A framework for incorporating Circular Economy in the Design of Energy Efficient Residential Buildings in Nigeria

By

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Thesis Submitted in fulfilment of the requirement for the Award of Doctor of Philosophy

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Welsh School of Architecture
Cardiff University, United Kingdom

Date of submission: 9th May 2022

Abstract

For buildings to meet the energy-demand in maintaining the required conditions for thermal-comfort, residents, most especially in developing-countries, are compelled to seek alternative sources of electricity due to inadequate power supply. This has resulted in the use of environmentally polluting equipment like generators to compensate for the required energy-demand, thus, leading to an increase in carbon-emissions. Passive design strategies have proven to be effective in reducing energy-demand in buildings, thus reducing carbon-emissions as well as improving building performance. There is also a substantial-drop in the availability of building materials due to poor recycling culture and the use of materials from non-renewable sources. Consequently, unrecycled building wastes pose environmental hazards. Buildings are seen to be material-banks for a circular economy, therefore incorporating a circular economy into passively designed buildings will not only safely-protect the climate but also improve resource-efficiency. This study focuses on incorporating circular economy principles into passive-design strategies for energy and resource-efficient residential buildings in Nigeria. Carbon-dioxide (CO_2) concentration in the atmosphere is still on the increase as buildings are responsible for a significant amount of this emission globally. It is therefore imperative that prompt measures are taken to combat the effect of global-warming and associated threats. Nigeria is rapidly growing in human-population, resources on the other hand have receded greatly, and there is an urgent need for circularity of building materials. The research offers an effective and efficient approach for the combination of passive-design and circular economy. The study is divided into two major aspects: Passive-design strategies and Circular economy. Passive-design strategies for the tropical-savannah climate of Nigeria were examined to assess the requirements for the climatic region. This involved a dynamic-energy simulation of a base-case residential building-typology and a further quantitative comparison with an optimised case to reflect the values of energy-efficiency between the base-case and the optimised-case. Circular economy was also subdivided into design for disassembly, and design for reuse/recycling. Recyclable/reusable building materials were sorted using the ReSOLVE framework and the building was divided into modules using the 7S model which informed the development of a material selection-matrix for identifying and selecting reusable, recyclable and energy-efficient building materials in a circular economy. After the optimisation, it was discovered that the building energy-demand improved. The research conclusively developed the approach and framework/guide for incorporating circular economy in the design of energy and resource-efficient buildings in the tropical savannah climate of Nigeria.

Keywords: Circular Economy, Energy Efficiency, Passive Design, Residential Buildings

Acknowledgement

Firstly, I thank God Almighty who has made it possible for me to do all things.

I also want to thank my supervisors - Dr Eshrar Latif and Dr Shan Shan Hou, for their inspiration and guidance throughout my PhD research.

I like to use this opportunity to appreciate my lovely Wife, for her relentless support and care.

My sincere thanks also go to the Welsh School of Architecture, Cardiff University, UK, for the enabling environment provided during my Doctoral research.

Last but not least, I appreciate my parents and family for their prayers and support.

Thank you All, I am grateful.

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Chapter One

1.0. Introduction

1.1. Research Background

The tropical region of Nigeria is relatively hot and humid, consequently, thermal discomfort occurs. Occupants try to cool down their indoor spaces with methods that are usually environmentally hazardous, unsustainable, ineffective, and inefficient which has been attributed to inadequate supply of electricity (Abatan et al. 2018; Onyenokporo and Ochedi 2018). Abbakyari and Taki (2017) revealed that at least 50% of Nigerians are without access to electricity which has led to high reliance on backup generators by households and businesses (Abbakyari and Taki 2017). Residential buildings in Nigeria are the highest consumer of energy, almost 90% of the energy consumed in Nigeria is for residential usage (Ley et al. 2015; Hussaini 2018). Carbon emissions generated from domestic generators in Nigeria are greater than those from commercial sources which pose threat to health and the environment due to extended noise and emissions, as well as a reduction in the standard of living (Olotuah 2016; Oseni 2016; Amasuomo et al. 2017).

There are three major residential building typologies within the Nigerian building stock, the three major residential typologies include multi-unit apartments, bungalows duplexes, and bungalows (Federal Ministry of Power 2017). According to Awosusi (2018), the bungalow in the Nigerian building stock is the most built among the 3 major typologies (Awosusi 2018). This is because bungalows are largely affordable to build and maintain in Nigeria (Biobaku 2018). This is true because most residential developments are executed by private individuals usually with low income who may not be able to afford larger buildings like multi-unit apartments, and bungalows duplexes since a typical bungalow are far cheaper and easier to build (Bankole 2019). However, these residential buildings are often built with little or no bio-climatic considerations thereby increasing the need for alternative energy systems (which are usually environmentally hazardous) to compensate for the poor building performance. The climate is endangered by these alternative energy supplies and the knowledge of green building practices among the built environment practitioners is low in Nigeria (Nduka and Ogunsanmi 2016).

Across the world, there are high volumes of construction waste being generated. According to the Australian Bureau of Statistics (2013), the Australian construction industry was responsible for 30.7% of the total 53.7 million tonnes accumulated in 2009 and 2010. In 2014, the United States of America generated 40% of solid waste from the construction industry, also in Europe, and waste resulting from economic activities accounted for 33.5% in 2014, one-third of total waste generated that year (Eurostat 2014). In 2016, the Official Statistics of Finland recorded about 13.8 million tonnes of generated waste (Finland Statistics 2016).

These figures clearly call for the need to redefine the design and construction of the built environment by incorporating circular economy principles which have the potential of recovering up to 80-90% of deconstruction/demolition waste (Resource-deutschland 2014). Most construction wastes end up in landfills, less than one-third is reused or recycled (WEF 2016). In Nigeria, circular economy principles are still yet to be incorporated in buildings, there are no recycling programmes, waste minimisation policies and exposure to sustainable construction concepts for buildings. As a result, building materials are scarce and the available ones are very expensive – one of the results of the increase in global population (Nwokoro and Onukwube 2015). The World Bank (2012) estimates that municipal solid waste may increase by 900 million tonnes by 2025 (World Bank 2012). This indicates an increase in the pollution of the environment and the need for interventions to reduce waste.

There is a need for the adoption of circular economy principles due to significant drops and the high cost of building materials. Studies have identified that ecological destruction and resource depletion are the major environmental consequences of the development of the built environment as the outcome of unrecycled resources amounts to increased waste and pollution (Plagányi et al. 2013; Song et al. 2015; Vieira and Pereira 2015). Oko & Emmanuel (2013) noted that high volumes of waste are usually associated with pollution, climate change and resource depletion as waste from the construction industry has negative impacts on the environment (Oko John and Emmanuel Itodo 2013). Recycling of buildings is not yet a common practice in Nigeria, the practice has great potential in reducing finite resources through reuse and recycling while resources are conserved (Ogunmakinde et al. 2019). The transition into a circular economy would start from the design of products to the adoption of contemporary business models, and an embracement of innovative consumer consumption models, thus a holistic approach is needed (Smol et al. 2015).

Passive design strategies and circular economy principles are two areas of great prospects in the Nigerian building sector which are new areas for exploration and implementation. Also, these two interventions have not been combined in Nigerian residential buildings, which is one of the novelties of this research. Therefore, this research is focused on creating a framework for the application of passive design strategies and circular economy principles in the delivery of residential buildings that are energy and resource efficient.

1.2. Statement of Problem

Nigeria is estimated to have a deficit of 17 million housing units (World Bank 2015). In 2018, Nigeria's population grew by 14 million between 2015 to 2018, further increasing the demand for housing and infrastructure (World Bank 2018). An indication that more residential buildings are required. However, this could also mean more CO_2 pollution if appropriate measures are not taken to deliver homes that are energy and resource-efficient. According to the National Bureau of Statistics (2018), the construction of buildings in Nigeria is expected to grow according to the country's population and generate increasing amounts of waste (National Bureau of Statistics 2018).

Power supply is also insufficient as about 60 million Nigerians rely on private generators which are constantly causing noise, pollution, stress and high expenditures for occupants (Abbakyari and Taki 2017; Geissler et al. 2018). Despite the failing electricity supply, coupled with fuel scarcity posing problems for individuals to run personal generators in Nigeria, new buildings are predominantly designed with little or no bioclimatic considerations - a design approach that does not take advantage of the climatic characteristics of the building's location (Uyigue et al. 2009). Instead, residents try to balance local conditions with increased use of building services usually associated with an enormous amount of energy for air-conditioning, lighting, etc., thereby increasing energy cost (Abbakyari and Taki 2017; Geissler et al. 2018).

The awareness of passive design strategies is still very low, there is also negligence in incorporating sustainable concepts in the construction of buildings (Dania et al. 2013), as a result, best design considerations and basic design standards are not taken for optimal performance in Nigerian residential buildings. This problem can also be attributed to the local town planning authorities due to inadequacy in the provision of responsive master plans and proper monitoring of building projects (Agbola 1988; Iheme et al. 2011). Consequently, residential buildings often perform poorly with regard to energy and resource efficiency since most residential buildings fail to employ passive design strategies (Uyigue et al. 2009). This is so because the detached bungalow which is the most commonly built residential building typology in Nigeria is usually privately built by individuals with the least expertise and awareness on passive strategies for the Nigeria environment, therefore, pressuring residents to use crude means to maintain some relative comfort in these buildings (Uyigue et al. 2009). The tropical region of Nigeria is hot, and the weather condition can be managed to benefit residential developments (Holmes and Hacker 2006). Geissler et al. (2018) stated that climate-adaptive design is key to reducing electricity consumption for cooling in a cost-efficient way (Geissler et al. 2018). This is yet to be a reality in Nigeria

Building materials on the other hand have also receded greatly and have become very scarce and expensive in Nigeria due to poor recycling culture and building waste prevention systems. This is mainly a result of a lack of waste reduction policies (Nwokoro and Onukwube

2015). There are high potentials for building waste to be reused or recycled in Nigeria but often they are sent to landfills or left abandoned and thus becomes a residing hazard to the environment (Nwokoro and Onukwube 2015).

Nigerian residential buildings are mostly not built to be deconstructed or recycled and this makes it more difficult to maximise the longevity of the building, thus, contributing to environmental degradation (Somorin et al. 2017). Previous research has reported that recycling is the least considered waste management measure in Nigeria (Eze et al. 2017). In Nigeria, the construction waste management system is generally poor because there are little or no provisions for it (Oladiran 2009). Ogunmakinde (2019) noted that much work has not been done in the exploration of circular economy concepts in the construction industry, despite it being identified as a sustainable concept (Ogunmakinde 2019). John Alonge from the National Environmental Standards and Regulations Enforcement Agency (NESREA) in Nigeria asserted that "Green economy supports a circular economy in which the use of materials and generation of waste are minimised and any remaining waste recycled, remanufactured or retreated in a way that causes the least damage to the environment and human health" (Alonge 2018).

The building sector has been said to account for approximately 40% of the total energy consumption and most of this energy is used to maintain adequate indoor climate (Nielsen 2012). Buildings are also responsible for approximately 40% of carbon emissions (IEA 2019). Building resources on the other hand are constantly being depleted. Studies in Nigeria, Egypt, Thailand and India revealed that 1 among 25 factors contributing to causes of non-excusable construction delays is attributed to material inaccessibility, and shortage of material (Kırbaş and Hızlı 2016; Rahman et al. 2017).

Energy-efficient building interventions are still in their infancy in Nigeria which is rarely considered in residential building design and construction nor principles towards building disassembly or recycling in a circular economy system mentioned (Uyigue et al. 2009). Globally, circular economy is still a new trend, hence, programmes, policies and designs are yet to fully kick off to remedy this potential threat especially in Nigeria. In the UK, over 60 million tonnes of the construction sector waste are disposed to landfills every year of which some are hazardous to the environment due to inadequate recycling culture (WRAP 2019). Therefore, it is expedient that Nigeria employs a framework that ensures the delivery of residential buildings that are energy and resource-efficient.

1.3. Importance of the Research

The study focused on the establishment of an energy and resource efficient design framework which will serve as a guide for incorporating circular economy in the design of energy-efficient residential buildings in Nigeria. Our world is constantly changing due to the environmental activities orchestrated mainly by humans. Climatic change continues to pose a threat as the built environment continues to build up carbon dioxide (CO_2) concentrations. Greenhouse Gas (GHG) is on the increase on the planet and globally, buildings are responsible for approximately 40% of carbon emissions (IEA 2019). Prompt measures need to be taken to combat the effect of global warming and associated threats. On the other hand, building resource has receded greatly due to inadequate or no recycling culture for construction waste (Oladiran 2009; Nwokoro and Onukwube 2015). Nigeria is a population hot spot that is expected to have the third-largest population of about 500 million people by 2050, after India and China (World Bank 2015; NPC 2018). The country currently has a population of 198 million according to the National Population Commission of Nigeria (NPC 2018) and a shortfall of 17 million homes (World Bank 2015). Against this background, it is critical that Nigeria meets this demand in an energy and resource efficient manner also with a bid to reduce building material waste and recession by adopting circular economy strategies as well as providing residential buildings that are energy efficient. The reuse and recycling of building waste will not only help prevent waste but provide usable building materials to support the already receding resources (Rahman et al. 2017). In Nigeria, sustainable energy and resource-efficient design strategies are still at their infancy stage (Uyigue et al. 2009; Ogunmakinde 2019). This justifies the need for a framework that will serve as an energy and resource efficient design framework for developers.

1.4. Aim of Research

To develop a framework that will serve as a guide for incorporating circular economy in the design of energy-efficient residential buildings in the tropical savannah climate of Nigeria.

1.5. Scope and Focus

1.5.1. General purpose of the research: This study is geared towards the development of a guide for the design of new residential buildings in Nigeria using passive design strategies, the components of which can be reused/recycled after the first life by potentially designing the buildings for disassembly and recycling in the tropical savannah climate of Nigeria.

