UTILIZING LANDSCAPE FEATURES IN ACHIEVING THERMAL COMFORT IN HIGHRISE RESIDENTIAL BUILDING IN ABUJA FEDERAL CAPITAL CITY

BY

GURAMA, Mohammed Awal
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ABSTRACT

Humans are complex social beings with constant need for shelter, the types of shelter needed evolves with the evolution of technology and social trends. Due to factors such as space optimization and increase in the complexity of societal and social needs, these shelters have evolved in the form of high-rise buildings. These type of buildings in hot dry climates have a major problem of thermal comfort due to the increase in exposure with increase in height. This study is aimed at evaluating the effects of landscape elements in high rise residential buildings as a tool to enhance thermal comfort in Abuja, the capital city of Nigeria. To achieve the above stated aim, the research adopted a mixed research approach, using case studies and computer simulation as instruments of data collection. While visual surveys and simulations was used as the tools for data collection. The research samples purposely three case studies which satisfy at least two of the three selection criteria set through examples from previous similar studies. Results from the study shows that, application of green walling systems increase the internal thermal comfort of high-rise residential buildings and 95 percent of high-rise buildings withing FCT do not adopt this. These findings revealed that, a 200mm air cavity is 50 percent more effective than a 400mm air cavity for green walls in the bid to enhance thermal comfort in high-rise residential buildings. The research closes out by making a few recommendations of which the most prevalent one is the importance of the use of green walling systems especial on building envelops on the sun path.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of Study

One of the fundamental requirements of buildings is the protection of the people who live and work within them from the inclement of weather. Humans are complex social beings with constant need for shelter, the types of shelter needed evolves with the evolution of technology and social trends. Due to factors such as space optimization and increase in the complexity of societal and social needs, these shelters have evolved in the form of high-rise residential buildings (Alabi, 2017).

Buildings with several numbers of floors on a small footprint usually referred to as high-rise buildings, have become a trend in our contemporary world and now booming in cities of developing countries due to unavailability of land or land scarcity (Batagarawa *et al.*, 2011; Alabi, 2017). But the presence and concentration of these high rise buildings bring about many environmental issues which affect the climate and in turn the overall thermal comfort of the buildings and their immediate surroundings (Chau, 2016), furthermore studies such by UNEP (2015) and Edomah (2016) have opined that buildings contribute to around one third of the global greenhouse gas emissions GHG, which is caused by the absence of green areas, lack of proper building orientation and forms, and ultimately a lack of passive measures to curb the effects of harsh climatic conditions on buildings. The culmination of these problems leads to a greater challenge faced by high-rise buildings which is that of passively achieving thermal comfort, which leads to staggering cost of energy usage through the use of HVAC systems. Studies by the US Department of energy showed that green buildings generate 34% lower carbon emissions than their more active counterparts. Advancements in technology have relegated to the background passive temperature control measures such as operable windows and shading techniques to achieve thermal comfort especially in high rise buildings (Taib *et al.*, 2010).

Thermal comfort is achieved when occupants of a particular space are perceived to be satisfied with the present temperature and indoor air quality of that particular space. This is more difficult to achieve in high rise buildings than low rise buildings especially in tropical climate regions due to the fact that high-rise buildings are more exposed to harsh climatic elements such as wind, sun and rain compared to low rise buildings, which are most often adjacent structures surrounded by trees and other landscape elements that help shade them from harsh climatic conditions (Alabi, 2017; Batagarawa *et al.*, 2011).

The need for high rise buildings to achieve thermal comfort using passive methods cannot be understated due to the staggering cost of installation and maintenance of these active systems, furthermore these active systems contribute heavily to the depletion of the climate (Edomah, 2016; Alabi, 2017). A number of previous studies including but not limited to those of Abed (2012); Taib *et al.* (2010); Alabi (2017) have all proffered solutions to the problem of achieving thermal comfort in high rise buildings through the use of diverse design and landscape design models. The majority of these previously named studies concentrate on the solutions to mitigate this exposure of high-rise buildings to the climate using different design and landscape elements. One of such landscape elements is the green walling systems, which have been shown in tropical climatic regions to act as an additional layer of thermal insulation which helps in shading exterior walls from incoming solar radiation, protect the exterior wall from wind exposure, and temperature cooling of the air adjacent to the exterior walls (Taib, *et al.*, 2010). With all the previously cited arguments from existing literature, this study ventures into the exploration of landscape features, precisely green walls as a tool for achieving thermal comfort in high rise residential buildings in Abuja the capital city of Nigeria.

1.2 Statement of Research Problem

High rise residential buildings have been explored as an effective solution to meet housing needs in cities such as Abuja the capital city of Nigeria where there is scarcity and relative high price of land (Vincent *et al.*, 2017), like all other building typologies in hot dry climates, high rise residential buildings struggle with the problem of achieving thermal comfort, but more peculiar to this building typology is the problem of passively achieving thermal comfort. This is as a result of the fact that high-rise buildings are more exposed to harsh climate elements such as wind, sun and rain compared to low rise buildings, which are most often adjacent structures, surrounded by trees, and other landscape elements that help shade them from harsh climatic conditions (Chau, 2016). This study ventures into providing a solution to the problem stated above.

1.3 Aim and Objectives of the Study

This research is aimed at utilizing landscape features especially green walls in achieving thermal comfort in high rise residential buildings in Abuja.

The objectives set to achieve the aim of this research are as follows:

i. To investigate the determinants of thermal comfort in high rise residential buildings in Abuja.

ii. To explore the principles of passively achieving thermal comfort in high rise residential buildings in Abuja.

iii. To investigate how green walls can be used to enhance thermal comfort in high rise residential buildings in Abuja.

iv. To proposed a high-rise architectural design using green walls in achieving thermal comfort.

1.4 Research Questions

The following questions have been structured carefully so that their answers help achieve the objectives of the research and ultimately the aim of the research:

i. What are the determinants of thermal comfort in high rise residential buildings in Abuja?

ii. What are the principles of green walls that can be used to enhance thermal comfort in high rise residential buildings in Abuja?

iii. How can green walls be used to enhance thermal comfort in the design of high-rise residential buildings in Abuja?

1.5 Scope of study

There are many passive design strategies for thermal comfort. This study is focused on landscape features, specifically the use of green walls as it relates to enhancing thermal comfort in high-rise residential buildings in Abuja, which is located in the hot humid climate of Nigeria.

1.6 Justification of Study

The fundamental reason for creating buildings is to control the immediate environment around people, by providing shelter from harsh external environments so that occupants can live and work comfortably. This is the junction where thermal comfort comes into play, thermal comfort is achieved when occupants of a particular space are satisfied with the present temperature and indoor air quality of that particular space (Wei *et al.*, 2020).

The fact that high rise buildings are more exposed to harsh climatic elements such as wind, sun and rain compared to low rise buildings which are most often surrounded by trees and adjacent structures that help shade them, means that this very essential reason for buildings which is thermal comfort is much harder to achieve in high rise residential buildings. This is usually achieved through active elements which require a lot of energy, this translates into more money spent on cooling or heating high rise buildings according to previous studies (Taib *et al.*, 2010).

All the above stated facts point to the need for sustainable approach to high rise residential buildings that are more friendly to the environment and reduce the energy needed to run the building, that will subsequently reduce the running cost of the building, and Improve quality of life, and wellbeing of occupant of high rise residential buildings. Hence the need for this study to provide that solution through the utilization of landscape elements in the design of high-rise residential buildings in Abuja.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 High Rise Residential Buildings

A High-Rise building according to the International Building Code and The Building Construction and Safety Code is a building of height equal to 75feet (22.5 meters) or greater, measured from the lowest level of fire department vehicle access to the floor of the highest habitable storey. In Nigeria, factors encouraging the sprouting-up of high-rise buildings include urban needs, constraints, and a booming economy (Asiedu, 2012).

High-rise buildings in Nigeria are each day growing in prominence. In Lagos, the commercial capital of Nigeria there is a high number of tall buildings with some dating as far back as the 1970s (Alabi, 2017). According to Asiedu (2012), the shift of Federal Capital Territory (FCT) from Lagos to Abuja in the late 1980's is a key factor that led to the decline in the state of these High-rise buildings in Lagos, shifting the focus to the new federal capital, Abuja. The scarcity and stagerring cost of land had led to the neccesity of high rise residential buildings within the capital city of Abuja (Alabi, 2017).

2.2 High Rise Building Envelope

According to Ahsan (2009), the building envelope includes all the building components that separate the indoors from the outdoors. Building envelopes include the exterior walls, foundations, roof, windows and doors. The performance of the building envelope is impacted by a number of sub-systems, such as heating, cooling and ventilating equipment, plumbing and electrical systems (Cheung *et al.*, 2005). The building envelope is an important component of a building that affects the indoor thermal comfort, energy consumption and thermal performance of a building. The use of shading devices has a positive effect in enhancing indoor thermal comfort, showing the importance of solar heat gains control (Nevesa and Marquesb, 2017). The thermal insulation of the envelope increases the thermal performance of buildings and also reduces the indoor temperature, which directly affects the thermal comfort of occupants (Kozáková *et al.*, 2014). The selection of materials with appropriate thermal and optical properties for the building envelope also has a great influence over all aspects of the indoor thermal comfort. Ihara *et al.* (2015) investigated facade properties of office buildings in Tokyo, Japan, in order to enhance indoor thermal comfort. The analysis showed that increasing the insulation of the building envelop materials has a great effect of the indoor thermal comfort.

2.3 Thermal Comfort in High rise Residential Buildings

Increased living standards in the developing world using non-climatically responsive architectural standards have made air conditioning quite popular which has directly reduced the use of passive strategies to achieve thermal comfort. Thermal comfort is more difficult to achieve passively in high rise residential buildings than low rise especially in tropical climate regions. Due to the fact that high rise buildings are more exposed to climate elements such as wind, sun and rain compared to low rise buildings which are most often surrounded by trees and adjacent structures that help shade them from harsh climatic conditions (Aflaki *et al.*, 2014).

Challenges such as rising cost of energy, global warming, problems with material usage and waste disposal have made professionals to welcome more sustainable approach into the design of high-rise buildings. Amongst other techniques to alleviate this thermal discomfort in high-rise building design is the introduction of urban vegetation i.e. ground level trees, green roof and vertical landscapes i.e. façade greening or green walls.

Harnessing vegetated surfaces on the building facades will help in improving the microclimate around buildings and also the human thermal comfort in the built environment (Ojebode and Gidado, 2018).

2.4 Thermal Comfort

Understanding thermal comfort is important to architecture, since it not only lays the foundation for building design, but also affects the field of sustainable design. Thermal comfort can be defined as a condition of mind that expresses satisfaction with the immediate thermal environment. Thermal comfort is maintained when the heat generated by the human metabolism is allowed to dissipate at a rate that maintains thermal equilibrium in the body (Auliciems and Szokolay , 2012). Contemporary models of thermal comfort recommend that a narrow temperature range be applied equally across all building types, climatic zones, and populations, often this can result in an exaggerated need for air conditioning (Raish, 2018). New research and innovative Heating, Ventilating, and Air Conditioning (HVAC) design systems are challenging the accepted notions of universal thermal comfort parameters on the basis that they overlook important cultural, climatic, and contextual factors of comfort (Shafizal and Phillip , 2017), in this case thermal comfort in high rise residential buildings in Abuja a hot and humid region.

Several previous studies including but not limited to (Abed, 2012; Al-Ajmi and Loveday, 2010; Alabi, 2017) all mention the greatest challenge to passively achieving thermal comfort in high rise buildings as exposure to harsh climatic conditions, which is brought on by poor design decisions, Furthermore the authors of all the previously mentioned studies advocate for the use of various landscape elements as tools for enhancing thermal comfort in high rise buildings, studies such as (Asiedu, 2012; Berkovic *et al.,* 2012) support landscape elements such as various types of gardens and courtyards as measures to achieving thermal comfort (Asiedu, 2012; Berkovic *et al.*, 2012). The review of these studies will show how to reduce this exposure of high-rise residential buildings to harsh climatic conditions and in turn passively enhance the thermal comfort within high rise residential buildings through the use of green walling systems.

2.5 Determinants of Thermal Comfort

To achieve the afore mentioned aim of this section of the literature review it is important to understand the determinants of thermal comfort as they relate to high rise residential buildings. Although the most important parameters affecting thermal comfort in high rise buildings according to Auliciems and Szokolay (2012); Raish, (2018); Shafizal and Phillip (2017), are the environmental parameters which are air temperature, air movement, radiation, and relative humidity which have become the biggest constraints in providing passively comfortable indoor environments for this region, the personal parameters which are the clothing and activity levels, and the contributing factors also all have to also be considered in order to understand fully the effect of these factors on thermal comfort of high rise residential buildings.

2.5.1 Environmental parameters

These are considered by previous studies as the more important determinants of thermal comfort in high rise residential buildings because they are the biggest constrains in providing passively comfortable indoor environments for hot and humid regions and they are as follows.

2.5.2 Air temperature

According to Auliciems and Szokolay (2012), air temperature also referred to as ambient temperature can be defined as the temperature of the immediate surrounding. This will determine the convective heat dissipation, together with air movement. In the presence of air movement, the surface resistance of the body or clothing is much reduced. Many previous studies regard ambient temperature as the most important environmental factor in determining thermal comfort and it is measured by the dry bulb thermometer (DBT) (Alwetaishi, 2016).

As far as the optimum indoor temperature is concerned, Fanger has recommended an optimal indoor temperature for human thermal comfort to be 25.6°C Celsius in Northern temperate zone. On the other hand, other studies according to Shafizal and Phillip (2017), have recommended 27°C Celsius with 80% relative humidity and 0.4 m sec−1 air velocity (Jang *et al.*, 2007). Furthermore, both of the suggested figures can be appropriate when applying the variation of relative humidity and air velocity as they play a major role in determining the optimum indoor temperature (Alwetaishi, 2016).

2.5.3 Radiant temperature

In an easy to understand language, radiant temperature is the temperature of the surfaces around us. According to Alwetaishi (2016), It is the heat that radiates from a heated object which is existing in the environment. In some cases, this factor could have a greater influence than air temperature itself. The sun is considered to be the most important radiated object to consider, however, there are several other examples such as cookers, dryers, hot surfaces and ovens which might become more important depending on the conditions (Health and Safety Executive, 2020).

As regards the effect of warming or cooling of walls and ceilings in increasing the discomfort in buildings, it can be noted that warming or cooling the ceiling and cooling the wall could have a significant impact on the occupant’s dissatisfaction. In terms of ceilings, there is no noticeable difference between the cooling and warming, but there are noticeable differences in the case of walls (Alwetaishi, 2016). According to studies by Atmaca *et al.,* (2007) and Memon *et al.,* (2008) the effects of radiation can be controlled in buildings from the inception stage of design, furthermore, these studies opined that it is possible to achieve thermal comfort for most of the time over the year in less temperate regions. However, in the case of hot locations the solar radiation that is generated from the sun has to be controlled and blocked based on the climatic condition in the region and this can be achieved using various landscape elements in various innovative ways as this study will later proffer.

2.5.4 Air movement

Air movement can be defined as the speed of air moving across an individual and may help cool the individual if it is cooler than the environment, affecting heat loss from the body through convection (Gabril, 2014). Air movement also referred to as air velocity is quite an important factor as people are very sensitive to it, as a result, it could lead to cooling or heating the space based on the given indoor condition such as indoor temperature and relative humidity. Those two factors and air speed have the most effect on human thermal comfort indoors (Raish, 2018).

The key point to note with air velocity is that it influences the convective heat exchange between a person and the environment which as a result will affect the general heat loss (Alwetaishi, 2016). This relationship relies heavily on the temperature and the relative humidity in the surrounding environment. With regarding the limit of indoor air velocity, the relation between air speed and improvable comfort has not established yet. But, modifying air speed indoors allows more acceptable temperature under certain conditions (Al-Ajmi and Loveday, 2010).

2.5.5 Humidity

Humidity is expressed as water vapour pressure in the air which influences the evaporative heat loss from a person. If water is heated and had evaporated, it will increase the percentage of humidity in the air. Relative humidity is the percentage between the current amount of evaporative water and the actual amount of water that the air can hold at a given air temperature (Liu *et al.,* 2014). In terms of the impact of humidity, it is very connected to the current air temperature in the environment as well as the air speed which allows the skin to loss heat. However, when the relative humidity is between 40-70% it would not have a considerable effect on human comfort (Alwetaishi, 2016). High humidity in hot regions is a major problem since it will prevent skin sweating in order to cool the skin. Previous studies on the subject have expressed the importance of sweating when the body temperature rises; sweat is the main and most effective method to cool the skin when evaporation takes place (Sakka *et al.,* 2012).

2.5.6 Personal parameters

These are those factors that are peculiar to an individual that affect thermal comfort. Previous studied have included under personal parameters the below highlighted factors.

2.5.7 Activity levels

There are many types of buildings and each one has its own function, and activities that accompany those functions. Activity is one of the main personal factors that affects thermal comfort, as a result, thermal sensation differs invariably in people with change in activity levels, which is determined by the function carried out in a particular setting (Al-Ajmi and Loveday, 2010). Activity levels in this case can be defined as the heat we generate internally as we carry out physical activities, the more active we are; the more heat we produce (Mustapa *et al.*, 2016). Activity levels which is sometimes referred to as metabolic rate may be influenced also by food and drink, and the state of acclimatization. Short-term physiological adjustment to changed conditions is achieved in 20 - 30 minutes, but there is also long term, endocrine adjustments that may extend beyond six months, which constitute the acclimatization process (Auliciems and Szokolay, 2012).

2.5.8 Clothing insulation

Both clothing and the human skin can be considered as the body’s insulation which protects it from the environment. Clothing is one of the dominant factors affecting heat dissipation of the human body, which also greatly affects thermal comfort of individuals (Al-Ajmi and Loveday, 2010). With regard to clothing insulation it provides a thermal resistance between the body and the environment, it also keeps the body in an acceptable thermal state with respect to different climates (Alwetaishi, 2016).

For the purposes of thermal comfort studies, a unit has been devised, named the clo (Auliciems and Szokolay , 2012). one clo is the amount of thermal resistance which “is necessary to maintain thermal comfort for a sitting – resting subject in a normally ventilated room (air movement 0.1m/sec) at a temperature of 21.1oC and RH< 50%” (1 clo = 0.155m2K/W). International standards have set one clo equal to the value of a standard Western business suit. Shorts with short-sleeved shirts would be about 0.25 clo, heavy winter suit with overcoat around 2 clo and the heaviest arctic clothing 4.5 clo (Gabril, 2014).

2.5.9 Thermal balance models

Gagge was the first to propose a thermal balance model in 1936, which can be summarized as $M \pm R \pm C \pm E = \Delta S$ (Gabril, 2014). This simple equation has been modified and upgraded through the years. The basic equation for thermal balance is:

$$M - W = C + R + E + (Cres + Eres) + S$$

where (M) is the metabolic rate, (W) is the mechanical work done (C) is the convective heat loss from the clothed body, (R) Is the radiative heat loss from the clothed body, (E) is the evaporative heat loss from the clothed body (due to sweat and insensible evaporation), (Cres) is the convective heat loss from respiration, (Eres) is the evaporative heat loss from respiration, (S) is the rate at which heat is stored in the body tissues.

However, most models use the Fanger heat balance equation and the two-node model developed by the J. B. Pierce Foundation (the Pierce Two-Node Model) and researchers at Kansas State University (the KSU Two-Node Model). The thermal comfort equation is only applicable to a person in thermal comfort equilibrium with the environment (Auliciems & Szokolay, 2012).

2.5.10 Fanger's heat balance

The simple thermal balance equation has been modified and upgraded through the years. The most used model is Fanger's heat balance equation developed by P. O. Fanger, who in 1967 introduced his thermal comfort equation, setting the storage component to zero, concluding that physiological neutrality is the mean for comfort, (Alwetaishi, 2016). This equation can be written as follows: $\boldsymbol{M} \ - \ - \ 0.\mathbf{3543}-\mathbf{0.061}\boldsymbol{M}\ \boldsymbol{AD}\mathbf{1}- \ \eta-\boldsymbol{pa}-\mathbf{0}\ .\mathbf{42}\boldsymbol{M}\ \boldsymbol{AD}\mathbf{1}- \quad \eta-\mathbf{500.0023}\boldsymbol{M} \quad \boldsymbol{AD}\mathbf{44}-\boldsymbol{pa}-\mathbf{0.0014}\boldsymbol{M} \quad \boldsymbol{AD}\mathbf{34}-\boldsymbol{ta}= \quad \mathbf{35}.7!\mathbf{0.032}\boldsymbol{M}\ \boldsymbol{AD}\mathbf{1}! \ \eta!\boldsymbol{tcl}\mathbf{0}\ .\mathbf{18}\boldsymbol{Icl}=\mathbf{3}.\mathbf{4}*\ \mathbf{10}!\mathbf{8}\boldsymbol{fcltcl}+\mathbf{2374}\ -\ \boldsymbol{tr}+\mathbf{2374}+\ \boldsymbol{fclhc}(\boldsymbol{tcl}-\boldsymbol{t}\ \boldsymbol{a})$

Where M is the metabolic rate, AD is the DuBois area, !!(1- η), is the heat generated in the core, pa vapour pressure of ambient air (mmHg), **Icl** is the insulation of clothing in clo units, **ts** is the skin temperature tcl is the clothing surface temperature, **tr** is the mean radiant temperature, **tcl** is the temperature of outer surface of clothing, **fcl** is the ratio of clothed to exposed body surface and **hc** is the convection conductance (kcal/m2h°C).

