behavior in Case C indicates the uneven temperature pattern in the peripheral zones as well. In Case C, indoor temperature levels remain below the ambient outdoor temperature. But marginal temperature difference is evident in indoor peripheral and outdoor ambient temperature zones during Non AC period. Thus denote potential condition for indoor overheating in the building interior. In contrary, fairly consistent peripheral temperature behavior is evident in Case E during Non AC period. Temperature elevations in peripheral zones during AC period vary with the cardinal direction. But temperature level in each peripheral zone remains at a consistent level throughout the working hours. Further, North and south peripheral zones are evident for lower temperature level than the average indoor temperature level in the core. Thus indicate comfortable thermal environment in north and south peripheral zones.

Temperature difference between outdoor and indoor temperature levels in the periphery indicate the cooling energy load to condition the space. Lower and higher temperature difference in Non AC period indicates higher and lowers cooling energy demand. Case C and D have a similar temperature difference pattern. In Case C, positive temperature difference was evident in all for peripheral zones with the highest temperature difference in North zone followed by west and south. Negative temperature difference is evident in west and south facades which indicate overheating condition of the building interior. Highest positive temperature difference is evident in east façade followed by north peripheral zone. Rapid fluctuation in the temperature difference is evident in both Case C and D. In contrary temperature difference in Case E remains consistent throughout the day and all the temperature differences are positive values. Thus it indicates that Case E has a low temperature level in the interior.

5 SECTION-C: ANALYTICAL INVESTIGATION ON BUILDING MORPHOLOGY & ENERGY INDEX

Preface

This chapter is focus on analysing the impact of façade composition, building form, orientation and physical configuration of the buildings on energy index. The morphological characteristics are recorder in 100 office buildings dispersed in the selected Wards in CMC region. The impact of these building morphological characteristics on building energy index is further analysed using regression analysis. Performance models are derived for each energy index categories by considering all four orientations. Wall to window ratio (WWR) is taken as the façade configuration in the buildings. Impact of WWR on building energy is analysed in all four orientations namely, east-west, north-south, northeast-southwest and northwest-southeast in the identified energy index categories. The derived performance models of the façade configuration help to give an outline over the amount of glazing required for the building facade in each orientation. Moreover, it helps to give a baseline on how to improve the façade configuration in the existing office buildings.

Aspect ratios of the buildings are considered as building plan forms. Impact of aspect ratio on building energy index is analysed only in east-west and north-south oriented buildings in the three energy index categories. Further, effect of aspect ratio and façade configuration on building energy index is also analysed using multiple linear regression analysis tool. The derived performance models help to identify the optimal length to width ratio for buildings in east-west and north-south oriented buildings. Moreover, it helps to give an outline of the façade configuration along with the aspect ratio for the buildings.

5.1 Investigation structure of the Performance models

Building investigation is structured in three stages. The first stage is clustering the buildings based on the energy index category which are Accepted Range, Average Range and Critical Range. Stage two is segregating the buildings in each category based on the orientation namely; east west (EW), north south (NS), northeast southwest (NE-SW) and northwest southeast (NW-SE).linear and square shape plan forms were identified in each orientation category. Stage three investigates the window to wall ratio (WWR) of all four building facades in each energy index category under all four building orientations. The summary of the investigation structure is illustrated in Figure 41

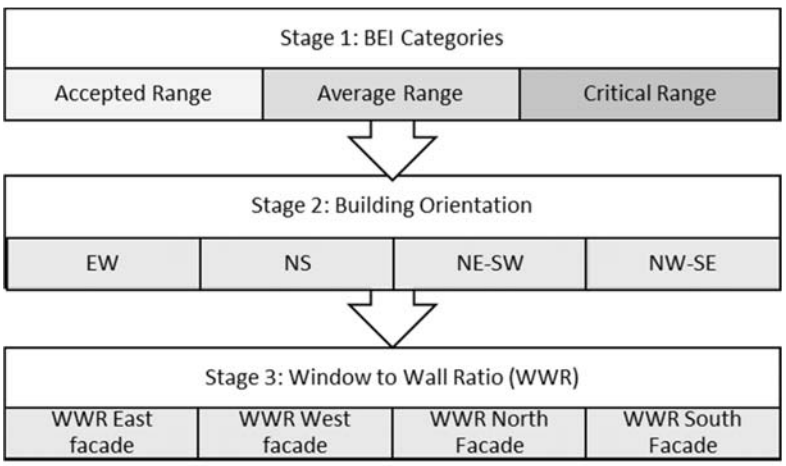


Figure 41: The investigation Structure to cluster buildings

Nexus between BEI and morphological characteristics are analyzed based on WWR and aspect ratio in the office buildings. All four building orientations were taken when investigating nexus between BEI and WWR. Analysis was performed in all three energy index categories by considering all four different orientations namely, east west (EW), north south (NS), northeast southwest (NE-SW) and northwest southeast (NW-SE). The structure of the analysis is illustrated in Figure 42. Impact of building plan form on energy index is analyzed in both east west and north south oriented buildings. Hence plan form was represented as aspect ratio in this investigation. East west and north south oriented buildings were taken for this investigation since these facades have the most impact on energy consumption in tropics. Further, the analysis also attempted to identify the nexus between WWR and aspect ratio in east west and north south oriented buildings on building energy index. The analysis structure is illustrated in Figure 43.

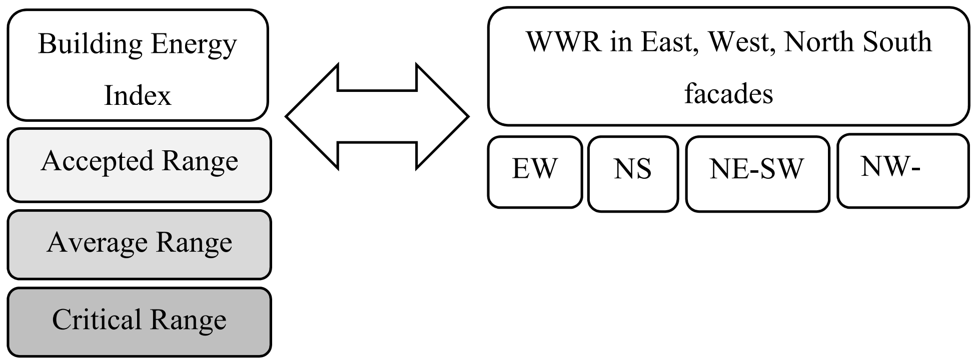


Figure 42: The Structure of the Analysis in Stage 1

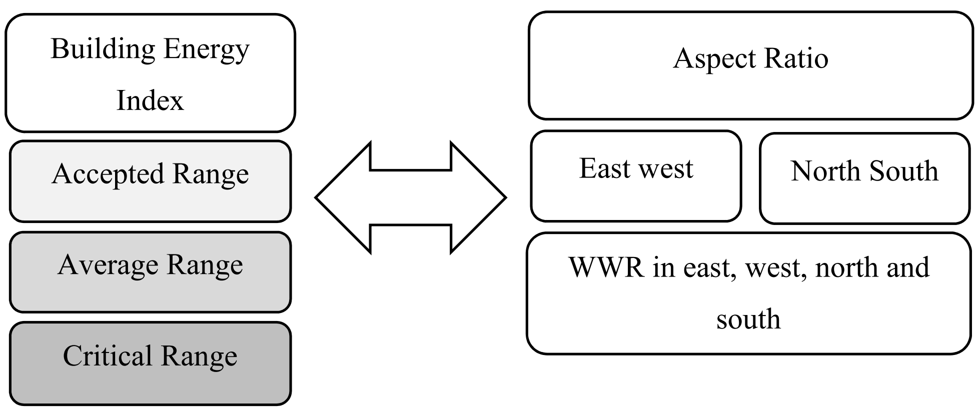


Figure 43: The Structure of the Analysis in Stage 2

5.1.1 Analysis Protocol

Building morphological characteristics such as façade composition, building form, building orientation and physical configuration has an influence towards increase/decrease of energy required to heat or cool the occupied space (Tiberiu Catalina1, Joseph Virgone2, and Vlad Iordache, 2014). Conventional wisdom reveals that the amount of glazing in the building façade and the length to width ratio of the building has an impact on the energy consumption. All the buildings are segregated according to the identified building energy categories. In order to simplify the analysis orientation of the buildings are taken as a constant factor. Hence all the identified buildings in each energy index category is further separated based on its orientation. This helps to identify the impact of façade configuration and length to width ratio of the building on energy consumption based on the orientation of the building. Since there are multiple factors affecting the energy consumption of the buildings multiple linear regression models are applied to identify the relationship between these morphological parameters and building energy index. It intends to develop a model to interpret the association between two or more explanatory variables and response variable by adjusting the linear equation to observed data. The multiple linear equation is as follows:

$$y = B_0 + b_1X_1 + b_2X_2 + \cdots bnXn$$

Building Energy Index of the office building is known as the predicted or expected value of the dependent variable of y. whereas, X_1 through Xn are n different independent variables. These independent variables are the building morphological parameters. B_0 is the value of Y when all of the independent variables (X_1 through Xn) are equal to zero, and b1 through bn are the premeditated regression coefficients. Each regression coefficient signifies the change in Y relative to one unit change in the respective independent variable.

The main aim of the regression analysis is to develop a model to interpret the building energy consumption. Further, regression model allows to study how the demand for building energy fluctuates with modifications in individual building parameters. The egression coefficient indicates how energy consumption changes for each variable while all the other predictors continued unchanged. The importance of the corresponding regression coefficient is indicated by the p value. In the regression model, when the predictors with p-values equal or less than 0.05 are traditionally considered as important. Confidence interval of 95% was taken in this investigation. It is important to guarantee that regression models fulfill all correlation assumptions including normality, independence, linearity and homoscedasticity

Development of a regression model to identify the nexus between morphological parameters and BEI has three folds which is illustrated in Figure 44. The analysis comprises of two phases. The first phase is to assess whether independent variables in regression models correlate with each other to avoid multicollinearity. The assessments of independent variables are based on the analysis of the p values and correlation confidents. Phase two is subset regression analysis to determine the relationship between dependent variable of BEI independent variables of morphological features such as façade configuration and aspect ratio. Subset regression analysis enables to determine all conceivable regression models, reassessed based on R Squared Value, R Squared Adjusted value and Mallow Cp Value. The best fit model is determined by considering the highest values obtained for R Squared Value and R squared adjusted value with lesser Mallow Cp value. The marginal value taken for R squared is taken as 50 % which represent 50% of the predicted value of BEI is explained by the model. Stepwise regression analysis was performed to evaluate the predictors in the selected models. Both R Squared and P vales were considered when evaluating the best fit model. Moreover, polynomial regression analysis was performed during the occasions when R squared value is marginal.

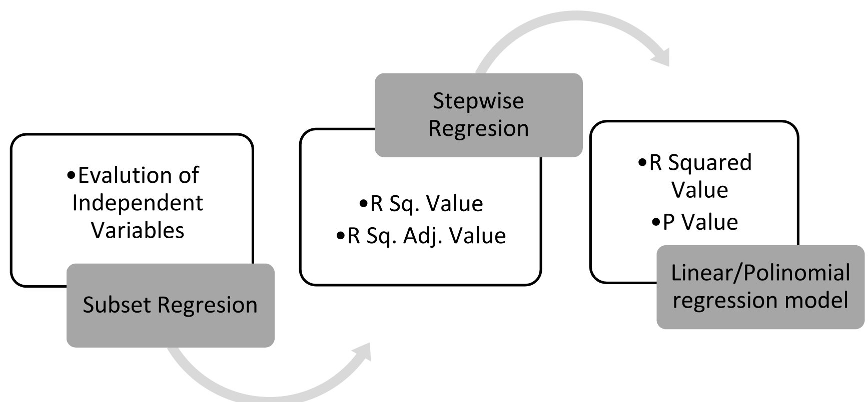


Figure 44: The structure of developing a regression model

5.1.2 Limitations

Several limitations were observed during the analytical investigation of the morphological parameters and energy index. Investigation was carried out in buildings which were taken for the investigations were intermediate rise buildings which were exclusively functioned as offices with normal working hours.

In this study, buildings were clustered according to its orientation and energy index category. Regression analysis was conducted in each cluster of buildings with the same energy index category and orientation. Number of buildings to run the regression analysis in each sample was not adequate enough. Hence derived models are an indication of the energy performance of each cluster which could be taken as a guideline. Adequate information of the buildings were not available/difficult to obtain due to security measures. Further, sub metering was not available in the buildings where it was difficult to calculate the energy consumption of the building and equipment separately.

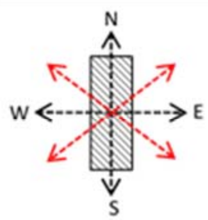
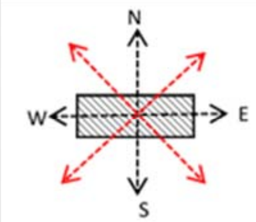
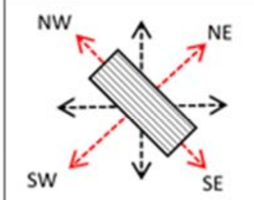
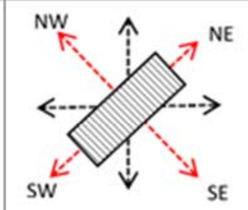
5.2 Nexus between façade configuration and energy consumption

Building envelop and its different components are most effective with respect to energy consumption (Ghiai et al., 2014). This research examines the relationship between WWR and energy consumption in office buildings in Colombo Municipal Council. WWR can have a clear effect on energy conservation in terms of heating and cooling in buildings. Impact of façade composition of building energy index was analyzed when the building orientation, building plan form and physical configuration are constant. In this investigation orientation of the critical façade, which is the long side of the building plan form was taken into consideration. Façade composition was observed in all four cardinal directions. Namely, East, West, North and South. Nexus between building façade composition and BEI were investigated in all three identified energy index categories.

5.2.1 Nexus between WWR and Building Energy Index in Accepted Range

35.72% of the buildings are in Accepted Range where building energy index is within the range of 100-150 kWh/m² per annum. Of which 28.57%, 17.14%, 34.29% and 20% of the buildings are east west (EW), north south (NS), northeast southwest (NE-SW) and northwest southeast (NW-SE) buildings. Nexus between building energy index and WWR in all four building facades are developed using regression analysis tool when orientation and building form are constant parameters. Thus this study investigates the relationship between WWR and energy index in EW, NS, NE-SW and NW-SE orientations. Summary of the findings are illustrated in Table 6.

Table 6: WWR & Building Energy Index in Accepted Range

WWR and Building Energy Index in Accepted Range			
East-West (EW)	**North-South (NS)**	**Northeast-Southwest (NE-SW)**	**Northwest-Southeast (NW-SE)**
			
28.57%	17.14%	34.29%	20.00%
133.45 kWh/m^2yr.	122.71 kWh/m^2yr.	130.66 kWh/m^2yr.	125.79 kWh/m^2yr.

5.2.1.1 Nexus between WWR and Building Energy Index in East West Oriented buildings in Accepted Range

28.57% of the office buildings are east west oriented buildings where elongated side of the façade is facing towards east and west direction. Summary of the morphological parameters are illustrated in Table 07. The analysis protocol was followed to develop a model to represent the nexus between BEI and WWR in building facades in EW oriented buildings. The first step is to identify whether independent variables correlate with each other to prevent multi-co-linearity. Summary of the correlation is illustrated in Table 08.

Results indicate that none of the independent variables are correlating with each other. Thus, these independent variables are further analyzed through subset regression analysis to identify the best fit models. Table 09 illustrates the summary of the subset regression analysis of the independent variables and dependent variable. It is significant to note that the variation between R squared values and R Adjusted values are high in all four possible models. Thus denote that these models do not represent an association between building energy index and façade composition in Accepted Range

Table 7:Morphological Characteristics of EW Oriented Buildings in Accepted Range

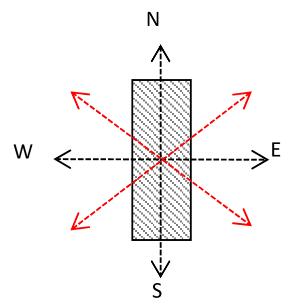
Morphological characteristics of East West (EW) Oriented buildings in Accepted Range				
				
Building percentage	**28.57%**			
Average Building Energy Index	**133.45 KWhm⁻²/yr.**			
Building façade	**East**	**West**	**North**	**South**
WWR	36%	49%	11%	8%

Table 8: Evaluation summary of the independent variables in east west oriented buildings in Accepted Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			-0.53	0.115
		X_3	X_4	-0.535	0.111
X_1		X_3		-0.435	0.21
X_1			X_4	0.414	0.234
	X_2	X_3		0.532	0.113
	X_2		X_4	-0.346	0.327

Table 9: The summary of subset regression analysis of the independent variables and dependent variable

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	38.3	30.6	9	6.1	6.0155	X_1			
1	8.3	0	0	11.9	7.3325				X_4
2	63.6	53.2	29.7	3.1	4.9392	X_1		X_3	
2	51.2	37.2	0	5.6	5.7226	X_1	X_2		
3	71.5	57.2	15	3.6	4.7221	X_1		X_3	X_4
3	66.6	49.9	0	4.5	5.1089	X_1	X_2	X_3	
4	74.4	54	0	5	4.8989	X_1	X_2	X_3	X_4

5.2.1.2 WWR in Accepted Range: North South Oriented Buildings

17.14% of the buildings in Accepted range are north south oriented buildings where long side of the façade is facing towards this direction. The average energy building energy index in this range is 122.71 $KWhm^{-2}$per annum and the average WWR for east, west, north and south facades are 3%, 18%, 32% and 53% respectively Morphological characteristics of the north south oriented buildings in Accept range is summarized in Table 10. Correlation summary in Table 11 indicate that some independent variables in NS oriented buildings are highly correlating with each other. Thus these variables are not taken together when developing the regression model. Table 12 and 13 represent the summary of Subset regression analysis for WWR in east west and north south facades respectively. Subset regression summary illustrated in Table 14 indicate that there is a relationship between BEI and WWR in north and south facades by evaluating the results based of R Sq. and R. Sq. Adjusted Values. Regression analysis confirm that WWR in west façade is a good fit model since the R square value is 70.32% and the p value= $0.037<0.05=\alpha$. Moreover, a graphical representation of the relationship between WWR in west façade and BEI is illustrated in Figure 45.