1.5.2. Geographical location and research area: The research area is Nigeria. The study site for assessment is Abuja of Nigeria which represents the largest climatic zone of the country (tropical savannah climate).

1.5.3. Major topics/theories for discussions. The research is centred on two major topics: Passive design strategies and Circular economy principles. The studies are focused on the exploration of passive design strategies for Nigerian residential building as it relates to bioclimatic considerations and circular economy principles for energy and resource-efficient buildings. In assessing circular economy principles, the study used the 7S model (System, Site, Structure, Skin, Services, Space, and Stuff) for the "design for disassembly" and the ReSOLVE (Regenerate, Share, Optimise, Loop, Virtualise, Evaluate) framework for "design for recycling".

1.5.4. Research Inclusions: Nigeria is in a tropical warm climate region which requires more cooling needs. Electricity is inadequate in Nigeria and residents seek alternative methods towards an energy-efficient building (Abbakyari and Taki 2017). There is also little awareness of passive design solutions (Uyigue et al. 2009). Hence, there is a need to start with basic design interventions by the adoption of passive design strategies which are very effective in achieving energy efficiency also considering the inadequacy in power supply considering the running cost of the building. Consequently, the research is focused on major passive design solutions which are feasible in the tropical savannah climate of Nigeria. This includes Building orientation, Daylighting, Natural ventilation, g-value, Window to Wall Ratio, Thermal insulation and Thermal mass. Also, the exploration of circular economy principles (i.e. design for disassembly and design for recycling) for the incorporation into the design of energy-efficient residential buildings in Nigeria. Therefore, the heart of this research is the exploration and development of passive design strategies and circular economy principles with regard to energy and resource efficiency for residential buildings in the Nigerian climate. The major residential building typology as identified from the Nigerian building stock by the Nigerian Federal Ministry of Power, National Building Energy Efficiency Code (BEEC), Edge, Arup and The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) is the detached bungalow (Arup (Madrid & Lagos offices) and Design Genre 2016; Federal Ministry of Power 2017; Solid Green Consulting 2017). Detached bungalows are the most built residential buildings in Nigeria as confirmed by the above sources. Hence, the justification for the building type selection for this research. Nigerian residential buildings consist of a large chunk of the building stock as they are the most common and are built without proper climate control measures (Agbola 1988; Osuizugbo 2018). They also are the highest consumer of energy and generators of carbon emissions (Oseni 2016; Hussaini 2018). This also justifies residential buildings for this research.

1.5.5. Duration of the research: The research was executed within three years.

1.6. Research Gap

The following literature reviews are excerpts from previous investigations and findings on energy and resource efficiency of the built environment with major emphasis on energy and resource efficiency in residential buildings which is related to this research (Oyedepo 2012a,b; EMF 2013; Oko John and Emmanuel Itodo 2013; Ley et al. 2015; Adewuyi and Odesola 2016; Abbakyari and Taki 2017; Adams et al. 2017; Federal Ministry of Power 2017; Akanbi et al. 2018; Hussaini 2018; Kanters 2018; Ranta et al. 2018; Ogunmakinde 2019; WRAP 2019; O'Grady et al. 2021). These papers focus on the current trends in reducing material waste by the adoption of various waste management strategies. Most of these studies have been conducted on a wide spectrum, cutting across the sources, effects, categories and management systems of waste in the construction industry.

From a global perspective, Al-Hajj & Hamani (2011); Kofoworola & Gheewala (2009) assessed the various phases of the construction process to identify the causes and impact of construction waste (Kofoworola and Gheewala 2009; Al-Hajj and Hamani 2011). The study also discussed measures for minimising waste at stages of design, procurement and construction. Other studies such as Li, Tam, Zuo, & Zhu, (2015); Emmanuel, Ibrahim, & Adogbo, (2014) have investigated the perceptions and attitudes of construction professionals as regards waste management and sustainability in the construction industry (Emmanuel et al. 2014; Li et al. 2015). However, there is practically no holistic approach to mitigating waste in the various stages.

Some studies explored how generated waste can be reduced if monetary incentives are included, thus, reducing the construction waste going to landfills. For example, Crawford, Mathur, and Gerritsen (2017) identified the lack of financial incentives as one of the setbacks in construction waste management (Crawford et al. 2017). A similar study by Park & Tucker in 2017 also suggested incentives as a major motivator for waste reduction (Park and Tucker 2017). This strategy may not sit well with circular economy principles that are keen on waste control right from the design stage. For example, the principle termed “design for deconstruction” which focuses on modular designs right from the conceptual stage. Pan et al., (2015) also emphasized the need to include disassembly technics in the process of construction as well as in deconstruction phases (Pan et al. 2015).

These studies have critically explored and suggested approaches for the adoption of a waste management system, but a holistic approach in all phases is yet to be developed in a circular economy but in a linear economy. WRAP (2009, 2010, 2013) proposed strategies for reusing and recycling waste (WRAP 2009,2010,2013), which was a similar proposition at CIB World Building Congress (Chini 2001). Wang, Li, & Tam (2014) also identified various waste mitigation plans but were only at the design and procurement phases (Wang et al. 2014). However, these strategies were aimed at recovering part of the waste sent to landfills but not reducing waste at the source or at the conceptual stage of projects.

Ogunmakinde (2019) proposed a holistic circular economy framework for minimising waste across construction phases at the design, procurement, and actual construction stages in the Nigerian construction industry (Ogunmakinde 2019; Ogunmakinde et al. 2019). However, these principles have not been combined with passive design strategies or any form of energy-efficient principles.

Secondly, the strategies did not define how to “design for disassembly” or “design for recycling” which are major components of circular economy in buildings.

Thirdly, the framework did not propose strategies for reusing and recycling building materials/components. These are the practicality of circular economy principles which forms the basis of this research.

Achieving energy efficiency in residential buildings with the use of passive design strategies is still alien to most developers in Nigeria, most especially as buildings are usually built by non-professionals (Taiwo and Afolami 2011; Oloke et al. 2017; Osuizugbo 2018). Uyigue, Agho, and Edevbaro (2009) reported on a survey conducted in Nigeria among general respondents and professionals revealed the lack of awareness of energy efficiency in buildings, 79% of the general respondents and 77% of professionals were not familiar with the term “energy efficiency”. The respondents that claimed they were aware could not properly explain what it means (Uyigue et al. 2009). Previous works of research conducted in Nigeria has always emphasised the use of active measures in achieving energy efficiency in residential buildings. For example, the use of photovoltaic panels, inverted air conditionals, lighting fixtures and appliances (Oyedepo 2012b,a; Ley et al. 2015; Hussaini 2018). Residential buildings in Nigeria will perform a lot better if basic passive measures are considered and implemented at the design stage of a building such as building orientation, daylighting, natural ventilation and thermal mass. But previous studies and interventions in Nigerian residential buildings have not emphasised these design requirements for an energy-efficient building.

Literature reviews revealed that there is no framework or guide for attaining and adopting passive design standards for Nigerian residential buildings. For example, the Nigerian building energy efficiency code (BEEC) only provides expectations of an energy-efficient building using mainly active measures, without a framework to achieve those expectations using passive design strategies (Federal Ministry of Power 2017; Solid Green Consulting 2017). The Nigerian Energy Support Programme (NESP) only accentuate renewable energy, active energy efficiency measures and rural electrification (Ley et al. 2015). Passive design measures are imperative in the Nigerian context, owing to the fact that the supply of electricity in Nigeria is currently inadequate, hence it is expected that attention is focused on passive design strategies (Amasuomo et al. 2017).

In order to effectively ensure a resource-efficient building, there is a need to incorporate circular economy in the design process. This process involves the reuse of building components or materials as well as upcycling, downcycling of these materials. Hence, it would be necessary to identify effective circular economy design principles for a resource-efficient residential building.

Passive design strategies awareness is still very low in the Nigerian building industry and there is the need to promote this awareness (Uyigue et al. 2009). Therefore, this research focuses on identifying passive design strategies for residential buildings in the Nigerian tropical climate. There are only a few studies on circular economy in Nigeria which is even a new sustainable strategy globally (Ogunmakinde 2019). Therefore, this research would be building on relevant findings from literature and addressing the above-identified research gaps with a focus on establishing a design framework that incorporates both circular economy and passive design strategies for the design of energy and resource-efficient residential buildings in the tropical savannah climate of Nigeria.

To this end, the research endeavour to engage the research problems by asking major questions in order to articulate the steps or objectives required to achieve the aim of this research. Amongst the objectives was to identify the components of passive design and circular economy in the Nigerian context. These interventions were analysed and evaluated within the makeup of the Nigerian climate. The research explored various passive design strategies and circular economy principles towards identifying and incorporating the optimal design variables, parameters and strategies for energy and resource efficient buildings in Nigeria. The findings from this research informed the development of the framework which will serve as a guide for the incorporation of circular economy in the design of energy efficient building in Nigeria.

1.7. Research Questions

1. What are the passive design and circular economy components for Nigerian residential buildings?
2. What are the recommendations for passive design in Nigerian residential buildings?
3. How can circular economy principles and passive design strategies be incorporated into the design of Nigerian residential buildings?
4. How can circular economy principles be applied in the design of energy-efficient residential buildings in Nigeria?

To answer the research questions the following research objectives were crafted to answer the research questions and achieve the aim of the research.

1.8. Research objectives and methods

1. To conduct literature reviews to identify the components for passive design and circular economy in Nigeria. – Literature review, and Quantitative analysis
   a) Review of the Nigerian tropical savannah climate. – *(Literature review, and quantitative analysis)*
   b) Analysis of the Nigerian weather data. – *(Literature review, and quantitative analysis)*
   c) Study of the residential building typology in Nigeria. – *(Literature review, and quantitative analysis)*
   d) An overview of energy efficiency in residential buildings. – *(Literature review, qualitative and quantitative analysis)*
   e) Study of Passive design strategies in Nigerian residential buildings. – *(Literature review, and quantitative analysis)*
   f) Study of circular economy principles. – *(Literature review, and quantitative analysis)*

2. To assess and optimise these passive design components (i.e., building orientation, thermal mass, daylighting, local shading, natural ventilation, thermal insulation, WWR, g-value) towards achieving optimal energy performance in Nigerian residential buildings. – *Numerical simulation and Quantitative analysis.*

   a) Identification of typical base case of Nigerian residential building typology for simulation. – *(Literature review)*

   b) Model, calibration and validation of base case building with respect to the Nigerian Federal Ministry of Power report and the obtained weather data. – *(numerical simulation)*

   c) Simulation preparations. – *(numerical simulation)*

   d) Setup for the base case and optimised case. – *(numerical simulation)*

e) Optimisation Simulation (one at a time, all at a time). – *(numerical simulation)*

f) Assessment of passive design strategies and optimisation of building. – *(numerical simulation)*

3. To compare, select, and recommend the best passive design case based on simulation results. – quantitative analysis

a) Comparison of results between the base case and optimised case. – *(quantitative analysis)*

b) Selection of best case based on performance. – *(quantitative analysis)*

4. To adopt circular economy interventions. – Literature review, Numerical simulation and Quantitative analysis

a) Design for disassembly.

(i) Classification of building components into the 7S model. – *(Literature review)*

(ii) Identification of "Design for disassembly" methods. – *(Literature review)*

(iii) Analysis of assembly and disassembly methods. – *(Literature review)*

(iv) Process for Design for Disassembly *(Literature review)*

b) Design for recycling.

(i) Selection of recommended recyclable materials. – *(quantitative analysis)*

(ii) Categorisation of materials according to building components into the 7S model. – *(quantitative analysis)*

(iii) Development of the material selection Matrix *(Literature review, Numerical simulation and Quantitative analysis)*

(iv) Sorting reusable and recyclable building materials into the ReSOLVE framework using the material selection matrix. – *(Literature review and quantitative analysis)*

(v) Energy dynamic simulation with circular economy materials incorporated to building model – *(Numerical simulation and Quantitative analysis)*

5. To establish an approach for the application of circular economy principles in Nigerian residential buildings - *Literature review, Numerical simulation and Quantitative analysis.*

a) Design to passive design recommendations. – *(Literature review and Quantitative analysis)*

b) Design for disassembly by splitting building components into the 7S model. – *(Literature review and quantitative analysis)*

c) Design for recycling by using the material selection matrix and Sorting of (reusable and recyclable) materials into building components and ReSOLVE framework. – *(Literature review and quantitative analysis)*

d) Design for end of life – deconstruction, reuse, and recycling. – *(Literature review and quantitative analysis)*

6. To develop a framework for the incorporation of circular economy in the design of energy and resource-efficient residential buildings in Nigeria. - *Literature review and Quantitative analysis*

    a) Requirements for energy and resource-efficient residential building in Nigeria based on research. – *(quantitative analysis)*

    b) Guidance on attaining set recommendations from research findings. – *(quantitative analysis)*

    c) Recommendations and Conclusion. – *(quantitative analysis)*

Chapter Two
2.0. Literature review
2.1. Passive Design Strategies and Circular Economy Principles

Passive design strategies and circular economy in buildings are two sustainable interventions that set the balance between energy and resource efficiency in buildings. Passive design includes the use of bioclimatic design considerations to achieve an energy-efficient building (Daemei et al. 2019). In other words, passive design reduces or eliminates the need for auxiliary/active measures in improving building performance (Home 2010). Circular Economy in buildings, on the other hand, refers to the process of reducing or preventing building waste by keeping building materials viable and usable for as long as possible even after the end of life of the building (Kanters 2018). Hence, the combination of both strategies and principles delivers a building that is energy and resource-efficient.