2.5.11 The 2-node model

The model was introduced in 1970 and was developed by the John B. Pierce Foundation at Yale University (The Pierce Two-Node model), followed by The KSU two-node model, which has been developed at Kansas State University, was published in 1977. It was developed specifically to formulate a new effective temperature scale; it determines the heat flow between the environment, skin and core body areas on a minute-by-minute basis. Starting from an initial condition at time=0, the model iterates until equilibrium has been reached (60 minutes is a typical iteration time). The final mean skin temperature and skin wetness are then associated with an effective temperature, which predicts thermal discomfort using skin temperature and skin wetness.

$\Delta S= M\ [(1-\eta) - 0.0173(5.87-pa)\ -0.0014(34-ta)]\ -\ 16.7(0.06+0.94Wrsw)\ hc\ (psk-pa)\ Fpcl\ -h\ (tsk-ta)\ Fcl$

where ΔS is the storage component, M is the metabolic rate, M(1- η) is the heat generated in the core. Respiration removes some of this, partly as evaporative loss (Eresp) = 0.0173 M (5.87-pa), and partly as sensible heat (Cresp) = 0.0014 M (34-ta) where 34°C is the exhaled air temperature and 5.87 kPa is the vapour pressure at a lung temperature of 35°C. The sensible heat loss from the body surface is R+C = h (tsk-ta) Fcl 2.5) where Fcl = insulation value of clothing = 1/(1+0.155 h Icl). (Auliciems & Szokolay , 2012).

2.6 Thermal Comfort Standards

There are three well-known and widely used international standards that relate specifically to thermal comfort: These are ISO Standard 7730(2005), ASHRAE Standard 55 (2004), and CEN Standard EN15251 (2007). According to ISO 7730 a standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose (Gabril, 2014).

2.6.1 The international standards organisation ISO 7730

The European thermal comfort standard organisation (ISO) was set up in 1947 and has over 130 member countries. The standard is related to human physiology and heat transfer, ISO 7730 also provides methods for the assessment of local discomfort caused by draughts, asymmetric radiation and temperature gradients. The standard is based upon the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) thermal comfort indices (Auliciems and Szokolay , 2012).

The validity of ISO 7730 can be considered in terms of to whom it applies and over what range of environmental conditions. The standard notes that deviations in the PMV /PPD index may occur due to age, ethnic, national-geographic deviations and for people who are sick or disabled. In addition, it applies to indoor environments where steady state thermal comfort or moderate deviations from comfort occur (Jang *et al.*, 2007).

2.6.2 ASHRAE standard 55

ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, founded in 1894, is an international organization with over 54,000 members. The ANSI/ASHRAE standard 55 was established to assist the industry and the public by offering a uniform method of testing for rating purposes (Alwetaishi, 2016). Standard 55 deals with thermal comfort in indoor environments. The new effective temperature, ET*, was used to develop ASHRAE 55, however, the ET* relates the room temperature and humidity to provide an index for sedentary persons in standard clothing only. Consequentially, in order to incorporate different activity levels and clothing, the Standard Effective Temperature (SET) was developed. In ASHRAE 55-92, the standard added the PMVPPD method of calculation to determine the comfort zone, and it became more consistent with another international standard such as ISO EN 7730 (Auliciems and Szokolay, 2012).

ASHRAE standard 55 is based on the assumption that the people prefer a “neutral” thermal sensation (a vote of zero on the 7-point ASHRAE thermal sensation scale), and that discomfort varies symmetrically as sensations differ from neutral on either the warm or cool side. According to ASHRAE the Standard specifies conditions acceptable to a majority of group of occupants exposed to the same conditions within a space. The acceptable zones for indoor temperature are defined by the indoor operative temperature and mean monthly outdoor air temperature (Berkovic *et al.*, 2012). The ASHRAE standard was the first international standard to include an adaptive component and an adaptive standard that applied to naturally conditioned buildings (Mustapa et al., 2016).

2.6.3 European standard EN152521

EN12521 was developed by the Comité Européen de Normalisation (CEN), as a part of a series of new standards intended as a backup to the Energy Performance of Buildings Directive (EPBD) (Aiman *et al.*, 2015). The standard was developed as response to the effect of indoor environment on energy consumption and productivity (work and learning performance). Studies proved that the cost of poor indoor environment is often considerably higher than the cost of the energy used in the same building. Therefore, the standard specifies the indoor environmental parameters, which have impacts on the energy performance of buildings, such as indoor air quality, lighting and acoustics. However, the major thrust of the standard is its definition of the thermal environment, the sections on other factors confining themselves largely to references to other standards, (Al-Ajmi and Loveday, 2010).

The standard also recognises the different experiences occupants have of thermal environments in mechanically and naturally ventilated buildings. The EN15251 uses categories for buildings, defined by the nature of the building rather than referring directly to the quality of their indoor environment. The standard categorises buildings in terms of the type and the expectation of the occupants, using the SCATS (Smart Controls and thermal comfort) database for its adaptive standard (Aiman *et al.*, 2015).

2.7 Passive Design Strategies in High-rise Buildings

Thermal comfort has a significant implication on health, psychology and productivity of the working population who form the foundation of a country's economy (Latha *et al.,* 2015). In tropical climates, buildings gain solar heat and penetration through building envelope and glazing. Hence, they become overheated during the day. As a means of achieve thermal comfort, passive design techniques are applied in buildings, usually to avoid or limit solar heat gain, optimise natural ventilation, engaging prevailing winds and to provide adequate daylight (Tatarestaghi *et al.,* 2018). As the most important passive design element, the building envelope is a separator from the external environment and a protective layer from climatic factors influencing the building directly. Hence, blocking off radiation of the sun, less heat absorption and transmission can lead to natural cooling in buildings. These techniques can also be termed as heat avoidance which can be applied to buildings to enhance thermal comfort (Aflaki *et al.,* 2014).

It is evident from the above section that thermal comfort in high rise residential buildings is vital for many reasons especially in hot humid regions, having justified the needs for thermal comfort it is now important to focus on the basic principles that can enhance thermal comfort in high rise residential buildings in hot and humid regions. A review of existing literature has established the basic passive principles for designing high rise residential buildings to achieve thermal comfort, and they have been broadly categorised into planning aspect and the building envelope, as discussed below:

2.7.1 Planning strategies

These can be described as the strategies for enhancing thermal comfort which are conceived from the initial stages of the design of buildings which constitute the planning stage. The following factors discussed below constitute the planning strategies.

2.7.1.1 Building form

Building orientation, geometric parameters and ratios have great influence on the thermal comfort experienced in buildings. The thermophysical properties of the building envelope determine the gain or loss of thermal energy. Its shape determines the size of the exchange surface and the orientation determines what areas receive direct solar radiation and those that may be affected by the wind (Rodriguez-Ubinas *et al.,* 2018). Certain common building shapes greatly increase envelope area to volume ratio such as thin high-rise towers, which can enhance building thermal performance in heating dominant buildings. A compact building shape significantly reduces the building's thermal insulation performance and reduces the need for active mechanical systems (Prietoa *et al.,* 2018). Ahsan (2009), have suggested forms with large surfaces rather than compact buildings as large surfaces favour ventilation and heat emission at night-time. The building forms should thus be open, outward oriented and built on slits. Using compact building shapes and open forms for naturally ventilated buildings. Compactness of the building minimizes the surface area of the building envelope, resulting in a reduction of the heat gain through the envelope (Aflaki *et al.,* 2014).

2.7.1.2 Building orientation

Properly oriented buildings take advantage of solar radiation and prevailing wind. According to Aiman *et al.* (2015), the longer axis of the building should lie along east-west direction for minimum solar heat gain by the building envelope. Several other studies have proved that the key to thermal comfort building design is choosing the best orientation for the building, which have also been to place the longer side of the building along the east-west axis (Aflakiet *et al.*, 2014; Al-Ajmi and Loveday, 2010; Ahsan, 2009). These studies also conclude that the cooling load for a residential building can be reduced by 8% -11% by following this orientation.

2.7.1.3 Room orientation and arrangement

Orienting the building to be along the east-west axis is not always possible, especially due to actual orientation of the site, that is, when the site itself is longer on the west and east sides. In such cases, the west facade needs more attention because it heats up in the afternoon and important rooms such as bedrooms are generally used later during the day when residents return from their offices. The east side is less problematic as it warm only in the morning when only few households occupy the major rooms. The west facade can be treated by locating auxiliary spaces, kitchen and staircase to minimize solar heat gain and openings should be avoided on the west and if they cannot be avoided, they should be adequately shaded by using verandas. It should also be noted that the orientation requirement for wind flow can conflict with the requirement for solar protection. Tatarestaghi *et al.* (2018), points out that when solar geometry cannot be changed, skilful use of elements such as roof overhang or wall-projecting wing can change the direction of air flow and also give shade. whereas, for solar protection, the west facade should not have openings on the west.

2.7.1.4 Landscaping

Vegetation surrounding buildings, as a traditional time-tested and proven method and a significant heat avoidance technique is encouraged in tropical climates to provide shading for buildings, roofs and the surrounding areas as indirect evaporative cooling by vegetation shows a promising performance in improving thermal comfort within buildings (Tatarestaghi *et al.*, 2018), Previous studies including but not limited to (Al-Ajmi and Loveday, 2010; Asiedu, 2012; Aiman *et al.,* 2015) also acknowledge the beneficial effects of trees, stating that proper landscaping can result in energy saving, reduction of noise and pollution, modification of temperatures and relative humidity and psychological benefits on humans. These studies conclude that the cooling loads of a house can be reduced by 10%- 40% by appropriate landscaping. They also note that trees can act complementary to window overhangs, as they are better for blocking low morning and afternoon sun, while overhangs are better barriers for high noon sunshine.

2.8 Building Envelope

Building envelope constitutes the limit between the interior and exterior conditions and its correct selection is one of the most effective ways to achieve interior thermal comfort. The following factors discussed below constitute the variables that affect building envelope as an effective tool for achieving thermal comfort in buildings.

2.8.1 External wall

The main goal in building design for thermal comfort in tropical climates is reduction of direct heat gain by radiation through openings and reduction of internal surface temperatures, the building should be designed with protected openings and walls, insulation in external walls is a significant heat avoidance technique (Abed, 2012). The walls can be protected by designing the roof so that it extends far beyond the line of walls and has broad overhanging eaves, the outer surface of the external wall should be reflective and light coloured (Cheung *et al.,* 2005). Previous studies by Wei *et al.* (2020) and TataresTaghi *et al.* (2018) shows that annual cooling has an almost linear relationship to the solar absorption of external surfaces, energy savings were found to be high with lower solar absorption. A 30% reduction in solar absorption can achieve a 12% saving in annual required cooling energy. The studies concluded that 12% saving on cooling energy could be obtained from using white or light colour external wall finishes and materials with high thermal insulation.

2.8.2 Insulation

Thermal insulation is one of the most effective passive measures for cooling and heating in buildings because it reduces heat transfer to and from the buildings, using thicker construction on external walls alongside East and West façades can prevent the larger solar heat gain (Wong and Li, 2007). Apart from the walls, Toe and Kubota (2015) stated that thermally insulated roof or ceiling can moderate the solar heat gain due to the solar altitude at noon in the tropics. However, this view seems to conflict with those of Shafizal and Phillip (2017) which states that thermal insulation has very little efficiency in warm–humid zones because the ambient air temperature inside and outside the building is same due to the free flow of air. The study added that in warm and humid regions, condensation might occur and this would demean the thermal performance of the building envelope and cause mildew problems. Moreover, other studies by Alabi, (2017) and Alwetaishi, (2016) also note that thermal insulation has a dual nature, it reduces daytime excess heat entering a building, but averts the building from cooling down at night. According to the studies, this dual nature makes insulation unsuitable for buildings with natural climate control.

2.8.3 Building materials

Ambient temperature and humidity are important factors that affect internal thermal comfort, and these factors themselves are influenced by the specified building materials (Hyde, 2013). Latha *et al.* (2015) particularly identified certain materials such as vacuum insulation panel, phase change materials, aerated autoclaved concrete/autoclaved cellular concrete, polymer skin with good thermal properties are potentially suitable to be incorporated into various components of the building envelope to enhance thermal comfort. Façades with light colours or reflective paints were also proven to reduce building heat gain by reflecting solar radiation year-round for buildings located in warm and temperate climatic conditions.

2.8.4 Windows

Windows are responsible for 20–40% of wasted energy on cooling in a building, the thermal performance of a building depends on the building envelop especially the windows (Hee *et al.,* 2015). Even though the existence of windows is for natural ventilation and to allow daylight into buildings, having a minimum size for windows will limit heat gain or heat loss. Studies by Al-Tamimi and Syed (2011) and Hee *et al.* (2015) found that window position, optimum glass size and application of natural ventilation should be appropriately specified to mitigate solar radiation and heat gain indoors for high rise residential buildings. Besides these, glass thermal and optical properties, window sizing and orientation are window characteristics that need to be considered (Ahsan, 2009). These are explained below;

2.8.4.1 Size

Openings are important design elements for admitting daylight, air flow, providing cross ventilation and views into high rise residential buildings. Studies by Ahsan (2009) and Hee *et al.* (2015) recommend that thermal comfort can be enhanced by the application of natural ventilation and window to wall ratio (WWR) of 25%, and that windows should be large and fully openable with inlets of a similar size on opposite walls for proper cross-ventilation in tropical climates, and if they were designed to be small-sized openings they should be designed on the East and West sides, where the radiation is received twice as much as on North and South elevations.

2.8.4.2 Orientation

Previous studies including but not limited to Aiman *et al.* (2015); Ahsan (2009); Blanc (2018) advised that openings in hot and humid regions should be placed according to the prevailing breeze so that air can flow through the internal space and the orientation of windows should aim at excluding solar penetration. However, this is difficult to achieve in high rise residential buildings due to the complexities and several variables involved. Other studies by Alabi (2017) and Daramola (2018) proffer the use of vertical greening systems as a solution to the previously stated conundrum of window orientation of high-rise residential buildings in hot climates.

2.8.5 Shading device

In order to control sun penetration to the interior of buildings in the tropics, it is important to provide shading for both glass and opaque surfaces on the facades, which will significantly improve thermal comfort inside buildings (Latha *et al.,* 2015). This can be done by having shading elements on the upper part of openings on the East and West facades, by the articulation and disposition of the building floors to create overhangs (Ahsan, 2009) or having features such as verandas and lattice screens as in vernacular Mughal architecture which provides cooler internal spaces (Aflaki *et al.*, 2014). Toe and Kubota (2015) recommended constant low roof eaves alongside the window top and strategically locating broadleaf trees which are taller than building height to shade the building.

According to Gabril (2014), shading devices can be categorized into three broad groups namely solar transmittance of glazing materials, interior shading and exterior window shades. Exterior shading is greatly preferred over interior shading and solar transmittance of glazing materials as it is important to keep the solar radiation or heat from entering the building.

Solar transmittance is defined as the heat admitting or rejecting characteristic of the glazing materials. Ahsan (2009); Latha *et al.* (2015) advice against heat absorbing, heat reflecting and tinted glazing. According to Hee *et al.*, (2015) heat absorbing glass, shading device, and tinted glazing reduces solar transmission by absorbing heat within the material itself, the absorbed heat can be uncomfortable to occupants because it adds heat to the interior by conduction and thermal radiation. Another disadvantage of heat absorbing and heat reflecting glazing types is that they block needed solar gain in winter and summer solar irradiation. In high rise residential buildings, Ahsan (2009) suggests the use of drapes and curtain for interior shading. Studies including but not limited to shows that use of venetian blinds can bring about an energy reduction of 14% through achieving thermal comfort passively (Ahsan, 2009; Hee *et al.*, 2015).

Cheung et al., (2005) Studied the effects of shading devices (overhangs and wing walls) along with five other passive design strategies on the cooling load for an apartment. Their results suggest that the longer the shading, the greater the reductions in both annual required cooling energy and peak cooling load which translates to better thermal comfort. However, according to Ahsan, (2009); Inayatia *et al.*, (2017), the length of shading devices depends on the orientations, width of the opening, height of the openings, horizontal shadow angle (characterises a vertical shading device) and vertical shadow angle (characterises a horizontal shading device).

2.8.6 Natural ventilation

Ventilation can be defined as the movement of air. According to Ahsan (2009), ventilation has three useful functions in the building sector, it is used to satisfy the fresh air needs of the occupants, increase the rate of evaporative and sensible heat loss from the body, and cool the building interior by an exchange of warm indoor air by cooler outdoor air.

The study further explains that the following two forces can generate natural ventilation:

i. Temperature difference between the outdoors and the indoors (thermal force). When a mass of air inside the room is heated, it expands and becomes less dense and rises. If openings are provided at different heights on the building's envelope, the indoor pressure is higher at the upper opening and lower at the lower opening. These pressure differences generate an inward flow at the lower opening and an outward flow at the upper one. When thermal forces discharge air from a building, the action is termed as stack effect (Omrany and Marsono, 2016).

ii. Wind flow against the building (wind pressure force). As wind blows against a building, the air in front of the building is compressed and creates a pressure zone.

The air next to the leeward wall and above the roof expands and the pressure is reduced, creating a suction zone. These pressure differences between any two points on the building's envelope determine the possibility for ventilation when openings are provided at these points (driving force) and if air can flow inside the building through openings with the higher pressure to openings exposed to a zone with lower pressure. Cross- ventilation is defined as the situation in which outdoor air can flow in through inlet openings, located in the pressure zone, and flow out via outlet openings located in the suction sections of the building (Al-Ajmi and Loveday, 2010).

2.8.7 Roof

The roof is an important element of design when it comes to achieving thermal comfort because this part of the building receives most of the solar radiation and its shading is not easy (Ahsan, 2009). Previous studies including but not limited to Aflaki *et al.,* (2014); Aiman *et al.,* (2015); Anderson, (2016) conclude that the heat entering into the building structure through the roof is the major cause for discomfort in case of non-air-conditioned buildings. However, Shafizal and Phillip (2017); Omrany and Marsono, (2016) argue that this is true for single storied buildings and the top floor of multi-storied buildings. But in high rise residential buildings, the roof area is very much less than that of the external walls, conduction heat gain through the roof in high rise residential buildings is thus less than that through external walls and windows. Evidences like these in literature push the study in the direction of exploring vertical greening systems in the form of green walls to enhance thermal comfort in a hot and humid region.

2.9 Green Walls

Green walls have been used for millennia for thermal comfort and aesthetics. The traditional green wall design of vines grown over a trellis, has recently been re-engineered into a variety of possible configurations (living walls, green façades and bio façades), in an attempt to enhance their performance in urban environments, and also to utilise the systems for treatment of domestic greywater (Oldham and Karima, 2018). The original concept of vertical vegetation, including a wide use of green walls, can be traced to the hanging gardens of Babylon (Blanc, 2018) as seen in figure 2.1 one of the seven ancient wonders of the world, dating from between 600 to 800 B.C.