The regression model for the independent variable of WWR in west façade and dependent variable of BEI in NS oriented buildings Accepted Range can be demonstrated as follows,

$$BEI\ (Accepted\ Range) = 116.12 + 36.0\ WWR\ (west)$$

Table 10: Morphological characteristics of the north south oriented buildings in Accept range

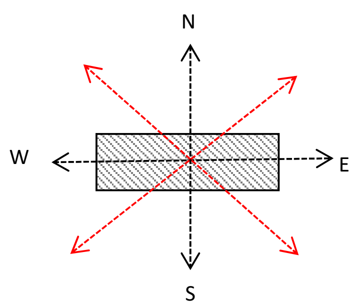
Morphological characteristics of North South (NS) Oriented Buildings in Accepted Range				
				
Building percentage	**17.14%**			
Average Building Energy Index	**122.71 KWhm^{-2}/yr.**			
Building façade	**East**	**West**	**North**	**South**
WWR	**3%**	**18%**	**32%**	**53%**

Table 11: Evaluation summary of the independent variables for North South Oriented buildings in Accepted Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlatio n	P-Value
X_1	X_2			0.933	0.007
		X_3	X_4	0.933	0.007
X_1		X_3		-0.726	0.102
X_1			X_4	-0.909	0.012
	X_2	X_3		-0.511	0.3
	X_2		X_4	-0.786	0.064

Table 12: Subset regression analysis for WWR east west facades with BEI in north south oriented buildings in Accepted Range

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort and south facades							
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)
1	70.3	62.9	24.8	1.3	7.0948		X_2
1	52.6	40.8	*	3.2	8.9627	X_1	
2	72.8	54.6	*	3	7.8465	X_1	X_2

Table 13: Subset regression analysis for WWR in north & south facades with BEI in north south oriented buildings in Accepted Range

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort and south facades							
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR north (X_3)	WWR south (X_4)
1	15	0	0	16.7	12.009		X_4
1	0.3	0	0	19.9	13.001	X_3	
2	86.3	77.2	0	3	5.5592	X_3	X_4

Table 14: Regression model summary for WWR in west facade in north south oriented buildings in Accepted Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
	1				X_2			7.09478	70.32%	62.90%	24.79%	9.48	0.037

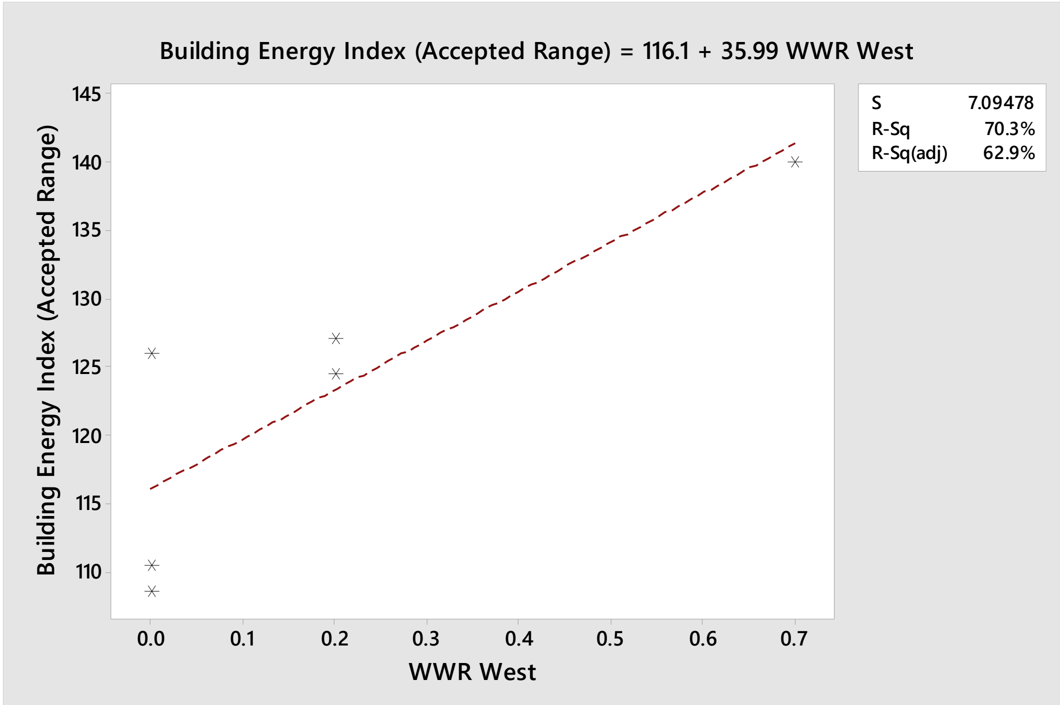


Figure 45: Linear regression output for WWR in west facade in north south oriented buildings in Accepted Range

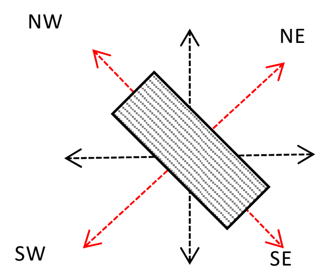
5.2.1.3 WWR in Accepted Range: Northeast-Southwest (NE-SW) Oriented Buildings

34.29% of the buildings are NE-SW oriented buildings where long side of the façade is facing towards NE and SW directions. The average energy building energy index in this range is 130.66 KWhm^{-2}per annum and the average WWR for east, west, north and south facades are 7%, 13%, 68% and 53% respectively. Morphological characteristics of the building stock are illustrated in Table 15. Correlation summary in Table 16 indicates that independent variables of WWR in east and west facades are correlating with each other which can cause multicolinearity.

Therefore these independent variables have not taken together when developing the regression model. Subset regression analysis was performed to evaluate all possible regression models.

Table 15:Morphological characteristics of the building stock in NE-SW Oriented Buildings in Accepted Range

Morphological characteristics of northeast southwest (NE-SW) oriented buildings in Accepted Range



Building percentage	**34.29%**			
Average Building Energy Index	**130.66 KWhm^{-2}/yr.**			
Building façade	**East**	**West**	**North**	**South**
WWR	**7%**	**13%**	**68%**	**53%**

Table 16: Evaluation summary of the independent variables for NE-SW Oriented buildings in Accepted Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			-0.649	0.022
		X_3	X_4	-0.386	0.215
X_1		X_3		-0.06	0.854
X_1			X_4	-0.373	0.232
	X_2	X_3		0.341	0.277
	X_2		X_4	0.398	0.2

Summary of the subset regression analysis is indicated in Table 17. Mallow Cp value, R Squared Adjusted value and R Squared Value is taken into consideration when re-assessing these regression models. Further, predictors of the selected models from subset regression analysis were evaluated based on Stepwise regression analysis. Summary of the findings are illustrated in Table 18. It is evident WWR in north and south façades have an R square (R sq.) value of 79.62% and the p value= $0.001<0.05=\alpha$. Thus the regression model is considered as good fit model. Therefore, the linear regression models for the dependent viable of BEI in Accepted Range in NE-SW oriented buildings can be illustrated as follows,

$$BEI\ (Accepted\ Range) = 98.10 + 25.10(WWR)north + 29.36(WWR)south$$

Table 17: Subset regression to evaluate the best fit model for NE-SW oriented buildings in Accepted Range

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	53	48.3	19	14	3.3211				X_4
1	38.1	31.9	9.8	21	3.809		X_2		
2	79.6	75.1	55	3.5	2.304			X_3	X_4
2	65.7	58.1	31.5	10.1	2.989		X_2		X_4
3	81.7	74.9	53.3	4.6	2.315	X_1		X_3	X_4
3	80.1	72.6	35.6	5.3	2.417		X_2	X_3	X_4
4	85.1	76.5	48.9	5	2.237	X_1	X_2	X_3	X_4

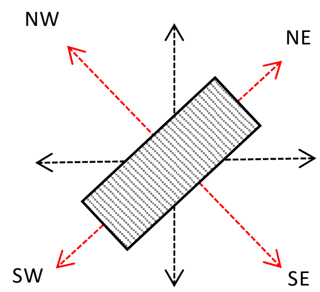
Table 18: Regression model summary for the NE-SW oriented buildings in Accepted Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
		1.18	1.18			X_3	X_4	2.30433	79.62%	75.09%	54.98%	17.58	0.001

5.2.1.4 WWR in Accepted Range: Northwest-Southeast (NW-SE) Oriented Buildings

20% of the buildings in Accepted Range are NW-SE oriented, where long side of the façade is facing towards NE and SE directions. The average energy building energy index in this range is 125.7 $KWhm^{-2}$per annum and the average WWR for east, west, north and south facades are 33%, 17%, 41% and 20% respectively. This is summarized in Table 19. Correlation summary in Table 20 indicates that independent variables of WWR in east and north facades are correlating with each other. Therefore, these variables have not taken together in multiple regression analysis to avoid multicolinearity. Subset regression analysis was performed to evaluate nexus between independent and dependent variables. The summary of the subset regression analysis is indicated in Table 21. Stepwise regression analysis was conducted to evaluate the predictors identified from subset regression analysis.

Table 19: Morphological characteristics of the building stock in NW-SE Oriented Buildings in Accepted Range

Morphological characteristics of northwest southeast (NW-SE) oriented buildings in Accepted Range				
				
Building percentage	20.00%			
Average Building Energy Index	175.79 KWhm^{-2}/yr.			
Building façade	**East**	**West**	**North**	**South**
WWR	33%	17%	41%	20%

Summary of the regression model in Table 22 indicate that WWR in east and west façades have an R Squared (R sq.) value of 97.14% and 89.5% with p values of = 0.0 and 0.001<0.05=α respectively. Thus denote that these two models with independent variables of WWR east and west are good fit models. Therefore, the multiple linear regression models for the independent variables of WWR in east and west facades with dependent variable of BEI in Accepted Range in NW-SE oriented buildings are as follows,

$$BEI\ (Accepted\ Range) = 112.16 + 41.49(WWR)east$$

$$BEI\ (Accepted\ Range = 114.43 + 66.2(WWR)west$$

The graphical output of the linear regression models are illustrated in Figure 46 and 47.

Table 20:Evaluation summary of the independent variables for NW-SE Oriented buildings in Accepted Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			0.911	0.04
		X_3	X_4	0.893	0.007
X_1		X_3		-0.721	0.068
X_1			X_4	-0.898	0.006
	X_2	X_3		-0.827	0.022
	X_2		X_4	-0.943	0.001

Table 21:Subset regression to evaluate the best fit model for NW-SE oriented buildings in Accepted Range

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	97.1	96.6	93.4	38.8	2.8713	X_1			
1	89.5	87.4	81.6	150.5	5.5052		X_2		
2	98.5	97.8	94.7	20.6	2.3062	X_1	X_2		
2	97.2	95.9	91.3	39.2	3.151	X_1			X_4
3	99.8	99.7	97.4	3.3	0.86522	X_1	X_2	X_3	
3	99	98	94.5	15.9	2.2124	X_1	X_2		X_4
4	99.9	99.6	95.9	5	0.99354	X_1	X_2	X_3	X_4

Table 22: Regression model summary for the NE-SW oriented buildings in Average Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
1				X_1				2.87133	97.14%	96.57%	93.35%	169.99	0
	1				X_2			5.5052	89.50%	87.40%	81.56%	42.6	0.001

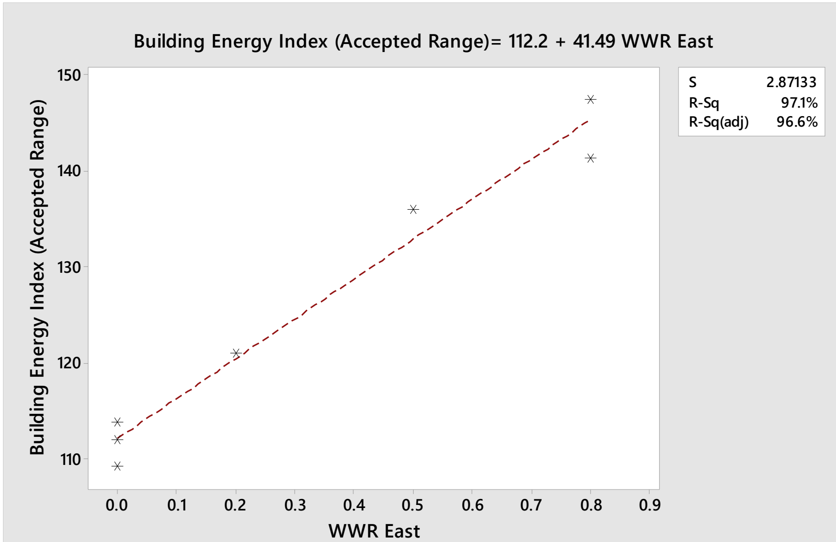


Figure 46: Linear regression output of the WWR east facade in NW-SE oriented buildings in Accepted Range

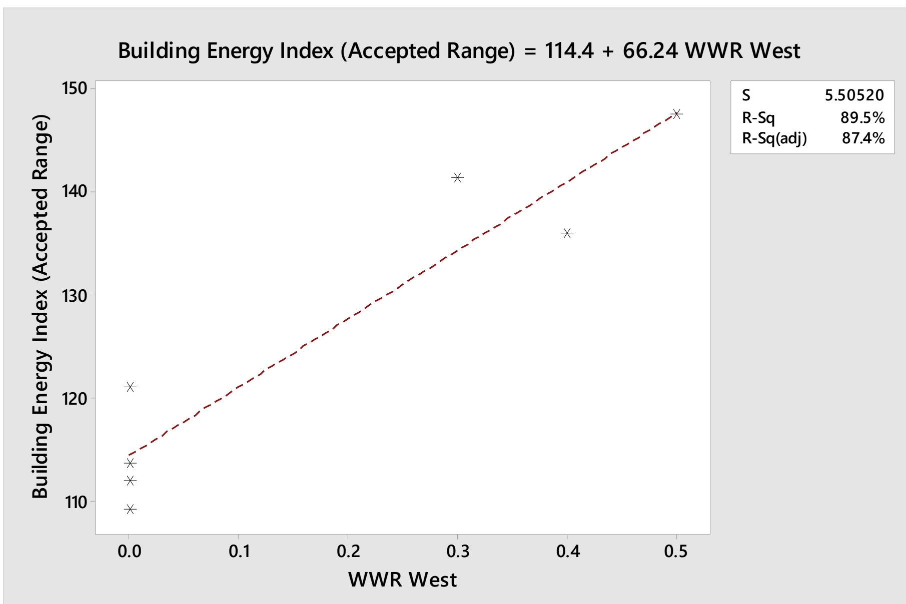
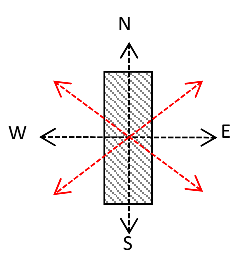
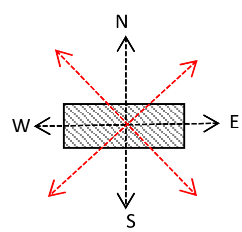
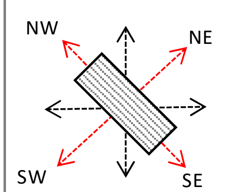
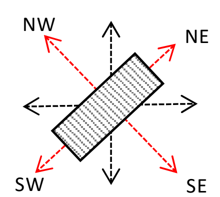


Figure 47: 29Linear Regression output for WWR in west facade in NW-SE oriented buildings

5.2.2 Nexus between WWR and Building Energy Index in Average Range

Building energy index in Average Range is within 150-250 kWh/m² per annum. 54.55% of the buildings in CMC region are within Average Range. Of which 37.03%, 18.52%, 27.78% and 16.67% of the buildings are east west (EW), north south (NS), northeast southwest (NE-SW) and northwest southeast (NW-SE) buildings. Summary of the morphological characteristics in Average Range is illustrated in Table 23. Nexus between building energy index and WWR in all four building facades are developed using multiple linear regression analysis and polynomial regression analysis. Orientation and building form are considered as constant parameters. Thus this study explores the nexus between WWR and energy index in EW, NS, NE-SW and NW-SE orientations.

Table 23: Morphological characteristics in Average Range

WWR and Building Energy Index in Average Range			
East-West (EW)	**North-South (NS)**	**Northeast-Southwest (NE-SW)**	**Northwest-Southeast (NW-SE)**
			
37.03%	18.02%	27.78%	16.67%
204.29 kWh/m²yr.	170.94 kWh/m²yr.	189.91 kWh/m²yr.	187.64 kWh/m²yr.

5.2.2.1 WWR and Building Energy Index in East West Oriented Buildings in Average Rang (150-250KkWh/m²yr.)

37.03% of the buildings are east west oriented, where long side of the building façade is facing towards these directions. The average energy consumption is 204.29 kWh/m² per annum and the average WWR for east, west, north and south facades are 76%, 63%, 13% and 2% respectively. Building characteristics are summarized in Table 24.

Correlation summary in Table 25 indicate that none of the independent variables are correlating with each other. Thus subset regression analysis was performed to identify the relationship with the independent and dependent variables.

Table 26 and 27 indicate the summary of the subset regression analysis and summary of the regression models retrieved from stepwise regression. Based on results WWR in east and west façades together have an R square (R. Sq.) value of 72.75% and R Adjusted value of 69.55% with a p value $=0.00<0.05=\alpha$. Thus it could be established that the regression model is a good fit. Therefore, the multiple linear regression model for dependent variable of BEI in Average Range and WWR of east and west facades are as follows,

$$BEI\ (Average\ Range) = 55.7 + 106.4(WWR)east + 107.9(WWR)west$$

Table 24: Morphological characteristics of the building stock in EW Oriented Buildings in Average Range

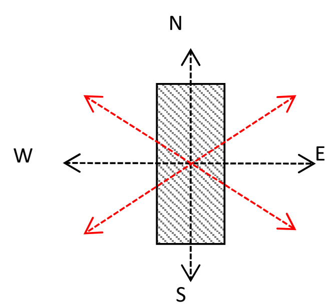
Morphological characteristics of East West (EW) Oriented buildings in Average Range				
				
Building percentage	**37.03%**			
Average Building Energy Index	**204.29 $KWhm^{-2}$/yr.**			
Building façade	**East**	**West**	**North**	**South**
WWR	76%	63%	13%	2%

Table 25: Evaluation of independent variables in EW oriented buildings in Average Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			-0.192	0.417
		X_3	X_4	-0.416	0.068
X_1		X_3		-0.13	0.586
X_1			X_4	-0.195	0.409
	X_2	X_3		0.392	0.088
	X_2		X_4	0.179	0.45

Table 26: Subset regression to evaluate the best fit model for EW oriented buildings in Average Range

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	36.5	33	23.6	22.6	18.309	X_1			
1	22.5	18.2	2.5	31.1	20.23		X_2		
2	72.8	69.5	63.9	2.6	12.344	X_1	X_2		
2	41.8	35	18.8	21.3	18.036	X_1		X_3	
3	74.5	69.7	62.5	3.5	12.317	X_1	X_2		X_4
3	72.8	67.6	59.8	4.6	12.724	X_1	X_2	X_3	
4	75.3	68.7	57.4	5	12.509	X_1	X_2	X_3	X_4

Table 27: Regression model summary for the EW oriented buildings in Average Range

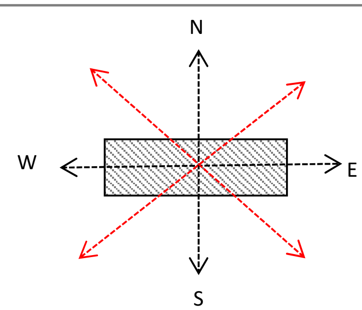
VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
1				X_1				18.3085	36.54%	33.01%	23.64%	10.36	0.005
	1				X_2			20.2304	22.51%	18.21%	2.47%	5.23	0.035
1.04	1.04			X_1	X_2			12.3439	72.75%	69.55%	63.92%	22.7	0

5.2.2.2 WWR in Average Range: North South (NS) Oriented Buildings

18.52% of the buildings in Average Range are NS oriented. The average building energy index is 170.94 kWh/m² per annum. The average WWR in east, west, north and south facades are 42%, 47%, 20% and 34% respectively. The morphological parameters of north south oriented buildings are illustrated in Table 28.

Independent variables of WWR in east, west, north and south facades are evaluated to prevent multicollinearity by conducting a correlation analysis. the evaluation summary of the independent variables in Table 29 indicate that WWR in north and south, WWR in east and north and, WWR in east and south are correlating with each other. Thus these variables are not taken together for further analysis. Subset regression analysis in Table 30 denotes the combinations of independent variables. The summary output of the stepwise regression analysis in Table 31 indicate that WWR in south façade has an R square value of 54.87% and R square adjusted value of 49. 22% with a p-value of $0.014<0.05=\alpha$. Polynomial regression analysis tool is used since the linear relationship between the variable are not strong.