In the tropics, there is a constant need to shut out the heat and cool down interior spaces (Emmanuel 2005). Consequently, occupants use diverse means to attain an energy-efficient residential building as it relates to ventilation, lighting and thermal comfort (Geissler et al. 2018). Most of the methods employed toward building efficiency and performance are often not responsive to the environment (Dania et al. 2013). As a result, there is the need for alternative strategies for a comfortable residence. This can be attributed to the inability of the buildings to respond to the comfort of occupants. This may be traced to inefficient design considerations most especially poor passive design considerations often at the design stage (Uyigue et al. 2009). Hence, there is a need to make residential designs energy efficient by using the natural features of the environment to complement the built environment (Adunola and Ajibola 2019).

Ortiz et al. (2010) defined a sustainable project as one that is designed, built, renovated, operated or reused in an ecological and resource-efficient manner (Ortiz et al. 2010). Most residential buildings in the tropics face the challenge of inadequate lighting, ventilation and excessive heating most of the year. In an attempt to make residential buildings comfortable, appliances like air-conditionals and lighting fixtures which have a high demand for electricity are compulsorily used (Geissler et al. 2018). This is because the buildings are not responsive and electricity is inadequate in most developing countries to power buildings, consequently, an alternate source of power supply is sought for such as the use of generators whose emission will increase the concentration of CO_2 (Oseni 2016; Abbakyari and Taki 2017; Geissler et al. 2018).

Passive design is an approach to building design that uses the building architecture to minimize energy consumption (Bhatt 2014). According to Bhatt, the ultimate vision of passive design is to fully eliminate design requirements for active mechanical systems and associated fossil fuel-based energy consumption with the aim of maintaining occupant comfort (Bhatt 2014). This implies that buildings should depend more on bioclimatic/natural strategies for their smooth running towards achieving a sustainable building (Adunola and Ajibola 2019).

Passive design involves an architectural concept of a self-sustainable building, especially in the area of energy economy as passive designs are usually recognized for their sustainable features (Bhatt 2014). The design of passive buildings has a variety of merits amongst which energy conservation and CO_2 emission prevention is of paramount importance. The concept of passive design helps to structure a building as a single interconnected system. Passive designs are like conventional designs; however, the major standout is in the use of the natural elements and features of the environment to run and sustain buildings (Daemei et al. 2019). Across the globe, the adoption of passive design strategies is imperative for the preservation of the climate (St. Clair and Hyde 2009; Hyde 2013). Warm regions with extreme temperatures are forced to seek measures in order to maintain habitable thermal comfort (Emmanuel 2005). Sometimes these measures do more harm than good. In Nigeria, electrical power is inadequate and alternative power sources are employed which may increase the concentration of CO_2 when passive design strategies can help reduce energy costs in the cooling and heating of buildings (Baker 1996; Holmes and Hacker 2006).

Circular economy seeks to reduce waste and increase resource availability. The fusion of both (circular economy and passive design) principles produces a building that is energy and resource-efficient. This will minimize energy demands and sustain buildings as material bank. Sunand Prasad - founder of Penoyre & Prasad and Trustee of United Kingdom Green Building Council (UKGBC) likened circular economy to how the natural world works in continual regeneration (Prasad 2019). He described circular economy as a powerful and challenging idea to guide humans in managing their material impact on the environment, so instead of steadily degrading, he continually regenerates it (Prasad 2019). Thus, in circular economy, waste from buildings becomes material for other processes in recycling. A proper circular economy program for buildings can allow new buildings to make use of 80-90% of deconstruction/demolition waste (Resource-deutschland 2014). The building itself is constructed with reusable, and recyclable materials that can be deconstructed. The concept of circular economy has in recent years been a major area of discussion. Geissdoerfer et al. (2017), reported that circular economy, as well as sustainability, has gained great popularity in industries, academics, and other sectors (Geissdoerfer et al. 2017). Hill and Bowen (1997) stated that building sustainability begins at the design stage and spans throughout the building's life to its deconstruction and recycling in order to reduce waste (Hill and Bowen 1997). The European Union has deemed it fit to create a shift from a linear system to a circular system, thus reducing economic loss by regarding waste materials from buildings as resources (Clark et al. 2006).

It has been reported that construction industries are one of the major sources of waste production globally (Clark et al. 2006). Statistically, an approximate amount of 45.8 m tons is derived from waste demolition in the United Kingdom (DEFRA 2016). Construction delays in Nigeria are attributed to a shortage of material or material inaccessibility, or a combination of both (Rahman et al. 2017).

The demolition and disposal of building materials have been a general practice, which has resulted in financial losses and the excess creation of waste materials. Deconstruction of buildings is now preferred over building demolition, thus benefiting the environment and economy (Coelho and de Brito 2011). The concept of circular economy was established to reduce building demolition and encourage building deconstruction for reuse or recycling. Circular economy and passive design strategies are two sustainable interventions that have rarely been combined and this research seeks to develop a framework for its application in residential buildings in the tropical region of Nigeria. The benefits of incorporating circular economy into passive design strategies are enormous not only in delivering energy and resource-efficient building but also in safeguarding the climate and the built environment (Morgan and Mitchell 2015).

There has been a vast interest in the concept of sustainability, focusing basically on the reduction of construction materials since building materials are receding and building waste pollution is on the rise (Kırbaş and Hızlı 2016; Rahman et al. 2017). The use of building appliances and equipment alone is insufficient if basic environmental factors are not considered (Boyle 2005). In order to incorporate circular economy into passive design strategies, Clients and building developers are expected to take into consideration the end of life of a building, in other words, design for reuse and recycling. At the design stages, it is necessary to determine what components/materials can be reused and recycled, and what circular economy principles can be adopted at end of life (EMF 2015; Akanbi et al. 2018).

Incorporating circular economy into passive design strategies will produce an energy-efficient building during its life span and produce resources for the construction of a new project at the end of life of the building. These principles are set to reduce waste, increase resources, and dynamism in residential building design.

2.1.1. Relationship between Passive Design Strategies and Circular Economy

This study has set aside some major passive design interventions for residential buildings in Nigeria. They include building orientation, thermal mass, daylighting, natural ventilation, g-value local shading, thermal insulation, and Window to Wall Ratio (WWR). These strategies have been selected because they form major components for influencing drastic changes as regards energy consumption in buildings. Also, they can easily be adopted at the design stage of a building making them very essential considerations in the design of an energy-efficient building.

Circular economy in buildings can be subdivided into two main aspects, design for disassembly and design for recycling. These two aspects have direct links with passive design strategies. Below are some major passive design strategies and their relation with circular economy.

2.1.1.1. Thermal mass

Thermal mass is the ability of a material to absorb and store heat energy through a mass of material (Gyoh 2017). Thermal mass is a passive strategy that is well related to the choice of material (in terms of its volumetric heat capacity and other properties) to be used to attain an expected performance and how this material can be reused and recycled after the end of life using circular economy principles.

2.1.1.2. Daylighting

Daylighting is maximized in buildings by providing and strategically positioning openings, windows, curtain walls or other forms of fenestration in buildings (Zaki et al. 2012; Rodriguez-Ubinas et al. 2014). These components are usually glazed or constructed with other materials whether transparent, translucent, frosted or opaque. The recyclability of these materials and attributes for performance as a component for daylighting in passive design are both considered as well as options for easy deconstruction are also considered as regards “design for disassembly” - a subdivision of circular economy.

2.1.1.3. Natural ventilation

Natural ventilation is a passive design strategy that is easily improved through stack effect, wind catchers, cross ventilation, nocturnal effect, building orientation, etc. (Hughes et al. 2012; Aflaki et al. 2015). These methods are facilitated by components such as vents, windows, wing walls, etc. whose material composition are integrated with circular economy principles for easy disassembly, reuse and recycling.

2.1.1.4. Building orientation

Building orientation has a great chance of increasing the energy efficiency of a building, the material used for each façade of a building in passive design is often influenced by the orientation of the building (Omrany and Marsono 2016). For example, façades exposed to high solar radiation are usually provided with shading devices or constructed with a material of low conductivity values and the building may be insulated (Tang 2002). Therefore, building orientation as a major passive design strategy has a direct link to the choice of material and construction method. This choice of material and construction methods gives room for potential ease of disassembly and recycling using circular economy principles.

Passive design interventions have a great effect/influence on the materiality of buildings and construction methods. Circular economy principles can fit into the two aspects using its subdivisions – "design for disassembly" and "design for recycling". This is achievable using the 7S model and ReSOLVE framework respectively. The ReSOLVE framework was developed by Ellen MacArthur Foundation, McKinsey & Co., and SUN (EMF 2013,2014). The framework identifies six different ways of applying circular economy. The acronym represents: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange (CE100 2016). In buildings, this means material components can undergo one or more of the six interventions to keep them in use, reuse and recycling phases for as long as possible.

The 7S model represents building in layers, the model was first proposed by Architect Frank Duffy and further developed by Stuart Brand. The model includes seven layers: System, Site, Structure, Skin, Services, Space, and Stuff (CE100 2016). These layers can be used to separate a building into modules or segments since buildings are usually made of separate and interlinking layers (EMF 2012). This model allows for easy assembling and disassembling into the 7S categories. Thus, allowing components to be Regenerated, Shared, Optimised, Looped, Virtualised, and Exchanged together or separately as the case may be. Therefore, the materiality of passive design in a circular economy system will be evaluated using the ReSOLVE framework while construction methods of passive design interventions will be evaluated using the 7S model. Both models complement each other and together can be integrated into the passive design for a resource and energy-efficient residential building in Nigeria.

2.2. Nigeria's Tropical Climate

2.2.1. Study location

Nigeria is a Federal Republic comprising 36 States and its Federal Capital Territory is Abuja. In West Africa, Nigeria shares land borders with the Republic of Benin in the West, Chad in the top East and Cameroon in the East, and Niger at the top North. In the South lies its coast on the Gulf of Guinea, bordering Lake Chad to the Northeast (Wikipedia Contributors 2020). The Adamawa highlands, Mambilla Plateau, Jos Plateau, Obudu Plateau, Niger River, River Benue and Niger Delta are notable geographical features in Nigeria. Nigeria is in the Tropics, where the climate is seasonally damp, very humid and often hot. Nigeria is affected mainly by four climatic configurations which are distinguishable as it moves from the South of Nigeria to the North of Nigeria (Wikipedia Contributors 2020).

Figure 1: Current City Map of Nigeria, American Historical Association (AHA 2018)

In Nigeria, states are grouped into six geopolitical zones, the North Central (NC), North East (NE), North West (NW), South West (SW), South East (SE) and South (SS) (Okorie et al. 2013). Nigeria has a ground cover of approximately 923,768 sq. km and has a large low plateau intersected by two major rivers, Niger and Benue Rivers through the central regions of the country. Nigeria is Africa's most populated country. The National Population Commission (NPC) puts Nigeria's current population at 198 million people, the 7th largest in the World with an urban population growing at an average annual growth rate of about 6.5 per cent (NPC 2018).

2.2.2. Nigeria's Climate

The local climate zone (LCZ) of Nigeria from its metadata from Google Earth, falls mainly under the open midrise and open low-rise of the built types according to Stewart and Oke (2012) Local Climate Zone classification (Stewart and Oke 2012). This has an open arrangement of low-rise buildings between 1–9 stories with an abundance of pervious land cover of low plants, scattered trees and construction materials consisting of wood, tile, stone, brick, concrete, steel and glass (Stewart and Oke 2012). This is classed under the LCZ 5 and 6.

Table 1: Values of geometric and surface cover properties for local climate zones (Stewart and Oke 2012)

Local climate zone (LCZ)	Sky view factor	Aspect ratio	Building surface fraction	Impervious surface fraction	Pervious surface fraction	Height of roughness elements	Terrain roughness class
LCZ 5	0.5–0.8	0.3–0.75	20–40	30–50	20–40	10–25	5–6
LCZ 6	0.6–0.9	0.3–0.75	20–40	20–50	30–60	3–10	5–6

Table 2: Values of thermal, radiative, and metabolic properties for local climate zones 5 and 6 (Stewart and Oke 2012)

Local climate zone (LCZ)	Surface Admittance	Surface albedo	Anthropogenic heat output
LCZ 5 *Open midrise*	1,400–2,000	0.12–0.25	<25
LCZ 6 *Open low-rise*	1,200–1,800	0.12–0.25	<25

The open low-rise has a departure from traverse mean temperature (K) of 0.75 and departure from a group mean diurnal temperature range (K) of 2.05 for open midrise and 0.95 for open low-rise (Stewart and Oke 2012).

The tropical monsoon climate, designated by the Köppen climate classification as "Am", can be found in the southern part of the country (Arnfield 2020). This climate is often influenced by the monsoons from the Atlantic Ocean. This is conveyed into the country by the maritime tropical air mass. It is warm with high humidity which gives it a strong tendency to ascend and generate abundant rainfall (College Park MD (SPX) 2004).

The tropical monsoon climate has a very close temperature range which is almost constant throughout the year. Warri town for example in the southern part of Nigeria records a maximum of 28 °C during its hottest month while its lowest temperature is 26 °C during its coldest month, the temperature difference in Warri town is about 2 °C (Okorie et al. 2013).

The southern part of Nigeria experiences heavy rainfall which is usually accompanied by storms. These storms are often convectional in nature due to the region's proximity, to the equatorial belt, the annual rainfall is very high in this region, usually above the 2,000 mm rainfall totals given for tropical rainforest climates worldwide, the rainfall received in the coastal region of Nigeria is over 4,000 mm around the Niger Delta area, the rest of the southeast receives a range of 2,000 and 3,000 mm of rain yearly (Wikipedia Contributors 2020).

The first rainy season starts around March and lasts to the finish of July with a crest in June, this stormy season is trailed by a short dry break in August known as the 'August break' which is a short dry season going on for a little while in August, this break is broken by the short rainy season beginning around early September and enduring to Mid-October with a pinnacle period toward the finish of September (Okorie et al. 2013). The completion of the short stormy season in October is trailed by the long dry season, this period begins in late October and keeps going till early March with extremely dry conditions between early December and late February (CANUK 2011).