Figure 2.1: Hanging garden of Babylon
Source: Blanc, (2018)

Self-clinging climbers and self-supporting woody plants can attach themselves directly to the façade surface or grow along the façade without any added support (Haggag *et al.*, 2014). Green walls can absorb heated gas in the air, lower both indoor and outdoor temperature, thereby providing a healthier indoor air quality as well as a more beautiful space (Carpenter, 2014). Green Walls are generally made up of the following elements

i. plants

ii. planting media

iii. structures that support and attach plants to the façade

iv. The irrigation system

Green walls can be divided based on differences in the elements mentioned above into two major categories, which are Green Facades and Living walls, both of which are discussed below. As seen below in figure 2.2 the graphical definitive categorization of green walls using a branch diagram

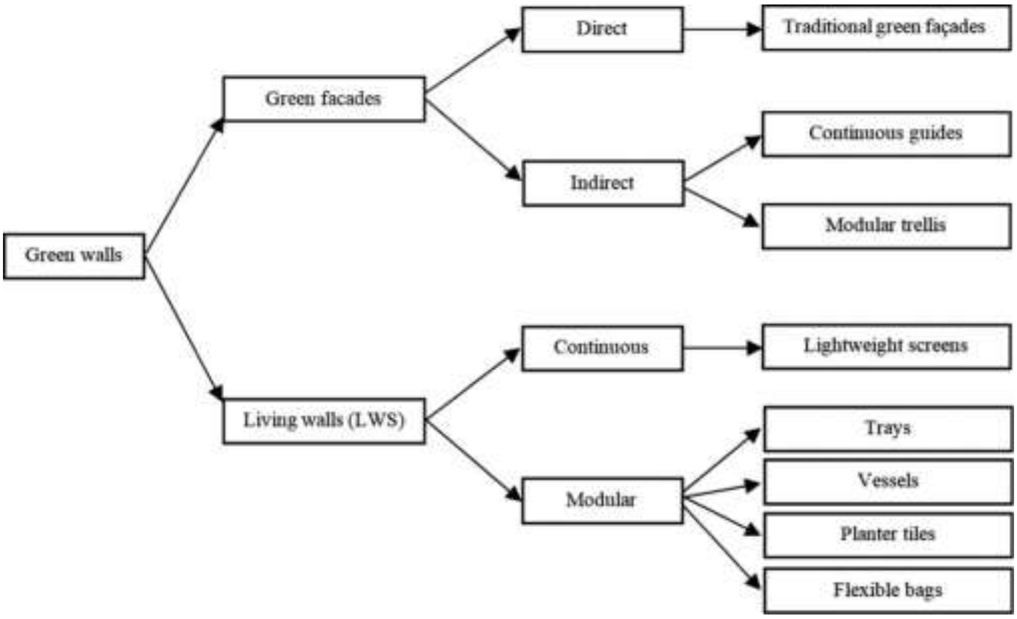

Figure 2.2: Categories of green walls
Source: Kumar, (2017)

2.9.1 Green façade

Green facade can be described as system where vegetation, typically creepers or climbers, are rooted into the ground or in large planters, and is grown directly up a supporting structure that can be freestanding (detached green façade) or immediately adjacent to the wall (attached green façade) (Fowdar *et al.,* 2017). Such systems have been variously termed bio-façades, green façades or green walls (Manso and Gomes, 2015). While green façades have been used for millennia, their optimisation for specific outcomes thermal comfort and water purification has become an emerging green technology, with promising potential for high density urban areas (high rise residential buildings) because of their small footprint and multiple benefits. Green facades are further sub divided into two as explained below;

2.9.1.1 Attached green facades

In this configuration, the vegetation (typically climbers) is rooted in the ground at the base of a building and climbs up a supporting structure attached to a building wall. While this configuration is the cheapest green wall system to install, it may cause damage to the building wall. This green façade configuration has also been termed direct green façades or traditional green façades (Sclar, 2013).

2.9.1.2 Detached green facades

In this configuration, the vegetation is rooted in the soil and climbs up a structural support that is separate from the building wall (Sclar, 2013). The distance between the structural support and the building wall may vary; distances of > 1-2 m have been used for walkways/breezeways, verandas or sun shades, while distances < 0.5 m have been used for temperature and sound control. The initial establishment cost may be higher than an attached living wall as a freestanding support is needed. These systems have been variously termed indirect green façades, double skin green façades and green curtains (Oldham and Karima, 2018).

2.9.2 Living walls

Living walls have recently been developed and are configured using prefabricated modular or monolithic vertical soil or hydroponic systems to root plants on a vertical plane (Carpenter, 2014). The modules are typically made of plastic or metal panels, the plants are pre-cultivated prior to installation and the panels subsequently fixed to either a vertical structural support or directly to a building wall (Oldham and Karima, 2018). In the latter case, waterproofing is applied to the supporting building wall. Flowerpots and ornamental hanging pots have been used in these systems to create a green curtain. Living walls have been classified into two, according to size of the substrate layer.

i. Extensive living walls; use thinner substrate layers.
ii. Intensive living walls; use thicker substrate layers.

The extensive systems have been more commonly used because they are cheaper to implement (Sclar, 2013).

2.9.3 Green wall system in tropical regions.

Cities in tropical regions are experiencing high urban growth, and this is expected to accelerate in the future, urbanization has caused many environmental problems, such as urban heat island effect, global warming, and climate change (Zaida *et al.,* 2018). Therefore, the mitigation of Urban heat island effect (UHI) and its climate change impacts are crucial, as climate change causes adverse effects to not just the earth, but also, its occupants (Jaafara *et al.,* 2013). The integration of green walls in urban areas is one effective strategy to mitigate UHI impacts, as vegetation provides carbon sequestration potential, shading and lowering urban temperatures, and providing fresh air and oxygen to urban inhabitants in closer proximities especially in high rise residential buildings in tropical climates (Manso and Gomes, 2015).

2.9.4 Green walls application parameters.

Most recent developments in green walls are mainly focused in systems design and their elements (supporting elements, growing media, vegetation, irrigation and drainage) in order to achieve more efficient technical solutions and a better performance in all building phases (installation, maintenance and replacement) (Carpenter, 2014). The adaptability to more building types (commercial spaces and high-rise buildings), construction methods (new or existing building walls) and types of surfaces (Sloping surfaces, indoor partition walls and free-standing structures), is also the concern in the evolution of green wall systems (Irga *et al.*, 2016). The following are the elements to consider when designing a green walling system;

2.9.4.1 Supporting elements

According to Othman (2016), Traditional or direct green facades usually have no support structure. They rely on the capacity of climbing plants to attach themselves to the vertical surface. However, when the vegetation fulfils full coverage it can become too heavy and the risk of falling is increased. Indirect green facades function as “double-skin facades”, creating an air gap between the building surface and vegetation (Othman, 2016). These systems, either modular or continuous, anchor and hold the vegetation weight, contributing to increase in the system resistance to environmental actions (wind, rain, and snow) (Manso and Gomes, 2015).

2.9.4.2 Growing media

In the context of green facades only modular systems require the selection of a growing media, which must be lightweight, considering that each element will be suspended, and adapted to the selected plant species and environmental conditions (Irga *et al.*, 2016). As mentioned before, these systems use lightweight absorbent screens where plants are inserted in pockets. Continuous LWS are commonly based on a hydroponic method, requiring a permanent supply of water and nutrients due to the lack of substrate (Jaafara *et al.,* 2013). Hydroponic systems allow the growth of plants without soil, using screens constantly moist by the irrigation system.

2.9.4.3 Drainage

According to (Carpenter, 2014) Excess fluid drainage in green walls takes place by gravity. Continuous and modular LWS use geotextiles that encourage drainage along the permeable membrane while preventing roots proliferation**.** Materials (Rubber, plastics, piping thermos plastic, silicone and irrigation hose) containing different outputs (drip, sprinkler, holes, and pipe) with distribution and intensity adapted to the plants irrigation needs**, t**he irrigation system can also include a filtration system to prevent clogging (Manso and Gomes, 2015).

2.9.4.4 Plant species selection

Selecting the appropriate plant for any green wall is very crucial as the choice of plant strongly affects its function as well as the visual quality, inadequate selection of plants could lead to problems such as excessive growth, plant losses, pest or disease problem, high maintenance, poor public perception and unattractive structures. Climate should be taken into cognizance when choosing plants because weather affect plant growth, mostly native climbers are preferable to be used (Oldham and Karima, 2018).

2.9.4.5 Foliage density

According to Sari (2017), in order to achieve optimum performance of green walls in building, foliage density should be considered since shading depends on foliage density. In a single layer, a leaf approximately absorbs 50% visible and infrared radiation (Sclar, 2013).

2.9.4.6 Leaf area index

Leaf area index (LAI) is a critical parameter in many land-surface vegetation and climate models that simulate the carbon and water cycles. The vegetation canopy structure, including the LAI, directly influences the radiative transfer process of sunlight in vegetation and, therefore, determines the radiometric characteristics of the top of the canopy (TOC), such as reflectance (Susorova, 2015).

2.9.4.7 Orientation of the façade

Orientation of a building is the positioning of a building on site to take advantage of the climatic features such as the sun and air masses, according to (Susorova, 2015) this is a very important factor to consider when designing green walling systems.

2.9.4.8 Maintenance

Green facades and living walls need regular irrigation and fertilization. Plants in living wall systems are irrigated automatically through vertical or horizontal pipes installed behind the soil (Susorova, 2015). Water is treated and pumped to the top of a living wall where it is distributed to plants. Plants in green facade systems are easily irrigated either naturally by rain, manually, or automatically. Living walls must be periodically examined to ensure the integrity of building materials, the functioning of irrigation systems, and plant health depend greatly on wall height. Living wall maintenance may require the use of special equipment for maintenance, such as suspended platforms or scissor lifts. Green facades require less maintenance (plant pruning and visual inspection), which can usually be done easily from the ground level (Blanc, 2018).

2.9.5 Effects of green walls on thermal comfort.

The thermal comfort performance of green walls lies in their ability to reduce active heat transfer between a building's interior and exterior environment (Vox *et al.,* 2017). The main exterior factors of active heat transfer through a building's façade are (I) solar and thermal radiation from the atmosphere and the ground, (ii) air temperature, (iii) relative humidity, and (iv) wind speed (Susorova *et al.,* 2013).

Green walls have been implemented in different climatic conditions and have yielded positive results (Alwetaishi, 2016; Fowdar *et al.,* 2017; Blanc, 2018). These studies have shown green walls to have a wide range of positive effects on buildings, inhabitants and also the environment at large. The presence of Green walls reduces the façade temperature due to shading and cooling through evapotranspiration. The shading effect is as a result of the solar radiation been intercepted by the plant, and also the evaporation of water from the substrata and from the leaves in conjunction with the shading effect caused by the plants results to cooling effect. According to Vox *et al.,* (2017) the effects of green walls have been classified into four groups as follows:

i. Shade effect.
ii. Cooling effect.
iii. Wind barrier effect.
iv. Insulation effect.

2.9.5.1 Green walls to control wall surface temperature

Façades covered with vegetation can be used in passive design of buildings where the plants enhance thermal comfort by functioning as a natural shading element and thermal screen (Haggag *et al.,* 2014). In a study by Vox *et al.,* (2017) a green wall gives a good capacity of cooling in the warm periods; the daylight temperatures observed on the south oriented green façades were lower than the respective temperatures of the uncovered wall up to 9.0 °C. The façades also acted as thermal screen during the cold days; the night time temperatures for the vegetated walls were higher than the respective temperatures of the control wall up to 3.5 °C. The thermal effects of the façades at daytime was driven by solar radiation, wind velocity and air relative humidity. The highest cooling effect of such parameters occurred with a wind speed of 3–4 ms−1, an air relative humidity within the range of 30–60% and a solar radiation higher than 800 Wm.

2.9.5.2 Green walls to control ambient temperature

Studies have shown that Green envelope around buildings contribute to lower ambient temperature (Atmaca *et al.,* 2007; Gabril, 2014). The green wall creates insulating air layer between the vegetated layer and the facade, that acts as a thermal insulation layer and it has the ability to control heat gains and losses (Haggag *et al.,* 2014) and it also cools the microclimate around buildings through evapotranspiration. Green wall exploit sunlight in such that it reflects 5-30%, uses 5-20% for photosynthesis, transfers 10-50% into heat, uses 20-40% for evaporation and only 5-30% is passed through leaves via phototropism effect (Oldham and Karima, 2018).

Through the use of green wall solar radiation reaching the internal wall can be reduced by 40-80% via reflection and absorption thereby reducing the indoor and outdoor temperature fluctuation to about 50% (Irga *et al.*, 2016). Sclar (2013) opined that the green wall surface is about 10^{o}_{C} cooler than exposed wall; therefore, the U-value for the green wall is usually lower and it helps in enhancing thermal insulation.

2.9.5.3 Green walls to protect building envelope

Buildings are exposed to weathering elements and over time the construction materials start to wear out as a result of contraction and expansion. Green walls protect the building by reducing temperature fluctuation, UV radiation of the building envelope, as they act as a layer barrier which protects the building from radiation and heat penetration (Manso and Gomes, 2015).

2.9.5.4 Improved indoor air quality

Green walls have the ability to filter by purifying air borne pollution, harmful gasses moving across it and releasing oxygen. Improvement in air quality from plants has been measured to reduce coughs up to 30% and dry throat up to 20% (Carpenter, 2014).

2.9.5.5 Noise reduction

Green walls have an acoustic property that is far better than walls that are exposed. Factors that influence noise reduction include the depth of the growing media, types of the plant the material used as structural components, the overall coverage and the layer of air between the plant and the wall (Jaafara *et al.*, 2013).

2.10 Theoretical Framework

Thermal comfort is achieved when occupants of a particular space are perceived to be satisfied with the present temperature and indoor air quality of that particular space, and this is more difficult to achieve in high rise buildings than low rise buildings especially in tropical climate regions, this is due to the fact that high-rise buildings are more exposed to harsh climatic elements such as wind, sun and rain compared to low rise buildings which are most often adjacent structures surrounded by trees and other landscape elements that help shade them from harsh climatic conditions (Alabi, 2017; Batagarawa *et al.*, 2011).

It has been established from the above reviewed literature that the use of green walls can reduce this exposure of high-rise residential buildings to harsh climatic condition, and this study tries to investigate the optimum air cavity between the green wall and the external walls at various orientations. Using an air cavity of 200mm, 400mm, and 600mm.

2.11 Conceptual Framework

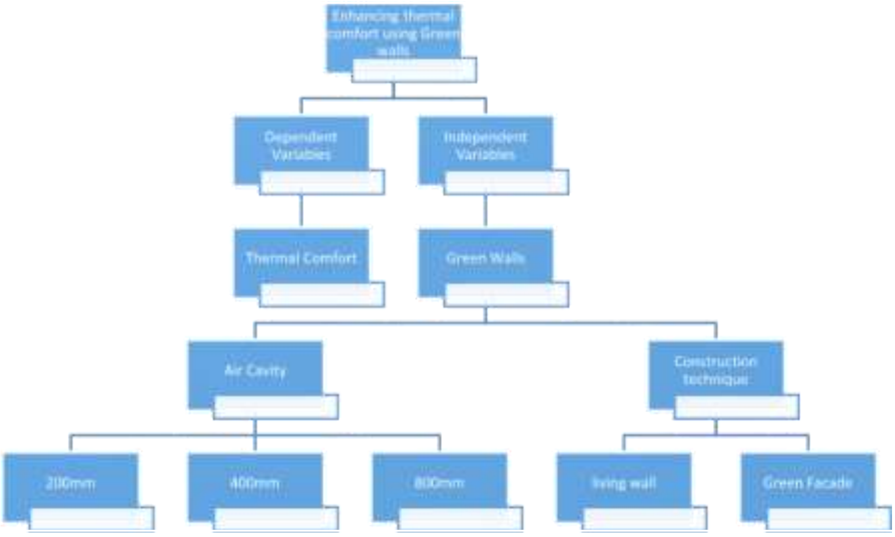

Figure 2.3: Conceptual framework
Source: Author’s work, (2019)

All the literature reviewed in this chapter has established that the use of green walls can enhance thermal comfort in high rise residential buildings by mitigating the exposure of these high rise buildings to harsh climatic conditions, this has been supported by previous studies including but not limited to (Ahsan, 2009; Aiman *et al.*, 2015; Fowdar *et al.*, 2017).

In the bid to enhance thermal comfort in high rise residential buildings using green walls, there are a number of key variables that have to be considered by the designer including variables in the planning stage and the building envelope as highlighted earlier in the literature review. Furthermore, from the above reviewed literature a standard acceptable criteria or elements that can be used to enhance the thermal performance of the green walls have been explored. These elements include the foliage density, leaf area index, growing media, orientation of the façade, and the air cavity. The correct combination of these elements can often represent the first step in developing more inclusive and functional green walls best suited to enhancing thermal performance in high rise residential buildings (Sari, 2017; Oldham and Karima, 2018). This research explores the impact of the air cavity of green walls on the thermal performance of the green walls as shown in figure 2.3 “Conceptual Framework”.

2.12 Review of Similar Studies

A number of previous studies including but not limited to Abed (2012); Taib *et al.* (2010); Alabi (2017), have all proffered solutions to the problem of achieving thermal comfort in high rise buildings through the use of diverse design and landscape design models. The majority of these previously named studies concentrate on the solutions to mitigate this exposure of high-rise buildings to the climate using different design and landscape elements. One of such landscape elements is the green walling systems, which have been shown in tropical climatic regions to act as an additional layer of thermal insulation which helps in shading exterior walls from incoming solar radiation, and protects the exterior wall from wind exposure, and temperature cooling of the air adjacent to the exterior walls (Taib *et al.*, 2010).

The concept of thermal comfort is not particularly a new one; there are a number of studies conducted in this field of enquiry. There are various architectural theories that proffer different but similar solutions for providing an optimum thermal environment in various building typologies but the use of landscape elements to tackle this problem of exposure to harsh climatic conditions takes a more sustainable approach (Deen, 2004). This section of the literature review is going to explore previous studies of similar nature, which deal with the concepts and spatial strategies that help to achieve an optimum thermal environment.

A thesis presented by Alabi Temitope Joseph to the department of architecture, Covenant university, Ota titled "Designing High Rise Housing for Lagos, Nigeria with Focus on Sustainable Building services 2017" is a study carried out to investigate sustainable building services. This thesis researched and related the application of sustainable building services to the design of a high rise residential building in Lagos, establishing from literature the relationship between sustainable building services and thermal comfort and then applying it in the context of a proposed high rise residential building in Lagos; furthermore, this study took a case study approach as the research method with computer simulation as a tool for data collection, investigating existing high rise residential buildings to check these principles explored by the research and then finally proposing a high rise residential building that optimally incorporates the principles into its design. Another similar study is the thesis presented by Maiyaki, S. to the department of architecture, Ahmadu Bello University, Zaria, 2017. titled "*Effect of building morphology on energy and structural performance in Highrise Mixed-Use Building in Lagos*". This study also took the case study approach with computer simulation as a tool for data collection, exploring the benefits of access to nature and building morphology and its current application in existing high-rise mixed-use buildings in Lagos.

There has been a lot of research concerning issues of thermal comfort in all forms of high-rise buildings as well as other building typologies especially in hot and humid regions. A long pedigree of studies and research have proffered guidelines to be adopted to help maximise thermal comfort in high rise buildings and reduce building exposure to harsh climatic conditions (Atmaca *et al.,* 2007; Ahsan, 2009; Carpenter, 2014; Blanc, 2018). However, there has been little and insufficient research in the area of documenting the standards of high-rise residential buildings with regards to thermal performance, enhancing thermal performance of high-rise residential buildings through the use of green walls and designing high rise residential buildings with passive cooling requirements in Nigeria. The steady increase in the temperature statistics of the nation and the staggering cost of energy required to run these buildings threatens the rise of potential investments in high rise residential buildings in the city. In addition, the gap this research is going to fill is to uncover the best air cavity suited to placing green walls on high rise residential buildings in Abuja the capital city of Nigeria.

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 Research Design

This research adopts a descriptive and a quasi-experimental approach to attain the answers to the research questions, paving way to realizing the research aim and objectives. The instruments of data collection employed include case studies, check list, notebook, and measuring tape, for the purpose of this study, purposive sampling was used. This is supported by the methods used in previous studies and the nature of the research.

3.1.1 Descriptive approach

The descriptive approach will be used for exploratory studies with little or no interest in finding out the relationship between the identified variables. For the objectives to investigate the determinants of thermal comfort in high rise residential buildings in Abuja, and to explore the principles of passively achieving thermal comfort in high rise residential buildings in Abuja.

3.1.2 Quasi-experimental approach

The assessment of the green wall parameters and design to determine the most effective for enhancing thermal performance is explorative in nature and therefore based on a quasi-experimental approach. By identifying key variables, computer simulations are used to determine their effects on thermal comfort.

3.2 Case Study Selection Criteria

The case studies selected for this study were sampled purposely to at least possess two amongst the following criteria:

i. A high-rise residential building that is located within Abuja, Nigeria.
ii. A building with adequate coverage in scope and facilities required to operate as a standard high-rise residential building.
iii. A high-rise residential building that represents a region, so as to look at factors involving regional and technological diversities.

Three facilities were chosen purposely, one local and two international case studies. Each one fulfilling at least two of the required criteria. The selected case studies are as follows:

i. Case Study I (World Trade Centre (Tower 1), Abuja).
ii. Case Study II (Newton Suites Singapore).
iii. Case Study III (Kuala Lumpur High Towers).