Table 28: Morphological characteristics of the building stock in NS Oriented Buildings in Average Range

Morphological characteristics of north south (NS) oriented buildings in Average Range				
				
Building percentage	**18.02%**			
Average Building Energy Index	**170.94 KWhm^{-2}/yr.**			
Building façade	**East**	**West**	**North**	**South**
WWR	**42%**	**47%**	**20%**	**34%**

Summary output in linear and polynomial regression analysis in Table 32 indicate that R squared and R squared adjusted values in polynomial regression analysis have increased from 11.8% and 7.9% respectively. Thus Polynomial regression model is taken to represent the relationship between dependent variable of BEI in Average Range and WWR of north and south facades in Average Range.

$$BEI\ (Average\ Range) = 185.3 - 92.12(WWR)south + 80.96(WWR)south^2$$

Moreover, the graphical representation of linear regression analysis and polynomial regression analysis is illustrated in Figure 48 & 49

Table 29: Evaluation of independent variables in NS oriented buildings in Average Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			0.174	0.63
		X_3	X_4	0.68	0.031
X_1		X_3		-0.74	0.014
X_1			X_4	-0.909	0
	X_2	X_3		-0.556	0.095
	X_2		X_4	-0.347	0.326

Table 30: Subset regression to evaluate the best fit model for NS oriented buildings in Average Range

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	54.9	49.2	32.1	0.1	9.3581				X_4
1	32.4	23.9	2.5	3.1	11.454	X_1			
2	61.1	50	7.5	1.2	9.284	X_1			X_4
2	58.1	46.1	0	1.6	9.6373		X_2		X_4
3	62.1	43.1	0	3.1	9.9071	X_1	X_2		X_4
3	61.9	42.9	0	3.1	9.9248		X_2	X_3	X_4
4	62.7	32.9	0	5	10.759	X_1	X_2	X_3	X_4

Table 31: Regression model summary for the NS oriented buildings in Average Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
			1				X_4	9.35813	54.87%	49.22%	32.10%	9.72	0.014

Table 32: Model summary of linear and polynomial regression analysis for the WWR in south facade in NS oriented buildings in Accepted Range

WWR in South façade in NS Oriented buildings in Average Range	Model Summary		
	S	R-sq	R-Sq(Adj)
Linear regression Analysis	9.3581	54.90%	49.20%
Polynomial Regression Analysis	8.59865	66.70%	57.10%

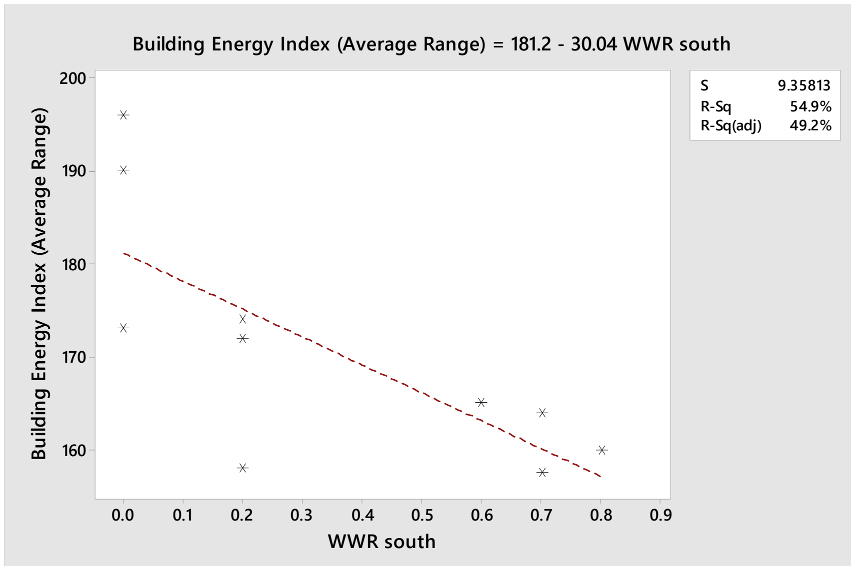


Figure 48 Linear regression output of the WWR east facade in NS oriented buildings in Average Range

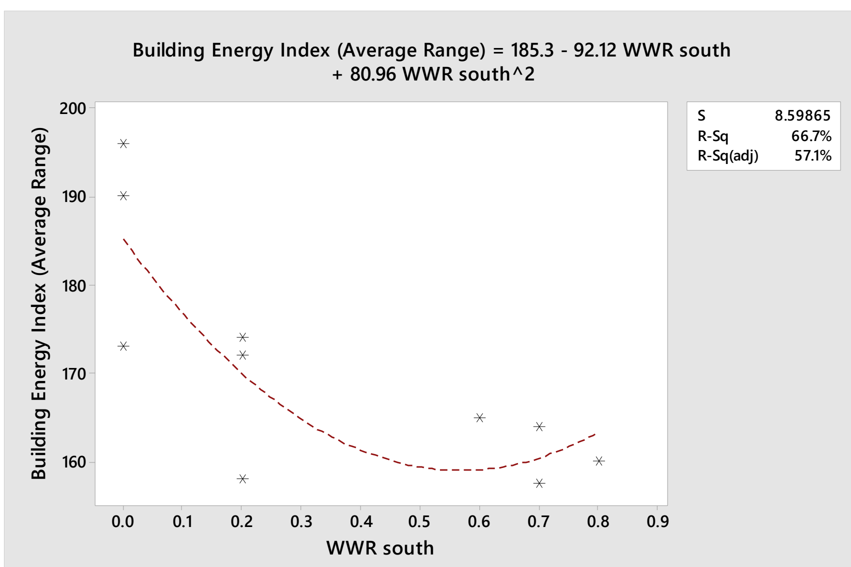


Figure 49: Polynomial regression output of the WWR east facade in NS oriented buildings in Average Range

5.2.2.3 WWR in Average Range: Northeast Southwest (NE-SW) Oriented Buildings

27.78% of the buildings in Average Range are NE-SW oriented. The average building energy index is 186.91 kWh/m² per annum. The average WWR in east, west, north and south facades are 54%, 54%, 27% and 31% respectively. The morphological parameters of northeast southwest oriented buildings are illustrated in Table 33.

Multiple regression analysis is conducted to identify the relationship between BEI in WWR in all four building facades. Evaluation of the independent variables of WWR in east, west, north and south facades are conducted to identify whether they correlate with each other to prevent multi co-linearity of the regression model. Evaluation summary of the independent variables in Table 34 indicate that WWR in north and south, and WWR in east and south correlates with each other. Thus these variables are eliminated from the regression model.

Table 35 indicate the summary of subset regression analysis to evaluate best fit regression models based on R Squared value, R squared adjusted value and Mallow cp value. The selected models are further analyzed through Stepwise regression analysis. Table 36 indicate the evaluated regression models with independent variables of WWR in north façade, WWR in south façade and WWR in east and west facades. These models have an R squared value of 56.09%, 79.76% and 84.81% along with a p value less than 0.05. Thus indicate the identified three models explain the predicted variable of BEI in Average Range. The summary of the linear regression models are as follows,

$$BEI\ (Average\ Range) = 203.90 - 54.06\ (WWR)south$$

$$BEI(Average\ Range) = 200.54 - 51.3(WWR)north$$

$$BEI\ (Average\ Range) = 127.97 + 59.98(WWR)east + 49.24(WWR)west$$

Further, Figure 50 & 51 illustrates the graphical representation of the simple linear regression models for the independent variables of WWR in north façade and south façade respectively.

Table 33: The morphological parameters of northeast southwest oriented buildings

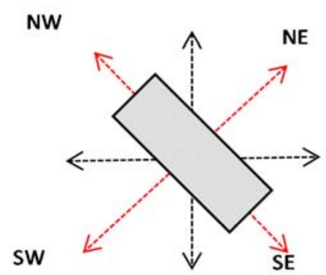
Morphological characteristics of northeast southwest (NE-SW) oriented buildings in Average Range				
				
Building percentag	27.78%			
Average Building Energy Index	$186.91 KWhm^{-2}/yr.$			
Building façade	**East**	**West**	**North**	**South**
WWR	54%	54%	24%	31%

Table 34: Evaluation of independent variables in NE-SW oriented buildings in Average Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			-0.186	0.506
		X_3	X_4	0.709	0.003
X_1		X_3		-0.428	0.111
X_1			X_4	-0.585	0.022
	X_2	X_3		-0.624	0.013
	X_2		X_4	-0.483	0.068

Table 35: Subset regression to evaluate the best fit model for NE-SW oriented buildings in Average Range

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	79.8	78.2	74.4	8.6	9.0553				X_4
1	56.1	52.7	42.4	31.6	13.336			X_3	
2	84.8	82.3	73.8	5.7	8.1631	X_1	X_2		
2	82.4	79.5	73	8	8.7791			X_3	X_4
3	89.6	86.8	81.3	3	7.0389	X_1	X_2		X_4
3	84.8	80.7	70.1	7.7	8.5261	X_1	X_2	X_3	
4	89.7	85.6	73.5	5	7.3677	X_1	X_2	X_3	X_4

Table 36: Regression model summary for the NE-SW oriented buildings in Average Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
			1				X_4	9.05533	79.76%	78.20%	74.44%	51.22	0
		1				X_3		13.3358	56.09%	52.72%	42.43%	16.61	0.001
1.04	1.04			X_1	X_2			8.16309	84.81%	82.28%	73.85%	33.51	0

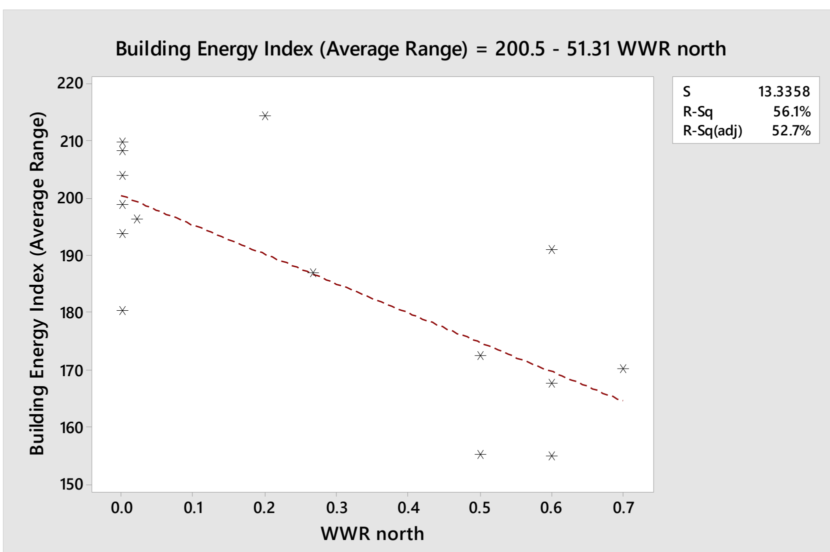


Figure 50:Linear regression output of the WWR north facade in NE SW oriented buildings in Average Range

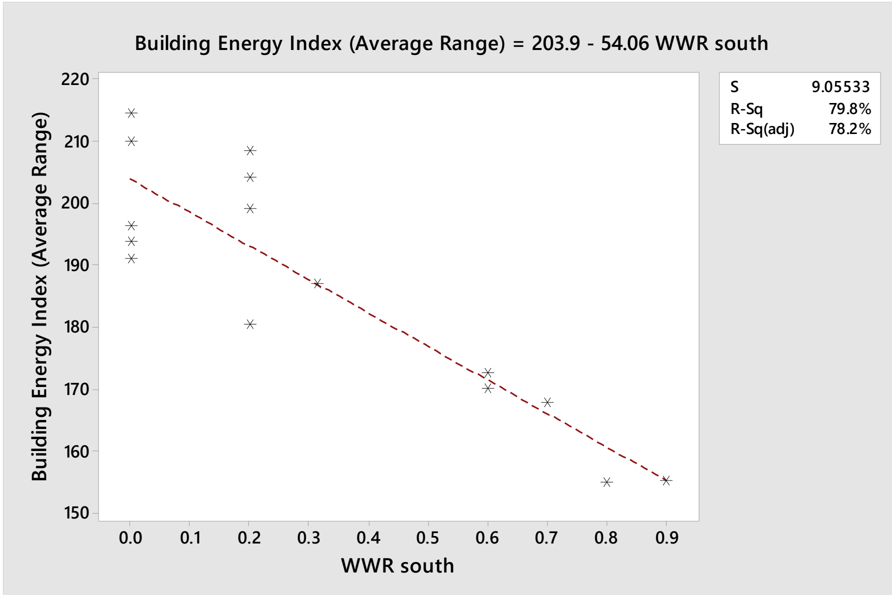
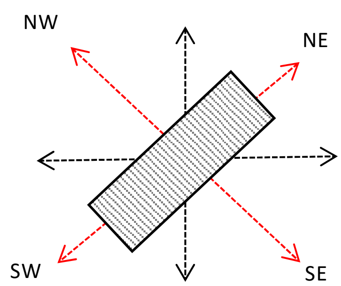


Figure 51: Linear regression output of the WWR south facade in NE SW oriented buildings in Average Range

5.2.2.4 WWR in Average Range: Northwest Southeast (NW-SE) Oriented Buildings

16.67% of the buildings in Average Range are NW-SE oriented. The average building energy index is 187.64 kWh/m² per annum. The average WWR in east, west, north and south facades are 38%, 39%, 48% and 40% respectively. The morphological parameters of northeast southwest oriented buildings are illustrated in Table 37

Table 37: The morphological parameters of northwest southeast oriented buildings

<table>
<tr><th colspan="5">Morphological characteristics of northwest southeast (NW-SE) oriented buildings in Accepted Range</th></tr>
<tr><td colspan="5">
</td></tr>
<tr><td>Building percentage</td><td colspan="4">16.67%</td></tr>
<tr><td>Average Building Energy Index</td><td colspan="4">187.64 $KWhm^{-2}/yr.$</td></tr>
<tr><td>Building façade</td><td>East</td><td>West</td><td>North</td><td>South</td></tr>
<tr><td>WWR</td><td>38%</td><td>39%</td><td>48%</td><td>40%</td></tr>
</table>

Multiple regression analysis tools are used to identify the nexus between the dependent variable of BEI and independent variables of WWR in all four building facades. Evaluations of the independent variables are conducted to identify whether they correlate with each other to prevent multicollinearity of the regression model. Correlation summary of the Table 38 illustrates that all the independent variables are correlating with each other except WWR in east and north facades. Thus these variables are not taken together in regression analysis. Table 39 illustrates the summary of the Subset regression analysis. Best fit regression models are evaluated based on R squared value, R Squared adjusted value and Mallow cp value. These models are further analyzed through stepwise regression analysis. Table 40 illustrates the summary of the multiple and simple linear regression models.

Table 38: Evaluation of independent variables in NW-SE oriented buildings in Average Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			0.83	0.006
		X_3	X_4	0.882	0.002
X_1		X_3		-0.896	0.001
X_1			X_4	-0.831	0
	X_2	X_3		-0.85	0.064
	X_2		X_4	-0.76	0.018

Table 39: Subset regression to evaluate the best fit model for NW-SE oriented buildings in Average Range

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	90.4	89.1	84.2	7	7.8373		X_2		
1	84.6	82.4	75.8	14.4	9.9428	X_1			
2	95.9	94.6	90.7	2.1	5.5328	X_1	X_2		
2	92.4	89.9	83.7	6.5	7.5302		X_2		X_4
3	96.8	94.9	91.2	3	5.3586	X_1	X_2		X_4
3	96	93.5	86.5	4.1	6.0269	X_1	X_2	X_3	
4	96.8	93.6	83	5	5.975	X_1	X_2	X_3	X_4

Figure 52 & 53 illustrate the graphical representation of the two simple linear regression models for the independent variables of WWR in east and west facades. Both regression models have an R squared value of 84.60% and 90.43% with a p value less than 0.05. The multiple linear regression model for independent variables of WWR east and west facades have an R squared value of 95.91% and the p value $=0.00<0.05=\alpha$. Thus indicate the identified three models explain the predicted variable of BEI in Average Range in NW-SE oriented buildings. Summary of the linear regression models are as follows,

$$BEI(Average\ Range) = 162.64 + 63.36(WWR)west$$

$$BEI(Average\ Range) = 165.38 + 58.91(WWR)east$$

$$BEI\ (Average\ Range) = 161.64 + 26.87(WWR)east + 40.16(WWR)west$$

Table 40: Regression model summary for the NW-SE oriented buildings in Average Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
	1				X_2			7.83732	90.43%	89.06%	84.19%	66.16	0
1				X_1				9.94282	84.60%	82.40%	75.83%	38.46	0
	3.21		3.21	X_1	X_2			5.53281	95.91%	94.55%	90.70%	70.4	0

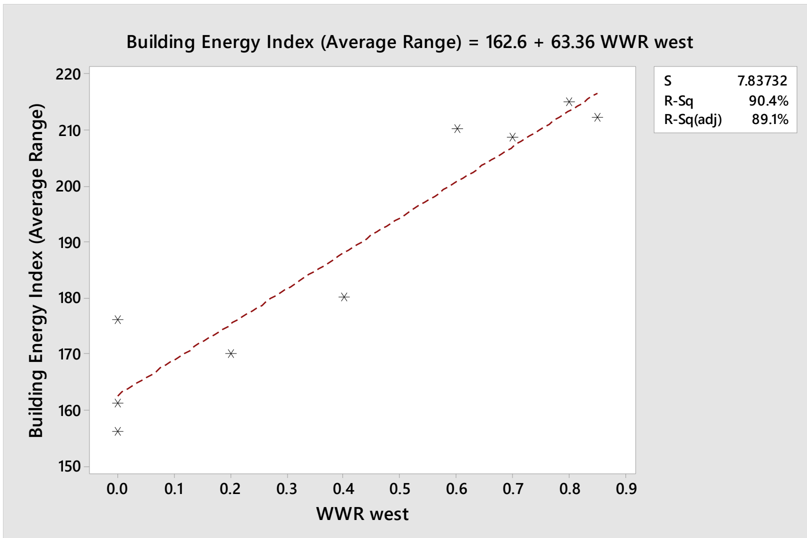


Figure 52: Linear regression output of the WWR west facade in NW-SE oriented buildings in Average Range

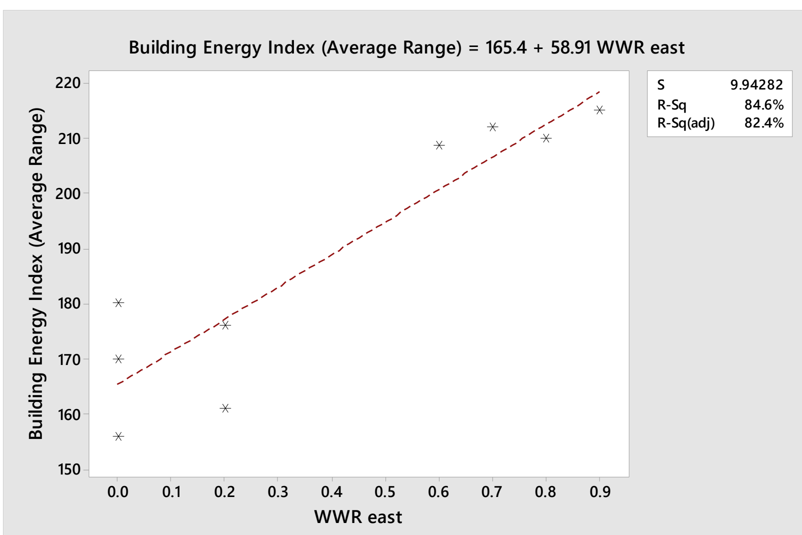


Figure 53: Linear regression output of the WWR east facade in NW-SE oriented buildings in Average Range

5.2.3 Nexus between WWR and Building Energy Index in Critical Range

Buildings in Critical Range have a BEI above 250 kWh/m² per annum. 10.10% of the buildings in CMC region are within Critical Range. Of which 70%, 10% and 20% of the buildings are east west (EW), northeast southwest (NE-SW) and northwest southeast (NW-SE) oriented. Common features observed in Critical Range office buildings are that these buildings have extended working hours and the building interiors are air conditioned with split type air conditioning systems. Summary of the building energy index and orientation in Critical Range is illustrated in Table 41. Since there are no adequate number of buildings to run a regression analysis in NE-SW and NW-SE orientated buildings, average WWR in all four cardinal directions and building energy index are presented in Table 42.

Table 41:The morphological characteristics of the EW, NE-SW and NW-SE oriented buildings in critical Range

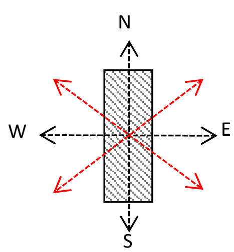
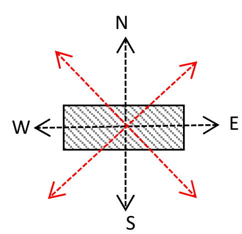
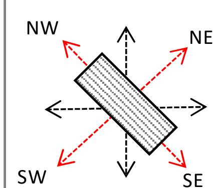
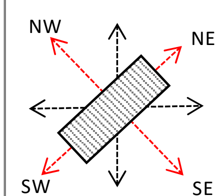
WWR and Building Energy Index in Critical Range			
East-West (EW)	**North-South (NS)**	**Northeast-Southwest (NE-SW)**	**Northwest-Southeast (NW-SE)**
			
70.00%	0.00%	10.00%	20.00%
272.34 kWh/m²yr.	0.00 kWh/m²yr.	262.14 kWh/m²yr.	262.33 kWh/m²yr.