The tropical savannah climate is also known as the tropical wet and dry climate which covers most of Western Nigeria to central Nigeria starting from the Tropical rainforest climate boundary in the south of Nigeria to the central part of Nigeria. The tropical savannah climate exhibits a well-marked rainy season and a dry season with a single peak known as the summer maximum as a result of its distance from the equator. Temperatures are usually above 18 °C (64 °F) all through the year. The capital city Abuja is found in central Nigeria with a temperature range of 18.45 °C (65.21 °F) to 36.9 °C (98.4 °F) and an annual rainfall of approximately 1,500 mm (Nigeria-weather 2011).

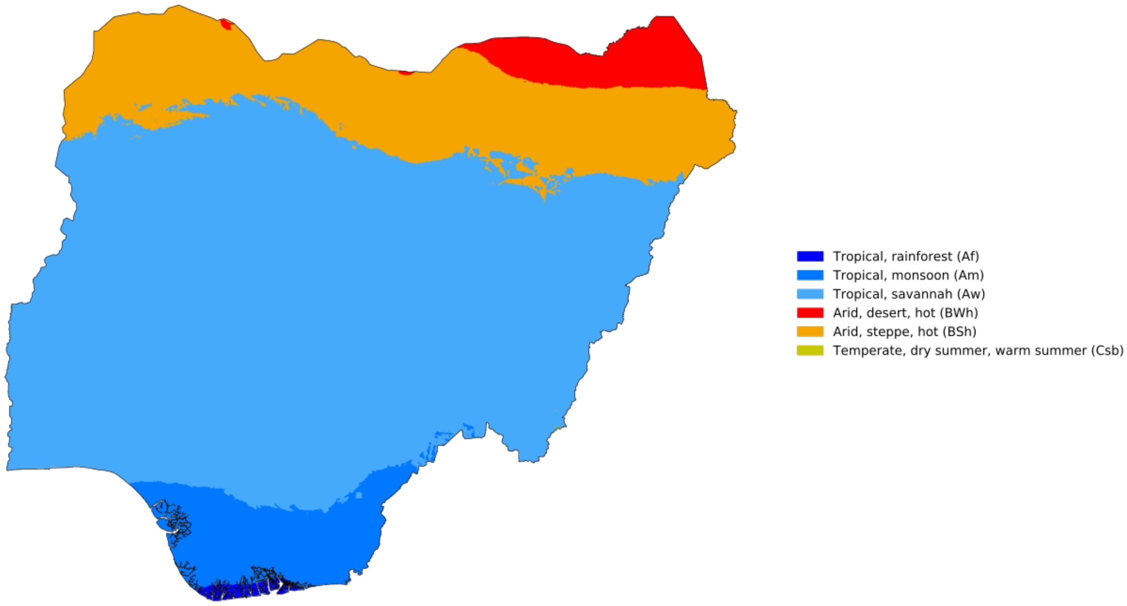


Figure 2: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Nature Scientific Data, (Arnfield 2020)

The tropical savannah climate in central Nigeria beginning from December to March is a hot and dry period accompanied by harmattan, a continental tropical air mass which blows with dust from the Sahara Desert. In April, the intertropical convergence zone swinging northward across West Africa from the Southern Hemisphere is followed by heavy showers from pre-monsoonal convective clouds taking the form of squall lines also known as the north easterlies formed mainly as a result of the interactions of the two dominant air masses in Nigeria (Nigeria-weather 2011). This phenomenon is known as the Maritime tropical (south westerlies) and the continental tropical begins in central Nigeria while the Monsoons from the south Atlantic ocean blow in central Nigeria around July with its high humidity, heavy cloud cover and heavy rainfall, usually, a daily occurrence lasting till September when the monsoons gradually begin retreating southward of Nigeria (Nigeria-weather 2011).

The Sahel climate or tropical dry climate is predominantly the climate type in the northern part of Nigeria. The annual rainfall is lower compared to the southern and central parts of Nigeria since the rainy season lasts for only three to four months (during the months of June–September) in the northern part of Nigeria. The remaining part of the year is hot and dry with temperatures rising as high as 40 °C (Geographical Alliance of Iowa 2010).

2.2.3. Temperature

Nigeria's location in the tropics has automatically made the country a tropical hot climate. Temperatures in Nigeria vary depending on the seasons of the year as with other lands found in the tropics. Nigeria's seasons are identified by rainfall with the rainy season and dry season being the major seasons in Nigeria (Wikipedia Contributors 2020).

It is often cooler during the rainy season in Nigeria as a result of the cloud cover that acts as a blockage to the intense sunshine in the tropics by blocking a considerable amount of the sun's rays in the rainy season (Nigeria-weather 2011). But afternoons in the rainy season can be hot and humid, a major feature of tropical climates.

The dry season of Nigeria is mostly characterised by little cloud cover in the southern part of Nigeria and almost no cloud cover in the northern part of Nigeria. Therefore, the sun shines through the atmosphere with little or no obstructions from the clear skies making the dry season in Nigeria a period of hot weather conditions (Wikipedia Contributors 2020). A dusty dry wind from the Sahara Desert called the harmattan enters Nigeria in the middle of the dry season around December from the north-eastern part of the country blocking sun rays partially from shining and creating haze in the atmosphere (Nigeria-weather 2011). These activities of the wind lower temperatures considerably saving inhabitants from the scorching sun that would have occurred as a result of clearer skies during the dry season. At the same time, this wind causes drought but with the withdrawal of this wind around March to April following the start of the rainy season, temperatures can go as high as 44 °C in some parts of Nigeria (Nigeria-weather 2011). On the highlands in central Nigeria above 1,200 metres above sea level, Semi temperate weather conditions prevail, namely the Jos Plateau. Temperatures on the Jos plateau ranges between 16 °C to 25 °C thereby making the regions cool all year round (Wikipedia Contributors 2020).

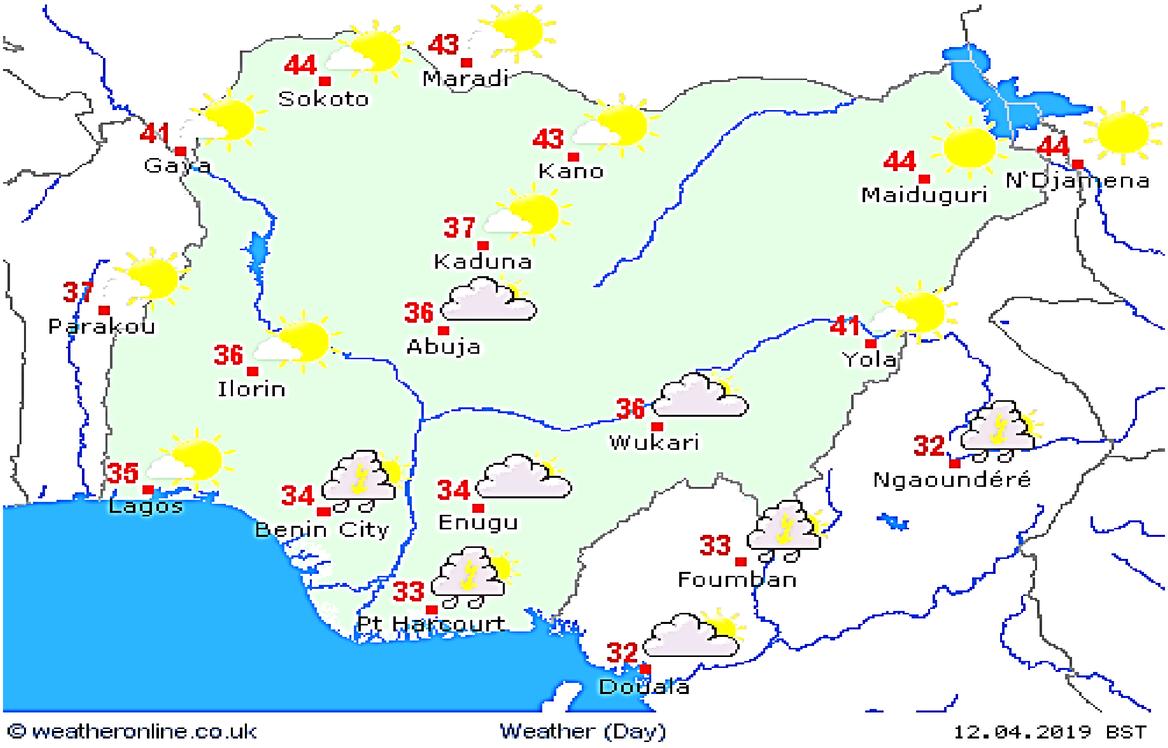


Figure 3: Map of Nigeria showing the weather condition of some cities, Nigeria Weather Online Ltd. - (Meteorological Services 2019)

2.2.3.1. Average Temperature figures all year round of some major cities of Nigeria.

The North is often cool during the night-time and sometimes even cold. From March to May, the temperatures usually increase rapidly, and the sun becomes scorching. The temperature decreases when the monsoon wind arrives, but at the same time, the humidity increases.

Kano

The average temperatures of Kano in the North. Kano is located at 500 meters about 1,600 feet above sea level.

Table 3: Kano - Average temperatures (World Climate Guide 2019).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min (°C)	12	14	18	22	23	22	21	20	21	19	15	12
Max (°C)	30	33	37	39	38	34	31	29	31	34	34	31
Min (°F)	54	57	64	72	73	72	70	68	70	66	59	54
Max (°F)	86	91	99	102	100	93	88	84	88	93	93	88

Abuja

Below are the average temperatures in Abuja - the Federal Capital Territory, located at the centre of the country, at 500 meters (1,600 feet) above sea level.

Table 4: Abuja - Average temperatures (World Climate Guide 2019).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min (°C)	20	26	24	25	20	18	22	18	18	21	16	16
Max (°C)	35	37	37	36	33	31	29	29	30	32	34	35
Min (°F)	68	79	75	77	68	64	72	64	64	70	61	61
Max (°F)	95	99	99	97	91	88	84	84	86	90	93	95

Jos

Jos, Plateau which is the highest benchmark of the country. The temperature is cool. Jos is the capital of the Plateau State, located at 1,200 meters (3,900 feet), the daytime temperatures range from 28 °C (82 °F) in January to 31/32 °C (88/90 °F) in March and April, while the temperature drops to around 24/25 °C (75/77 °F) in July and August.

Table 5: Jos - Average temperatures (World Climate Guide 2019).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min (°C)	14	16	18	19	18	18	17	17	17	17	16	14
Max (°C)	28	30	32	31	29	27	25	24	27	29	29	28
Min (°F)	57	61	64	66	64	64	63	63	63	63	61	57
Max (°F)	82	86	90	88	84	81	77	75	81	84	84	82

Southern cities

The cities are located in the coastal area at the south of Nigeria (Lagos, Benin City, Port Harcourt, Calabar), with temperatures around 30/32 °C (86/90 °F), but it's also more humid which is usually tempered by afternoon breezes and cloudy skies, especially in the morning.

Table 6: Southern cities (World Climate Guide 2019).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min (°C)	22	24	24	24	23	23	22	22	22	22	23	22
Max (°C)	32	33	33	32	31	29	28	28	29	30	31	32
Min (°F)	72	75	75	75	73	73	72	72	72	72	73	72
Max (°F)	90	91	91	90	88	84	82	82	84	86	88	90

Table 7: The table below shows characteristic climatic conditions in zones and regions of Nigeria (Imaah 2008)

No	Climate zone	Some locations	Predominant climate conditions
1.	Coastal	Lagos, Port Harcourt, Calabar	Temperature ≥ 24℃ ≥ 27℃, Relative humidity is ≥ 80% Warm weather at 24℃ – 25℃, this is predominantly hot weather at ≥ 25°C
2.	Forest	Ibadan, Oshogbo	Temperature ≥ 27℃, Relative humidity≥ 60%≤ 80% Hot and relatively humid weather
3.	Transitional	Lokoja, Enugu, Ilorin	Temperature ≥ 24℃ ≥ 27℃, Relative humidity ≥ 60% ≤ 80% Predominantly warm weather
4.	Savannah	Abuja, Kaduna, Bauchi	Temperature ≥ 24℃ ≤ 27℃, Relative humidity ≥ 20% ≤ 40% Warm and dry weather
5.	Highland	Jos plateau, Obudu plateau	Temperature ≥ 24 ◦C ≤ 27◦C, Relative humidity≥ 40% ≤ 60%, this is a comfortable weather
6.	Semi-desert	Katsina, Nguru	Temperature ≥27◦C Relative humidity ≤ 20% Hot and very dry weather

Table 8: Table showing the average temperature in the Nigerian climatic regions at the geopolitical zones (Nigeria-weather 2011; Meteorological Services 2019; World Climate Guide 2019)

Average Temperature in the Nigerian Climatic Zones						
	South South	**South West**	**South East**	**North Central**	**North West**	**North East**
Tropical Savanah Climate		The annual mean temperature range between 21.9 and 30.4 degrees °C. Minimum and maximum temperatures varied from 13 to 26 and 21.5-39.6 degrees °C, respectively.	Over the course of the year, the temperature typically varies from 64°F (17.8°C) to 87°F (30.6°C) and is rarely below 57°F (13.9°C) or above 91°F (32.8°C).	Temperatures are above 18 °C throughout the year. Abuja, Nigeria's capital city found in central Nigeria, has a temperature range of 18.45 °C to 36.9 °C	Climate not found here	Climate not found here
	South South	South West	South East	North Central	North West	North East
Monsoon Climate	A maximum of 28 °C (82.4 °F) for its hottest month while its lowest temperature is 26 °C (78.8 °F) in its coldest month. The temperature difference of Warri town is not greater than 2 °C.	Climatic condition not experienced here.	Climatic condition not experienced here.	Climatic condition not experienced here.	Climate not found here	Climate not found here
	South South	South West	South East	North Central	North West	North East
Warm semi-arid climate	Climate not found here.	Climate not experienced here.	Climatic condition not experienced here.	Climatic condition not found here.	The wet season is usually hot, oppressive, and mostly cloudy and the dry season is sweltering and partly cloudy. Throughout the year, the temperature typically varies from 62°F to 104°F and is rarely below 57°F or above 108°F.	Climate not found here
	South South	South West	South East	North Central	North West	North East
Warm Desert Climate	Climatic condition not found here.	Climatic condition not experienced here.	Climate not experienced here.	Climatic condition not found here.		The rest of the year is often hot and dry with temperatures reaching about 40 °C.