3.3 Population of Study

Population of study is made up of all the subjects that have the characteristics that are of interest to the researcher and to whom the result obtained can be generalized. The population of this study comprises of high-rise residential buildings in Abuja. The selection of this population of study is appropriate because it captures a specific range of data required for the study and also represents similar social-cultural elements of the area while comparing them to internationally accepted standards.

3.4 Sampling Procedure

The sampling technique adopted in this research was purposive in nature, identifying the high-rise residential buildings in the city been studied and screening them according to the case study selection criteria. While for the international case studies, high rise residential buildings that optimally incorporated green walls in their design were studied. This procedure is supported by past studies carried out in this field, and the nature of the research.

3.5 Instruments of Data Collection

There are many instruments which can be used to collect data from a case study. For the purpose of this study, the instruments for the primary collection and documentation of data were visual surveys, participant observation, and computer simulation.

i. Visual survey: tools included checklist, notebook, and sketchpad.
ii. Participant observation: tools included Camera, Video recorder, notebook and sketchpad.
iii. Computer simulation: tools included laptop, simulation software, documentation software.

3.6 Research Variables

From the literature review, the independent variables to be examined are Green wall parameters; air cavity; 200mm,400mm and 800mm cavity will be tested and green wall construction technique; living wall and green façade. These independent variables mentioned above will be used to create a suitable analytical model to test the dependent variable (thermal comfort). The dependent variable, indoor thermal comfort is measured in terms of indoor dry bulb air temperature and operative temperature both measured in degree Celsius.

3.7 Procedure for Data Collection

The Procedures for data collection in the local case studies involved visiting the selected existing high-rise residential buildings Abuja, Nigeria, and taking visual analysis/surveys of their architectural elements as they reflect passive strategies for achieving thermal comfort. Photographs of relevant physical elements of the case studies were taken to ascertain the extent or level of application of passive strategies in the design, planning, and construction of the selected case studies. Sketches of some relevant parts of the case studies were necessary to further describe some features of spatial organization, or to enhance the quality of some details that might not be too clear from the pictures taken. Notes were also taken on the field work to outline the account and extent of the independent variables on the case studies as they relate to the dependent variables.

3.8 Data Analysis and Presentation

The techniques used for data analysis in this research will include; descriptive, statistical and parametric analysis.

3.8.1 Descriptive statistical analysis

The descriptive analysis will be conducted to describe the existing characteristics and report the thermal performance of the building using data collected such as the, materials used, geometry of the building, orientation and annual temperature data. Statistical analysis will be used to describe relationships between the variables. Data will be presented in form of descriptions given, photographs and tables/figures.

3.8.2 Parametric analysis

Parametric analysis will be used to further analyse the variables. The aim of the parametric analysis is to observe the response following a change in a variable. Various green wall design strategies will be simulated in order to identify their impacts on thermal comfort of the building. The data will be presented in tables, graphs and charts.

3.8.3 Building performance modelling tools

Building performance models are a valuable tool that can be used to evaluate the effects of different building designs, technologies, and control strategies before the construction of a building (Anderson, 2016). It has been determined from the literature that the most feasible tools for this research are Design Builder and Energy Plus.

Validation: An experimental study will be used to check the validity of the simulation software (Design builder). It will be done by taking readings of a physical model with green wall using a thermometer for a week and comparing it with reading from simulation model to find out the reliability of simulation tool.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

A base case model was developed based on the variables acquired from the review of literature and used to assess the local case study selected based on the outlined criteria in the methodology with the aim of gathering sufficient data for analysis.

The research aims at enhancing thermal comfort; therefore, emphasis will be on hottest day peak, hottest day average, coldest day peak, and coldest day average of the day. Simulations were conducted using two cavity depths 200mm and 400mm, density of plant coverage, natural ventilation and building material. Results obtained would be presented through charts and tables. The Table below shows the thermal properties of the building element used in the simulations.

Table 4.1: The thermal properties of the building element used in the test.

Wall (Hollow Sandcrete block Uninsulated)	
Thickness (mm)	230
Km – Internal heat capaity (Kj/m2-k)	144.8000
Radiative heat transfr coefficient (W/m2-K)	5.540
R-Value (m2-K/W)	0.556
U-Value (W/m2-K)	1.8
Green wall (Plants)	
Thickness (mm)	50-100
Conductivity (W/m-k)	0.0350
Density (Kg/m3)	1200
Thermal resistance (m2-K/W)	0.1500
U-Value (W/m2-K)	0.3
Slab (Concrete floor Uninsulated)	
Thickness (mm)	150
Km – Internal heat capaity (Kj/m2-k)	93.96
Radiative heat transfr coefficient (W/m2-K)	5.130
R-Value (m2-K/W)	4.001
U-Value (W/m2-K)	0.250

Ceiling (Wooden-joist internal ceiling - plasterboard)	
Thickness (mm)	20
Km – Internal heat capaity (Kj/m2-k)	8.750
Radiative heat transfr coefficient (W/m2-K)	5.540
R-Value (m2-K/W)	0.990
U-Value (W/m2-K)	1.010
Roof (Reinforced concrete roof uninsulated)	
Thickness (mm)	150
Km – Internal heat capacity (Kj/m2-k)	240.0000
Lower resistance limit (m2-K/W)	0.227
R-Value (m2-K/W)	3.999
U-Value (W/m2-K)	0.250

Source: Design Builder, (2019)

4.1 Case Study I (World Trade Centre (Tower 1), Abuja).

Brief history

The World Trade Centre (Tower 1), Abuja is a residential high-rise tower amongst the eight buildings within the world trade centre complex located in the central business district of Abuja, FCT in Nigeria. The world trade centre (tower 1) which was topped out in 2015 is the tallest residential building in Nigeria standing at 110m high with 24 floors. The tower was designed by architects Wood Bagot, and is been funded by a mix of public and private entities. When the world trade centre is completed it will be the largest mixed-use development on the west African subcontinent.

Figure 4.1: Perspective view of the world trade centre
Source: https://wtcabuja.com/apartments/, (2019)

The tower contains 120 apartments which range in sizes from 1 to 6 bedrooms, duplex, 2 exquisite penthouses and pool villas, with a rectangular building form. Below in Figure **4.2** is a typical layout plan of the building. The world trade centre is a High-Tech architectural design which uses new advance technology and building materials as can be seen in Figure 4.1 above. It made extensive use of steel, glasses and concrete as seen below in Figure 4.3.

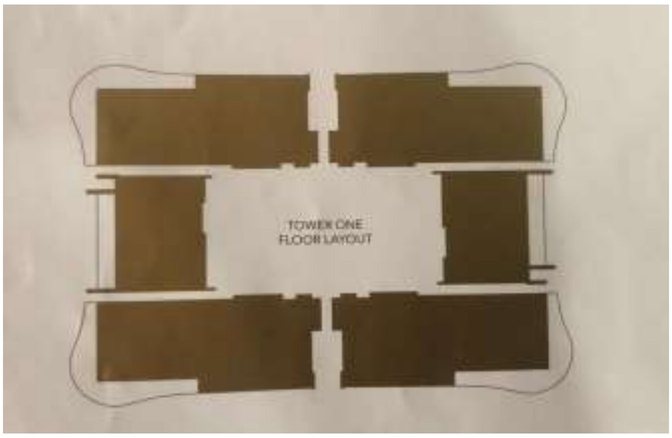

Figure 4,2: Layout plan for tower 1
Source: https://wtcabuja.com/apartments/, (2019)

Figure 4.3: 3d site view of world trade centre, Abuja
Source: https://wtcabuja.com/apartments/, (2019)

4.1.1 Architectural significance related data

The World Trade Centre residential tower was modelled in the design builder interface as shown in Figure 4.3. with all its thermo-physical properties, and observations were made based on the variables to identify the impact of green walls on internal thermal comfort. They are highlighted as follows:

4.1.2 Base case model without green walls

The World Trade Centre residential tower was modelled in the design builder interface as shown in Figure 4.3 above with all its thermo-physical properties, location and weather of Abuja imputed, results are measured on the hottest day peak, hottest day average, coldest day peak and coldest day average and used to compare the base case model with and without green walls, and comparing the effects of the air cavity on internal thermal comfort. The internal temperature was estimated for the 24 hours of the hottest day peak

(16th March), hottest day average (17th February), coldest day peak (29th December) and coldest day average (12th January).

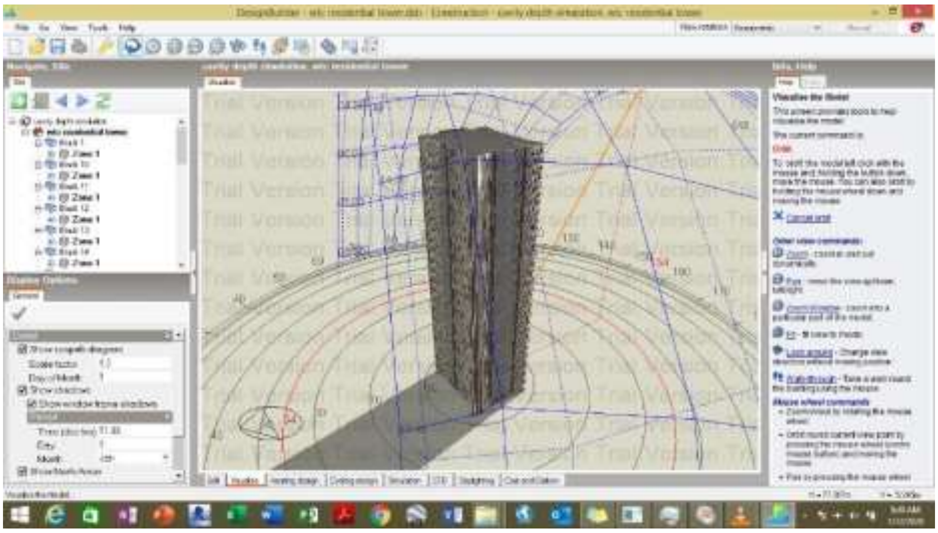

Figure 4.4: Base case without green wall on design builder interface
Source: Author's work, (2019)

4.1.2.1 Hottest peak day

The readings of design builder indicate that during the hottest peak day, the highest temperature of the day is observed at 12pm to be 32.5^0 and lowest temperatures were recorded for 24^0 for night periods as seen in Figure 4.5. As shown in Figure 4.5, lowest temperatures were recorded for night time periods and an increase in temperature for the day time.

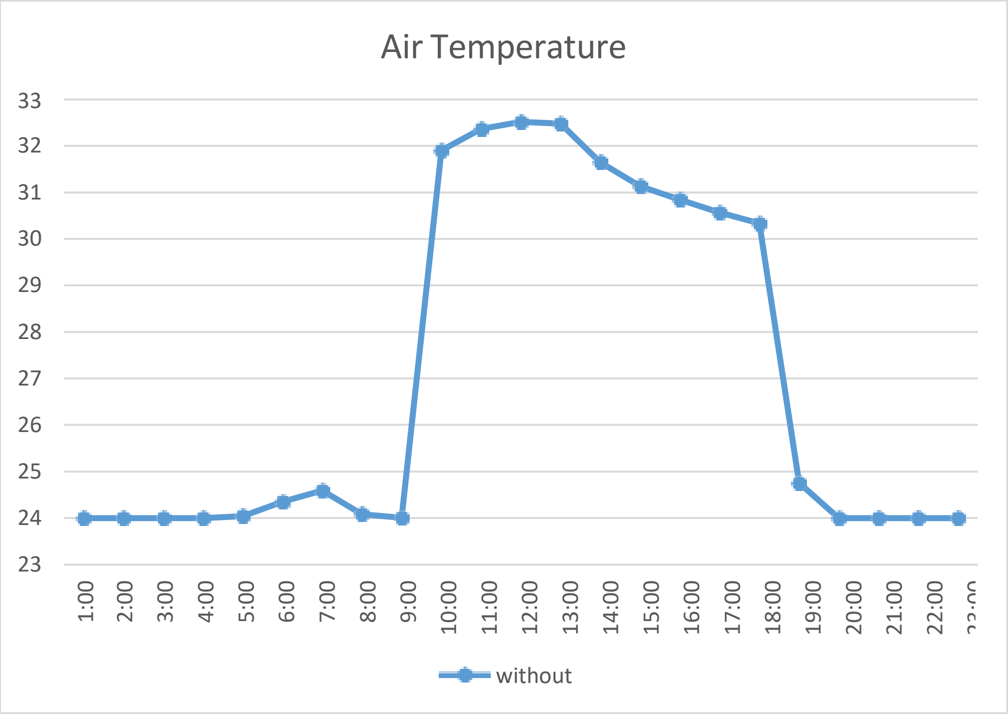

Figure 4.5: Air temperature for the hottest peak day.
Source: Author's work, (2019)

4.1.2.2 Hottest average day

The readings from design builder indicate that for the hottest day average, highest temperatures of the day were observed at 5pm to be 39.7^0 while the lowest temperature was recorded for 28.3^0 around 7am as can be seen in Figure 4.6 below. As shown in the Table 4.2 and Figure 4.6 below, lowest temperatures were recorded for night time periods and an increase in temperature for the day time.

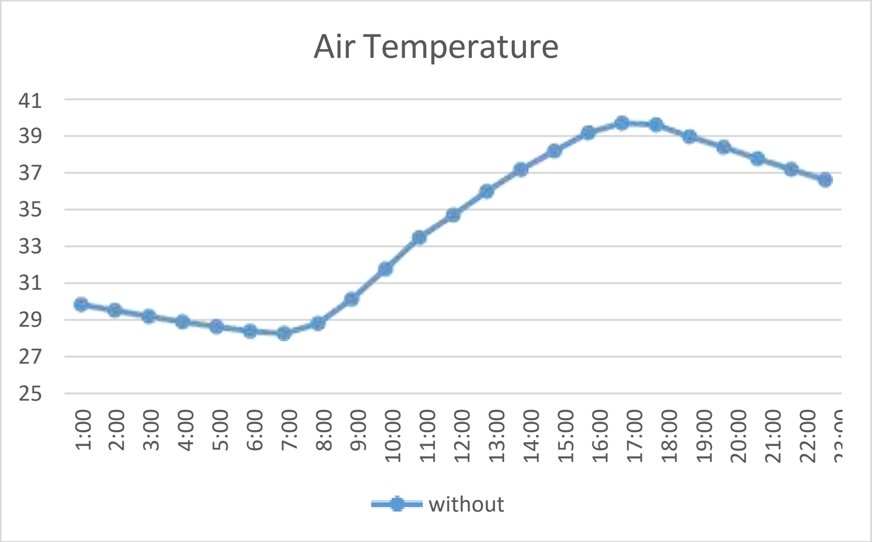

Figure 4.6: Air temperature for the hottest average day.
Source: Author’s work, (2019)

Table 4.2: Hottest peak day and hottest average day air temperature without green walls.

Time	Hottest peak day(^{0}C)	Hottest day average(^{0}C)
1:00	29.83218	29.83218
2:00	29.51978	29.51978
3:00	29.20029	29.20029
4:00	28.90307	28.90307
5:00	28.63616	28.63616
6:00	28.39485	28.39485
7:00	28.26604	28.26604
8:00	28.80255	28.80255
9:00	30.12652	30.12652
10:00	31.76885	31.76885
11:00	33.46127	33.46127
12:00	34.69061	34.69061
13:00	35.97426	35.97426
14:00	37.15049	37.15049
15:00	38.16131	38.16131
16:00	39.14789	39.14789
17:00	39.67845	39.67845

18:00	39.59436	39.59436
19:00	38.94845	38.94845
20:00	38.37509	38.37509
21:00	37.74993	37.74993
22:00	37.17606	37.17606
23:00	36.59518	36.59518

Source: Author’s work, (2019)

4.1.2.3 Coldest peak day

The readings of design builder indicate that during the coldest day peak highest temperatures of the day is observed at 11am to be 29.4^0 and 29.0^0 and lowest temperatures were recorded for 24^0 for night periods as seen below. As shown in the Figure 4.7 below, lowest temperatures were recorded for night-time periods and an increase in temperature for the daytime.

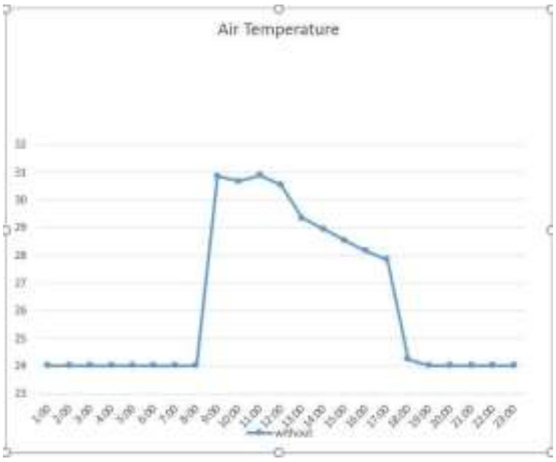

Figure 4.7: Air temperature for the coldest peak day.
Source: Author’s work, (2019)

4.1.2.4 Coldest average day

As for the coldest day average highest temperature of the day of is observed at 9am and 1pm to be 30.9^0 as can be seen in Figure 4.8 below while the lowest temperatures were recorded for 24^0 for night periods. As shown in the Table 4.3 and Figure 4.8, lowest temperatures were recorded for night time periods and an increase in temperature for the day time.

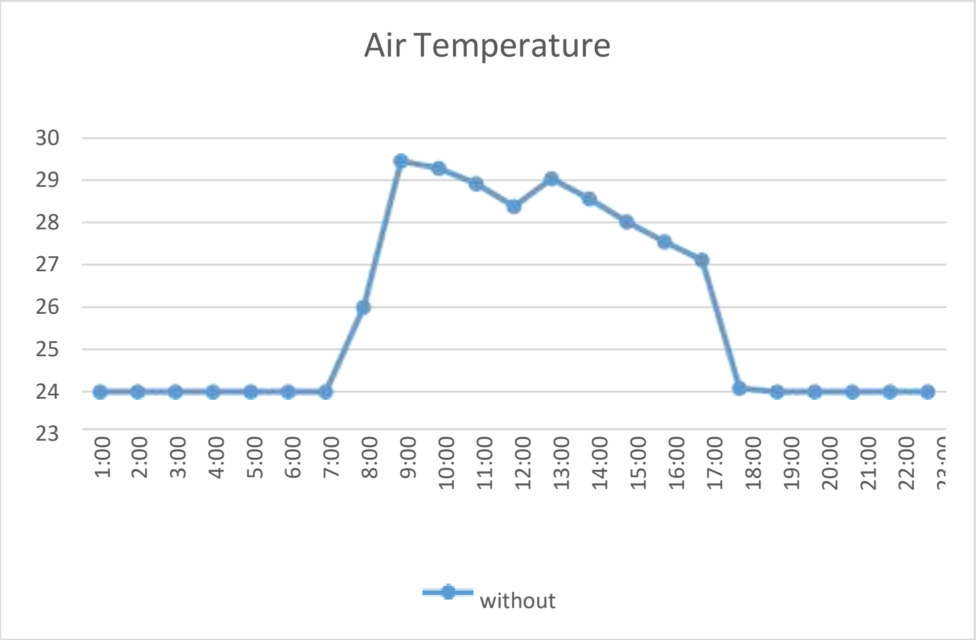

Figure 4.8: Air temperature for the coldest average day.
Source: Author’s work, (2019)

Table 4.3: Coldest peak day and coldest average day air temperature without green walls.

Time	Coldest peak day(^{0}C)	Coldest average day(^{0}C)
1:00	24	24
2:00	24	24
3:00	24	24
4:00	24	24
5:00	24.00699	24
6:00	24.00309	24
7:00	24.00049	24
8:00	24.00007	26
9:00	30.85802	29.44718
10:00	30.66859	29.27159
11:00	30.8933	28.91043
12:00	30.54627	28.37529
13:00	29.33847	29.03228
14:00	28.94985	28.55387
15:00	28.52916	28.01219
16:00	28.15589	27.53752
17:00	27.84188	27.11294
18:00	24.23575	24.08216
19:00	24.00044	24
20:00	24.00002	24
21:00	24	24
22:00	24	24
23:00	24	24

Source: Author’s work, (2019)

4.1.3 Base case simulation with green walls

The building was modelled using design builder as shown in Figure 4.9 and green walls were placed which had a variation of air cavity of 200mm and 400mm, it was done to observe the effect of the green wall and increase in cavity on the air temperature of the building.