Table 42: Summary of the WWR in all four cardinal directions and average BEI in NE-SW and NW-SE Oriented Buildings in Critical Range

	Northeast-Southwest(NE-SW)				**Northwest-Southeast(NW-SE)**			
Average Building Energy Index	262.14 kWh/m²yr.				262.33 kWh/m²yr.			
WWR	**East**	**West**	**North**	**South**	**East**	**West**	**North**	**South**
	0.65	**0.65**	**0.7**	**0.55**	**0.7**	**0.45**	**0.4**	**0.5**

5.2.3.1 WWR in Critical Range: East West Oriented Buildings

70% of the buildings in Critical range are comprised with east west oriented buildings. The average energy consumption of the buildings in Critical Range is 272.34 kWh/m² per Yr. Further, WWR in east, west, north and south facades are 81%, 63%, 14% and 6% respectively. The summary of the characteristics are indicated in Table 43.

Nexus between building energy index and WWR in all four building facades are developed using multiple linear regression analysis and polynomial regression analysis. Orientation and building form are considered as constant parameters. Hence, this research explores the nexus between WWR and energy index in EW oriented buildings.

Multiple regression analysis tool is conducted to ascertain the nexus between the dependent variable of BEI and independent variables of WWR in all four building facades. Table 44 indicates the summary of the correlation analysis of the independent variables. It is evident that none of the independent variables are correlating with each other. Table 45 illustrates the summary of the Subset regression analysis. R Squared Value, R Squared Adjusted Value and Mallow Cp Value were taken into consideration when evaluating the best fit regression models. These models are further analyzed through stepwise regression analysis. Table 46 illustrates the summary of the regression model. The R squared value is 62.76% and the p value $= 0.034 < 0.05 = \alpha$. Thus denote the identified regression model explain the predicted variable of BEI in Critical Range in EW oriented buildings. Summary of the linear regression model is as follows,

$$BEI\ (Critical\ Range) = 159.9 + 138.1(WWR)east$$

Figure 54 illustrates the graphical representation of the simple linear regression model for the independent variable of WWR in east facade.

Table 43: Summary of the building characteristics in east west oriented buildings in Critical Range

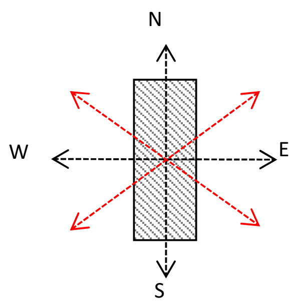
Morphological characteristics of East West (EW) Oriented buildings in Critical Range				
				
Building percentage	**70.00%**			
Average Building Energy Index	**272.34 KWhm^{-2}/yr.**			
Building façade	**East**	**West**	**North**	**South**
WWR	81%	63%	14%	6%

Table 44: Evaluation of independent variables in NW-SE oriented buildings in Critical Range

independent variables				Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Pearson Correlation	P-Value
X_1	X_2			0.3	0.513
		X_3	X_4	-0.645	0.117
X_1		X_3		0.411	0.36
X_1			X_4	-0.141	0.762
	X_2	X_3		0.571	0.181
	X_2		X_4	-0.636	0.124

Table 45: Subset regression to evaluate the best fit model for EW oriented buildings in Critical Range

Best Subsets Regression: Building Energy Index (Critical Range) and WWR in east,west, nort and south facades									
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)
1	62.8	55.3	22.4	103.9	8.042	X_1			
1	43.3	31.9	0	159.9	9.927		X_2		
2	82.1	73.2	67.9	50.3	6.226	X_1	X_2		
2	65.5	48.2	0	98.1	8.6591	X_1		X_3	
3	97.4	94.8	87.5	8.4	2.7316	X_1	X_2		X_4
3	82.7	65.3	29.2	50.8	7.0828	X_1	X_2	X_3	
4	99.3	97.9	91.6	5	1.7393	X_1	X_2	X_3	X_4

Table 46: Regression model summary for the EW oriented buildings in Critical Range

VIF				independent variables				Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
1				X_1				8.04199	62.76%	53.31%	22.39%	8.43	0.034

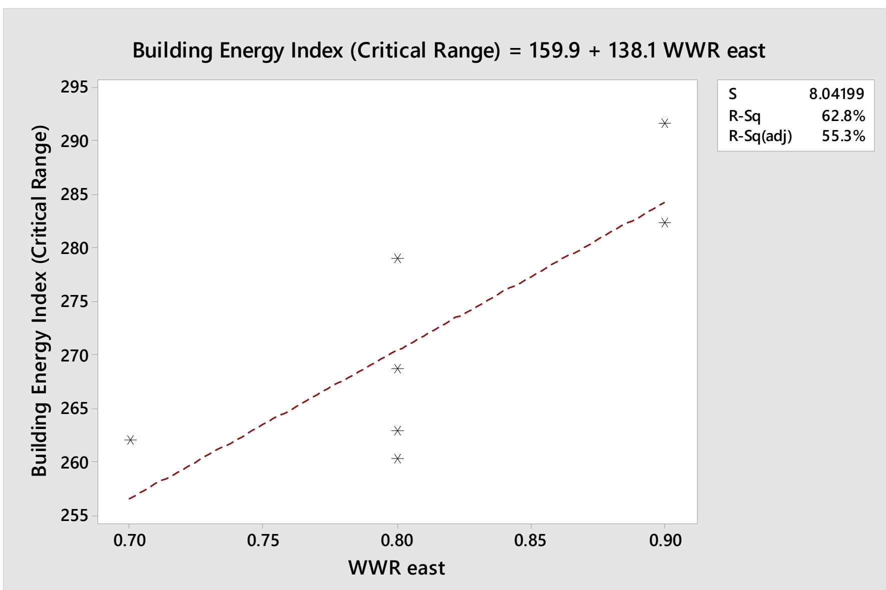


Figure 54: Linear regression output of the WWR east facade in EW oriented buildings in Critical Range

5.3 Nexus between Building form and energy consumption

Building form is represented as the aspect ratio of the office buildings. It is a key geometric parameter when optimizing the building energy consumption (Timothy L Hemsatha, Kaveh Alagheband Bandhosseini, 2015). Aspect ratio is one of the most significant factors to consider in terms of building energy efficiency. Aspect ratio describe the surface are of the building by which the heat us transmitted between the inner and the outer atmosphere along with the building are which receive solar heat gain (Philip McKeen, Alan S. Fung, 2014). The level to which solar heat gain can be useful or harmful relies on the aspect ratio and the climate. This research therefore assesses the connection between the geometry of building and the building energy index. Simple Linear regression analysis tool is conducted to develop by considering only one parameter and keeping all the other factors constant such as building form and orientation. Building energy index was taken as the dependent variable (y) and aspect ratio was taken as the independent variable (x). Thus simple linear regression model is illustrated below,

$y = B_0 + b_1 X_1$

Ratio of the length and width of the buildings foot prints is known as aspect ratio (x:y). The shift in the aspect ratio can be defined as an increase in building dimensions relative to the east-west or north-south axis for rectangular shape building arrangement (Philip McKeen, Alan S. Fung, 2014). The change in the aspect ratio may differ depending on the quantity of the building envelop exposed to solar radiation. Selected buildings represent east west and north south oriented buildings in all three levels of Energy Index categories namely, Acceptable Range, Average Range and Critical Range. Aspect ratio in east west oriented buildings increase along north south axis whereas aspect ratio in north south oriented buildings increase along east west axis. This is illustrated in Figure 55.

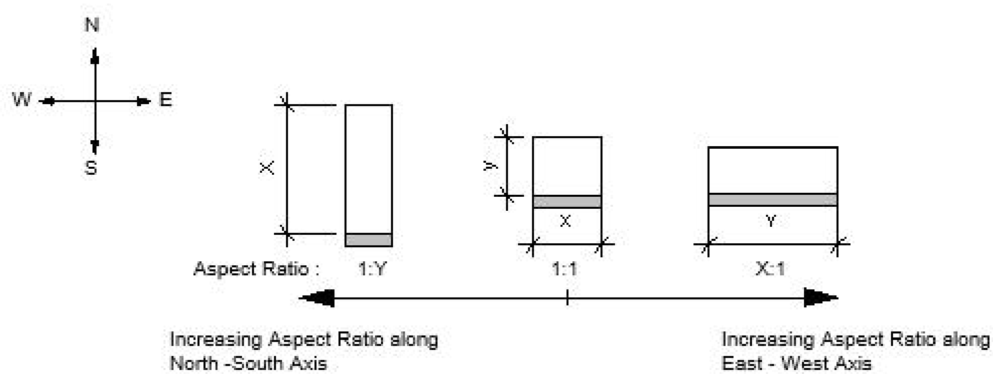
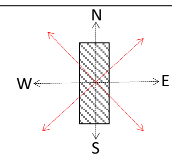
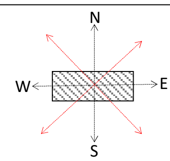
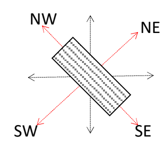
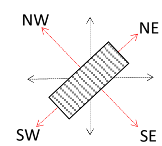


Figure 55: change in aspect ratio along a particular axis due to the increase in building dimensions (x,y) (Philip McKeen,Alan S. Fung, 2014)

The average building height for the buildings is taken as five floors and floor to floor height is taken as 3m. The floor to floor heights for all the buildings are considered same. Table 47 illustrates the summary of BEI and WWR of the identified office buildings in Accepted Range, Average Range and Critical Range. East west and north south oriented buildings were taken into account since they are the most significant orientations in a building for direct solar radiation. Thus the investigation was primarily focused on EW and NS oriented buildings to analyze the impact of aspect ratio on identified energy index categories. Energy consumption vary with the amount of glazing used in building façades.

Table 47: Summary of BEI, WWR and aspect ratio of identified office buildings in Accepted Range, Average Range and Critical Range

	EW Oriented	**NS Oriented**	**NE-SW Oriented**	**NW-SE Oriented**
Orientation				
Accepted Range	**Average BEI** **133.45 KWh/m²/yr.**	**Average BEI** **122.71 KWh/m²/yr.**	**Average BEI** **130.66 KWh/m²/yr.**	**Average BEI** **125.79 KWh/m²/yr.**
	WWR	**WWR**	**WWR**	**WWR**
	East West North South	East West North South	East West North South	East West North South
	0.36 0.49 0.11 0.08	0.03 0.18 0.32 0.53	0.07 0.13 0.68 0.53	0.33 0.17 0.41 0.2
Total Units =35	**Number of Units=10**	**Number of Units=06**	**Number of Units=12**	**Number of Units=07**
Average Rage	**Average BEI** **204.29 KWh/m²/yr.**	**Average BEI** **170.94 KWh/m²/yr.**	**Average BEI** **186.91 KWh/m²/yr.**	**Average BEI** **187.64 KWh/m²/yr.**
	WWR	**WWR**	**WWR**	**WWR**
	East West North South	East West North South	East West North South	East West North South
	0.76 0.63 0.13 0.02	0.42 0.47 0.2 0.34	0.54 0.54 0.27 0.31	0.38 0.39 0.48 0.40
Total Units =55	**Number of Units=20**	**Number of Units=10**	**Number of Units=15**	**Number of Units=10**
Critical Range	**Average BEI** **272.34 KWh/m²/yr.**	**Average BEI**	**Average BEI** **262.14 KWh/m²/yr.**	**Average BEI** **262.33 KWh/m²/yr.**
	WWR	**WWR**	**WWR**	**WWR**
	East West North South	East West North South	East West North South	East West North South
	0.81 0.63 0.14 0.06		0.65 0.65 0.7 0.55	0.7 0.45 0.40 0.5
Total Units =10	**Number of Units=7**	**Number of Units=0**	**Number of Units=1**	**Number of Units=2**

This study investigates the impact of façade configuration and aspect ratio on BEI in EW and NS oriented buildings. Figure 57 illustrate the graphical representation of aspect ratio in Accepted Range, Average Range and Critical Range with building energy index in EW oriented buildings. Literature reveals the optimal aspect ratio for buildings which are 90º perpendicular to the east west axis are between 1: 1.5 and 1: 1.3. It is evident that aspect ratio of 0.70 (1:1.43) in Accepted Range is within the optimal range. Whereas, aspect ratio in Average and Critical Ranges are 0.3 (1: 3.33) and 0.26 (1:3.85) respectively. Thus indicate a substantial deviance from the optimal aspect ratio for EW oriented buildings

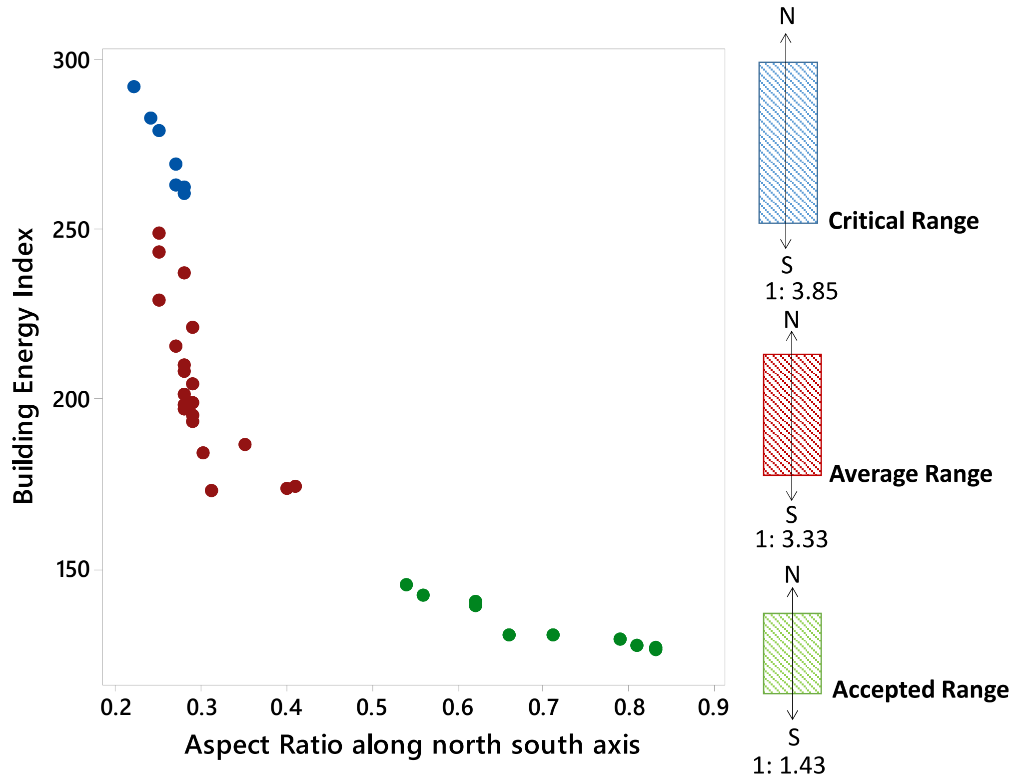


Figure 56: BEI in Accept, Average & Critical Range with Aspect Ratio along north south axis

Aspect ratio increase along east west axis in NS oriented buildings. The optimal aspect ratio for buildings along east west axis are within the range of 1.27:1 to 1.5:1. Further increase of aspect ratio beyond this range result in increase of energy consumption in buildings. The average aspect ratio for NS oriented buildings in Accepted Range is 1.49 (1.49:1), which is within the optimal range. Nonetheless, the average aspect ratio for NS oriented buildings in Average Range is 3.22 (3.22:1), which is beyond the optimal range. Figure 58 illustrate the graphical representation of aspect ratio with building energy index in NS oriented buildings in Accepted and Average Range.

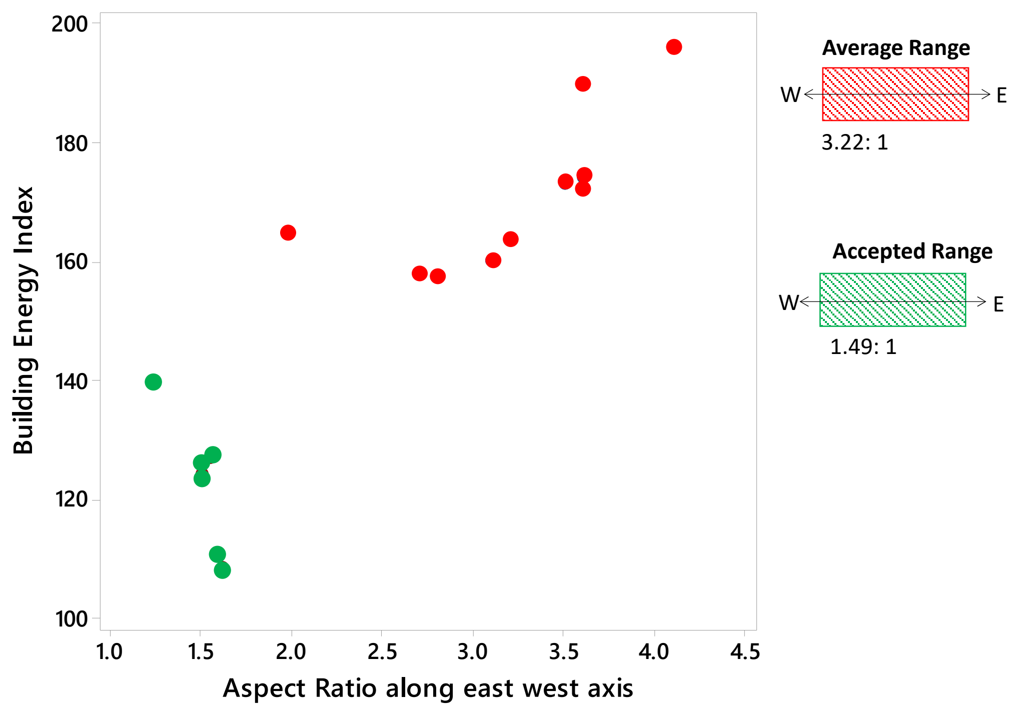
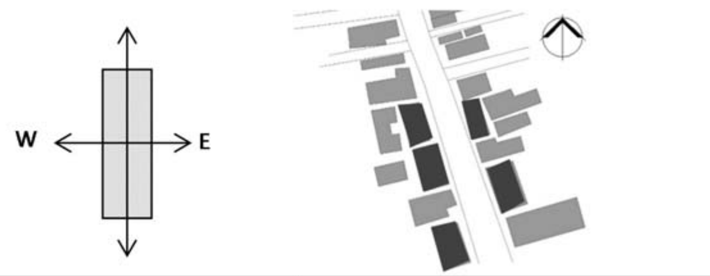
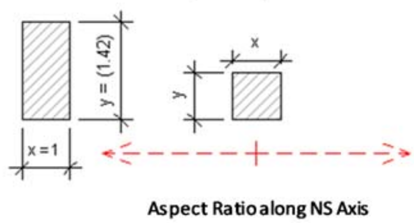


Figure 57: BEI in Accept, Average & Critical Range with Aspect Ratio along east west axis

5.3.1 Nexus between Building Energy Index and Aspect Ratio along north south Axis in Accepted Range

35.72% of the buildings in Colombo Municipal Council Region are within Accepted Range of energy consumption. Out of which 28.5% of the buildings are east west oriented. Where aspect ratio increase along north south axis. This enables direct solar radiation to the building. Thus promotes increase energy consumption. The average building energy index is 133.45 kWh/m² per annum and the average numbers of floors are five. The WWR in east, west, north and south facades are 36%, 49%, 11% and 8% respectively. Building morphological characteristics are summarized in Table 48. The average aspect ratio for east west oriented buildings are 0.7 (1:1.42). The optimal aspect ratio for buildings which are 90º perpendicular to the east west axis are between 1: 1.5 and 1: 1.3 (McKeen & Fung, 2014). Thus denote the average aspect ratio in the existing building stock is within the optimal range.