2.3. Nigerian residential buildings

2.3.1 Historic review of residential buildings in Northern and Southern Nigeria with respect to material use and their effect on thermal comfort

2.3.1.1. Vernacular Architecture in Northern Nigeria.

In order to understand the building types in Nigeria with regards to material use and their effect on thermal comfort, it is necessary to carry out a historic review of literature on the characteristics of previous residential buildings as regard to their vernacular Architecture. Hence, a review of Northern and Southern Nigeria's old Vernacular Architecture as it relates to material use and its effect on thermal comfort. In Nigeria, the relics of earth buildings are seen in our traditional city centres as reminiscences of history, the old earth buildings are being replaced by modern structures (Egenti et al. 2014)

Figure 4: Traditional mud brick house, Hausa Architecture (Jehosafats 2011)

Figure 5: Hausa Architecture (Jehosafats 2011)

Hausa traditional Architecture was famed for its ribbed vaulting, doming, sculpted and painted external murals, a special art that has been modified by modern Architecture. Old residential buildings were composed of individual egg-shaped units of adobe (locally known as *tubali*) this had been earth-plastered as a monolithic structure. Wide walls were made of mud and thickened to reduce heat transmission due to hot weather conditions. A typical homestead comprised both rectilinear and circular spatial units which were linked together by wall segments constituting a perimeter wall. The roofs were essentially wooden slabbed with mud decking, it consisted of linking shallow domes and vaults which evolved from an intricate arrangement of lengths of palm-tree timber, termed *azara*, which was overlaid by processed laterite together by small stretches of earth, laid relatively flat (Dmochowski 1990a).

Rain-water run-off was led out of corrugated metal spouts fitted into the framing parapet wall (Dmochowski 1990a).

Figure 7: Hausa Architecture (Jehosafats 2011)

Figure 6: Tubali Hausa Architecture (Odeyale and O. 2008)

The materials used in the construction of these buildings are prominently stone, straw, and earth which have been independently and dependently used, skillfully applied (Ejiga et al. 2012). There are four basic building materials in Hausa land, namely, earth, timber, reeds/grasses, and stones. Stones are less used in most cities, mud is more tolerant to climate because of its poor conductivity (Moughtin 1985; Dmochowski 1990a; Eneh and Ati 2010) These building materials were locally processed or fabricated (Adeyemi 2008). Some of the local materials used in achieving outstanding architectural monuments are stabilized mud brick and plaster, thatch, timber, shingles. Examples of these buildings are The Kano mud wall and vegetable material, Centenary Hall, Ake, which consisted of stone, mud, timber (D'Ayala and Fodde 2008; Odeyale and O. 2008). One of the distinct features of Hausa Traditional Architecture is 'Zanko' which are horns of mud. It served as a facade decoration along the parapet of the building. This gives Hausa structure a lighter and picturesque appearance. The traditional designs of the savannah and southern Sahel appear as an unimpressive array of thatch and dried earth, but with closer inspection, its anthropomorphic brilliance emerges. These buildings exist because the communities actively tend to them. Their annual maintenance is due to the abundance of palm sticks to enable construction.

The main materials in traditional houses are stones, wood, bricks, and metals. Some of them prevent moisture and humidity which are used in building foundations and other sensitive components of the building. With the emergence of modern materials such as sand-cement block, and reinforced concrete which can be used more rapidly, local artisans and building industries have abandoned the use of mud and other vernacular materials as the main building material and therefore vernacular architecture is now history (Karpuz 1984; Kırbaş and Hızlı 2016).

2.3.1.2. Vernacular Architecture of Southern Nigeria

The Architecture of Southern Nigeria is familiar with the North in terms of material used. Generally, these dwellings are constructed monolithically as cob structures which as in the South. In both instances, properly cured earth is used as wall fabric material, which is usually thick, while *gbodogi* (sarcophrynium) leaves in the south, and elephant grass fibre in the north, these were used for roofing, as well as termite-resistant timber such as various palms. Roofs are invariably high-pitched hipped, or hip-and-gable due to the heavy rainfall in the south (Amole 2000). The actual building processes in a community enterprise are devoid of specialists. There is greater individuality, more conscious decision-making, and specialization resulting in the division of labour with the vernacular (Osasona 2005).

Figure 8: Mud house with zinc roof (ArchAfrica 2017)

The Benin of the mid-west, have a traditional house form very similar to that of the Yoruba, consisting of many rectilinear spaces disposed around several courtyards serving essentially as impluvia. The main impluvium (termed *eghodo*), traditionally served as a unifying space for family members and for the performance of religious activities, marriage and other ceremonies, evening entertainment, family discussions and planning (Osasona 2002).

Figure 9: A mud house with zinc roof (Jehosafats 2011)

Figure 10: Mud house with thatch roof (Cole 1973)

Popular building materials in vernacular expressions are being refined since the 1970s, research into locally sourced building materials has been ongoing by the Nigerian Building and Road Research Institute (NBRRI), Sango-Otta and other research institutions (Osasona 2007). This is with a view to optimize the structural capacities of these materials, lowering the cost of production, and generally promoting them as better alternatives to imported building materials. Also, since the '80s, the French Centre for Teaching and Documentation (CFTD), Jos, has been concerned with popularizing the use of cement-stabilized earth bricks since this technique does not require either plaster or paint render with good heat-resisting properties and significant savings can be made in building construction costs (Osasona 2007). Local industries producing fired bricks and other components such as decorative blocks for screen-walling are not left out in contributing to giving alternatives to boost vernacular building (Osasona 2007).

A few mud houses still exist in many rural areas in Nigeria, although they are being reconstructed into modern Nigerian buildings. These buildings were built by homeowners using mud, palm fronds, raffia matting, straw and wood to build their houses (Prucnal-Ogunsote 2001).

Figure 11: Mud houses (Jehosafats 2011)

2.3.2. Vernacular residential building materials

The use of earth as a building material date back to 12000 BC (Pacheco-Torgal and Jalali 2012). Walls as buildings envelop most of the traditional architecture in Nigeria were built of earth material in simple low-cost and self-help construction arrangements (Egenti et al. 2014). Very few adobe mud/ brick architecture have lasted, apart from some of the monuments and temples. However, the endured cultural practices of rural people is an indication that mud has been one of the most common and abundantly obtainable material (Ejiga et al. 2012). Wattle-and-daub earth was the most common technology and method employed (Dmochowski 1990b; Fathy 2010; Ejiga et al. 2012). Immediately it was plastered and properly covered with overhanging roofs, these earth buildings were structurally firm, environmentally sound as it relates to thermal conductivity and could exist for years provided the day to day maintenance was kept (Ejiga et al. 2012). The building earth greatly differs in quality from the excellent brown clay to the black clay (Eneh and Ati 2010). The development of the adobe brick, a modular masonry unit of sun-dried mud came into existence with higher civilization (Niroumand et al. 2013). Unfortunately, modernization affects the sustainability of these practices as they are being replaced with new ones made of modern building materials like sand-cement, cement blocks, concrete and glass. Most of the earth buildings have been abandoned and therefore crumbled due to a lack of proper preservation and conservation.

Thatch and Grass as building materials gained wider usage in vernacular architecture in Nigeria. The combination of grass and earth forms a composite material. The grass is the reinforcement, the earth serves as a binder by surrounding the straw or thatch. The thatch/ straw has tensile strength while the earth has compressive strength (Danja et al. 2017), thatch is one of the oldest known building materials, the grass is a good insulator and easily harvested, this property played a very important role in reducing heat gain into the building. African tribes have lived in homes built completely of grasses and sand for ages (Awosusi 2018; Wikipedia Contributors 2020). Thatch as a construction material uses matted or baled straw from wheat, oats, barley, rye, rice and others as a wall or covered by earthen or lime stucco (Ejiga et al. 2012). Thatch is still employed by builders usually with low-cost, local vegetation and in special buildings (Oluwagbemiga and Modi 2014; Biobaku 2018). The introduction of zinc, aluminium, slate roofing sheets, and cement as a binder in building practices has replaced most vernacular practices.

Timber as a building material is still in current usage, it was a major element in vernacular Architecture which saw a variety of usage because of its combined tensile and compressive properties. One of the best timbers used in Hausa traditional buildings are obtained from the trunks of male palm trees locally called Daleb or Giginya, the timbers are commonly called “Azara” beams (Eneh and Ati 2010). They are usually rigid and heavy with strong resistance to termite attack, they serve as wooden reinforcement as a structural component to strengthen the structures of the wall and pillars (Eneh and Ati 2010). The “Azara” beams are also used to make frame members, beams, brackets and corbels as elements for carrying flat and domed roofs. The ashes of the timber were commonly used as an insulating layer by simply spreading it on top of flat roofs and then treated with infusions from pods. Due to the availability of modern construction materials such as steel rods and other steel sections with concrete, the use of Azara as building material has vanished completely invariably affecting the Nigerian vernacular sustainable practices (Dmochowski 1990b; Eneh and Ati 2010).

2.4. Residential building typologies in Nigeria

2.4.1. Residential building typology in present-day Nigeria

In present-day Nigeria, residential building typology falls in the following category irrespective of location (North or South) or climatic zones as the weather conditions are relatively the same in tropical Nigeria.

Figure 12: Condominiums (Bankole 2019)

Condominiums

In modern-day construction in Nigeria, condominiums are springing up rapidly, these are high-rise buildings that are equipped with elevators and usually have at least six stories (Bankole 2019). These buildings are possible due to the emergence of modern building materials such as sand, cement, granite, steel, reinforced concrete, etc.

Figure 13: Terrace house (Biobaku 2018)

Terraced Houses

Terraced houses fall under the category of Nigerian house types that are in high demand, a row of identical houses shares sidewalls. A terraced house is built as part of a continuous row in a unified design or arrangement (Biobaku 2018). They may be referred to as row houses in some countries and cities, row homes or linked houses. In Nigeria, terrace houses are also very common all over the world. Terraced houses are two- or three-multi-storey buildings, which can stand separately or as a row of buildings with shared walls. This is one of the most popular types of dwelling in the Lagos area. A terrace can be both private and shared depending on the architecture of the building.

Figure 14: Mansion (Author, 2017)

Mansion

Accommodation on two floors, living residence with facilities on both floors usually for a single living. Several mansions can be found in virtually almost all neighbourhoods in the North and South of Nigeria. These buildings in the South are often with steep roofs because of heavy rainfalls (Biobaku 2018).

Figure 15: Bungalows (Awosusi 2018))

Bungalows

A bungalow is a building with only ground floor or having only one storey, in some cases, upper rooms set on the roof, typically with dormer windows. Bungalows are the most common building in Nigeria. Semi or detached bungalows are largely affordable to maintain and cut across several neighbourhoods in Nigeria (Awosusi 2018).

Figure 16: Town house (Biobaku 2018)

Townhouses

A townhouse refers to units that look like a detached homes, which are attached in a multi-unit complex or apartments. Townhouses in Nigeria have identical homes joined into a row of houses. They can be found in estates in Nigeria as well as private and government-powered housing schemes. They are also common in the private sector, often come with terraces. Townhouses occupy entire neighbourhoods and provide vast opportunities for socializing (Awosusi 2018).

Figure 17: Semi-detached house (Biobaku 2018)

Semi-detached house

Semi-detached houses are apartments separated by a party wall or walls. The thermal comfort is usually satisfactory in semi-detached houses compared to the condominium due to the clustered design of the condominium (Awosusi 2018).

Figure 18: Detached house (Biobaku 2018)

Detached House

A detached house is one that stands independently. It can either be a multi-storey or a one-storey building. This building type is common in Nigeria as they are usually privately owned and cheaper to build. It is quite popular in Nigeria because most detached house designs open to the out environment for increased thermal comfort (Biobaku 2018).

Figure 19: Penthouse (Biobaku 2018)

Penthouse

A penthouse refers to an apartment, house or other accommodation that is on the roof of a building. In Nigeria, the penthouse design is not very common due to heated roofs as a result of high temperatures all year round. The position on the top of the building provides the occupants with an expansive view of the city (Biobaku 2018).

Figure 20: Penthouse (Biobaku 2018)

Some penthouses have two levels, several bedrooms, amazing entertainment areas, and other ancillary facilities. Such luxurious apartments can be found in cities, like Lagos, Abuja, Port Harcourt, and several others. Penthouses are more common in hotels than among private property options (Biobaku 2018).

Figure 21: Hybrid building (Author 2017)

Hybrid buildings

These are rare residential buildings, built during the transition period from mud houses to sandscrete buildings. They are a combination of old building elements such as mud, timber and recent building components as seen in modern-day construction in Nigeria (Awosusi 2018). Most of these buildings form the vernacular architecture in the Nigerian built space. They are usually naturally cooler than the recent residential buildings due to the material used in the construction. These materials may include mud, timber, stones. Etc.