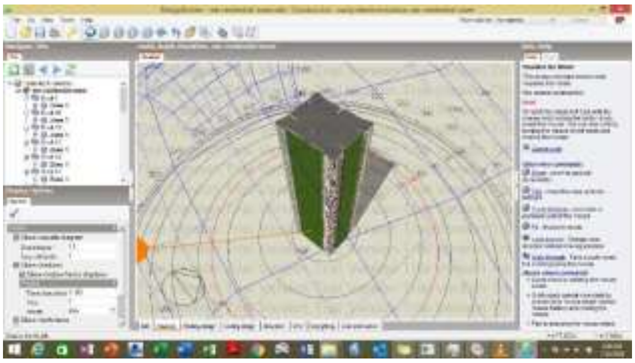

Figure 4.9: Base case with green wall on design builder interface.
Source: Author's work, (2019)

A green wall was placed on all the four glazed sides of the building to test the effect of the green wall on the building as can be seen in Figure 4.9 and Figure *4*.10. This was also done to reduce the effects of solar orientation on the simulation runs.

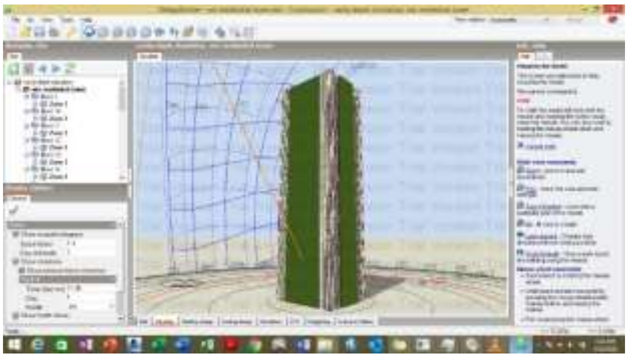

Figure 4.10: Base case with green walls placed on all four glazed sides.
Source: Author's work, (2019)

Results revealed that an increase in the cavity depth of the green wall to 400mm resulted in increase in temperatures compared to 200mm cavity depth. Results are measured on the hottest day peak, hottest day average, coldest day peak and coldest day average and presented below.

4.1.3.1 Hottest peak day

Tests revealed that during hottest day peak the hourly internal temperature of the base case with the proposed green wall recorded a lowest temperature reduction around 9:00am to 5:00pm. From 3:00am to 9:00am the temperature of the base case increases. Table 4.4 and Figure 4.11 below show the internal temperature of the base case with proposed green wall variations.

Table 4.4: Comparing base case without green wall and base case with green walls with different cavity depth during the hottest peak day.

Time	without	Green wall 200mm (^{0}C)	Green wall 400mm (^{0}C)
1:00	24	24	24
2:00	24	24	24
3:00	24	24.06322	24.13722
4:00	24	24.3122	24.4323
5:00	24.0442	24.99491	25.32713
6:00	24.3509	25.53011	25.63461
7:00	24.59113	25.76381	26.81122
8:00	24.08338	24.53865	25.43322
9:00	24.00742	24.11896	24.01264
10:00	31.90869	31.07257	31.56429
11:00	32.36422	32.00485	32.21674
12:00	32.51866	31.77114	31.99256
13:00	32.48063	31.67227	31.79853
14:00	31.65419	30.83597	31.00112
15:00	31.13488	30.31578	30.76932
16:00	30.84928	30.05791	30.45632
17:00	30.57381	29.80968	30.12421
18:00	30.3335	29.6076	29.89754
19:00	24.75694	24.62414	24.70154
20:00	24	24	24

21:00	24	24	24
22:00	24	24	24
23:00	24	24	24

Source: Author’s work, (2019)

i. *200mm cavity depth*

The results from the simulation has revealed that for air cavity of 200mm, lowest internal temperature is obtained having a maximum temperature reduction of 0.9°C achieved in hot season particularly during the day time at 2:00pm. The peak hours between 11am to 6pm experienced a temperature range of 32.0°C to 29.6°C as opposed to the initial range of 32.4°C to 30.3°C which can be seen in Table 4.4 above.

ii. *400mm cavity depth*

The results from the simulation has revealed that for air cavity of 400mm, lowest internal temperature is obtained having a maximum temperature reduction of 0.7°C achieved during the day time at 2:00pm. The peak hours between 11am to 6pm experienced a temperature range of 32.2°C to 29.9°C as opposed to the initial range of 32.4°C to 30.3°C as shown in Table 4.4 above and Figure 4.11 below.

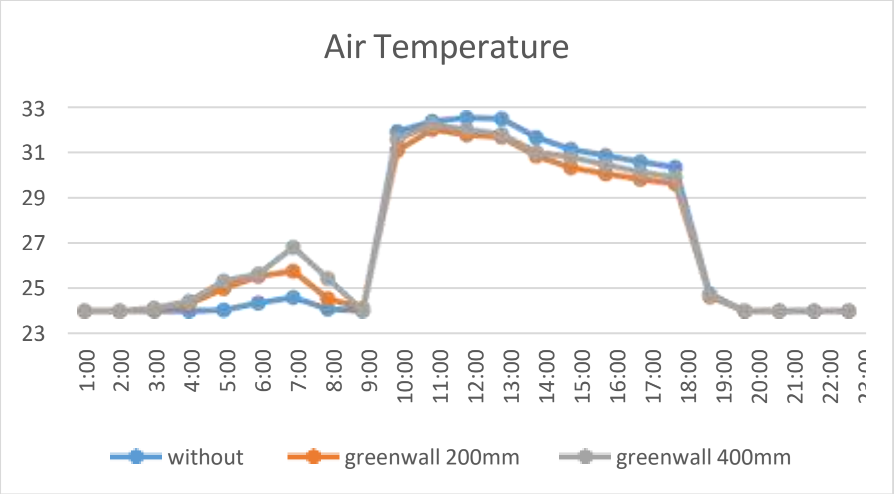

Figure 4.11: Air temperature hottest peak day with green walls and cavity depths.

Source: Author’s work, (2019)

4.1.3.2 Hottest day average

The simulations have revealed that during hottest day average the hourly internal air temperature of the base case with the proposed green wall recorded a lowest temperature reduction around 1:00am to 6:00am. From 9:00am to 6:00pm the temperature of the base case increases after which it begins to drop. Table 4.5 and Figure 4.12 below show the internal temperature of the base case with proposed green wall.

Table 4.5: Comparing base case without green wall and base case with green walls with different cavity depth during the hottest average day

Time	without	Green wall 200mm (^{0}C)	Green wall 400mm (^{0}C)
1:00	29.83218	28.54086	28.99578
2:00	29.51978	28.2735	28.86457
3:00	29.20029	27.99315	28.34357
4:00	28.90307	27.7346	28.23643
5:00	28.63616	27.51005	27.943445
6:00	28.39485	27.31173	27.76523
7:00	28.26604	27.17986	27.66941
8:00	28.80255	27.41708	27.91132
9:00	30.12652	28.14311	29.18432
10:00	31.76885	29.26805	30.22348
11:00	33.46127	30.51982	31.38952
12:00	34.69061	31.74416	32.74321
13:00	35.97426	32.83551	33.98542
14:00	37.15049	33.73824	35.68924
15:00	38.16131	34.63462	35.87692
16:00	39.14789	35.24026	36.84654
17:00	39.67845	35.53628	36.98681
18:00	39.59436	35.40498	36.57763
19:00	38.94845	34.85049	35.86744
20:00	38.37509	34.36697	35.38865
21:00	37.74993	33.93148	34.84626
22:00	37.17606	33.4896	34.37532
23:00	36.59518	33.06268	34.14774

Source: Author (2019)

iii. 200mm Cavity Depth

The results from the simulation has revealed that for air cavity of 200mm, the lowest internal temperature is obtained having a maximum temperature reduction of 4.2°C achieved in hot season particularly during the day time at 5:00pm. The peak hours between 11am to 5pm experienced a temperature range of 30.5°C to 35.5°C as opposed to the initial range of 33.5°C to 39.7°C, as shown in Table 4.5 above and Figure 4.12 below.

iv. 400mm Cavity Depth

The results from the simulation has revealed that for air cavity of 400mm, lowest internal temperature is obtained having a maximum temperature reduction of 2.7°C achieved during the day time at 5:00pm. The peak hours between 11am to 5pm experienced a temperature range of 31.4°C to 37.0°C as opposed to the initial range of 33.5°C to 39.7°C, as shown in Table 4.5 above and Figure 4.12 below.

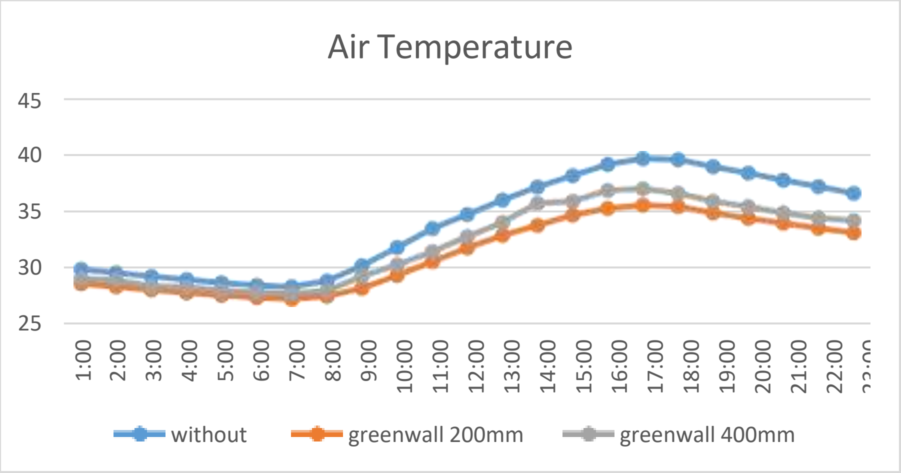

Figure 4.12: Air temperature hottest average day with green walls and cavity depths.
Source: Author’s work, (2019)

4.1.3.3 Coldest peak day

The results from the simulation has revealed that during coldest day peak the hourly internal air temperature of the base case with the proposed green wall recorded a lowest temperature reduction around 7:00pm to 8:00am. From 8:00am to 5:00pm the temperature of the base case increases after which it begins to drop. Table 4.6 and Figure 4.13 below show the internal temperature of the base case with proposed green wall.

Table 4.6: Comparing base case without green wall and base case with green walls with different cavity depth during the coldest peak day.

Time	**without**	**Green wall 200mm (^{0}C)**	**Green wall 400mm (^{0}C)**
1:00	24	24	24
2:00	24	24	24
3:00	24	24	24
4:00	24	24.00019	24.00027
5:00	24.00699	24.0011	24.0045
6:00	24.00309	24.00035	24.00022
7:00	24.00049	24.00004	24.00006
8:00	24.00007	24	24.00001
9:00	30.85802	29.5014	29.99567
10:00	30.66859	29.88221	29.82357
11:00	30.8933	29.39673	30.20111
12:00	30.54627	29.0078	30.18495
13:00	29.33847	27.73416	28.43752
14:00	28.94985	27.40315	27.03254
15:00	28.52916	27.03401	27.01243
16:00	28.15589	26.71175	26.64553
17:00	27.84188	26.45263	26.25433
18:00	24.23575	24.07052	24.17823
19:00	24.00044	24	24.00001
20:00	24.00002	24	24

21:00	24	24	24
22:00	24	24	23
23:00	24	24	24

Source: Author (2019)

v. 200mm Cavity Depth

The results from the simulation has revealed that for air cavity of 200mm, lowest internal temperature is obtained having a maximum temperature reduction of 1.5°C achieved in hot season particularly during the day time at 12:0pm. The peak hours between 9am to 6pm experienced a temperature range of 29.5°C to 24.1°C as opposed to the initial range of 30.9°C to 24.2°C, as shown in Table 4.6 above and Figure 4,13 below.

vi. 400mm Cavity Depth

The results from the simulation has revealed that for air cavity of 400mm, lowest internal temperature is obtained having a maximum temperature reduction of 0.9°C achieved during the day time at 10:00am. The peak hours between 9am to 6pm experienced a temperature range of 30.0°C to 24.2°C as opposed to the initial range of 30.9°C to 24.2°, as shown in Table 4.6 above and Figure 4,13 below.

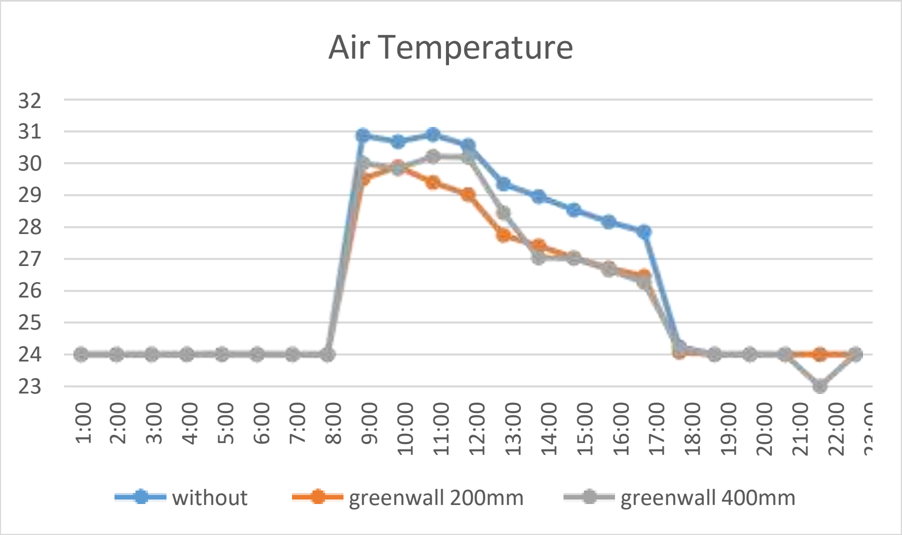

Figure 4.13: Air temperature coldest peak day with green walls and cavity depths.
Source: Author’s work, (2019)

4.1.3.4 Coldest day average

The results from the simulation has revealed that during the coldest day average the hourly internal air temperature of the base case with the proposed green wall recorded a lowest temperature reduction around 6:00pm to 7:00am. From 8:00am to 5:00pm the temperature of the base case increases after which it begins to drop. Table 4.7 and Figure 4.13 below shows the internal temperature of the base case with proposed green wall.

Table 4.7: Comparing base case without green wall and base case with green walls with different cavity depth during the coldest average day.

Time	**without**	**Green wall 200mm (^{0}C)**	**Green wall 400mm (^{0}C)**
1:00	24	24	24
2:00	24	24	24
3:00	24	24	24
4:00	24	24	24
5:00	24	24	24
6:00	24	24	24
7:00	24	24	24
8:00	26	24	24
9:00	29.44718	27.94322	28.86453
10:00	29.27159	27.51691	28.46432
11:00	28.91043	27.14364	28.14329
12:00	28.37529	26.63374	27.85355
13:00	29.03228	27.4493	28.05672
14:00	28.55387	26.99941	27.847984
15:00	28.01219	26.53276	27.37458
16:00	27.53752	26.12007	27.00023
17:00	27.11294	25.75093	26.45782
18:00	24.08216	23.96456	24.00234
19:00	24	24	24
20:00	24	24	24
21:00	24	24	24
22:00	24	24	24
23:00	24	24	24

Source: Author’s work, (2019)

vii. 200mm Cavity Depth

The results from the simulation has revealed that for air cavity of 200mm, lowest internal temperature is obtained having a maximum temperature reduction of 8.2°C achieved in hot season particularly during the day time at 12:0pm. The peak hours between 8am to

5pm experienced a temperature range of 24°C to 25.8°C as opposed to the initial range of 24°C to 27.1°C, this can be seen in Table 4.7 above and *Figure* 4.14 below.

viii. 400mm Cavity Depth

The results from the simulation has revealed that for air cavity of 400mm, lowest internal temperature is obtained having a maximum temperature reduction of 0.9°C achieved during the day time at 10:00am. The peak hours between 8am to 5pm experienced a temperature range of 24°C to 26.5°C as opposed to the initial range of 24°C to 27.1°C, this can be seen in Table 4.7 above and Figure 4.14 below.

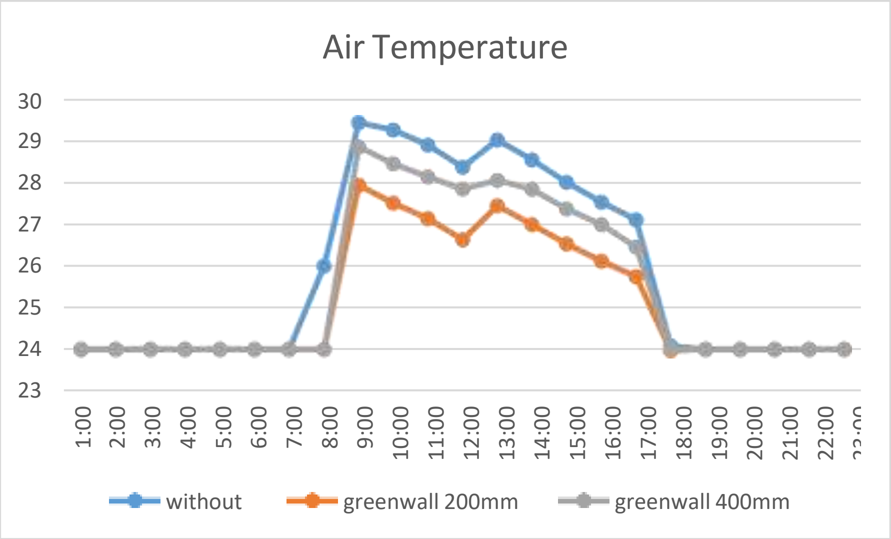

Figure 4.14: Air temperature coldest average day with green walls and cavity depths. Source: Author’s work, (2019)

4.2 Summary of Findings

The results show that for the hottest peak day in March the lowest internal temperature for 200mm and 400mm air cavity green wall is obtained having a maximum temperature reduction of 0.9°C and 0.7°C respectively achieved in hot season particularly during the day time at 2:00pm.

i. The lowest internal temperature during the hottest day average in February with 200mm and 400mm air cavity green wall obtained a maximum temperature reduction of 4.2°C and 0.7°C respectively in hot season particularly during the day time at 2:00pm.
ii. During the coldest peak day in December, the lowest internal temperature for 200mm and 400mm air cavity green wall temperature obtained a maximum temperature reduction of 1.5°C and 0.9°C respectively in cold season particularly during the day time at 12:00pm and 10:00am respectively.
iii. Results revealed that for the coldest day average in January, the lowest internal temperature for 200mm and 400mm air cavity green wall is obtained having a maximum temperature reduction of 8.2°C and 0.9°C achieved in cold season particularly during the day time at 12:00pm and 10:00am respectively.
iv. The result shows that green walls reduce the peak time indoor temperature by at least 0.9°C during the hottest month in March with a cavity depth of 200m. Therefore, green walls should be used in high rise buildings.

Results from the study shows that, application of green walling systems increase the internal thermal comfort of high-rise residential buildings and 95 percent of high-rise buildings withing FCT do not adopt this. These findings revealed that, a 200mm air cavity is 50 percent more effective than a 400mm air cavity for green walls in the bid to enhance thermal comfort in high-rise residential buildings.

4.3 Implication of Findings on Design

i. The design is going to look into thermal comfort holistically, exploring both planning strategies and the building envelope in order to achieve thermal comfort passively.

ii. The design is going to handle passively the problem of thermal comfort through the use of green walls.

iii. Balance is going to be achieved in the design of the high-rise residential building by considering a holistic approach to the core concept of the design.

iv. The design is going to make use of green walls with an air cavity of 200mm in order to achieve better indoor thermal comfort as supported by findings in the earlier parts of the chapter.

CHAPTER FIVE

5.0 STUDY AREA PROFILE

5.1 Site Selection

Site selection is a very important step while undertaking a design process, it involves the selection of a site based on key features such as proximity, suitability with the purpose of the proposed building, views, adjacent property uses, compatibility etc. Site B was chosen as it had a higher score based on the outlined site selection criteria as shown in Table 5.1 below. It has features and characteristics more suitable for the intended design over the characteristics of site A and C which had lower total scores.

Table 5.1 Site selection criteria

S/N	Criteria	Site a	Site b	Site c
1	Location/accessibility	4(8)	5(10)	4(8)
2	Access to Basic Amenities	4	4	3
3	Size of site, suitability & availability	2(4)	4(8)	0(0)
4	On-site natural elements to integrate into the design	2	2	0
5	Visual and aesthetic potentials	4	4	1
6	Land use compliance	2	3	1
	TOTAL	24	31	13

WEIGHING SCALE: EXCELLENT=**5**, VERY GOOD=**4**, GOOD =**3**, FAIR=**2**, POOR=**1**, VERY POOR=**0**.