Table 48:Building morphological characteristics in EW Oriented buildings in Accepted Range

East West(EW) Oriented Buildings in Accepted Range (100-150KWhm-²/yr.)				
				
Building Percentage	28.57%			
Aspect Ratio Along Noth South Axis	0.7 (1:1.42) 			
Average Number of Floors	5			
Average Building Energy Index	133.45 kWh/m²yr.			
WWR	East	West	North	South
	36%	49%	11%	8%

The orientation of profiles 90° to the east-west axis had a large influence towards energy consumption in buildings (McKeen & Fung, 2014) Thus it is important to consider the façade composition of the building stock. The average WWR in east, west, north and south facades are 36%, 49%, 11% and 8% respectively. Multiple linear regression models are developed to configure the nexus between WWR and aspect ratio in east west orientation. The independent variables for the multiple linear regression analysis are WWR in east, west, north, south and aspect ratio. The dependent variable is BEI in Accepted Range. Table 49 indicates the correlation analysis of the independent variables. Evaluation summary designate that WWR in east façade and Aspect Ratio are correlation with each other. Summary of the subset regression analysis in Table 50 stipulate the possible multiple regression models. These models are evaluated based on R squared value; R squared adjusted value and Mallow cp value. Stepwise regression analysis is conducted to identify the best fit models based on R Squared value, R squared Adjusted Value and P value. Summary of the regression models are illustrated in Table 51. Simple linear regression model for the independent variable of Aspect Ratio has an R Squared Value of 89.09% and a P value of 0.00<0.05=α. Graphical demonstration of the simple linear regression model is illustrated in Figure 59.

Table 49:Evaluation summary of the independent variables in east west oriented buildings in Accepted Range

independent variables					Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	Pearson Correlation	P-Value
X_1	X_2				-0.53	0.115
		X_3	X_4		-0.535	0.111
X_1				X_5	-0.646	0.044
	X_2			X_5	0.037	0.92
		X_3		X_5	-0.156	0.668
			X_4	X_5	-0.379	0.28

Table 50:Subset Regression summary of the multiple regression analysis for independent variables of WWR north, south, east, west and aspect ratio

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort,south facades and Aspect Ratio										
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)
1	89.1	87.7	85.1	-1.7	2.5293					X_5
1	38.3	30.6	9	18.1	6.0155	X_1				
2	89.7	86.7	77.4	0	2.6341				X_4	X_5
2	89.2	86.2	77.1	0.2	2.6863			X_3		X_5
3	89.7	84.6	69.6	2	2.8322	X_1			X_4	X_5
3	89.7	84.5	63.9	2	2.8411		X_2		X_4	X_5
4	89.8	81.6	67.3	4	3.0999	X_1		X_3	X_4	X_5
4	89.7	81.5	51	4	3.1024	X_1	X_2		X_4	X_5
5	89.8	77	36.2	6	3.4655	X_1	X_2	X_3	X_4	X_5

Table 51:Regression model summary for independent variable of Aspect Ratio

VIF					independent variables					Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	(X_5)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
				1					X_5	2.5293	89.09%	87.73%	85.07%	65.36	0

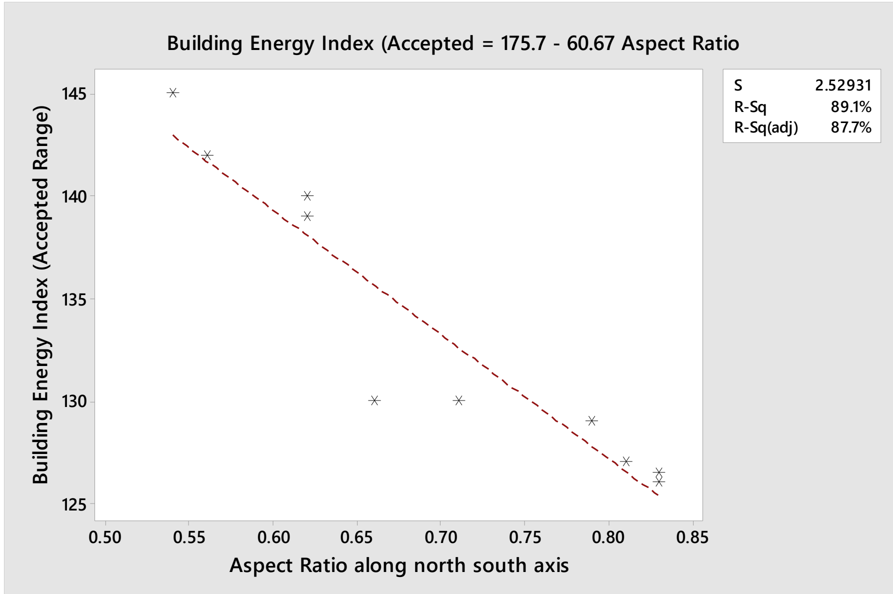


Figure 58: Linear regression output of Aspect Ratio and BEI

These independent variables are further analyzed using polynomial regression analysis. Summary output in Table 52 denote that the R squared value and R squared adjusted value have increased in polynomial regression model from 4.2% and 3.6% respectively. Graphical demonstration of the polynomial regression analysis model is illustrated in Figure 60. It is evident that these two regression models explain the predicted value of BEI in EW oriented buildings in Accepted Range. Summary of the regression models are as follows,

Regression Model: Building Energy Index and Aspect Ratio along north south axis

Linear Regression Model

$$BEI\ (Accept\ Range) = 175.73 - 60.67AR$$

Polynomial Regression Model

$$BEI\ (Accept\ Range) = 260.7 - 311.1AR + 180.2AR^2$$

Table 52:Model summary of linear and polynomial regression analysis

Regression model for Aspect Ratio along south axis	Model Summary		
	S	R-sq	R-sq(adj)
Linear regression Analysis	2.52931	89.1%	87.7%
Polynomial Regression Analysis	2.12454	93.3%	91.3%

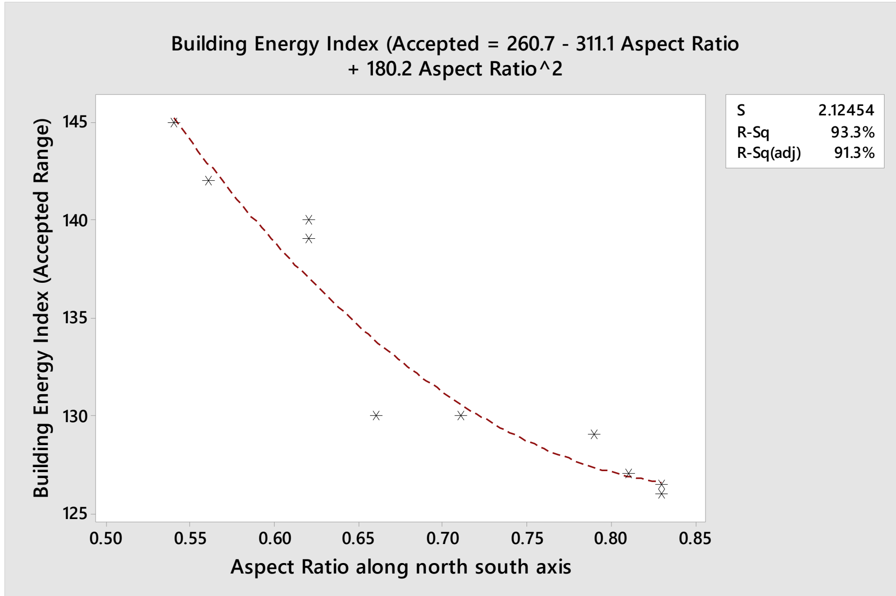
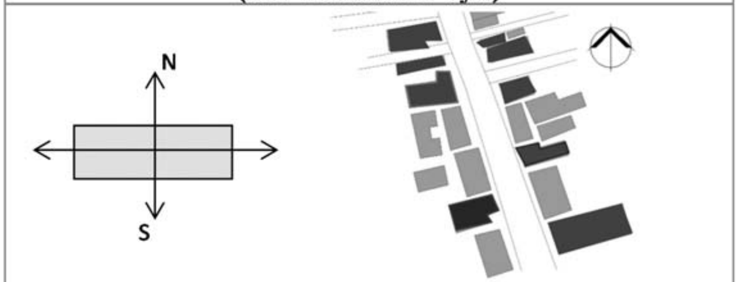
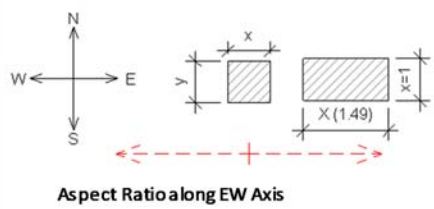


Figure 59: Polynomial regression output of WWR west facade and BEI

5.3.2 Nexus between Building Energy Index and Aspect Ratio along east west Axis in Accepted Range

35.72% of the buildings in Colombo Municipal Council Region are within Accepted Range. Out of which 17.14% of the buildings are north south (NS) Oriented where aspect ratio is increasing along east west axis. The average building energy index is 122.71 kWh/m² per annum and the average numbers of floors are 5. WWR in east, west, north and south facades are 3%, 18%, 32% and 53% respectively. Morphological characteristics of the buildings are summarized in Table 53. Demand for cooling decrease when the aspect ratio increase along the east west axis until it reaches the optimum aspect ratio which is between 1.5:1 and 2.7:1 for NS oriented buildings. Any further increase in aspect ratio along this axis will increase the cooling energy consumption (McKeen & Fung, 2014). The average aspect ratios in NS oriented buildings are 1.49 which is within the stipulated range. Energy consumption varies with the amount of glazing used in the building façades. Buildings with increased aspect ratio in east west axis get less solar radiation towards critical facades Thus this study investigate the nexus between WWR and aspect ratio on building energy consumption in NS oriented buildings in Accepted Range.

Table 53:Morphological characteristics of the buildings in NS oriented buildings in Accepted Range

North South (NS) oriented Buildings in Accepted Range (100-150KWhm-²/yr.)				
				
Building Percentage	17.14%			
Aspect Ratio Along Noth South Axis	1.49 (1.49:1) 			
Floors	5			
Average Building Energy Index	122.71 kWh/m²yr.			
WWR	East	West	North	South
	3%	18%	32%	8%

Correlation analysis in Table 54 indicates that all the independent variables are correlating with each other except WWR in east façade and Aspect Ratio. Subset regression analysis is conducted to identify the possible regression models and these models are evaluated based on R squared value, R squared adjusted value and Mallow cp value. Stepwise regression analysis is conducted to identify the best fit models based on R Squared value, R squared Adjusted Value and P value. The summary of the subset regression analysis is indicated in Table 55 & 56. Table 57 indicates the linear regression models for WWR in west façade and Aspect Ratio. Simple linear regression model for the independent variable of WWR in west façade has an R Squared Value of 70.32% and a P value of $0.037<0.05=\alpha$. Figure 61 illustrate the graphical representation of the simple linear regression model for WWR in west façade.

Table 54:Evaluation summary of the independent variables in north south oriented buildings in Accepted Range

independent variables					Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	Pearson Correlation	P-Value
X_1	X_2				0.933	0.007
		X_3	X_4		0.933	0.007
X_1				X_5	-0.936	0.006
	X_2			X_5	-0.922	0.009
		X_3		X_5	0.469	0.348
			X_4	X_5	0.717	0.109

Simple linear regression model for the Aspect Ratio has an R Squared value of 78.44% and the P value=0.019<0.05=α. These independent variables are further analyzed using polynomial regression analysis. Summary output in Table 58 denote that substantial increase in R squared value and R squared adjusted value is evident in Aspect Ratio. Graphical representation of both simple linear regression analysis model and polynomial regression analysis model is illustrated in Figure 62 & 63. The identified regression models explain the predicted value of BEI in NS oriented buildings in Accepted Range.

Table 55:Subset Regression summary of the multiple regression analysis for independent variables of WWR east, west and aspect ratio

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort,south facades and Aspect Ratio								
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	Aspect Ratio (X_5)
1	78.4	73	0	4.1	6.0474			X_5
1	70.3	62.9	24.8	6.4	7.0948		X_2	
2	87.1	78.5	*	3.6	5.3949	X_1		X_5
2	78.8	64.6	0	6	6.9303		X_2	X_5
3	92.9	82.4	*	4	4.8929	X_1	X_2	X_5

Table 56: Subset Regression summary of the multiple regression analysis for independent variables of WWR north, south and aspect ratio

Best Subsets Regression: Building Energy Index (Accepted Range) and WWR in east,west, nort,south facades and Aspect Ratio								
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)
1	78.4	73	0	13.1	6.0474			X_5
1	15	0	0	57.4	12.009		X_4	
2	94.9	91.5	0	3.6	3.4007	X_3		X_5
2	91.2	85.3	0	6.2	4.4728		X_4	X_5
3	97.1	92.8	0	4	3.1173	X_3	X_4	X_5

Table 57:Regression model summary for independent variables of WWR west and Aspect Ratio

VIF					independent variables					Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	(X_5)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
				1					X_5	6.047	78.44%	73.04%	0.00%	14.55	0.019
	1					X_2				7.095	70.32%	62.90%	24.79%	9.48	0.037

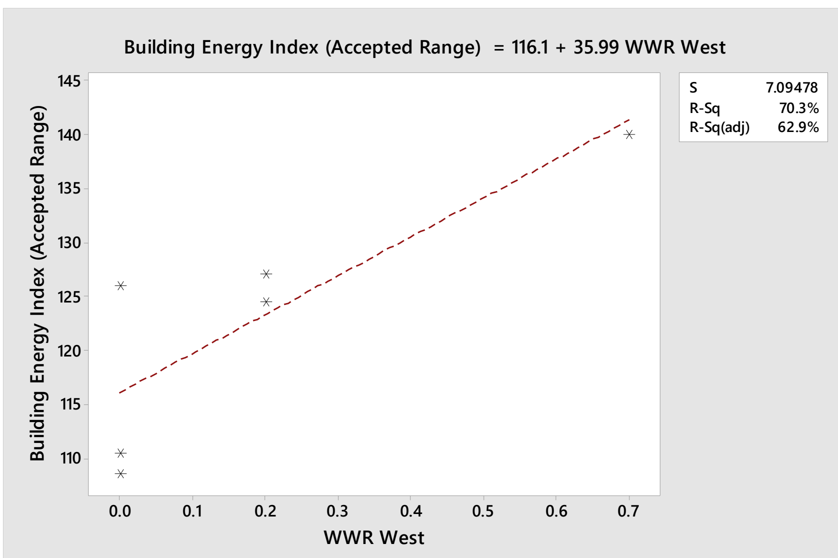


Figure 60: Linear regression output of WWR west facade and BEI

Summary of the regression models are as follows,

Linear Regression Model

$$BEI\ (Accepted\ Range) = 233.9 - 74.4 * (AR)$$

Polynomial Regression Model

$$BEI\ (Accepted\ Range) = 254.2 + 624.9 * (AR) - 247.5 * (AR)^2$$

Regression Models: Building Energy Index and WWR West façade

$$BEI\ (Accepted\ Range) = 116.12 + 36.0(WWR)west$$

Table 58: Model summary of linear and polynomial regression analysis

Regression model for Aspect Ratio along east west axis	model summary		
	S	R-sq	R-sq(adj)
Linear regression Analysis	6.047	78.4%	73.0%
Polynomial Regression Analysis	5.177	**88.1%**	80.2%

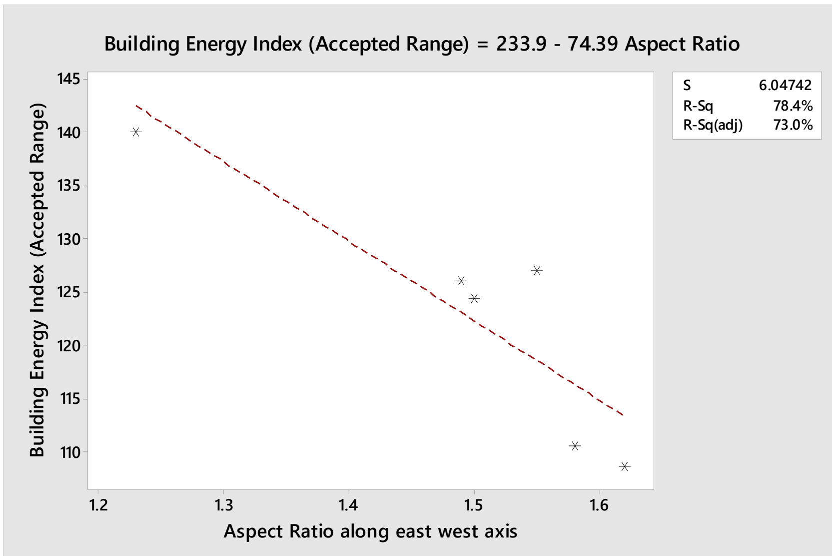


Figure 61: Linear regression output for Aspect ratio along east west axis and BEI in Accepted Range

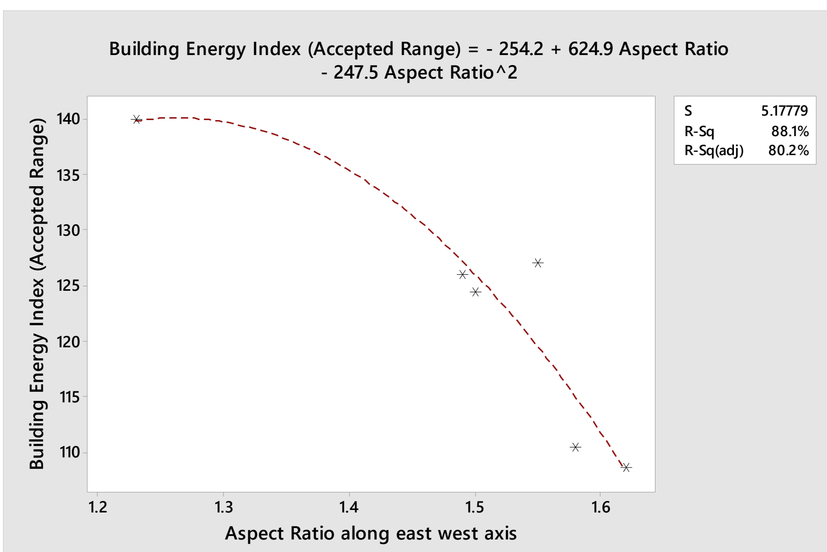
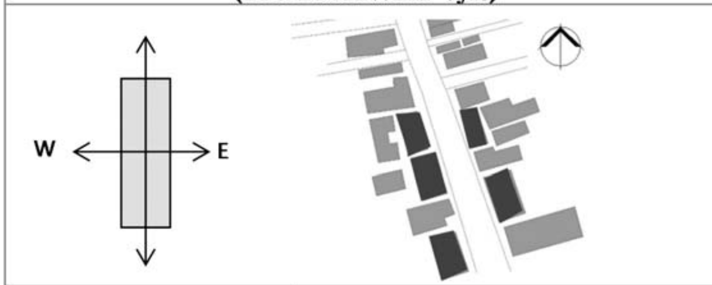
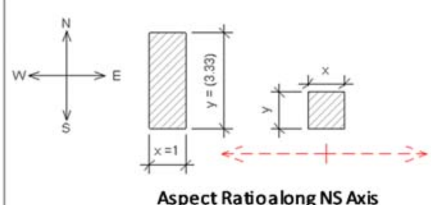


Figure 62: Polynomial Regression output of Aspect ratio along east west axis and BEI in Accepted Range

5.3.3 Nexus between Building Energy Index and Aspect Ratio along north south Axis in Average Range

54.08% of the buildings in Colombo Municipal Council Region are within Average Range. Out of witch with 37.04% of the buildings are east west oriented. The average energy consumption is 204.29 KWhm⁻² per annum and the average numbers of floors are six. Morphological parameters of the building stock are illustrated in Table 59.

Table 59:Morphological Parameters of the EW oriented buildings in Average Range

East West(EW) Oriented Buildings in Average Range (150-250KWhm-²/yr.)				
				