2.4.2. Nigerian Buildings with respect to Material use

The introduction of modern building materials such as sand-cement, concrete, steel, etc. led to the fading away of vernacular architecture in Nigeria, which was predominantly the use of earth materials, thatch, grasses, bamboo, etc. (Egenti et al. 2014). Although these locally sourced materials had their limitations, they had an excellent thermal performance. In recent times, most used Nigerian building materials include sandscrete blocks as enveloping walls, reinforced concrete for structural members such as beam, column and slabs, sand-cement as plaster/rendering or wall panels, glazed windows/doors, timber doors/steel doors, tile/terrazzo/cement/rug floor finish, composite ceiling materials such as asbestos, PVC (Polyvinyl Chloride)/ POP (Plaster of Paris) as ceiling materials, Aluminium/zinc/slate as roofing sheets (Isinkaye and Agbi 2013; Adeleye 2014; Akanni et al. 2014; Guardian contractors 2017).

According to Bahadoori (1998), the thermal behaviour of a building is determined by the extent of thermal controls provided in the building and the existing outdoor conditions (Bahadori 1978). Buildings have been used to provide the microclimate required for human existence. It defines spaces for all human activities. As observed by Olanipekun (2002), buildings are essential modifiers of the microclimate, a space isolated from environmental temperature and humidity fluctuations, sheltered from prevailing winds and precipitation, and with an enhancement of natural light. It has also been observed that the effect of extreme climatic conditions, which is discomfort, could be reduced by the provision of environmental services (Luff 1984; Olanipekun 2002). Passive design strategies seek to improve the thermal performance of the building by paying attention to the utilization of natural ventilation through orientation, insulation, window placement and designs (Larsen 1998). The tropical savannah climate of Nigeria is relatively hot and humid (Emmanuel 2005). Consequently, thermal discomfort occurs as occupants try to cool down their indoor spaces with methods that are usually not sustainable and efficient (Abbakyari and Taki 2017). In hot humid regions, natural ventilation is an effective method for reducing the effects of high temperature and humidity. The building members should be designed to provide optimal ventilation through the building envelope in relationship with the external features (Amasuomo et al. 2017). A spread-out building is one of the most effective ways of achieving cross-ventilation, this may imply providing more wall areas in different directions to convey the wind (Givoni 1994).

The indoor environment of a building influences the health, productivity, and comfort of its occupants (Nduka and Ogunsanmi 2016; Ochedi 2018). The systems used to maintain that environment also significantly affect the overall energy consumption of the building, therefore, the building systems installed are one of the most important aspects of building design.

2.4.3. Energy Efficiency in Nigerian Residential Buildings

There are several conditions for any system to be termed energy efficient. In residential buildings, it applies to a sum of factors for the system to be cost-effective which may translate through equipment, resources, maintenance and recycling, responsive buildings, natural environment, and the overall sale of energy to the grid (Barreiro et al. 2009). Some of these factors may include aspects of cost, energy generation predictions, climatic data, compliance with regulations and the operating agreement following predictions on renewable resources (e.g., photovoltaic panels).

Energy efficiency in residential buildings is imperative for the sustainability of the built environment. The integration of energy efficiency concepts throughout the different stages and scales of a community's planning, design, and building process is very important. This involves developing and defining generic and site-specific conditions, creating a set of alternatives to naturally reduce energy demand and then generate supply, evaluating and choosing the most suitable alternatives. The thermal comfort in a building design is an important aspect in achieving low carbon buildings and energy efficiency in buildings (Hou et al. 2016). The evaluation of different energy efficiency alternatives such as energy modelling for buildings within the building fabric and energy generation and storage planning is imperative considering the maximisation of energy efficiency within an economically viable context (Barreiro et al. 2009). Thus, making it possible for practical implementation of the proposed solutions.

Residential Buildings are primarily designed to shelter, comfort and provide safety for their occupants. Therefore, buildings are designed and organised to meet certain codes and regulations (Khalil and Husin 2009; Khalil et al. 2009). There are several indicators that do not fit into the Nigerian context, this is mainly due to the climatic configurations of these regions. Some assessment tools such as Building Energy Efficiency Code (BEEC), Comprehensive Performance Assessment System for Nigeria (CPASN) were previously introduced to cater for the Nigerian environment and her socio-cultural influences in buildings. These aspects indicate the main criteria for establishing a new template for assessment in Nigeria thereby highlighting the excluded aspects in the already existing assessment tools. Comprehensive Performance Assessment System for Nigeria (CPASN) was the proposed assessment framework introduced. It consisted of three major performance tools: the outcome, the indicators, and the sustainability level. It was an attempt to evaluate the current building practices keeping in mind the environmental performance of buildings in Nigeria. It was however identified that the social and economic aspects of the Nigerian context are key to the developmental strategies of any performance assessment tool. Therefore, to develop a credible framework, these aspects were specifically added to the proposed criteria for the Nigerian performance assessment tool development (Amasuomo et al. 2017).

However, it is the prerogative of designers to pay detailed attention to the natural features of the proposed sites and locations of residential buildings. Residential buildings unlike any other building are sensitive in their attributes and components as it forms a living space for people in as well as other commodities.

The Nigeria tropical climate has given its built environment a distinctive Architectural character (Imaah 2008; Oluwagbemiga and Modi 2014; Otto and Ukpere 2014; Nwokoro and Onukwube 2015). The architecture of buildings is traditionally designed by the challenges and opportunities of the presiding regional climate. Climate as a principal factor in residential buildings is the impetus for all the sensual characteristics that build up to a responsive tropical architecture (Givoni 1994). Every designer should ensure the required indoor conditions are met with little or no use of energy whilst taking advantage of renewable sources (Szokolay 2014). The thermal performance of a building is a product of bio-climatic considerations which translates to the interaction between Architecture and Climate. This phenomenon has a great effect on the energy consumption and sustainability of the building. Fulfilment of thermal comfort within living spaces will also improve user satisfaction. It is imperative to design low energy buildings without compromising the internal and external environmental quality.

2.5. Building energy efficiency intervention in Nigeria

2.5.1. The Nigerian Building Energy Efficiency Code (BEEC)

The Nigerian Government have made several attempts within the last two decades to resolve the electricity accessibility gap in the country. They have focused on major aspects such as electricity supply, however, they have not given attention to how end consumers use the electricity (GIZ 2020). Therefore, there has been emphasizing on the need for energy efficiency in the country as increasing supply alone is most likely not going to fix the problem (Solid Green Consulting 2017).

Buildings in Nigeria are one of the biggest consumer sectors of energy. Hence, residential buildings account for about 78% of the total energy consumption in Nigeria (GIZ 2020). In Nigeria, the major causes of energy consumption are cooling and lighting. The building design, building materials and construction, occupants' demands, and the enveloping micro-climate are directly related to the amount of energy necessary for lighting, cooling, and running appliances (Solid Green Consulting 2017; GIZ 2020).

Energy efficiency in buildings as a first design decision will reduce energy consumption in buildings in an effort to enable a more sustainable built environment (Ley et al. 2015; Federal Ministry of Power 2017). This can be done by reducing the energy demand/consumption rates in buildings by employing energy-efficient measures most especially at the early stages of the building (GIZ 2020). Thus, the building sector as a major energy consumer in Nigeria can significantly cut down the energy demand in Nigeria.

In Nigeria presently, the Building Energy Efficiency Code (BEEC) is currently voluntary, it sets the minimum energy efficiency benchmark or requirements for the design of new buildings and it also provides long long-term energy solutions, cost-efficient and a cleaner environment throughout the building's lifespan (Federal Ministry of Power 2017; GIZ 2020). According to GIZ, when the code is implemented, the BEEC may potentially save a minimum of 40% energy in buildings. Although, the implementation of these improvements would require the support of local policymakers and the states. Another major mitigation is the knowledge awareness of practitioners (GIZ 2020).

It is imperative for local policymakers and State governments to adopt the building code (BEEC) of the existing building regulations as a starting point to create the necessary awareness and gradual acceptance (Federal Ministry of Power 2017). This will help the building sector to realize the possible benefits of the Nigerian Building Energy Efficiency Code (BEEC), thereby, establishing a background for energy efficiency at the same time overcoming the market challenges to renewable energy and energy in the Nigerian building industry.

The Federal Capital Territory (FCT) began the pilot activities towards the implementation of the building code (Solid Green Consulting 2017). There have been plans to adopt the BEEC at the state level using six states in Nigeria (GIZ 2020). This is planned to be done in addition to building projects designed and constructed using the BEEC to demonstrate the implementation of the BEEC Code of practice. Also, existing buildings would require design and construction measures to facilitate a reduction in energy consumption. According to GIZ, there is a need for energy auditing in pre-existing buildings towards the implementation of audit recommendations (GIZ 2020).

To achieve high levels of BEEC compliance, many local actors and a variety of supporting resources would be needed and required for participation which is not currently tenable presently. GIZ has recommended that critical resources to the realisation of the Building Energy Efficiency Code compliance should include available support systems (GIZ 2020). The support systems according to GIZ may include technical coaching sessions which should go beyond group training on the technicality of the Code requirements through the adoption of such techniques such as the digitalisation of BEEC and the review of building designs (GIZ 2020).

2.5.2. Proposition of the Nigerian Building Energy Efficiency Code (BEEC)

The Federal Republic of Nigeria proposed Nigerian Building Energy Efficiency Code (BEEC) to ensure energy efficiency in buildings. It was a call to duty when President Buhari signed the Paris Agreement committing to the minimum nationally determined contributions to be made by Nigeria to reduce the impact of global warming, he reiterated Nigeria's commitment to remain a respected and respectable member of the civilized global community (Federal Ministry of Power 2017). A project that was undertaken by the Nigerian Energy Support Programme (NESP) and other relevant stakeholders. The Federal Republic of Nigeria's National Building Energy Efficiency Code first edition was published in 2017. The responsibility for delivering on that commitment henceforth lay with the Nigerian public and private sectors of the Nigerian society with the Nigerian Government agencies having the power to implement and enforce formulated policies. The Federal Ministry of Power, Works and Housing have a leadership role to play in making regulations and developing or approving programmes that guide the conduct of public and private operators in the use of climate impacting resources, such as energy (Solid Green Consulting 2017).

According to BEEC (2017), The Building Energy Efficiency Code gives a comparative advantage when employed effectively in the planning and construction of buildings. The Code also specifies the minimum energy required to achieve energy efficiency in buildings which has various impacts on the socio-economic wellbeing of citizens and the country (Federal Ministry of Power 2017). The National building code for Nigeria sets minimum standards on building pre-design, design, construction, and post-construction stages with a view to ensuring quality, safety, and proficiency.

It was said that the code has the capacity to save 40% of the Nigerian current energy usage in buildings when implemented which is expected to complement the demands for energy-efficient buildings in detail (Federal Ministry of Power 2017). The code had the expectations to provide thermally comfortable and healthy buildings. Therefore, setting the minimum efficiency requirements for new buildings to achieve reductions in energy use and gas emissions over the life of the building (Solid Green Consulting 2017).

The various groups who contributed to the technical Study carried out to develop the First Edition of the National Building Energy Efficiency Code include (Solid Green Consulting 2017):

- Professionals in the building industry and their respective regulatory bodies.
- Development control, federal capital territory (FCT), Abuja.
- Ministries, departments, and agencies.
- Private sector stakeholders.

- The Nigerian Energy Support Program NESP, funded by the German Government and the European Union.
- Resource persons at various stages of the development of this edition of the Code.

The research was conducted primarily in the Federal Capital Territory of Abuja and the requirements can be adopted by any state in Nigeria (Solid Green Consulting 2017). In an attempt of developing a labelling and incentive scheme with procedures for Control and Enforcement of the minimum energy efficiency requirements and finally recommendations on calculation and compliance, the BEEC had the following chapters. chapter 1: minimum energy efficiency requirements, chapter 2: building energy labels and energy efficiency incentives, chapter 3: control and enforcement, chapter 4: calculation methods and tools.

The energy efficiency interventions included:

• Overall Window to Wall Ratio not exceeding 20%.
• Requirement for shading when Window to Wall Ratio exceeds 20%.
• Reduction of installed lighting power density.
• Minimum requirements for roof insulation.
• Minimum performance of AC equipment specified.
• Installation of non-inverter split units to be restricted.

The code featured two compliance methods (Solid Green Consulting 2017):
• Prescriptive: adherence of projects to all the requirements as a checklist, no energy calculations were required.
• Performance: This considered the whole building analysis using energy simulation software.
The code provided flexibility for project teams to deviate from the prescriptive requirements, provided that the theoretical energy use of the building is less than or equal to that of the building with every prescriptive requirement included (Federal Ministry of Power 2017).

2.5.3. Objectives and Procedure of BEEC

The objectives set out for the operations of BEEC are stated below (Federal Ministry of Power 2017).
Description of objectives: The development of minimum energy efficiency requirements for new residential and office buildings in Nigeria proposes recommendations for the effective use of energy in new buildings. The overall aim was to propose recommendations, that:

- Consider bioclimatic aspects.
- Encourage the design of new buildings in a manner that reduces the use of energy without constraining creativity in design, building function and the comfort or productivity of the occupants.

- Optimize passive cooling strategies.
- Deal with cost considerations and market access to construction materials and building fabrics.
- Deal with the absolute minimum requirements for energy efficiency in such a way that they can be applied anywhere in the country.

  There was also a two-year voluntary period to allow an individual state an adoption and inception phase, after which the state can then make the requirements mandatory.

2.5.4. Scope of the BEEC

The BEEC consists of the following elements (Federal Ministry of Power 2017; Solid Green Consulting 2017).

- Minimum energy efficiency requirements and verification methods.
- Calculation methods and tools.
- Building energy labels and energy efficiency incentives.
- Control and enforcement.
- Qualification of experts.
- Review and adaptation.

The structure of the BEEC provides a minimum rating for major building components to achieve efficiency, for example, the overall Window to Wall Ratio not exceeding 20%. The passive design components for Nigerian buildings were building orientation, window to wall ratio, local shading, thermal mass, thermal insulation, daylighting, and natural ventilation (Federal Ministry of Power 2017).

The code provides two methods for buildings to demonstrate compliance with the BEEC requirements.