Source: Author’s work, (2020)

5.1.1 Site location

The site is located in Umarawa along the Kano-Katsina express road on the outskirts of Abuja metropolis in the FCT with Latitude 10.6371N, 10.0807E and 628m above sea level. The FCT is bordered by Niger, Kogi, Nassarawa and Kaduna states to the north-west, north-east, south-east, and south-west respectively. It covers a total land area of 20,131 square kilometers.

The proposed site for this study is located in Umarawa along the Kano-Katsina express road on the outskirts of Kano metropolitan city the capital of Kano state bounded by seasonal traditional farmlands on both eastern and western ends and bounded by Ishiaku Rabiu city to the south and the sparsely populated residential area across the Kano-Katsina express road to the north.

5.1.2 Site analysis

The several features and distinctive characteristics of the selected site are presented and discussed under this section.

5.1.3 Climatic characteristics

The unique characteristics of every site affects the general design outcome. With that in mind, it is necessary to understand the climatic conditions of a site and accommodate them. This particular site in the FCT is classified as a tropic climate (Climate-data.org, 2020) and the following are the key features considered and catered for through various design strategies.

5.1.3.1 Temperature

At an average temperature of 29.3 °C, April is the hottest month of the year. December is the coldest month, with temperatures averaging 22.4 °C throughout the year, temperatures vary averagely by 6.9 °C. The minimum, maximum and average temperature values for all the months can be seen in Table 5.2 with colour annotations for the intensity of the temperature as well as the amount of rainfall for the corresponding months.

Table 5.2: Abuja climate table.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Avg. Temperature (°C)	22.6	25	27.6	29.3	28.2	26	24.6	23.8	24.2	25.4	24	22.4
Min. Temperature (°C)	13.8	16.4	19.3	22.1	22.1	20.5	19.9	19.4	19.3	18.8	15.5	13.3
Max. Temperature (°C)	31.5	33.7	36	36.6	34.3	31.5	29.3	28.2	29.2	32.1	32.6	31.5
Precipitation / Rainfall (mm)	0	2	4	29	88	138	255	287	170	36	0	0

Source: Climate-data.org, (2020).

From the above information on temperature and precipitation on the site, the following design strategies are going to be explored to cater for the temperature and precipitation on site.

i. Shading devices or mechanism would be employed such as- canopies, covered walkways, wide verandas, and trellis beams.

ii. Water bodies like pools and fountains around and within the building should be provided for.

iii. Shaded windows and openings to encourage good natural ventilation.

iv. Minimum use of dark colored materials outside and inside buildings to reduce absorption of heat and radiation.
v. Good orientation of building to take advantage of prevailing conditions.

5.1.3.2 Rainfall

The rainy season in the FCT lasts for about six months spanning from April to September with precipitation at the lowest in January, with an average of 0 mm. The highest amount of rain here falls in August, averaging 287 mm as seen in Table 5.2 and Figure 5.1 below. Between the driest and wettest months, the difference in precipitation is 287 mm. Proper onsite drainage is necessary to avoid unwanted ponding and stagnation on site, other design considerations are listed below:

i. Roof form would encourage effective discharge of rain water.
ii. Provision would be made for adequate drainage channel to avoid flooding.
iii. Landscaping elements would be used to discourage erosion on site.
iv. Canopies, eaves, window hoods and veranda would be employed to prevent driving rain from building through external windows and openings.
v. Building materials used would withstand moist and wet environment.

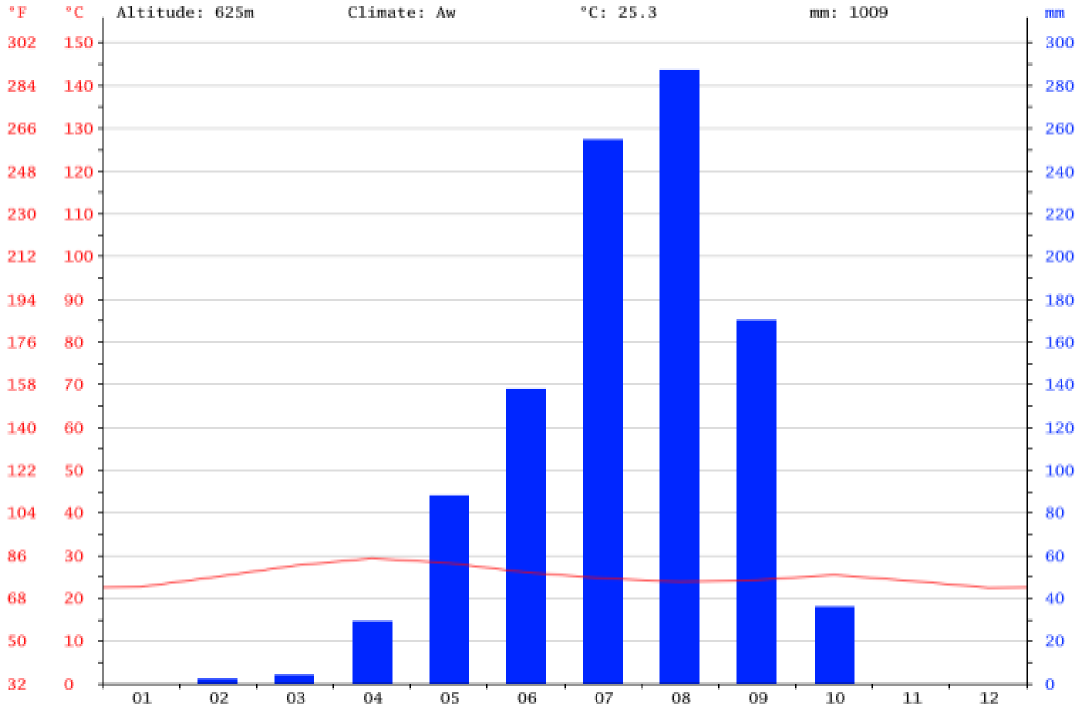

Figure 5.1 Chart of yearly precipitation in the FCT.

Source: Climate-data.org, (2020).

5.1.3.3 Wind pressure

The prevailing wind from the southwest is cool and damp, while the wind from the northeast is hot and dry. Proper orientation to optimize penetration of the southwest trade wind for adequate ventilation was adopted. Other design considerations are listed below:

i. Proper bracing of the building structure to withstand strong wind was necessary.
ii. Trees would be utilized as buffers to reduce effects of wind on the buildings.
iii. Good orientation of the building in relation to wind flow was attempted.
iv. Windows and openings are of appropriate sizes, operable and are not placed directly to the wind direction.

5.1.3.4 Solar radiation

The month with most sunshine is November with an average daily sunshine of 10 hours while the month with the least sunshine is August with an average sunshine of 5 hours as shown in Table 5.3 below. The high amount of rain witnessed in this month is the prime contributor to the very low amount of sunshine. Design considerations to cater for this are listed below:

i. Good landscaping is necessary to reduce solar radiation in the outdoor exterior.
ii. The use of sun shades and sun breakers is necessary in the building design.
iii. Good orientation of the building on site and spaces in the building is important to take advantages of the sun radiation.

Table 5.3 Average humidity and sunshine values for the FCT.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Humidity (%)	42	35	40	63	79	86	92	94	93	88	65	51
Sunshine (hrs.)	8.9	9.6	8.8	7.5	8.1	7.6	6.0	5.0	7.2	9.1	10.0	9.9

Source: Climate-data.org, (2020).

5.1.3.5 Soil and vegetation

The site is predominantly made of loamy of soil and patches of laterite. There are sparse trees and dense ground cover all around the site as the site seems to be used as a traditional seasonal farm.

5.1.3.6 Topography

The site is relatively flat all around as all parts of the site can be seen from any point, which is good for security and surveillance purposes.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

As we continue to battle with issues regarding urbanization; climate change; diminishing biodiversity; energy use; and noise pollution; plus, numerous others, there is need to take a step back and learn from nature. Nature has provided answers to many questions to enable use deal with these predicaments. The aim of this research is to utilize green walls as a tool in enhancing thermal comfort in high rise residential buildings. The study indicates how the landscape morphology influences the variation and distribution of climatic parameters and therefore gives birth to local climate which in turn influences the thermal comfort of high-rise building.

The research also reaffirms that landscape and greenery have many positive impacts in the moderation of local climate in high rise buildings. The simulation analysed a base case model without green walls and a base case with green walls using Design Builder software and the result indicated that there can be a temperature reduction of about 0.9°C during the hottest day peak with a cavity depth of 200mm

This establishes the fact that the over dependence on non-renewable energy sources, global warming, energy cost, Urban Heat Island can be reduced and there are possibilities that in the near future, green wall system can be an alternative solution to architectural developments in developing countries like Nigeria.

6.2 Recommendations

Several passive strategies were considered in the simulation, including insulation, solar shading and ventilation, as well as their two combination with each other. From the research, the effect of the most effective parameters on the indoor air temperature can be deduced as follows;

i. Thermal insulation showed the most profound effect in reducing the internal temperature during the peak hours, with an average of 2.7º below the ambient temperature outside and 4.2º below in the baseline case. The utilization of insulated walls and roofs would assist in lowering the loads in the building and are therefore worth integrating into building

ii. Adding the three strategies (ventilation, shading and insulation) has proved to be the most effective strategy to regulate the indoor temperature to approximately 37.29, that is 0.2ºC above the ambient out door temperature when it reaches 37.11ºC

iii. However, it has also been noticed that the passive strategies or their combinations could drop the temperature to comfortable levels, mainly because of the very high outdoor temperature during the hot humid season and high heat gain.

iv. Also, natural ventilation had a very limited effect, mainly due to the high ambient outside temperatures, indicating temperature of 0.6ºC above ambient temperature outside and 0.9ºC below baseline, so more landscape and green area should be incorporated in to high rise buildings for it to be effective

v. The study suggests the importance of landscape features in high rise building. This indicates that high rise buildings are more effective with green features of landscape.

vi. The study also suggests that practitioners in landscape architectural profession should have basic understanding of the relationship between native vegetation and the local climate of buildings and there by adapting it in their designs to influence the physical environments in high rise buildings.

6.3 Contribution to Knowledge

The following are the contributions made by this research:

i. The research shows that a 200mm air cavity is more effective than a 400mm air cavity for green walls in the bid to enhance thermal comfort in high-rise residential buildings.

ii. The research supports statements by previous studies on the effectiveness of green walls as a tool for enhancing thermal comfort in high-rise residential buildings.

iii. The design produced an archetypal design; showing the integration of green walls in the design of the proposed high-rise residential building.

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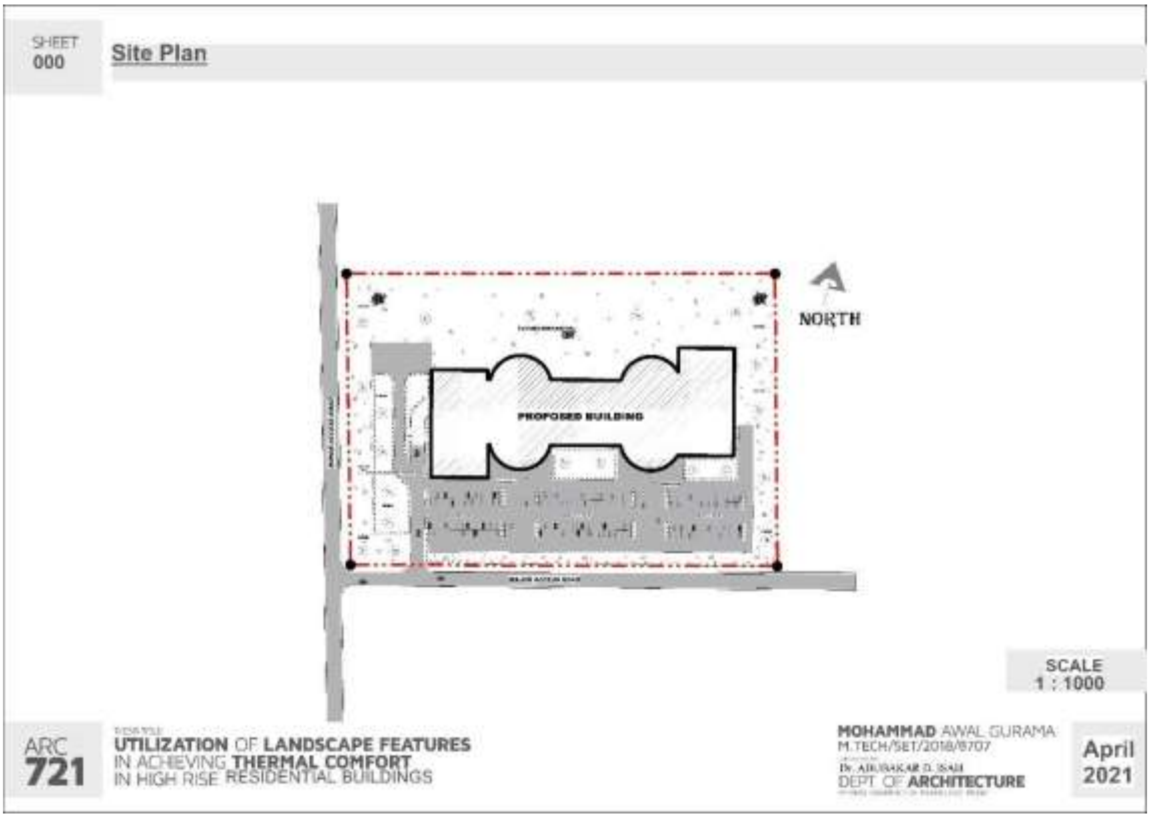
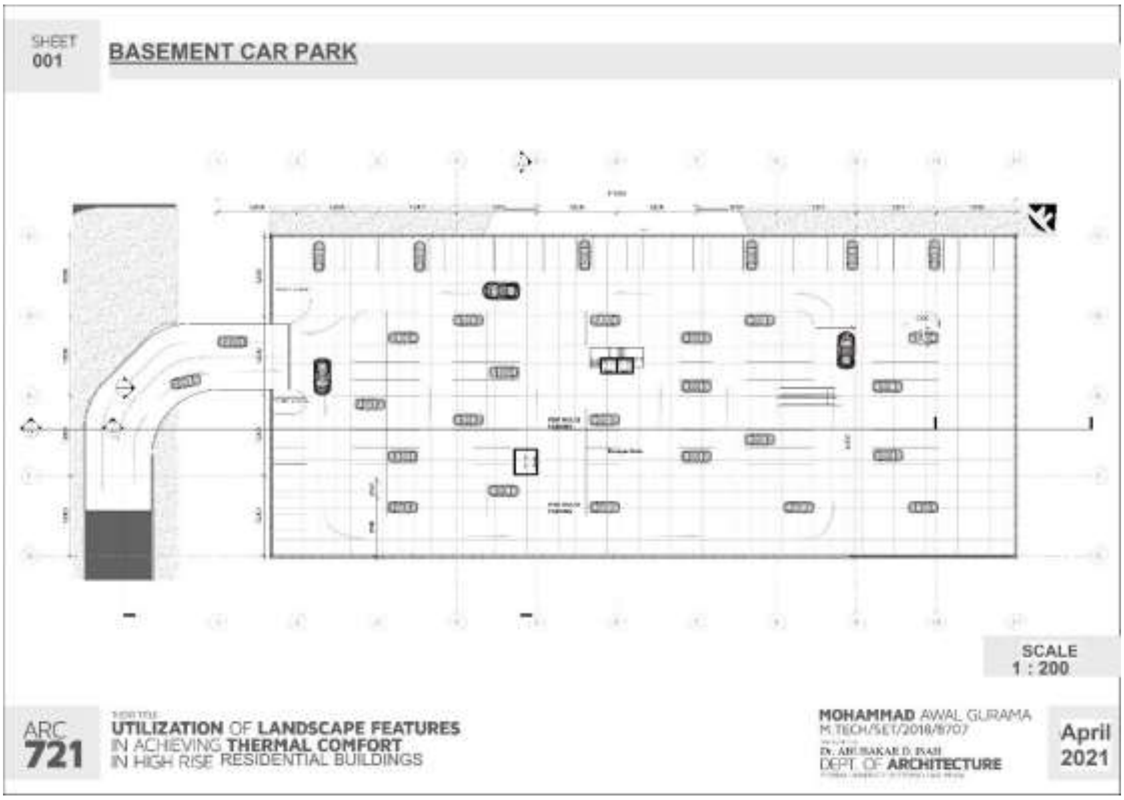
APPENDICES