Building Percentage	37.04%			
Aspect Ratio Along Noth South Axis	0.3 (1:3.33) 			
Average Number of Floors	6			
Average Building Energy Index	204.29 kWh/m²yr.			
WWR	**East**	**West**	**North**	**South**
	76%	63%	13%	2%

Literature reveals that the optimum aspect ratio for EW oriented buildings are within the range of 1:1.5 to 1: 1.3 (McKeen & Fung, 2014). But the average aspect ratio of the building stock is 0.30 (1:3.33) which is twice the amount of optimum range. Further, In terms heating and cooling in buildings, WWR has a definite effect towards energy conservation (Alwetaishi, 2017).The average WWR in this office building stock in east, west, north and south facades are 76%, 63%, 13% and 2%

respectively. It is evident that east and west critical facades have higher glazing percentage. This is mainly due to the positioning of the access road to the building from east west direction. Despite the aesthetic benefits, glazed facades can result in over heated building interiors which lead to an increased energy consumption for the end user. Thus the impact on building façade configuration and aspect ratio on building energy index is further analyzed through multiple and polynomial regression analysis. Dependent and independent variables for the regression models are BEI in Average Range and WWR in east, west, north, south and Accept Ratio respectively.

Table 60 indicates the correlation summary of the independent variables where WWR in east facade and Aspect Ratio are correlating with each other. Subset regression analysis in Table 61 indicates the regression models for all the variables. Mallow Cp Value, R Squared Adjusted Value and R Squared Values were taken into consideration when assessing these models. Further, the best fit regression models are derived by conducting Stepwise regression analysis.

Table 60: Correlation summary of the independent variables

independent variables					correlations	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	Pearson correlation	P-value
X_1	X_2				0.3	0.513
		X_3	X_4		-0.645	0.117
X_1				X_5	-0.837	0.019
	X_2			X_5	-0.571	0.181
		X_3		X_5	-0.514	0.238
			X_4	X_5	0.043	0.927

Table 63 indicates the summary of the regression models and they are evaluated based on R Squared values and p values. All the selected simple and multiple linear regression models have an R squared and R squared adjusted value above 50% and the p values less than 0.05. Thus denote the predicted value of BEI in east west orientation in Average Range is explained by these regression models. Summary of the regression models are as follows,

Regression Models:

$$BEI\ (Average\ Range) = 265.6 + 89.5(WWR)west - 396.7 * AR$$

$$BEI(Average\ Range) = 55.7 + 106.4(WWR)east + 107.9(WWR)west$$

$$BEI(Average\ Range) = 186.6 + 49.1(WWR)east + 98.9(WWR)west - 275.9 * AR$$

Table 61:Summary of the subset regression analysis

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort,south facades and Aspect Ratio										
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)
1	55.6	53.1	44	33.2	15.312					X_5
1	36.5	33	23.6	54.3	18.309	X_1				
2	81.5	79.3	75.8	6.5	10.181		X_2			X_5
2	72.8	69.5	63.9	16.2	12.344	X_1	X_2			
3	86.7	84.2	82.2	2.7	8.8921	X_1	X_2			X_5
3	81.7	78.3	73.2	8.2	10.421		X_2	X_3		X_5
4	86.9	83.4	80.5	4.5	9.1189	X_1	X_2	X_3		X_5
4	86.8	83.3	80.5	4.6	9.1437	X_1	X_2		X_4	X_5
5	87.4	82.8	78.7	6	9.2648	X_1	X_2	X_3	X_4	X_5

Table 62:Summary of the regression analysis model Regression model summary for independent variables of WWR west, WWR east and Aspect Ratio

VIF					independent variables					Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	(X_5)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
				1					X_5	15.3115	55.61%	53.15%	44.01%	22.55	0
1				1		X_2			X_5	10.1813	81.46%	79.28%	75.84%	37.36	0
1.04	1.04				X_1	X_2				12.3439	72.75%	69.55%	63.92%	22.7	0
2.12	1.06			2.05	X_1	X_2			X_5	8.89211	86.69%	84.20%	82.24%	34.75	0

Polynomial regression analysis is conducted on independent variable of Aspect Ratio since the R Squared and R Squared Adjusted values are marginal. Graphical representation of both linear and polynomial regression models are illustrated in Figure 64 & 65. Polynomial regression summary in Table 63 is evident for a substantial increase in R squared and R Squared adjusted values from 19.8% and 19.5% respectively. Thus the regression model is as follows,

$$BEI\ (Accepted\ Range) = 834.9 + 360.2 * AR - 247.5 * AR^2$$

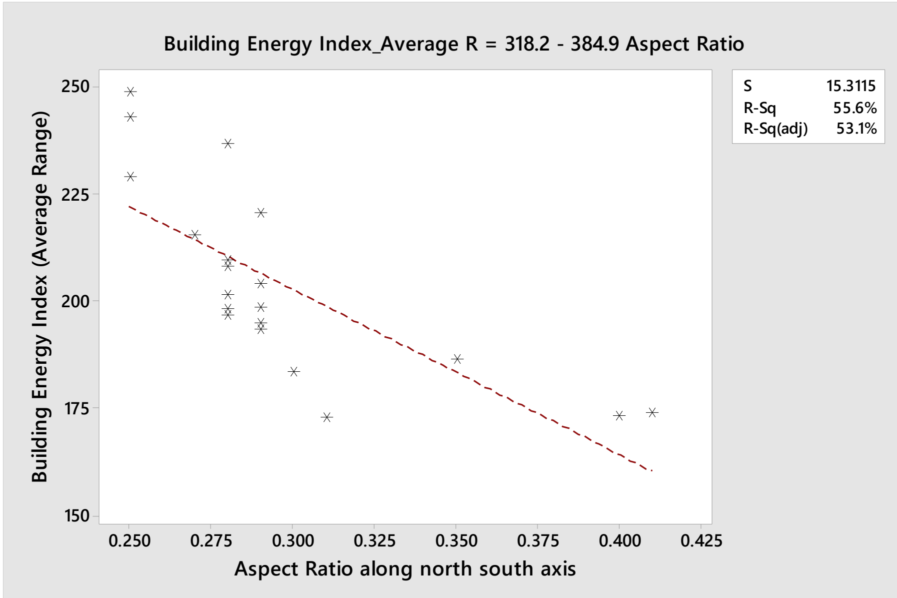


Figure 63: Linear regression output for Aspect ratio along north south axis and BEI in Average Range

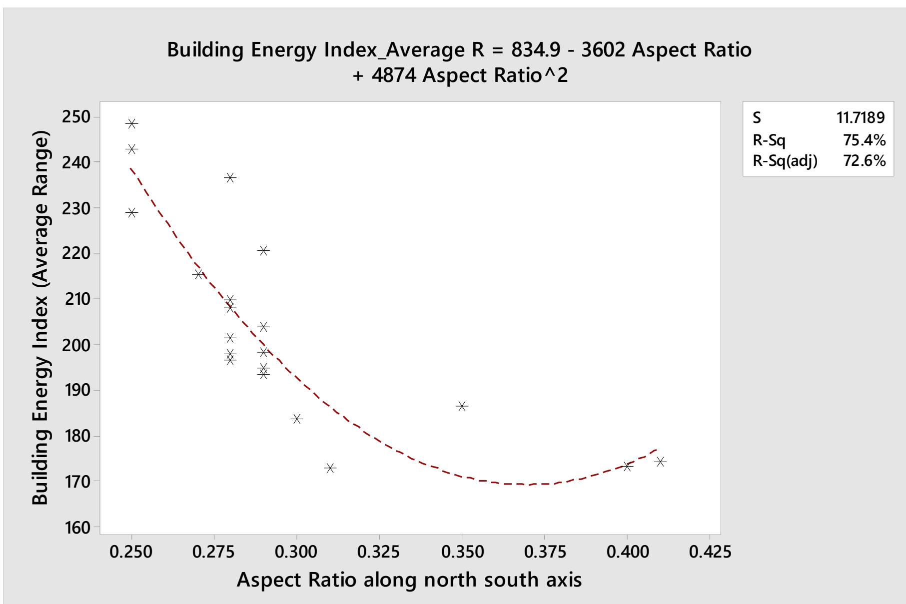


Figure 64: Polynomial regression output for Aspect ratio along north south axis and BEI in Average Range

Table 63: Polynomial regression summary

Regression model for Aspect Ratio along north south axis	Model Summary		
	S	R-sq	R-sq(adj)
Linear regression Analysis	15.3115	55.6%	53.1%
Polynomial Regression Analysis	11.7189	75.4%	72.6%

5.3.4 Nexus between Building Energy Index and Aspect Ratio along east west Axis in Average Range

54.08% of the buildings in Colombo Municipal Council Region are within Average Range. Out of which 18.52% of the buildings are north south oriented. Where aspect ratio increases along east west axis. .The average energy index is 170.94 $KWhm^{-2}$ per annum and the average numbers of floors are six. Morphological parameters of the building stock are illustrated in Table 64.

The optimum aspect ratio along east west axis is between 1.27:1 to 1.5:1 and energy consumption increase when the aspect ratio increase from the optimum level (McKeen & Fung, 2014). The average aspect ratio for this building stock is 3.22, which is beyond the optimum level of aspect ratio. The building energy consumption varies with façade composition. Thus WWR in all four facades are taken into consideration. WWR in east, west, north and south facades are 42%, 47%, 20% and 34% respectively.

The impact of aspect ratio and WWR in north south facades on building energy index was analyzed using multiple regression analysis tool. BEI is the dependent variable and independent variables are WWR in east, west, north and south facades. Correlations of the independent variables are summarized in Table 65. It is evident that WWR in east façade and west façade, WWR in east façade and Aspect Ratio and WWR in north façade and Aspect Ratio are not correlating with each other.

Table 64: Morphological parameters of the NS oriented buildings in Average Range

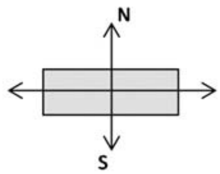
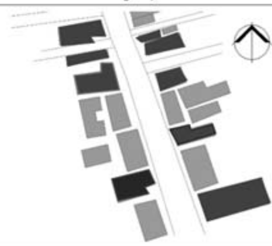
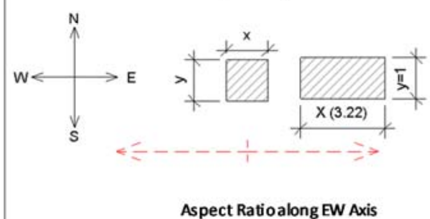
North South (NS) oriented Buildings Average Range (150-250KWhm-²/yr.)				
				
Building Percentage	18.52%			
Aspect Ratio Along Noth South Axis	3.22 (3.22:1) 			
Average Number of Floors	6			
Average Building Energy Index	170.94 kWh/m²yr.			
WWR	East	West	North	South
	42%	47%	20%	34%

Table 65:Summary of the Correlation analysis for the independent variables

independent variables					Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	Pearson Correlation	P-Value
X_1	X_2				0.174	0.63
		X_3	X_4		0.68	0.031
X_1				X_5	0.47.	0.17
	X_2			X_5	0.84	0.002
		X_3		X_5	-0.586	0.075
			X_4	X_5	-0.621	0.055

Table 66:Summary of the subset regression analysis

Best Subsets Regression: Building Energy Index (Average Range) and WWR in east,west, nort,south facades and Aspect Ratio										
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)
1	54.9	49.2	32.1	2.2	9.3581				X_4	
1	54.2	48.4	0	2.3	9.4305					X_5
2	67.6	58.3	0	1.9	8.4774		X_2			X_5
2	67.3	57.9	0	2	8.519				X_4	X_5
3	72.8	59.2	0	2.9	8.3887		X_2		X_4	X_5
3	71.2	56.8	0	3.2	8.6355			X_3	X_4	X_5
4	77.4	59.4	0	4.1	8.3686	X_1	X_2		X_4	X_5
4	73.9	53	0	4.8	9.0065		X_2	X_3	X_4	X_5
5	78	50.5	0	6	9.239	X_1	X_2	X_3	X_4	X_5

All possible regression models derived from subset regression analysis is indicated in Table 66. Mallow Cp Value, R Squared Adjusted Value and R Squared Values were taken into consideration when assessing these models. Stepwise regression analysis is conducted to identify the best fit regression models.

Table 67 indicates the summary of the regression models which are assessed based on R Squared values and p values. Evaluated simple linear regression models have an R squared and R squared adjusted value above 50% and the p values less than 0.05. Polynomial regression analysis is conducted since these models the R Squared value and R squared adjusted value is marginal.

Table 67:Summary of the regression models

VIF					independent variables					Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	(X_5)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
			1					X_4		9.35813	54.87%	49.22%	0.321	9.72	0.014
				1					X_5	9.43049	54.16%	48.44%	0	9.45	0.015

Graphical representation of the polynomial regression models for WWR south façade and Aspect Ratio along east west axis are illustrated in Figure 66 & 67. Polynomial regression summary in Table 68 indicate the R Squared and Squared Adjusted values obtained for the linear and polynomial regression models for WWR in south façade. Out of which, Polynomial regression model was taken since there is a substantial increase in R Squared and R Squared Adjusted values. Table 69 summarize the R Squared and R Squared Adjusted values obtain from linear and polynomial regression models for Aspect Ratio along east west axis and BEI in Average Range. Out of which, polynomial regression model was taken due to the higher value obtained for R Squared Adjusted and R Squared Values.

Table 68: Linear and polynomial regression models for WWR in south façade

Regression model for WWR in south facade	model summary		
	S	R-sq	R-sq(adj)
Linear regression Analysis	9.358	54.87%	49.22%
Polynomial Regression Analysis	8.59865	66.66%	57.13%

Table 69: Linear and polynomial regression models for Aspect Ratio along east west Axis

Regression model for Aspect Ratio along east west axis	model summary		
	S	R-sq	R-sq(adj)
Linear regression Analysis	9.43049	54.2%	48.4%
Polynomial Regression Analysis	5.71195	85.3%	81.1%

The summary of the regression models are as follows.

Polynomial Regression Model

BEI & WWR south Façade

$$BEI(Average\ Range) = 185.3 - 92.12(WWR)south + 80.96(WWR)south^2$$

BEI & Aspect Ratio along east west Axis

$$BEI\ (Average\ Range) = 273.5 - 89.85 * AR + 17.47 * AR^2$$

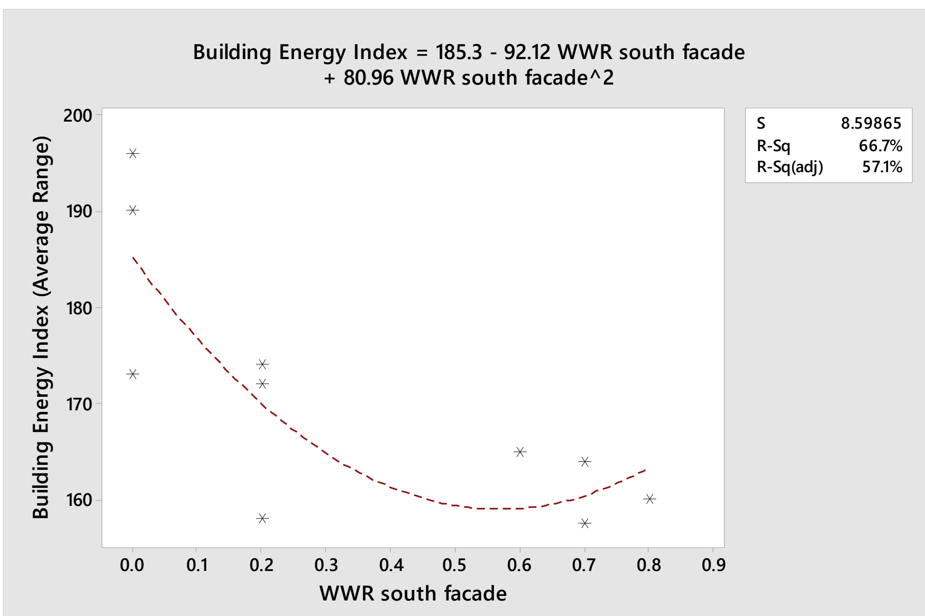


Figure 65: Polynomial regression output for WWR in south façade and BEI in Average Range

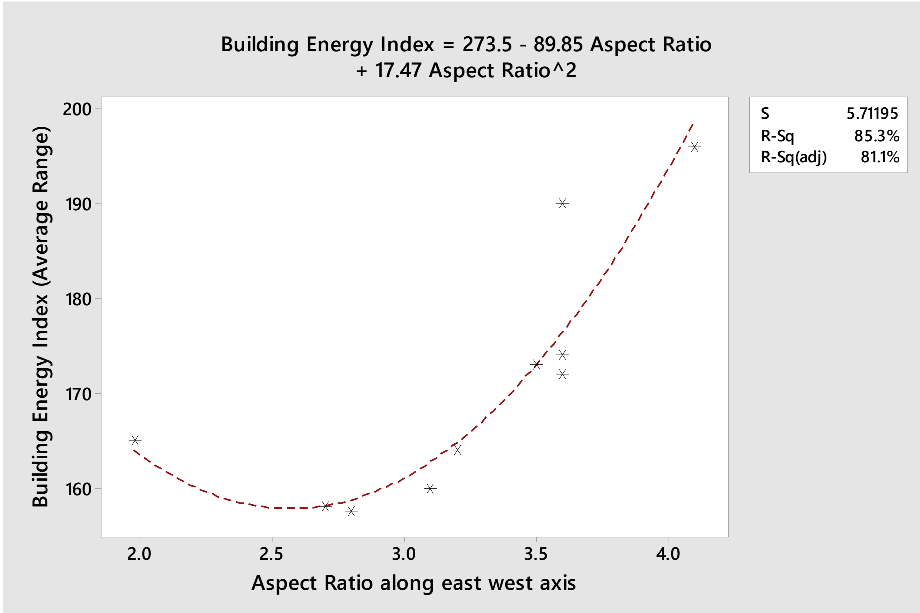


Figure 66: Polynomial regression output for Aspect ratio along east west axis and BEI in Average Range

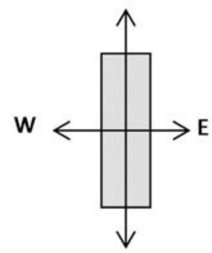
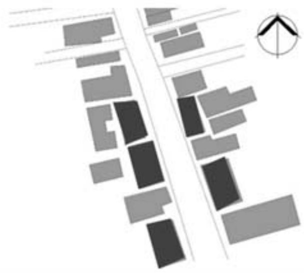
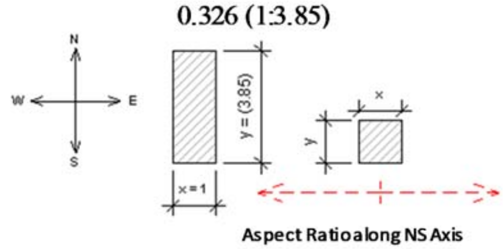
5.3.5 Nexus between Building Energy Index and Aspect Ratio along north south Axis in Critical Range

10.20% of the buildings in Colombo Municipal Council are predominantly composed of east west oriented buildings. Out of which 70% of the buildings are east west oriented and there are no buildings with north south orientation. Thus, this study investigates the nexus between building energy index and aspect ratio in east west oriented buildings. The average building energy index in Critical Range is 272.34 kWh/m²per annum and the average numbers of floors are six. Morphological parameters of the building stock are illustrated in Table 70.

Orientation of a building is a significant factor taken into account when designing buildings in tropics. Study indicates that aspect ratio and the building orientation has an impact towards energy consumption of the buildings. For instance, if a building has a larger (2 or greater) length to width ratio and the lengthy part of the building façade is facing towards east west, these buildings usually require greater capacity for cooling and heating and consume more energy throughout the year (Gilg & Pe, 2004). A study reveals that increasing aspect ratio along north south axis consume 13% more energy than buildings with aspect ratio increasing along east west axis (McKeen & Fung, 2014). This is due to the increased aspect ratio along north south axis create more surface area subjected to solar gain. The average aspect ratio for

Critical Range is 0.27 (1:3.85) which is beyond the optimum aspect ratio of 1:1.5 to 1:1.3.