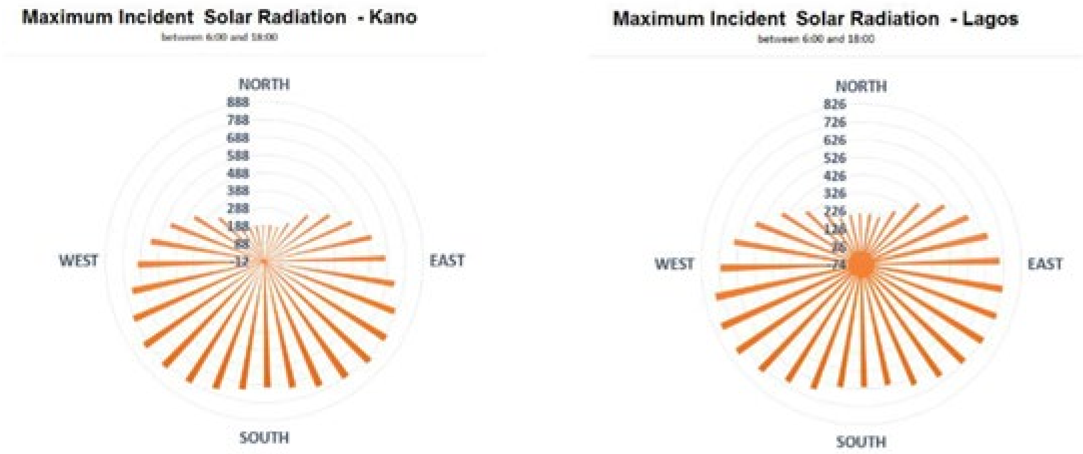
- The compliance Method 1: this is a prescriptive approach that requires building projects to meet all the requirements as a checklist.
- The compliance method 2: is a performance approach that allows project teams to deviate from the prescriptive requirements provided that the theoretical energy use of the building is less than or equal to the same building with all the prescriptive requirements included. This requires a whole-building analysis using energy simulation software.

The BEEC was able to meteorologically justify the reason for using one code or requirement that works for the country as stated on page 17 of the development of the national building energy efficiency code (BEEC). It stated that Nigeria falls between similar latitudes and the same minimum efficiency requirements have been provided for all Nigerian states (Solid Green Consulting 2017).

The Code went further to present the solar radiation graphs for Kano in the North and Lagos in the South, the study concluded that there is very little difference in solar radiation and not enough to justify different requirements.

It went on to evidently justify this action by conducting a solar radiation simulation in two extreme locations of the country - Kano in the North and Lagos in the South.

The graphs below show the similarity of solar radiation in the two locations.



Solar Radiation Kano **Solar Radiation Lagos**

Figure 22: Solar radiation graphs of Kano and Lagos (Solid Green Consulting 2017)

Although the BEEC intervention was a welcome development toward achieving energy efficiency in buildings, the steps and guidance for implementation in building designs were not specific and the practicalities for its usage were not defined as to the requirements of each design variable and parameters (Ochedi 2018; Odunfa K. M. et al. 2018; Gyoh 2020). This limited the application and use of the BEEC, as there are no clear descriptions or specifications on how to achieve its set building recommendations/standards as well as it was not a holistic approach toward energy and resource efficiency in Nigerian residential buildings (Gyoh 2017; Solid Green Consulting 2017; Ochedi 2018; Odunfa K. M. et al. 2018).

The BEEC code has five points rating with the description shown in the table below (Federal Ministry of Power 2017; Solid Green Consulting 2017).

Table 9: Star rating for energy efficiency label (Solid Green Consulting 2017)

Rating (star)	Intervention	Minimum Specification
1	• Window to wall ratio or shading	• 20%
2	• Window to wall ratio or shading • Lighting - Residential • Lighting -Office	• 20% maximum or shading as per BEEC Calculator • Maximum lighting power density 6 W/m² • Maximum lighting power 8 W/m²
3	• Window to wall ratio or shading • Lighting - Residential • Lighting -Office • Roof insulation	• 20% maximum or shading as per BEEC Calculator • Maximum lighting power density 6 W/m² • Maximum lighting power 8 W/m² • Minimum R-value 1.25m²K/W
4	• Window to wall ratio or shading • Lighting - Residential • Lighting -Office • Roof insulation • Air conditioning minimum performance (only if air conditioning is necessary for good indoor comfort)	• 20% maximum or shading as per BEEC Calculator • Maximum lighting power density 6 W/m² • Maximum lighting power 8 W/m² • Minimum R-value 1.25m²K/W • Minimum EER/COP 2.8 and Inverter Compressor
5	On application only. This has intentionally been omitted to allow for future additions (tightening of standards), such as PV, high performance glass, solar water heating	

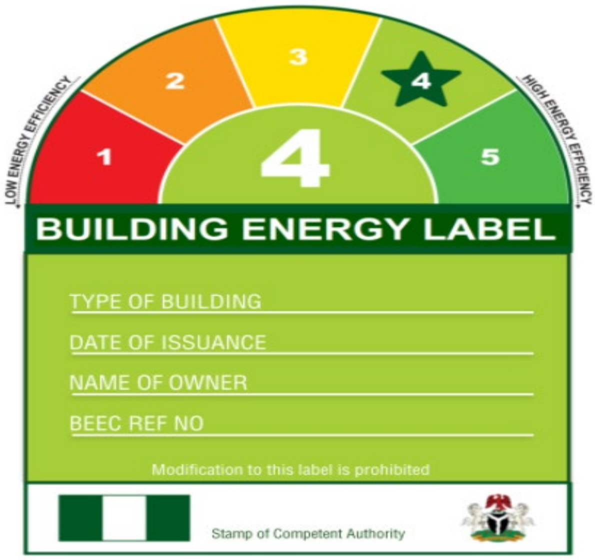


Figure 23: BEEC Star rating chart (Federal Ministry of Power 2017).

2.5.5. Energy efficiency recommendations for the Nigerian building sector based on literature reviews

The literature review in this research provides various recommendations or guidelines for various stakeholders with regard to energy and resource efficiency in residential buildings for the tropical savannah climate of Nigeria (Uyigue et al. 2009; Iheme et al. 2011; Nwokoro and Onukwube 2015; Adewuyi and Odesola 2016; Arup (Madrid & Lagos offices) and Design Genre 2016; Abbakyari and Taki 2017; Amasuomo et al. 2017; Eze et al. 2017; Federal Ministry of Power 2017; Solid Green Consulting 2017; Alonge 2018; Ochedi 2018; Osuizugbo 2018; Ogunmakinde 2019). The recommendations are categorised below according to the relevant stakeholders.

2.5.5.1. Practitioners

Following the progression of the literature review to the suggested interventions for the design of energy and resource-efficient residential buildings for the tropical climate of Nigeria, it is imperative that practitioners play vital roles in the delivery of energy and resource efficiency in buildings. From the literature reviews, the following are recommended for practitioners (Oladiran 2009; Uyigue et al. 2009; Iheme et al. 2011; Adewuyi and Odesola 2016; Olotuah 2016; Oloke et al. 2017; Ochedi 2018; Osuizugbo 2018).

1. Building practitioners should be versatile with energy-efficient building materials, design and construction strategies (in both passive design and circular economy). This will ensure that the right design considerations and decisions are taken towards eradicating inefficient design strategies, materials and practices.

2. Building experts should make efforts to pre-determine building performance with regard to energy and resource efficiency. This may involve conducting relevant building simulations to test the efficacy of design strategies. This process helps improve building performance by employing necessary optimisations.
3. Designs should be more human-centric and efforts should be made to improve the comfort and well-being of occupants.
4. It is the responsibility of building professionals to inform or educate clients on the requirements and benefits of energy and resource efficiency in buildings. Hence, the clients should be aware of the impact of each design strategy, performance and expectations.
5. Building professionals should ensure that their designs and construction allow for the reuse and recycling of building components and materials. Therefore, circular economy principles should be incorporated into every building project.
6. Building professionals or design teams should ensure that they are aware of and possess relevant expertise in energy and resource efficiency in buildings. This is to make sure the right professionals and design team are engaged.
7. Building experts should conduct proper studies of every project to understand their uniqueness and know how best to apply the recommendations of this research and framework.
8. There should be proper training of the design team in the area of energy and resource efficiency in residential buildings because this knowledge is very low in Nigeria as seen from this research. Therefore, relevant computer-aided design (CAD) tools should be employed and mastered in the delivery of sustainable projects as well as facilitating collaboration amongst professionals.
9. Professionals in practice should explore ways of collaborating with institutions, organisations, regulatory bodies, and the government in terms of developing energy and resource-driven projects in a bid to reduce energy consumption, building waste, and operational and embodied CO_2, thereby reducing the cost of energy, safeguarding the environment, and improving resource efficiency.
10. Practitioners should ensure that only registered/licensed individuals or companies are allowed to practise in order to eradicate quackery in the Nigerian building sector. This will ensure projects are carried out by professionals and experts in the building industry.
11. Experts and environmentalists in the field of sustainability should flag off campaigns and awareness programmes on safeguarding the environment by ensuring that best sustainable practices for energy and resource efficiency are implemented at all levels.

2.5.5.2. Policy-makers and Regulatory bodies

Government authorities, policy-makers and regulatory bodies have a significant role to play in setting the right principles and standards to be followed (Ochedi 2018). This is to say that if there are no policies and standards, there would be no minimum standards to be adhered to. The development of new housing prototypes without incorporating energy and resource efficient interventions will make buildings inefficient and unsustainable (Dania et al. 2013; Ogunmakinde 2019). From the works of literature, the following recommendations have been made for policy-makers and regulatory bodies in Nigeria (Imaah 2008; Iheme et al. 2011; Dania et al. 2013; Nduka and Ogunsanmi 2016; Osuizugbo 2018).

1. Policy-makers should ensure that energy and resource efficient regulations for buildings are enacted and implemented.
2. The relevant authorities should sensitise the building professionals and the general public on the need to design and construct buildings that are energy and resource efficient. This awareness should be created along with the guidelines on meeting the various requirements.
3. Policy-makers should develop road maps toward the implementation of policies for energy and resource efficiency in buildings. This also implies there should be regulatory bodies installed to ensure that buildings are designed and constructed to meet the minimum requirements.
4. The relevant authorities should ensure that only qualified individuals and companies are allowed to practice and have obtained the necessary training for the design of energy and resource efficient buildings in Nigeria.
5. Regulatory bodies should prioritise the training of professionals within the building sector on best practices and ethics for the delivery of energy and resource efficient buildings.
6. Practices should be required to possess the minimum criteria and expertise in energy and resource efficiency in order to undertake building projects in Nigeria.
7. Town planning authorities should ensure that building plans presented for approval meet the minimum energy and resource efficient requirements or expectations.
8. Government authorities should make sure that development is controlled and monitored in the country because this is a major problem observed in this research. Residential buildings and other related developments should be executed in conformity with proper and sustainable master plans. Therefore individuals, communities, organisations or companies should not be allowed to embark on unauthorised and unapproved developments.
9. The government should develop schemes and programmes for the reuse and recycling of building components and materials. Thus, engaging circular economy principles.

10. The relevant government regulatory bodies should ensure that there is no interference from local communities, individuals or organisations on regulatory standards, policies, processes and executions. Any matter of concern or interest should be communicated to the appropriate division using the appropriate channel. This is to ensure that the development of the built environment is managed by the relevant government authorities.
11. Town and city planning should be up to date with current trends in sustainable development, most especially as it relates to energy and resource efficiency in buildings.
12. Government should endeavour to partner with private and public sectors in the realisation of energy and resource efficient residential buildings in Nigeria.
13. The relevant authorities should ensure that energy and resource efficient training is embedded in the curriculum of students in the relevant disciplines.
14. Government should participate and invest in housing projects, and estate development. This way, they can be sure that buildings are constructed to approved standards.
15. The electricity situation of Nigeria should be addressed as well as the establishment of more sustainable power sources. This is a major struggle for the populace and it has contributed to the concentration of carbon emissions due to the alternative sources of electricity as seen in this research.
16. The relevant authorities should encourage the practice and culture of energy and resource efficiency in buildings by recognising, valuing, and rewarding the practice of building sustainability concepts.
17. Government bodies should put in place practicable policies and regulations for buildings to ensure that energy and resource efficiency campaigns are sustainable.
18. There should be in place policies to restrict the use of inefficient energy and resource building materials in the country and make available for use sustainable building materials. This will promote the use of ideal building products in construction.
19. The relevant authorities should ensure that organisations offering training programs for energy and resource efficiency in buildings possesses the right certification and accreditation for the program and institutions offering programmes on building design and construction have energy and resource efficiency training embedded in their curriculum.
20. Regulatory bodies should hire human resources that are experts in building sustainability and promote continuous professional training and development of staff.
21. The relevant authorities should pioneer the research and development of local building materials that are energy and resource efficient in the Nigerian tropical climate.
22. There should be policies to provide explicit guidelines on how to minimise waste and promote resource efficiency in buildings.

23. The government may need to support private practices and training organisations financially to conduct building sustainability research or to execute building projects in Nigeria.
24. The government should invest in demonstration projects for the general public to use as prototypes in achieving energy and resource efficiency in buildings.
25. Town planning authorities should be knowledgeable in passive design strategies and other bioclimatic considerations. This will enable them to factor in the orientation of future buildings, accessibility, local shadings, wind/sun path and other bioclimatic considerations during the preparation of masterplans.

2.5.5.3. Training and Education

Organisations such as colleges, technical schools, universities, etc. are the bedrock of teaching, training and learning (Uyigue et al. 2009). It is very important that learners are prepared to meet the demands of the building industry in order for them to deliver the expectations of an energy and resource efficient building (Uyigue et al. 2009; Olotuah 2016). The following recommendations have been made for training and education organisations in Nigeria (Iheme et al. 2011; Emmanuel et al. 2014; Ley et al. 2015; Abubakar 2018; Ochedi 2018; Ogunrin 2019).