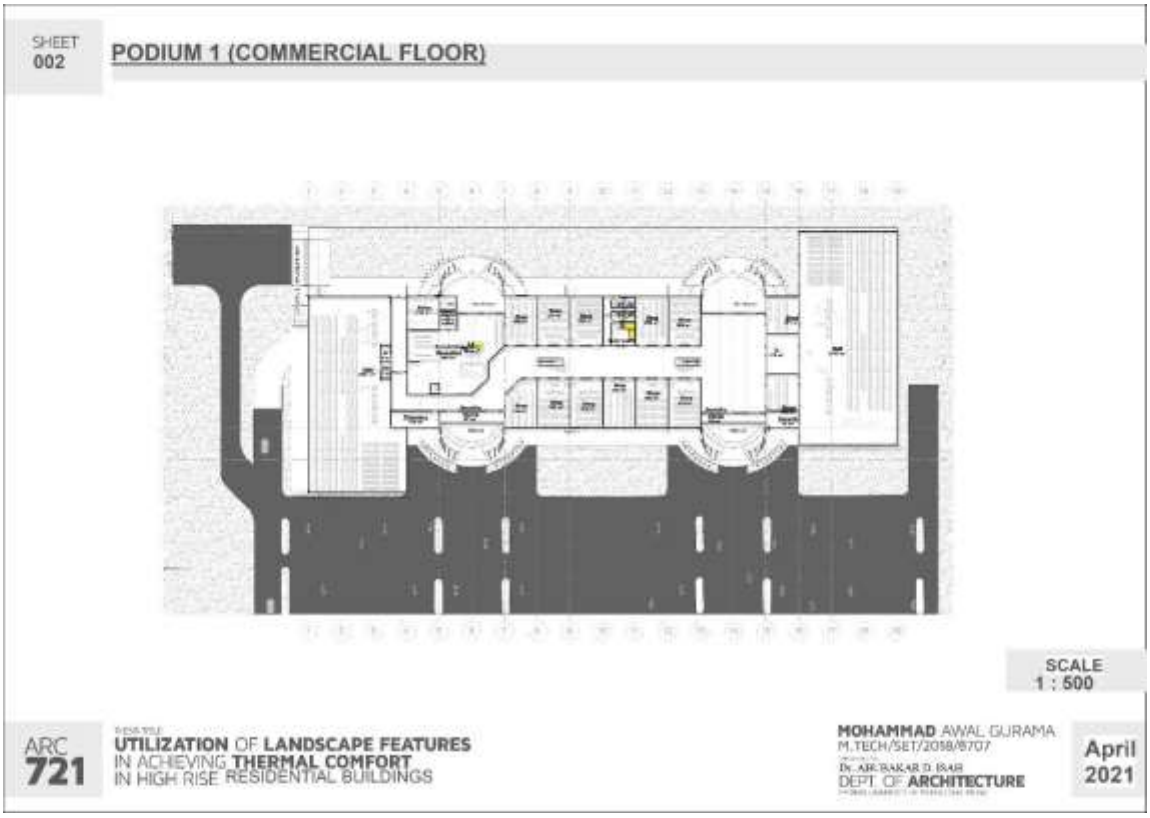
Appendix A: Site plan



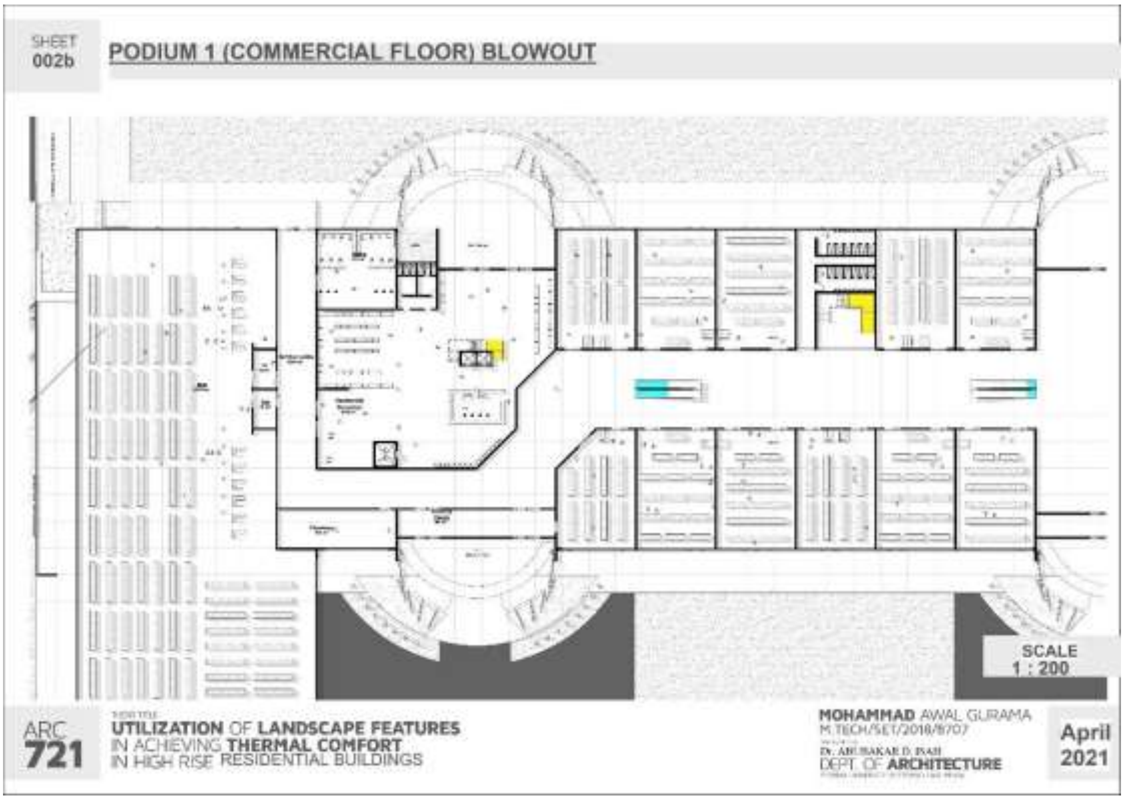
Appendix B: Basement plan



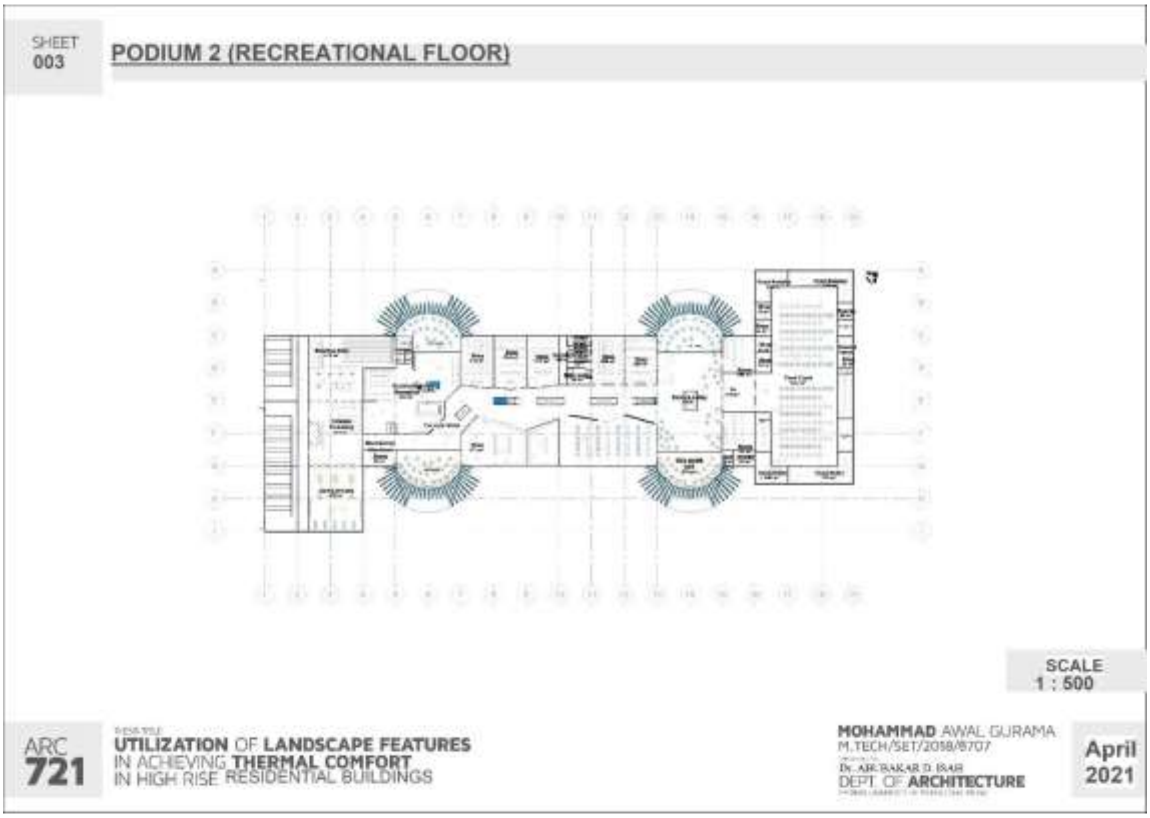
Appendix C: Podium 1 (commercial floor)



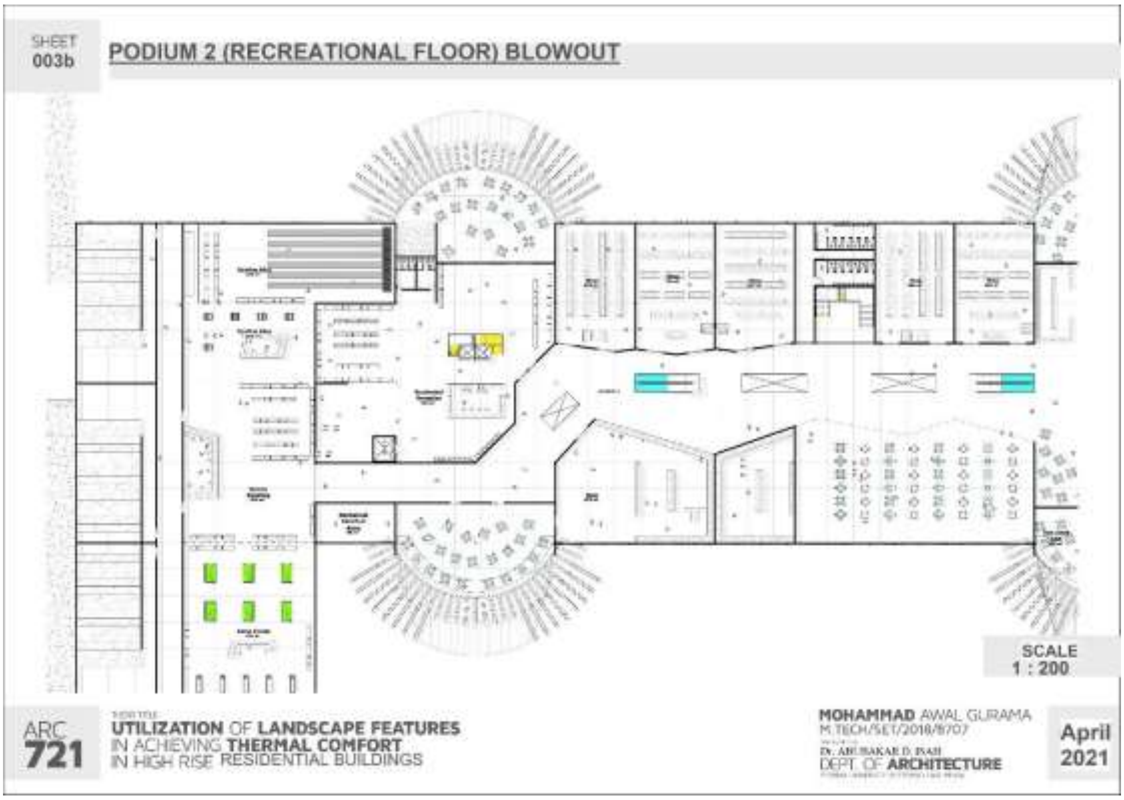
Appendix D: Podium 1 (commercial floor) blowout



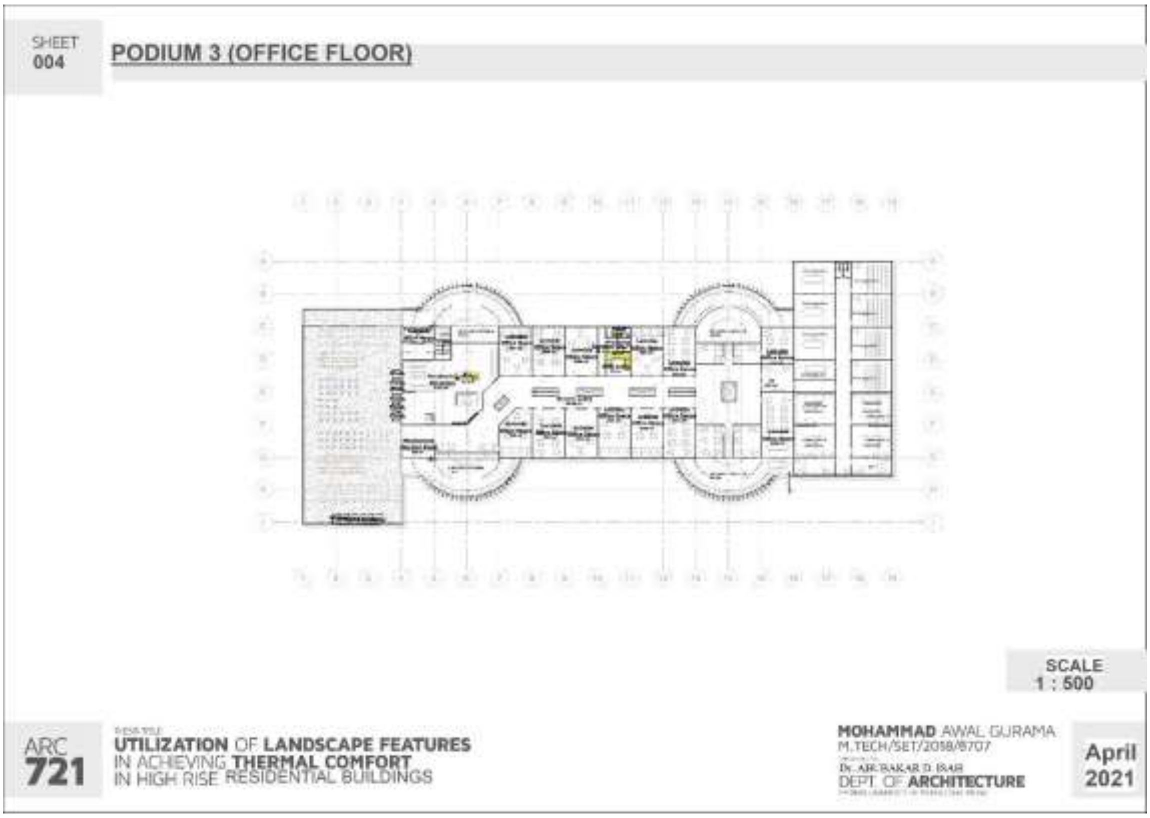
Appendix E: Podium 2 (recreational floor)



Appendix F: Podium 2 (recreational floor) blowout



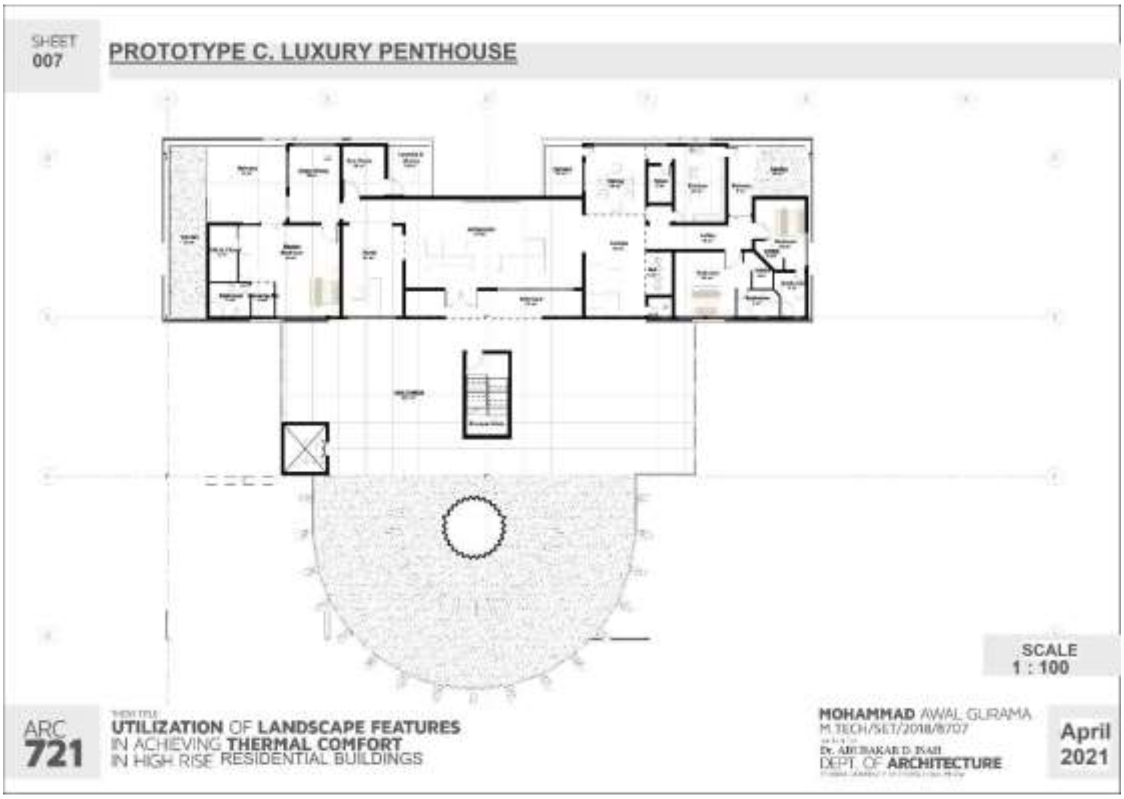
Appendix G: Podium 3 (office floor)



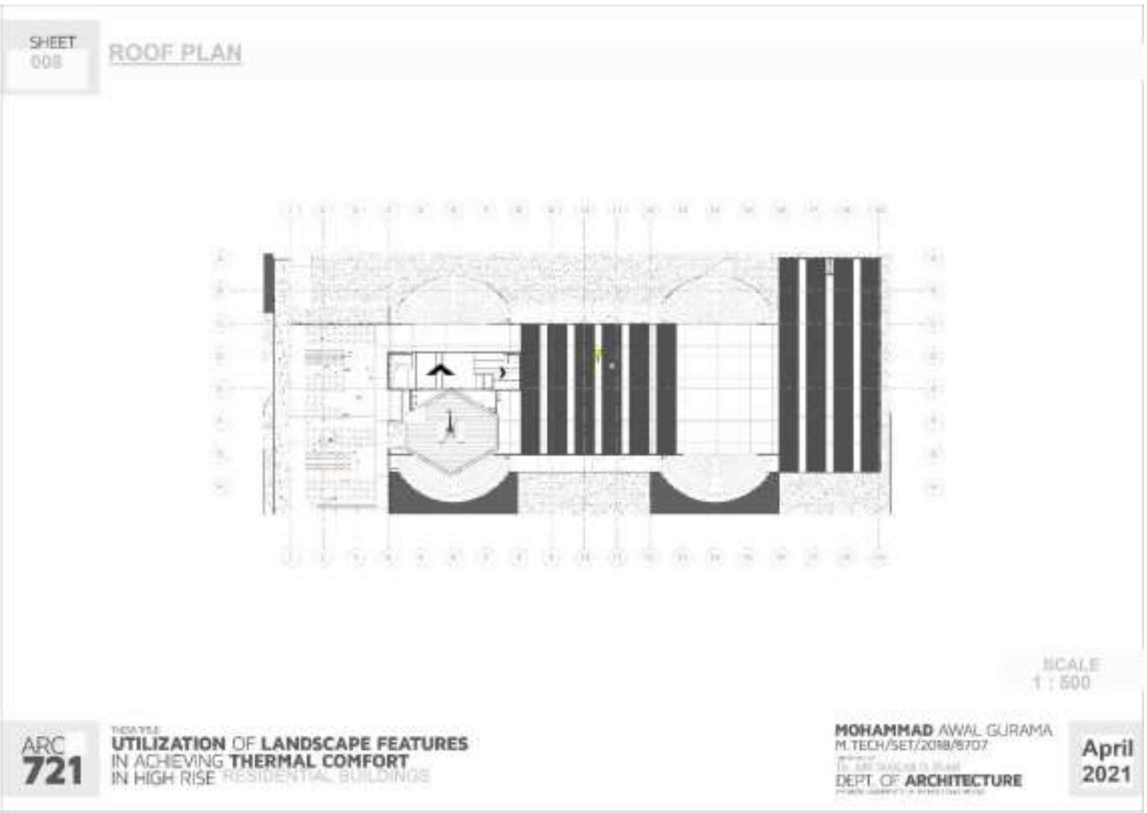
Appendix H: Prototype a (4th -16th floor)

Appendix I: Prototype b (17th -20th floor)

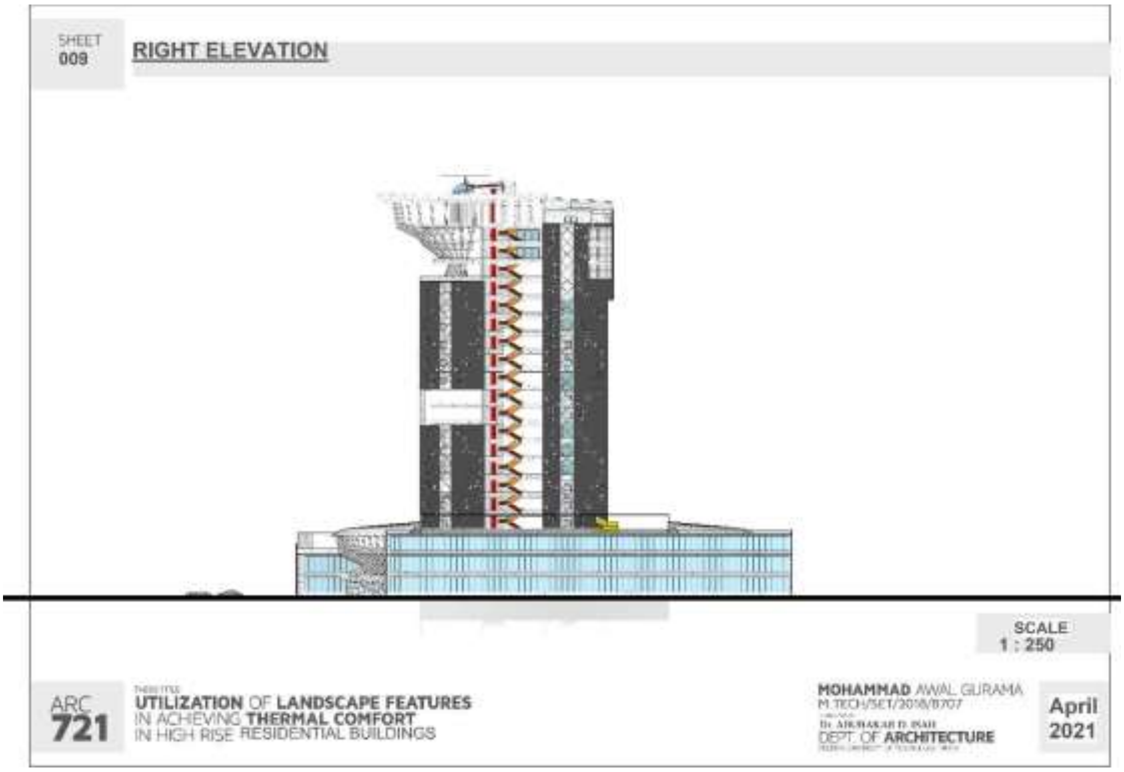
Appendix J: Prototype c (luxury penthouse)