Table 70: Morphological Parameters of the EW oriented office buildings in Critical Range

East West(EW) Oriented Buildings in Critical Range (above 250KWhm-²/yr.)				
				
Building Percentage	70.00%			
Aspect Ratio Along Noth South Axis	0.326 (1:3.85) 			
Average Number of Floors	6			
Average Building Energy Index	272.34 kWh/m²yr.			
WWR	East	West	North	South
	81%	63%	14%	6%

Façade configurations in buildings have an impact towards energy consumption. West facing large glazed facades with sealed envelopes are susceptible for overheating due to high solar radiation. As a result, these buildings have installed electro-mechanical systems to improve indoor thermal environment. This has an adverse effect on building energy consumption. The operational characteristics such as working hours also have an impact towards building energy consumption.

Office buildings in Critical Range have extended working hours thus increase energy consumption in buildings. The average WWR in east, west, north and south facades are 81%, 63%, 14% and 6% respectively. Thus, multiple linear regression analysis is conducted to develop a relationship between building energy index with WWR in all four building facades. BEI is the dependent variable and WWR in east, west, north, south facades and Aspect Ratio are the independent variables in east west oriented buildings. Analyses of the correlation of the independent variables are summarized in Table 71. It is evident that Independent variables of WWR in east façade and Aspect ratio are correlating with each other. Subset regression analysis is conducted to identify all possible simple and multiple linear regression models. Identified all the models are illustrated in Table 72 & 73. Mallow Cp value, R Squared Adjusted value and R Squared value are taken to assess these models. Stepwise regression analysis is conducted to identify the best fit regression models.

Table 71:Analysis of the correlation of the independent variables

independent variables					Correlation	
WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	Pearson Correlation	P-Value
X_1	X_2				0.3	0.513
		X_3	X_4		-0.645	0.117
X_1				X_5	-0.837	0.019
	X_2			X_5	-0.571	0.181
		X_3		X_5	-0.514	0.238
			X_4	X_5	0.043	0.927

Table 72:Summary of the subset regression analysis

Best Subsets Regression: Building Energy Index (Critical Range) and WWR in nort,south facades and Aspect Ratio								
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)
1	97.2	96.6	95	2.1	2.2216			X_5
1	22.6	7.1	0	134.9	11.594	X_3		
2	97.3	96	88.7	3.7	2.4018		X_4	X_5
2	97.3	95.9	93.3	3.8	2.425	X_3		X_5
3	98.3	96.6	91.9	4	2.2077	X_3	X_4	X_5

Table 73:Summary of the subset regression analysis

Best Subsets Regression: Building Energy Index (Critical Range) and WWR in nort,south facades and Aspect Ratio								
Vars	R-Sq	R-Sq(adj)	R-Sq(pred)	Mallows Cp	S	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)
1	97.2	96.6	95	2.1	2.2216			X_5
1	22.6	7.1	0	134.9	11.594	X_3		
2	97.3	96	88.7	3.7	2.4018		X_4	X_5
2	97.3	95.9	93.3	3.8	2.425	X_3		X_5
3	98.3	96.6	91.9	4	2.2077	X_3	X_4	X_5

Table 74:Summary of the regression model

VIF					independent variables					Regression Statistics (Linear regression)					
(X_1)	(X_2)	(X_3)	(X_4)	(X_5)	WWR east (X_1)	WWR west (X_2)	WWR north (X_3)	WWR south (X_4)	Aspect Ratio (X_5)	S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
				1					X_5	2.222	97.16%	96.59%	95.05%	170.92	0
1					X_1					8.042	62.76%	55.31%	22.39%	8.43	0.034

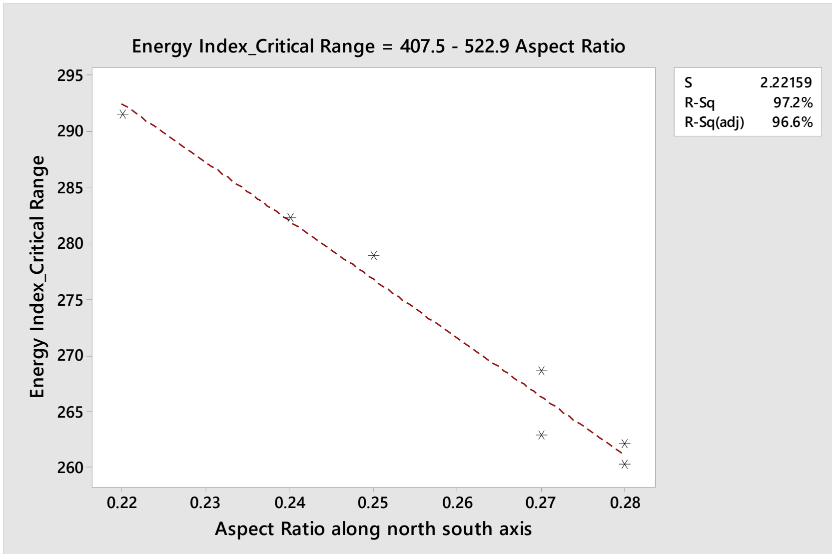


Figure 67: Linear regression model for the aspect ratio along north south axis in Critical Range

Table 74 indicates the summary of the regression models. R Squared Value, R Squared Adjusted Value and p values were assessed when evaluating these regression models. Conventionally p values equal or less than 0.05 is regarded as significant in regression model. Further the 95% confidence interval is taken into consideration in this study. Simple linear regression model for the independent variable of aspect ratio and dependent variable of BEI has an R Squared and R squared adjusted value of 97.16% and 96.59% respectively and p value=0<0.05=α. Regression model for the predicted value of BEI is,

$$BEI\ (Critical\ Range) = 407.5 - 522.9 * AR$$

The graphical representation of the simple linear regression model is illustrated Figure 68. Further, simple linear regression model for the independent variable of WWR in east façade has an R square and R square adjusted vale of 62.76% and 55.31% with a p value= 0.034<0.05=α. Thus the regression model is as follows,

$$BEI(Critical\ Range) = 159.9 + 138.1(WWR)east$$

The graphical representation of the simple linear regression model is illustrated Figure 69.

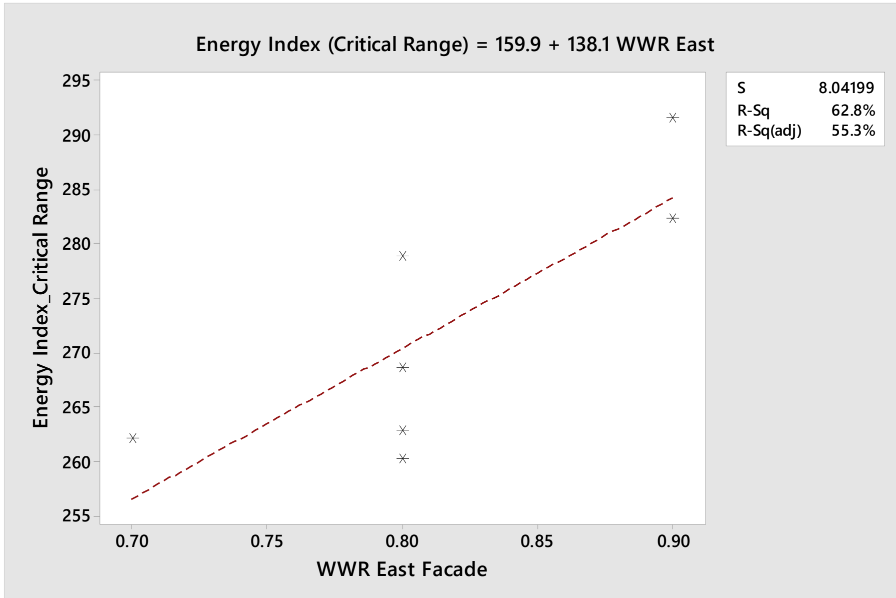


Figure 68: Linear regression model for WWR east facade in EW oriented buildings in Critical Range

5.4 Summary of the performance models and Morphological Characteristics

The investigation was performed in 100 office buildings dispersed in CMC region which was selected based on the activity. The morphological characteristics were recorded by conducting a walk through and photographic survey. BEI in all office buildings were calculated using electricity bills and usable area. Morphological characteristics such as building plan form, physical configuration, orientation and façade composition were recorded based on observation. The identified buildings were segregated into three categories constructed on BEI. These three categories were Accepted Range (100-150KWhm^{-2}/annum), Average Range (150-250 KWhm^{-2}/annum) and Critical Range (above 250KWhm^{-2}/annum). Office buildings in each energy index category was further separated according to the orientation namely east west, north south, northeast southwest and northwest southeast. The orientations of the buildings were recorded based on direction of the long façade of the building.

35.35% of the buildings in CMC Region have BEI within the Accepted Range. Out of which 28.57%, 17.14%, 34.23% and 20% of the buildings are EW, NS, NE-SW and NW-SE oriented buildings. Research suggests that the accepted WWR for buildings in tropical climate is 40%. East and west facades have the highest WWR for EW oriented buildings in Accepted Range. Whereas, WWR in all four building facades in NS oriented buildings are less than 40% in this energy index category.

54.55% of the buildings in CMC region are comprised within Average Range. In this category 37.03%, 18.02%, 27.78% and 16.67% of the buildings in the Average Range are EW, NS, NE-SW and NW-SE oriented buildings. Thus denote majority of the office buildings in CMR Region are east and west oriented. This is mainly due to the placement of buildings along the access roads where building entrance is facing towards east and west direction which promote direct solar radiation in to the buildings. Further, despite the critical orientation people tend to elaborate the entrance façades with glazed panels which create energy intensive building interiors. It is significant to note that both east and west critical facades are comprised with WWR more than 60% in EW orientated buildings in this energy index category. 10.10% of the buildings in CMC region are in Critical Range. Out of which 70%, 10% and 20% of the buildings are EW, NE-SW and NW-SE buildings. It is significant to note that majority of the office buildings in Critical Range are EW oriented. Moreover, WWR in east and west facades are above 60% in EW, NE-SW and NW-SE oriented in this energy index range.

Nexus between building façade configuration and building energy index is further analyzed using multiple and simple linear regression analysis. The analysis was conducted for buildings in each energy index category by considering all four orientations namely, EW, NS, NE-SW and NW-SE. Summary of the regression models for WWR and building energy index is illustrated in Table 75 for Accepted Range, Table 76 for Average Range and 77 for Critical Range . This is summarized based on the orientation in each energy index category.

Table 75: Summary of the regression models for WWR and BEI in Accepted Range

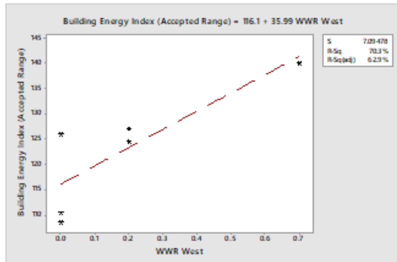
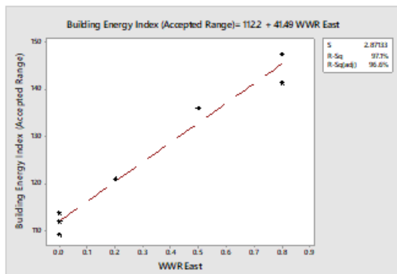
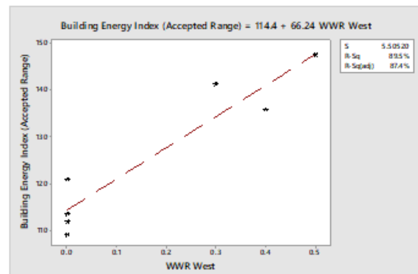
Orientation	Accepted Range (100-150 kWhm-²/yr.)	
NS	*BEI =116.12+36.0(WWR)west*	
		
NE-SW	*BEI =93.10+25.10 (WWR)north+29.36(WWR)south*	
NW-SE	*BEI=112.16+41.49 (WWR) east*	*BEI=114.43+66.2 (WWR) west*
		

Table 78 illustrates the summary of BEI, WWR and aspect ratio of identified office buildings in Accepted Range, Average Range and Critical Range. Building form is perceived as aspect ratio in this research, which is the ratio of length to width in the form of a building plan. In terms of direct solar radiation to buildings, aspect ratio is a crucial factor to consider. Thus EW and NS oriented buildings are considered for further investigation to evaluate the effect of aspect ratio on identified energy index categories. Energy consumption vary with the amount of glazing used in building façades.

This study investigates the impact of façade configuration and aspect ratio on BEI in EW and NS oriented buildings. Literature reveals the optimal aspect ratio for buildings which are 90° perpendicular to the east west axis are between 1: 1.5 and 1: 1.3. It is evident that aspect ratio of 0.70 (1:1.43) in Accepted Range is within the optimal range. Whereas, aspect ratio in Average and Critical Ranges are 0.3 (1: 3.33) and 0.26 (1:3.85) which indicate a substantial deviance from the optimal aspect ratio for EW oriented buildings.

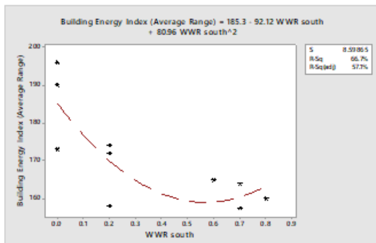
The optimal aspect ratios for buildings along east west axis are within the range of 1.27:1 to 1.5:1. Further increase of aspect ratio beyond this range result in increase of energy consumption in buildings. The average aspect ratio for NS oriented buildings in Accepted Range is 1.49 (1.49:1), which is within the optimal range. Nonetheless, the average aspect ratio for NS oriented buildings in Average Range is 3.22 (3.22:1), which is beyond the optimal range.

Table 76: Summary of the regression models for WWR and BEI in Average Range

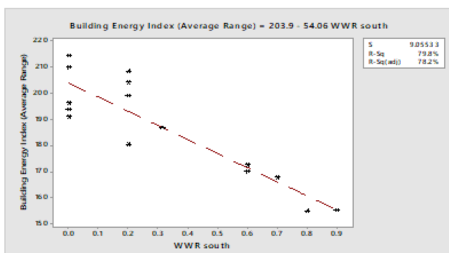
Orientation | **Average Range (150-250 kWhm-²/yr.)**

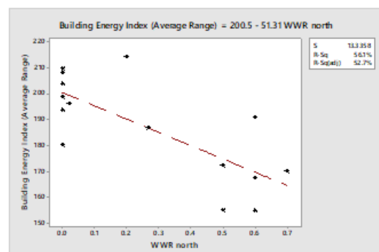
EW — *BEI =55.7+106.4 (WWR) east + 107.9 (WWR) west*

NS — *BEI =185.3-92.12 (WWR) south + 80.96 (WWR) south²*



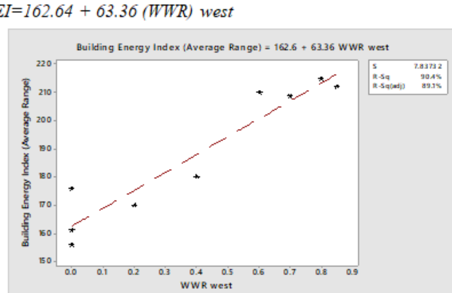
NE-SW — *BEI=203.90+54.06 (WWR) south* | *BEI=200.54-51.3 (WWR) north*

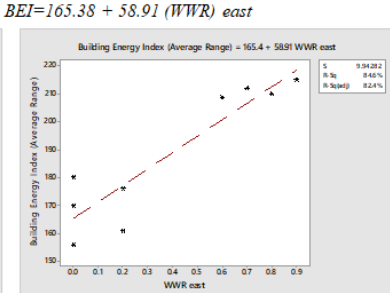




BEI=127.97+59.98 (WWR) east + 49.24 (WWR) west

NW-SE — *BEI=162.64 + 63.36 (WWR) west* | *BEI=165.38 + 58.91 (WWR) east*





BEI=161.64 + 26.87 (WWR) east + 40.16 (WWR) west

Table 77: Summary of the regression models for WWR and BEI in Critical Range

Orientation	Critical Range (Above 250 kWhm-²/yr.)
EW	*BEI =159.9+138.1 (WWR) east*

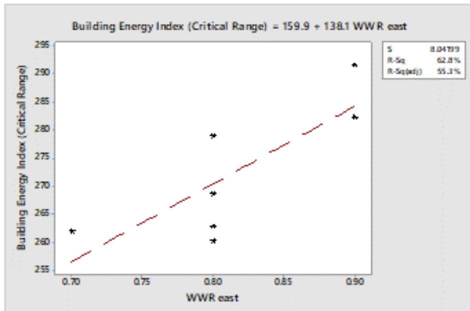
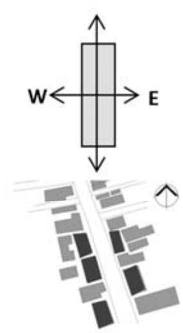
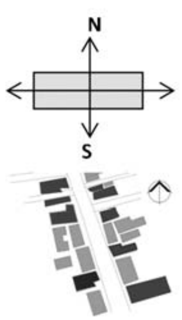


Table 78: Summary of BEI, WWR and aspect ratio of identified office buildings in Accepted Range, Average Range and Critical Range

orientation	Accepted Range				Average Range				Critical Range			
East -West	100-150 KWhm⁻²/yr.				150-250 KWhm⁻²/yr.				above 250 KWhm⁻²/yr.			
	WWR				WWR				WWR			
	east	west	north	south	east	west	north	south	east	west	north	south
	0.36	0.49	0.11	0.08	0.76	0.63	0.13	0.02	0.81	0.63	0.14	0.06
	Aspect ratio along north south axis (Length/Width)				Aspect ratio along north south axis (Length/Width)				Aspect ratio along north south axis (Length/Width)			
	0.7				0.3				0.26			
	Average No. Floors				Average No. Floors				Average No. Floors			
	5				6				6			
	Average BEI				Average BEI				Average BEI			
	133.45KWhm⁻²/yr.				204.29KWhm⁻²/yr.				272.34KWhm⁻²/yr.			
orientation	**Accepted Range**				**Average Range**				**Critical Range**			
North-South	100-150 KWhm⁻²/yr.				150-250 KWhm⁻²/yr.				above 250 KWhm⁻²/yr.			
	WWR				WWR				WWR			
	east	west	north	south	east	west	north	south	east	west	north	south
	0.03	0.18	0.32	0.53	0.42	0.47	0.2	0.34	0	0	0	0
	Aspect ratio along north east west (Length/Width)				Aspect ratio along north east west (Length/Width)				Aspect ratio along north east west (Length/Width)			
	1.49				3.22				0			
	Average No. Floors				Average No. Floors				Average No. Floors			
	5				6				0			
	Average BEI				Average BEI				0			
	122.71KWhm⁻²/yr.				170.94KWhm⁻²/yr.							

The identified buildings in each energy index categories are further analyzed based on morphological parameters such as WWR, aspect ratio and orientation. The analysis is conducted using multiple, linear and polynomial regression analysis tool. Summary of the regression models for Aspect Ratio and WWR with BEI are also illustrated in Figure 79 for Accepted Range, Figure 80 for Average Range and Figure 81 for Critical Range.

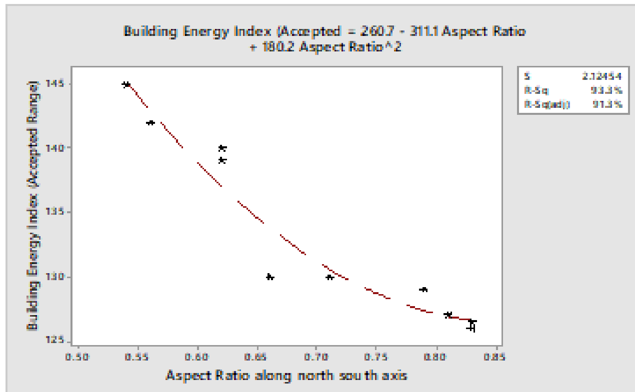
Table 79: Summary of the regression models and graphical represnetation of BEI , aspect ratio & WWR in Accepted Range

Accepted Range (100-150 kWhm-²/yr.)