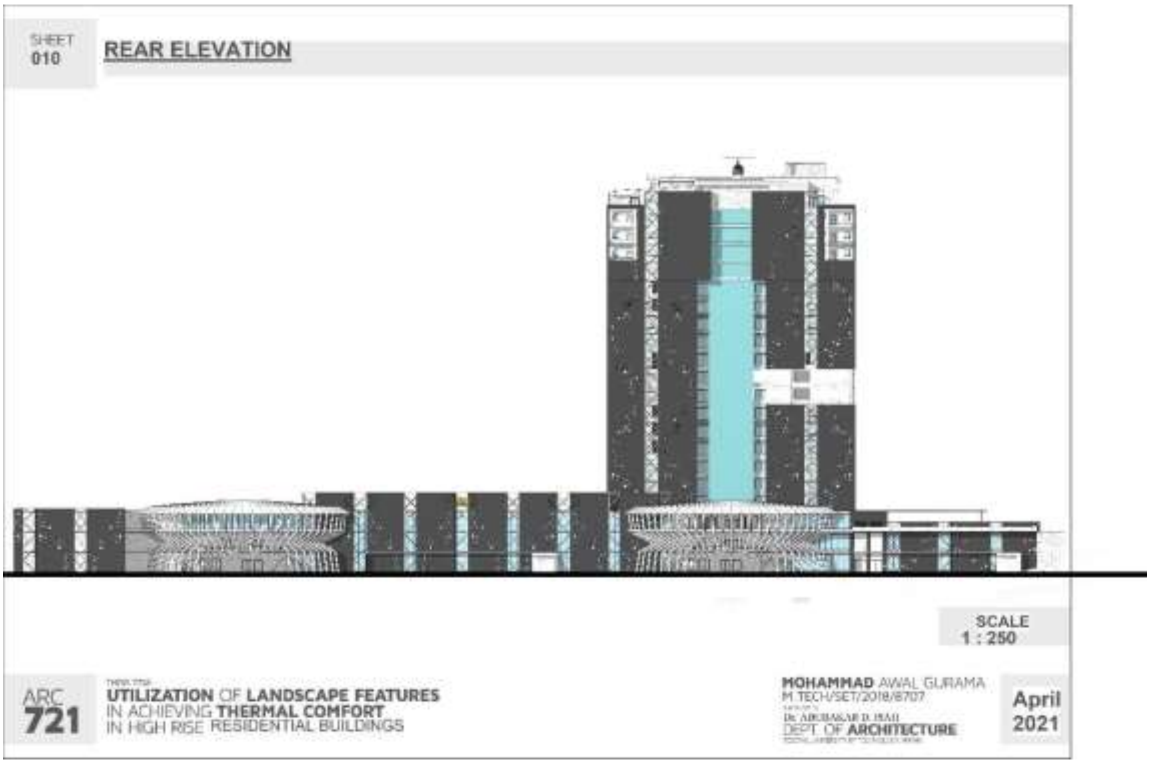
Appendix K: Roof plan



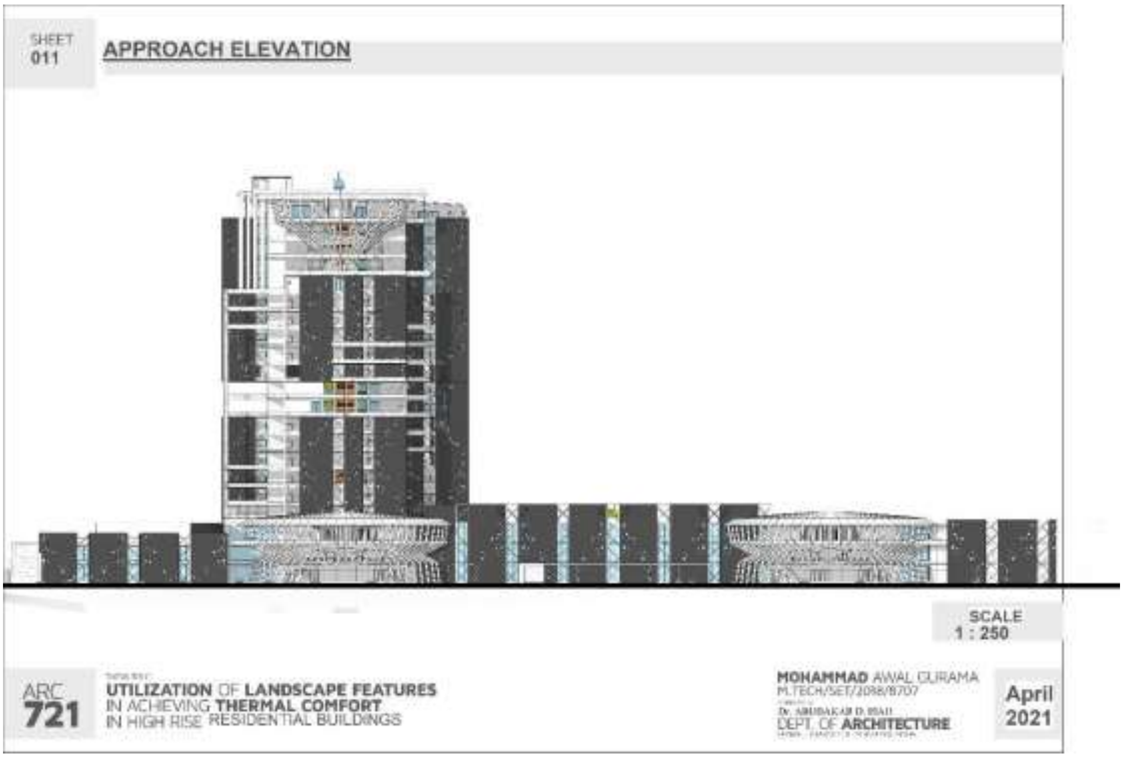
Appendix L: Right elevation



Appendix M: Rear elevation

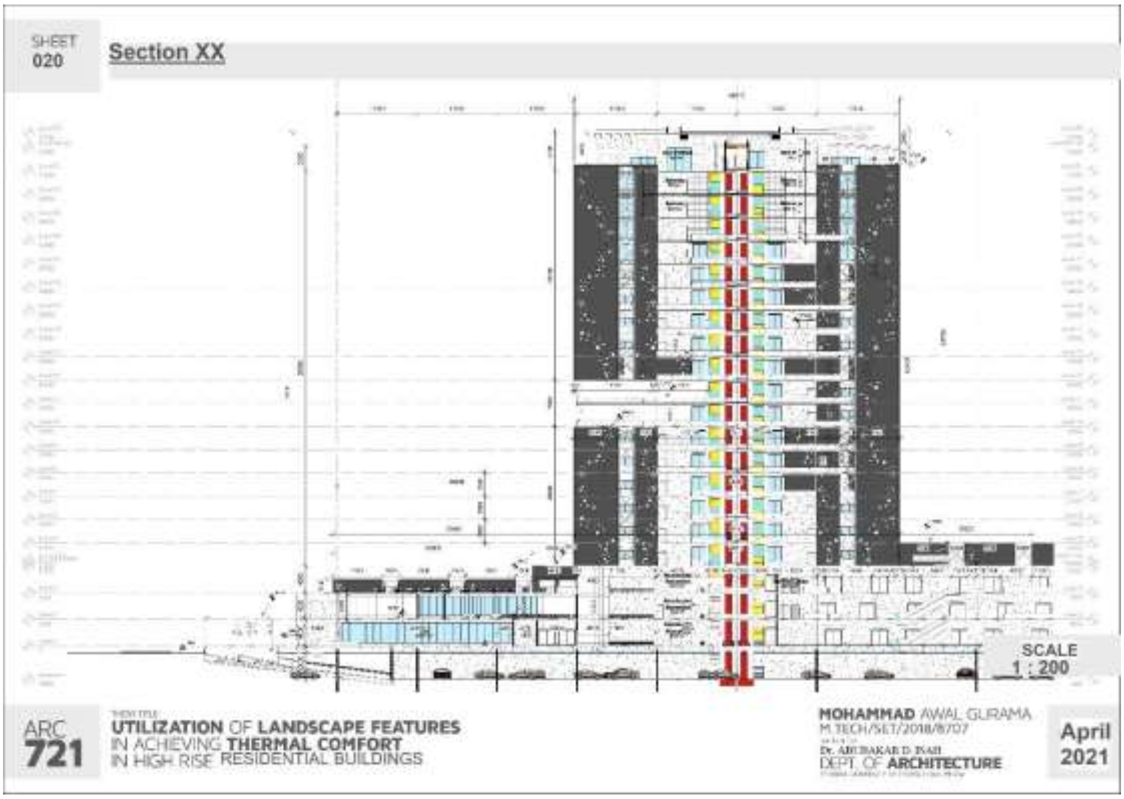


Appendix N: Approach elevation

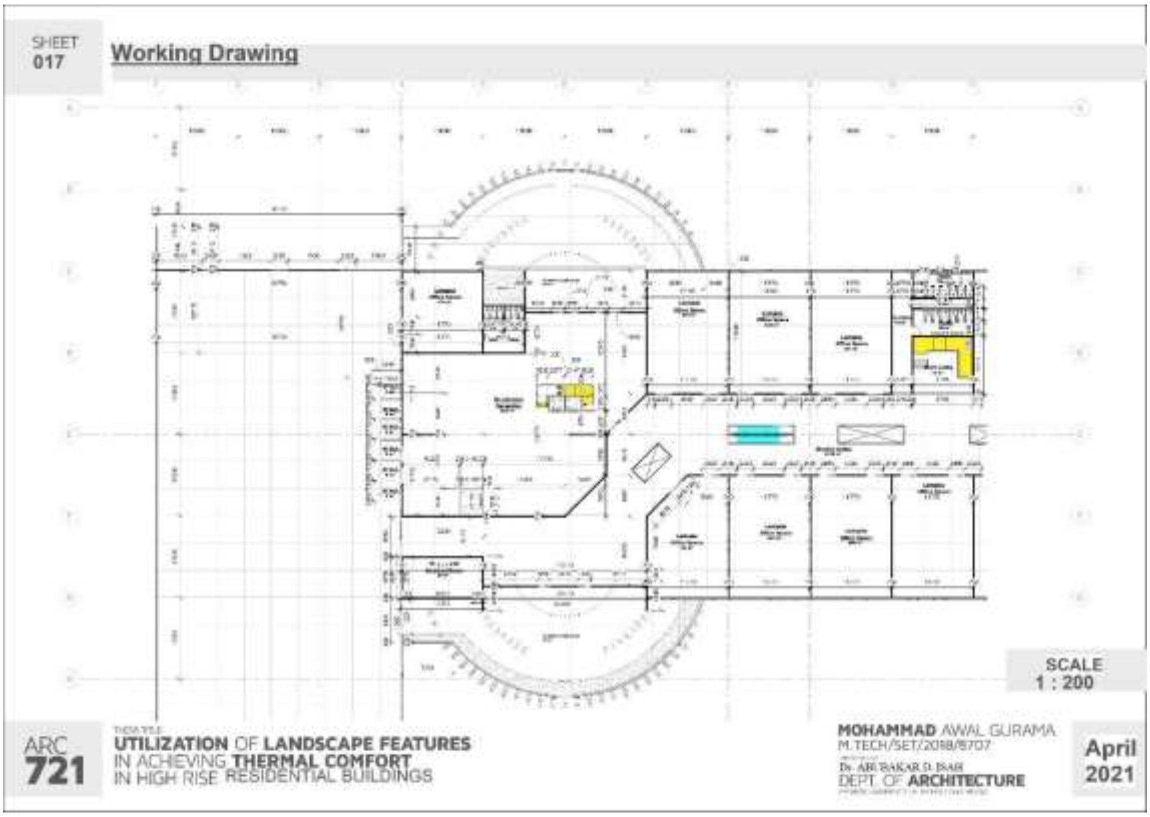


Appendix O: Section x-x

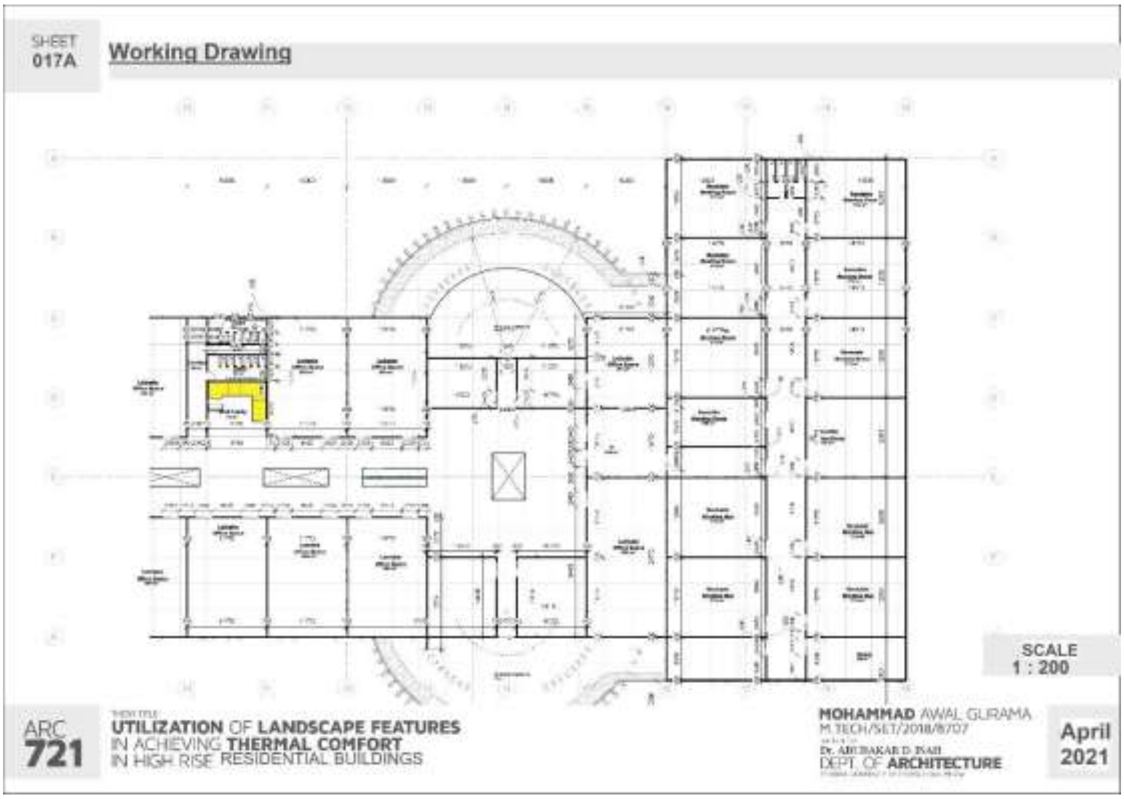
Appendix P: Section y-y



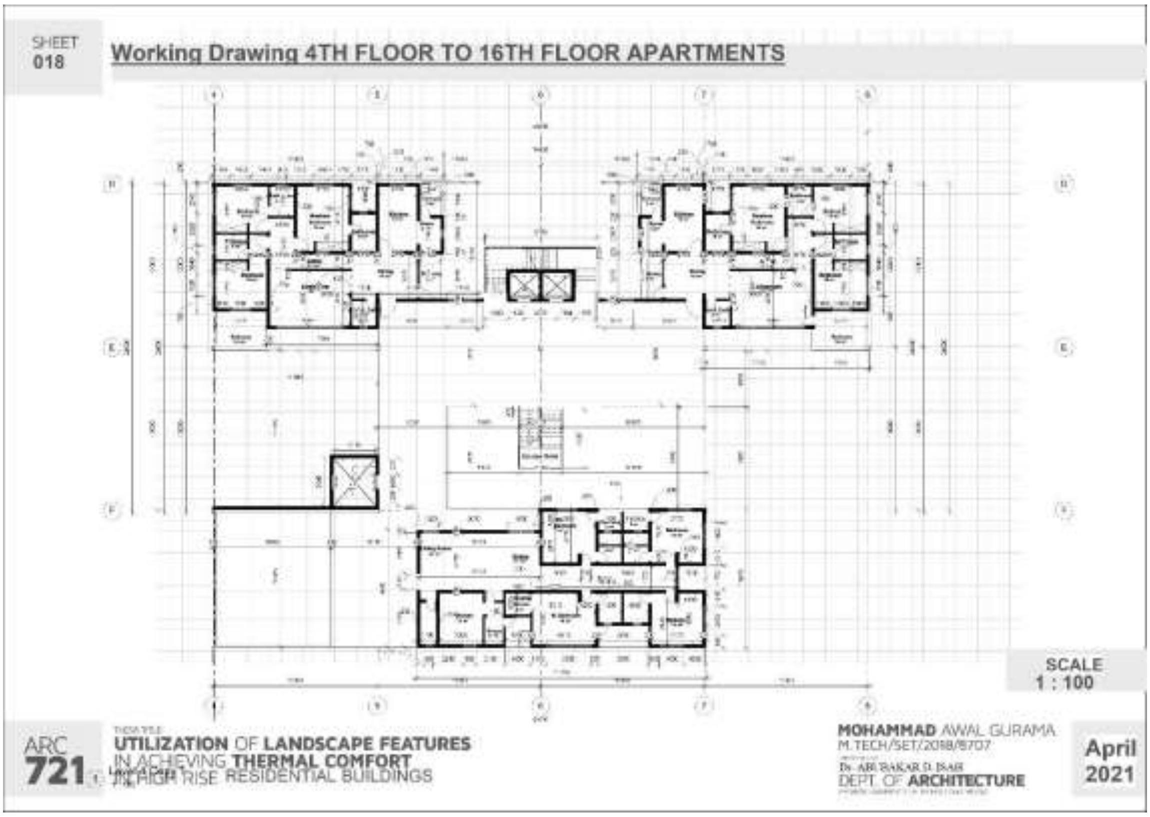
Appendix Q: Working drawing 1



Appendix R: Working drawing 2



Appendix S: Working drawing 3



Appendix T: Working drawing 4

Appendix U: 3D views (sheet 1)

SHEET
013

3ds

SCALE

ARC
721

UTILIZATION OF **LANDSCAPE FEATURES**
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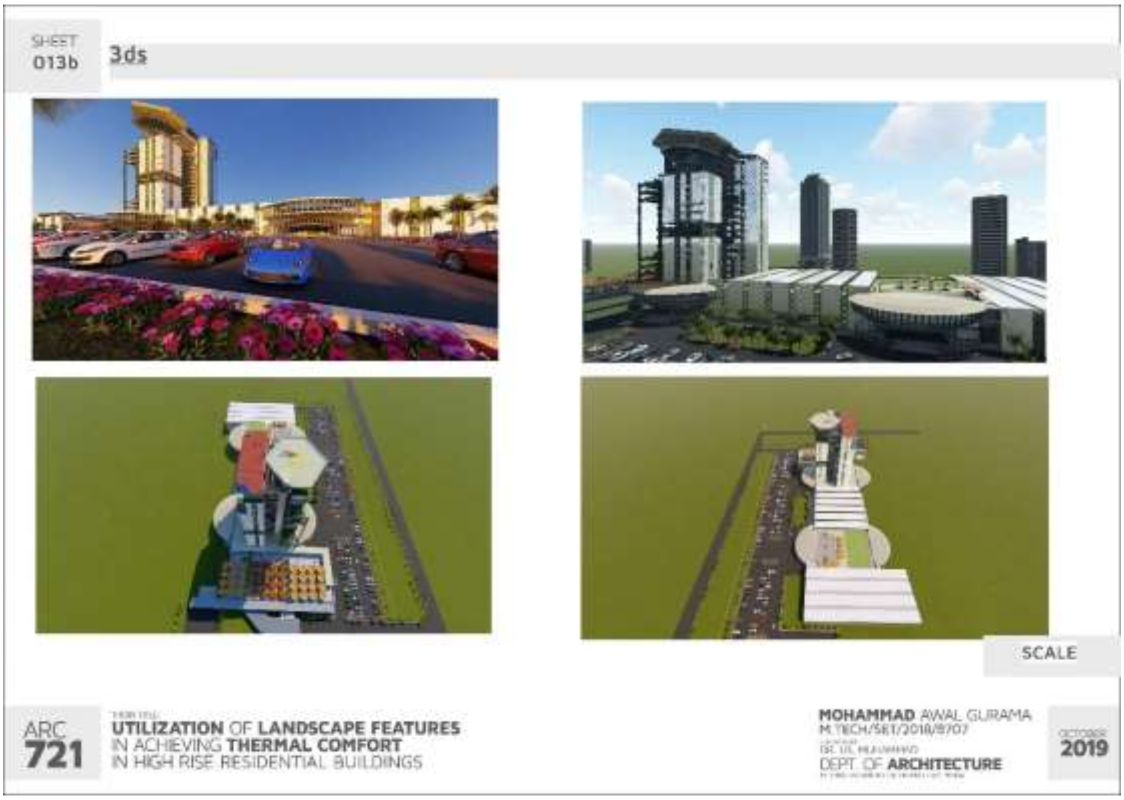
M.TECH/SET/2018/8707
DEPT. OF **ARCHITECTURE**

OCTOBER
2019

Appendix V: 3D views (sheet 2)



SHEET
013b

3ds

SCALE

ARC
721

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