Aspect Ratio Along North South Axis

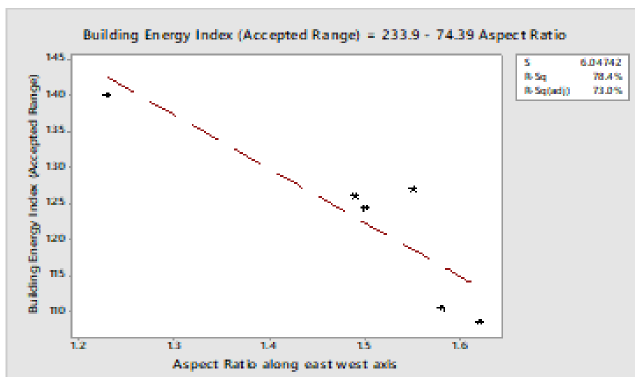
BEI =175.73-60.67 AR*

*BEI=260.7-311.1*AR+180.2 AR²*

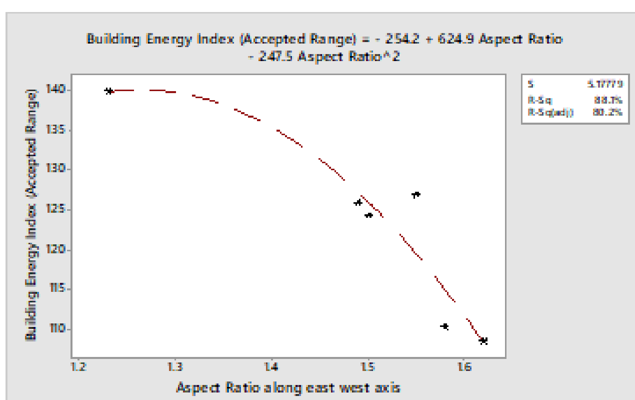


Aspect Ratio Along East West Axis

*BEI =233.9 - 74.4 * AR*



*BEI=254.2+624.9 *AR – 247.5 * AR²*



BEI=116.12 + 36.0 (WWR) west

Table 80 : Summary of the regression models and graphical represnetation of BEI , aspect ratio & WWR in Average Range

Average Range (150-250 kWhm-²/yr.)

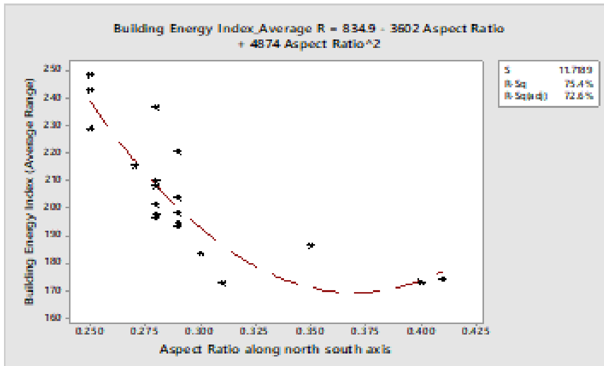
Aspect Ratio Along North South Axis

*BEI =265.6+89.5 (WWR) west – 396.7 * AR*

BEI=55.7 + 106.4 (WWR) east + 107.9 (WWR) west

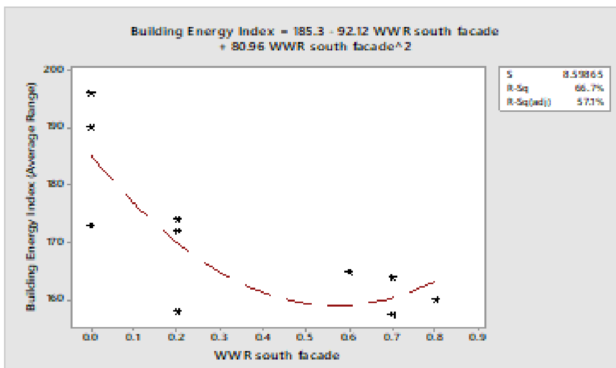
*BEI=186.6 + 49.1 (WWR) east + 98.9 (WWR) west – 275.9 * AR*

*BEI = 834.9 +360.2 * AR – 247.5 * AR²*



Aspect Ratio Along East West Axis

BEI =185.3-92.12 (WWR) south – 80.96 (WWR) south ²



*BEI=273.5 - 89.85 * AR + 17.47 * AR²*

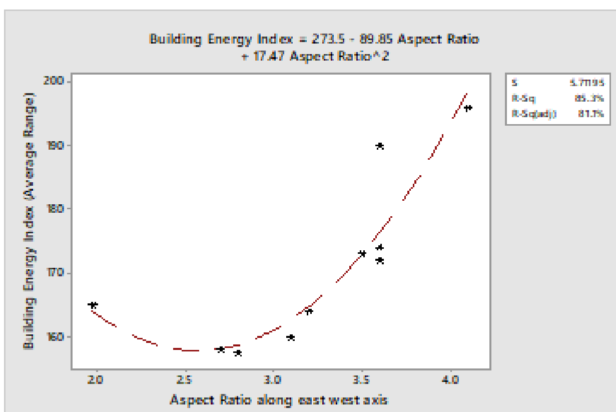
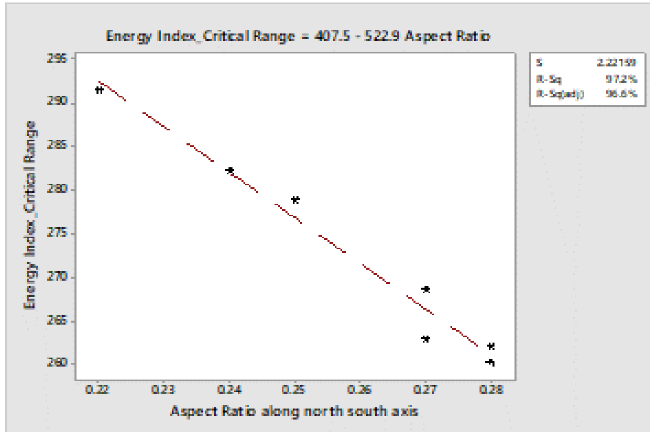


Table 81: Summary of the regression models and graphical represnetation of BEI , aspect ratio & WWR in Critical Range

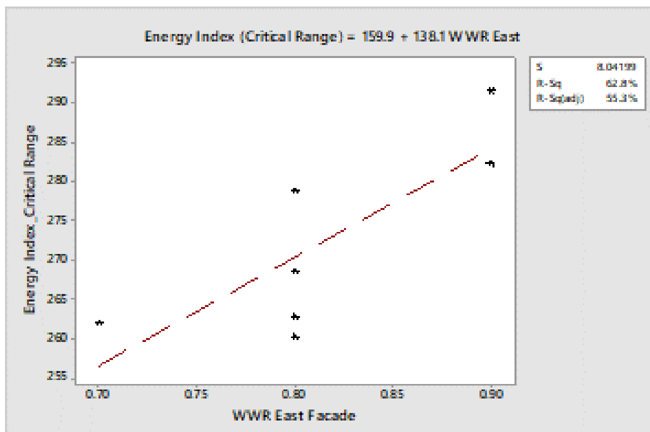
Critical Range (above 250 kWhm-²/yr.)

Aspect Ratio Along North South Axis

*BEI =407.5 – 522.9 * AR*



BEI=159.9 + 138.1 (WWR) east



7 CONCLUSION

Building industry is the single large contributor to global energy consumption and GHG emission (Allouhi et al., 2015). Hence understanding the energy consumption patterns in buildings are mandatory to formulate policy measures on climate change and depletion of energy resources for future. Energy consumption patterns in the buildings differ based on the morphological characteristics and activity in the building. Many scholars have investigated the energy saving technologies in the buildings. But the present knowledge on morphological characteristics of the buildings remains limited. The main aim of the investigation is to develop a data base of the morphological characteristics of the existing office building stock and ascertain a relationship between these characteristics and energy consumption of the office building stock in Colombo Municipal Council (CMC) region. Some of the primary features of this region are higher level of urbanization, concentration of secondary and tertiary financial operations, significant amount of vehicle population and fuel consumption along with decreasing vegetation cover and increasing synthetic floor areas. This investigation considered buildings which are exclusively used for administrative, bank and allied purpose. The total investigation is structured into three sections. They are,

- Section A- Formation of a Data Repository
- Section B-Detail Thermal Investigation of the Reference Buildings
- Section C-Analytical Investigation on Building Morphology and Energy Index

Section A is to formulate a data repository of the existing building stock in CMC region and this is conducted in four stages. Stage one is to identify the dispersion of office buildings in CMC region with the aid of GIS data, land use maps and walk through investigations. The study excluded high-rise office buildings due to the higher energy consumption for building services. Thus, intermediate and middle rise buildings (5-12 floors) are taken into consideration. Further, office buildings constructed within the last 30 years are considered since older buildings tend to consume more energy due to wear and tear. Stage II is to identify the areas with the highest concentration of office buildings in CMC region. The identified buildings are classified based on geometric and operational attributes of the office buildings. Stage III of the investigation is to develop a data profile of the sample office building stock. The energy index of these office buildings are calculated by using annual electricity consumption and gross floor areas. Three energy index categories are identified. They are Critical Level (above 250kWhm-^{2}), Average Level (150-250kWh-^{2}) and Accepted Level (100-150 kWhm-^{2}). The extracted sample office buildings are categorized based on these energy index levels. Stage IV of the investigation is to identify reference buildings which represent the energy index categories. The research revealed that office building stock of CMC region consist of two types of plan forms, namely basic and composite plan shapes. Square, linear and circular plan forms are considered under basic plan forms. Composite plan forms are generated from a variation of these basic plan forms. Thus, L shape, U shape and trapezium plan forms are demonstrated under composite plan forms. 85.05% of the office buildings in CMC region are composed of linear and square plan forms. Out of which, 62.07% and 22.98% were rectangular or square plan forms.

Circular or trapezoidal plan forms in the office building stock have an equal percentage of 2.3%, while 2.29% and 8.05% of office buildings are comprised of U and L composite plan forms. The average energy intensity of the building stock is 211.59 KWhm-^{2}/yr. Based on the collected data it was revealed that 38.% , 16%, 28% and 18% of the office buildings are facing East-West (EW), North-South (NS), Northeast-Southwest (NE-SW) and Northwest- Southeast (NW-SE) orientation. The average energy consumption in EW, NS, NE-SW and NW-SE buildings are 211.60KWhm-^{2} /yr., 200.21KWhm-^{2} /yr. 200.08KWhm-^{2}/yr. and 205.69KWhm-^{2} /yr. respectively. When considering the physical configuration, majority of the office building stock of CMC region consist of detached and attached plan forms. Out of which 63.22% of the buildings are attached to another structure from one side. Whereas, 36.78% of the buildings are combined to another structure from both sides. Buildings which are combined to another structure from both sides have relatively low BEI per annum (210.04 KWhm-^{2}/yr.) than the buildings which are combined to another structure from one side (211.04 KWhm-^{2}/yr.). This is mainly because buildings are less vulnerable for direct solar radiation. Further, BEI of the detached and attached from both sides are having similar energy intensity of 211 KWhm-^{2}/yr.

Section B of the research is to conduct thermal investigation of the identified 5 reference buildings which represent the morphological characteristics of the office building stock in CMC region. Further, these selected 5 reference cases represent each of the building energy index category as well. The selected five building cases represent as Case A, B, C, D and E. out of which Case A and B are with deep plan form and C, D and E are with shallow plan form. These building morphologies are widely distributed in city of Colombo due to the pattern of land sub division and road network. Each office interior was monitored for a typical weekday and weekend with the Air-conditioner switch on and off mode respectively. Thermal investigations were carried out in both central and peripheral zones. In addition, the difference in outdoor and indoor temperature was further studied to understand the cooling energy load needed to condition the interior space.

The thermal investigation resulted that peripheral zones of both shallow and deep plan forms are susceptible to overheating. As a result, the occupants tend to change the set point temperature below 24°C of the air conditioners. Further it was evident that the temperature variation during non AC and AC period in deep plan form is lesser than shallow plan form. As a result, office buildings with deep plan forms have great potential to control external heat gain and reduce the buildings' energy usage relative to shallow plan forms. Moreover, in both deep and shallow plan forms, periphery temperature closely follows the micro climate and outdoor ambient temperature. However, shallow layouts cannot benefit from this since the central zone is much lesser than the peripheral zone. Overheating potential of peripheral zones can be attributed to poor envelop performance. Higher WWR result in more intake of direct solar radiation. In urban context, adapting the microclimate to filter unfavorable conditions is an important consideration.

Section C of the study is to investigate nexus between building morphology and energy index in by developing performance models. In Section C, all the identified office buildings in each energy index category was further segregated according to the orientation of the long side of the building façade. It was evident that 35.35% of the buildings in CMC Region have BEI within the Accepted Range. Out of which 28.57%, 17.14%, 34.23% and 20% of the buildings are EW, NS, NE-SW and NW-SE oriented buildings. 54.55% of the buildings in CMC region are comprised within Average Range. In this category 37.03%, 18.02%, 27.78% and 16.67% of the buildings in the Average Range are EW, NS, NE-SW and NW-SE oriented buildings. Thus denote majority of the office buildings in CMR Region are east and west oriented. This is mainly due to the placement of buildings along the access roads where building entrance is facing towards east and west direction which promote direct solar radiation in to the buildings. Further, despite the critical orientation people tend to elaborate the entrance façades with glazed panels which create energy intensive building interiors. According to research, the accepted WWR for tropical climate is 40%. However, it is significant to note that both east and west critical facades are comprised with WWR more than 60% in EW orientated buildings in this energy index category. 10.10% of the buildings in CMC region are in Critical Range. Out of which 70%, 10% and 20% of the buildings are EW, NE-SW and NW-SE buildings. It is significant to note that majority of the office buildings in Critical Range are EW oriented. Moreover, WWR in east and west facades are above 60% in EW, NE-SW and NW-SE oriented in this energy index range. Nexus between building façade configuration and building energy index is further analyzed using multiple and simple linear regression analysis. The analysis was conducted for buildings in each energy index category by considering all four orientations namely, EW, NS, NE-SW and NW-SE. Building form is perceived as aspect ratio in this research, which is the ratio of length to width in the form of a building plan. In terms of direct solar radiation to buildings, aspect ratio is a crucial factor to consider. Thus EW and NS oriented buildings are considered for further investigation to evaluate the effect of aspect ratio on identified energy index categories. Energy consumption vary with the amount of glazing used in building façades.

This study investigates the impact of façade configuration and aspect ratio on BEI in EW and NS oriented buildings. Literature reveals the optimal aspect ratio for buildings which are 90º perpendicular to the east west axis are between 1: 1.5 and 1: 1.3. It is evident that aspect ratio of 0.70 (1:1.43) in Accepted Range is within the optimal range. Whereas, aspect ratio in Average and Critical Ranges are 0.3 (1: 3.33) and 0.26 (1:3.85) which indicate a substantial deviance from the optimal aspect ratio for EW oriented buildings. The optimal aspect ratio for buildings along east west axis is within the range of 1.27:1 to 1.5:1. Further increase of aspect ratio beyond this range result in increase of energy consumption in buildings. The average aspect ratio for NS oriented buildings in Accepted Range is 1.49 (1.49:1), which is within the optimal range. Nonetheless, the average aspect ratio for NS oriented buildings in Average Range is 3.22 (3.22:1), which is beyond the optimal range.

This research was able to develop a baseline of database matrix focusing on the existing office building stock in CMC region. Hence, enable to identify and categorize the building morphological characteristics of the existing office building stock as well its energy consumption. The developed database was able to give an overall picture of the energy usage of the existing building stock which helps to implement energy efficient retrofitting and face-lifting for the existing building stock. The database can be improved and make comprehensive by including information on building envelop materials, roofing material, type of shading devices, the type of glazing used in the building façade , the type of electrical appliances used in the buildings, type of lighting, mechanical ventilation and etc. Proper understanding of the geometric attributes of the existing building stock permits to configure the morphological attributes in new building constructions to minimize energy usage. Further detail thermal investigation was able to ascertain the indoor thermal behavior in deep and shallow plan forms during AC and non AC period. Thus permit to configure interior of the existing building plans and new layouts to prevent indoor overheating condition in tropical climate. This investigation only focused on identifying buildings which are exclusively used as office buildings. But, during the walk through investigation it was evident that many buildings have multiple functions along with the offices such as residential, retails institutional and etc. Hence, future studies should develop a database of the buildings which are used for multiple activities and the energy consumption of each activity shall calculate based on the area allocated for each activity.

Findings of this study represent the criticality of building morphology based on plan shape, orientation and interior planning has a significant impact of end use energy demand due to external heat loads. Thus it is paramount important to formulate design guidelines to improve building performance of the obsolete and ageing national office building stock. Better understanding of the current building stock is important when implementing energy efficient measures. Further, understanding current building stocks contributes towards opportunities for energy savings and supporting energy policy measures in an attempt to reduce urban energy consumption. Furthermore, by evaluating energy efficiency and carbon emission issues across the building sector, the development of a comprehensive database of the current building stock will assist develop design guidelines for a specific building type. Moreover, investigating the impact of climate and behavioral modifications on the prevailing building stock will help to retrofit design strategies. Thus lead to create a comprehensive data base of the existing building stock.

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9 APPENDICES

Appendix A: Percentage of Administrative, Bank and Allied buildings in all the 46 Wards in CMC Region

Ward	Area : Administration	Area: Bank & Allied	Built Up Area	% of administration, Bank and Allied
Thimbirigasyaya	11.45	0.70	162.72	7.46
Bambalapitiya	5.48	2.06	171.49	4.40
Jinthupitiya	0.00	0.22	16.50	1.35
Masangasweediya	0.00	0.86	19.79	4.34
Grandpass South	0.00	0.33	52.57	0.63
Maligawatta East	0.00	0.02	54.25	0.04
Aluthkade West	0.63	0.29	13.20	6.92
Maradana	0.00	0.03	27.73	0.10
Wellawatta South	0.44	0.06	53.01	0.93
Pamankada West	0.00	0.01	55.29	0.02
Kuppiyawatta West	0.66	1.04	34.61	4.91
Grandpass North	0.00	0.11	41.97	0.26
Narahenpita	3.18	0.00	172.33	1.84
Modara	0.00	0.07	62.12	0.10
Kotahena East	0.00	0.04	26.57	0.13
Bloemendhal	0.11	0.29	62.29	0.63
Keselwatta	4.65	0.35	26.57	18.79
Aluthkade East	0.00	0.70	23.03	3.04
Hunupitiya	3.68	4.76	68.84	12.25
Maligawatta West	1.27	0.16	44.48	3.21
Panchikawatte	0.00	0.10	23.25	0.41
Fort	10.05	9.33	169.72	11.42
Dematagoda	0.06	0.44	68.08	0.74
Maligakanda	0.02	0.04	16.17	0.35
Kollupitiya	5.64	5.09	71.14	15.07
Kuppiyawatta East	0.50	0.62	52.82	2.12

Wanathamulla	0.30	0.03	52.86	0.62
Borella North	2.24	0.23	91.02	2.71
Borella South	0.78	0.01	55.86	1.41
Cinnamon Gardens	27.49	3.82	314.70	9.95
Milagiriya	0.57	1.07	32.56	5.05
Havelock Town	0.84	1.23	109.06	1.90
Pamankada East	0.91	0.05	79.69	1.20
Wellawatta North	0.17	0.32	76.47	0.63
Kirula	9.17	1.95	160.45	6.93
Wekanda	0.35	4.29	49.40	9.39
Suduwella	9.14	7.51	102.78	16.20
Alutmawatha	0.16	0.48	59.89	1.07
Kochchikade North	0.00	0.20	25.57	0.77
Kochchikade South	0.00	0.16	18.94	0.85
Kirulapone	2.70	0.06	121.53	2.27
Kotahena West	0.05	0.38	30.50	1.39
Lunupokuna	0.16	0.36	98.76	0.52
New Bazaar	0.00	0.53	47.54	1.12
Kompannaweediya	3.16	0.05	55.53	5.77
Mattakkuliya	3.06	0.39	292.72	1.18
Mahawatta	0.00	0.91	77.59	1.18

Wards above 10% Administrative, Bank and Allied Buildings

Wards above 4% Administrative, Bank and Allied Buildings