1. Trainers and trainees should be exposed to practical building energy and resource challenges in buildings. This is necessary to shape their understanding of the situation and craft ideas on the applications of the required interventions in Nigeria.
2. Training organisations should invest in real building projects either through partnership or demonstration projects in order to gain practical knowledge from the field.
3. Ensure that the relevant disciplines are equipped with the required energy and resource efficient training programmes in Nigeria.
4. Training organisations should make sure they obtain the right accreditation to offer energy and resource sustainability programmes in buildings.
5. It is important that research grants and projects in the area of building sustainability are sought and conducted as well as taking advantage of opportunities to participate in field projects with practitioners and maximise sponsorship opportunities from both internal and external sources.
6. Trainers should be very knowledgeable on current trends in the field of energy and resource sustainability. This is to ensure they understand the dynamics of the building sector and policies.
7. Educators should ensure that trainers and trainees are exposed to computer-aided design modelling software and simulation tools.

8. Efforts should be made to promote continuous professional development programs in the area of building sustainability, so they are equipped with the required skills and knowledge.
9. Trainers should establish collaborative networks with practitioners and relevant regulatory bodies in the field of building efficiency. This is necessary to create support networks to aid learning and practice.

2.5.5.4. The general public

The public is usually the end-users of any social amenities or infrastructure most especially residential buildings (Osuizugbo 2018). It is therefore important that they are aware and equipped with basic knowledge of energy and resource efficiency in residential buildings. The following recommendations have been made for the general public (Dania et al. 2013; D 2014; Adewuyi and Odesola 2016; Nduka and Ogunsanmi 2016; Abubakar 2018; Alonge 2018; Ochedi 2018).

1. Clients should have a basic understanding of building physics or bioclimatic considerations for their buildings and ensure that energy and resource efficient strategies are incorporated into their building projects.
2. The general public should make sure they engage the right professionals in the delivery of sustainable residential buildings in line with building regulations.
3. Building occupants should understand the benefits of energy and resource efficiency in buildings and how they can maximise the energy and resource potentials of their buildings.
4. Building owners should ensure that reusable and recyclable building materials are used in the design and construction of their buildings. These buildings should be maintained, reused, and recycled when due thereby incorporating circular economy principles.
5. Building occupants should possess a working knowledge of how to possibly adapt to the building conditions in order to reduce energy consumption.
6. The building occupants should be able to regulate the building controls in order to maximise the performance of their buildings.
7. Clients should cooperate with practitioners and regulatory bodies to ensure that buildings are designed and constructed to meet set standards.

2.6. Aspects of Energy efficiency in buildings

Achieving energy efficiency in buildings can be categorised into three major groups using the cost-benefit pyramid. These categories include bioclimatic strategies, appliances, renewable energy technologies (RETs).

2.6.1. Bioclimatic strategies

Bioclimatic considerations involve the use of the geological, building fabric and natural features of the environment to improve the performance of the building (Daemei et al. 2019). This may include natural ventilation, daylighting, building materials, thermal mass, building orientation, etc. these strategies can also be described as passive design strategies (Daemei et al. 2019) The use of passive design strategies in building construction can reduce energy consumption in buildings thereby reducing operational CO_2 emissions (St. Clair and Hyde 2009; Pratt and Lenaghan 2015).

2.6.2. Appliances

The use of energy-efficient appliances is another building sustainable strategy that can be used to decrease residential energy use, although it is used most of the time to compensate for inadequate passive design considerations (Young 2008). It entails the use of appliances to either light up, ventilate, dehumidify, cool or heat as in the case of HVAC (Heating, ventilating and Air conditioning), etc. Most of the appliances adopted in this case usually have a low energy rating, such as energy-saving bulbs, inverted air conditionals and air handling units, which are usually expensive (Young 2008).

2.6.3. Renewable energy technologies (RETs)

These are active measures to attain sustainability but are very expensive in most cases. They include the use of advanced technology equipment and devices such as photovoltaic panels, wind turbines and hydro-power turbines, Biomass, etc. (Torio et al. 2009). These measures are usually massive projects and are not cost-effective in the long run for small scale use.

The cost-benefit pyramid shows the cost implications of three major categories of design strategies that can be adopted in order to improve the performance of a building. RETs simply refer to Renewable Energy Technologies that involve the use of active measures to improve the performance of a building such as photovoltaic panels and high-technology equipment which are usually expensive. Low energy appliances have a medium cost implication. The most efficient and cost-effective are Passive design strategies (PDS) which may also be referred to as bioclimatic considerations. It entails designing to take advantage of the natural features of the environment in order to improve building performance. e.g., building orientation, building materials or fabrics. It is imperative that passive housing strategies are adopted at the early stages of the design and construction of residential buildings.

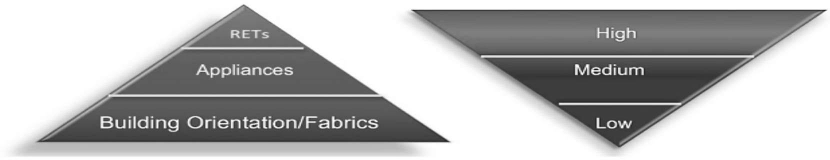


Figure 24: Cost benefit Pyramid (Gyoh 2017)

Thermal comfort in buildings is a very important consideration for occupants' productivity and satisfaction. Acoustics properties of buildings are another important aspect to be considered in residential designs and at the same time, the need to maximize daylighting is of the essence in order to reduce the cost of lighting which will also translate to improving ventilation (Gyoh 2017).

A building may not be sustainable in its performance when there is a lapse in its functionality; in residential buildings functionality is an integral aspect of space usage which should be taken into consideration bearing in mind the aesthetic features of the building. Safety and security are important considerations; using passive fire safety measures can be very effective in the protection and prevention of a building from fire. Also, designs for crime prevention are all security strategies needed to be adopted during the design and construction of residential buildings.

Passive Energy efficiency practices have proven to be a cost-effective strategy for building economies (Baker and Steemers 1999; Holmes and Hacker 2006). To avoid dependence on active energy mechanism, Hyde (2000) recommended passive design for indoor comfort and lighting (Hyde 2000). Morrissey and Horne (2011) described passive design as the use of solar energy and the bio-climatic characteristics in conjunction with selected building elements to maintain comfort within the built environment (Morrissey and Horne 2011). The climatic condition was considered from the findings as to the most important factor in considering thermal comfort in an analysis of climatic conditions with respect to thermal comfort in buildings (Givoni 1994). Active measures such as the use of mechanical cooling and heating in buildings have proven to be expensive as far as the sustainability of the built environment is concerned. The attainment of indoor thermal comfort at little or no cost to the building user is a sustainable way of enhancing the built environment (Baker and Steemers 1999; Edwards 1999). This is a major challenge in urban buildings within tropical climates in view of the impact of climatic elements and the emission produced in urban areas (Hyde 2000).

High intense solar radiation for long periods creates amazing measures of warmth in tropical regions. The warmth is felt inside buildings by the inhabitants as portrayed by the high indoor air temperature figures. The significant dimensions of heat action are also influenced by many residences as well as industrial activities in the tropical urban environment to build up the warmth. All these mean the inconvenience experienced in the tropical built environment. Urban change is presently at its crest in the tropical regions prompting congestion and thermal discomfort (Emmanuel 2005).

The urban air temperature is slowly ascending in all urban areas on the planet, brought about by an exceptional decrease in the green zone in urban communities (Jusuf et al. 2007). It was discovered in Ibadan city in Nigeria that maximal temperature has been on the increase from 30C in 1979 to 33.5C in 2009 (Adesoye 2011). The satisfaction level of indoor thermal comfort in such high temperate regions is of concern, particularly with the threat of climate change. Indoor and open-air temperatures remain the prevailing climatic factors influencing thermal comfort in the tropics. The afternoon time in the tropics is usually hot as a result of the impact of exceptional sun-powered radiation prompting high air temperatures during sun time. The constant effect of high insolation has a strong effect on buildings and influences levels of indoor comfort. Residential buildings must be able to provide considerable thermal comfort to be a resting place (Adunola 2014).

There are several recommendations from experts in the fields of environmental science. Most of these measures narrow down to passive housing which is one of the effective ways of improving the performance of residential buildings. Misni (2013) described landscaping as an integral part of building design with respect to energy efficiency in buildings because it has a profound effect on the microclimate (Misni 2013). It has a direct effect on the ambient temperature simply by shading the building from unwanted solar radiations and redirecting the air flow directly into the building for natural ventilation, and indirectly by evapotranspiration (Misni 2013). Therefore, the type of trees specified is important, they should be selected in respect to the shade they provide considering aesthetics and their ability to repel pests taking into cognizance the increase of vector-borne disease in the region. LEED (Leadership in Energy and Environmental Design) suggested that an outdoor space that is greater or equal to 30% of the total site area with a minimum of 25% of that area serving as a vegetative cover or overhead vegetated shading should be allowed (USGB Council 2016).

Building materials is an important factor that needs to be considered in the design and construction of buildings in the tropics of Nigeria as the efficiency of a building is largely dependent on the materials used in construction. Thermo-physical properties of the building materials directly affect the rate of heat transmission in and out of the building, thereby causing a change to the indoor thermal conditions. Thermo-physical properties include the thermal conductivity, absorptivity, emissivity and reflectivity, surface convective coefficient and heat capacity of the material (Amasuomo et al. 2017).

It is advisable that external walls be light coloured and highly thermally resistive, also the use of locally sourced materials like stabilized hydro-form bricks will help reduce heat transmission. Internal walls may be heavy if the annual range exceeds 20^{0}C (Givoni 1994). Roofing materials should also be lightweight and highly resistive. One easy and cheap way to reduce overheating is by providing reflective roof surfaces with little dependence on cooling devices. External wall/structural materials should be invulnerable to climatic influences preferably with the use of large roof eaves (Amasuomo et al. 2017).

Providing cross ventilation is the simplest approach for achieving indoor thermal comfort in hot humid regions by maximising the air exchange from the exterior through the building envelope into the interior spaces to improve the indoor air quality to provide a direct physiological effect. This would increase the rate of sweat evaporation, hence minimizing discomfort. Fenestrations should be large enough and properly shaded between 40 and 80% of the north and south walls taking cognizance of the wind direction and positions at relative heights below and above the door level to enhance stack effects including windows configurations as regards day lighting (DeKay and Brown 2014). Windows should be configured in response to sunlight to provide enough lighting into the building interior.

The increase in public environmental awareness in the building industry due to the adverse effect of climatic change has resulted in the development of creative solutions to reduce greenhouse gas (BREEAM 2014). There are assessment tools that are operational but are not very suitable for the tropical environment. Building assessment tools such as the Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) have assisted in providing an effective framework to measure the environmental performance of buildings and construction process (USGB Council 2016). The primary function of this apparatus is fundamentally on building specification and evaluation including the design, construction, and use (BREEAM 2014). It focuses on ensuring a healthy indoor space most especially as it relates to lighting, ventilation, acoustics, noise, thermal comfort, daylight and the protection of the occupant’s living condition (USGB Council 2016). Energy balancing in buildings is still in its infancy in Nigeria. There are a few LEED-certified buildings in Nigeria as shown in the table below.

Table 10: LEED-certified buildings in Nigeria (USGB Council 2016)

BUILDING	RATING	ASSESSMENT	LOCATION	Date of last certification
THE NOX BUILDING	Gold	LEED BD+ C: New Construction v3-LEED -2009	Abuja	Apr 08, 2015
THE HERITAGE PLACE	Certified	LEED BD+C Core and Shell v3-LEED-2009	Ikoyi, Lagos	Feb 23, 2018
RFA HS-CLASSROOM NORTH	Certification in process	LEED BD+C: School v3 –LEED-2009	Abuja	-
RFA HS-CLASSROOM SOUTH	Certification in process	LEED BD+C: Schools v3 - LEED 2009	ABUJA FCT, 00000 Nigeria	-
P&G NIGERIA MDO WAREHOUSE	Silver	LEED BD+ C: New Construction v3-LEED-2009	Agbara	Aug 31, 2015
AFDB NIGERIA FIELD OFFICE		LEED BD+ C: New Construction v3-LEED 2009	Abuja	-
NO 4 BOURDILON STREET	Certification in progress	LEED BD+C: New Construction v3 - LEED 2009	Lagos, 00000 Nigeria	-
ASDSDS	Certification in process	LEED BD+C: New Construction v3 - LEED 2009	Asdasdasda, AD Nigeria	-
NESTOIL TOWER	Silver	LEED BD+C: Core and Shell v3 - LEED 2009	Lagos, 101241 Nigeria	Sep 09, 2016
PROCTER AND GAMBLE LAGOS MASTER SITE	Certification in process	LEED BD+C: New Construction v3 - LEED 2009	Agbara, 00000 Nigeria	-
PROCTER AND GAMBLE LAGOS FACILITY	Silver	LEED BD+C: New Construction v3 - LEED 2009	Agbara Ogun, 00000 Nigeria	Sep 17, 2015

The impact of urban morphology and neighbourhood patterns on urban microclimate should be evaluated in relation to the thermal comfort within urban living zones. Tropical urban microclimate needs to be examined to properly approach the bio-climatic design consideration for indoor comfort, air temperature is, therefore, an important aspect in the tropics when considering the thermal comfort of urban residents (Adunola 2014). Intense solar radiation and high temperature, light winds, high humidity, and long periods of still air are clear characteristics of the tropics as there are mainly two broad seasons in Nigeria, namely the dry season (November to April) and the rainy season (May to October). The urban climate varies considerably from the synoptic climate as a result of the combination of anthropogenic and physical factors such as inadequate vegetative cover, increase in thermal mass, drainage systems, non-porous surfaces, and emission of heat and pollution which contributes to altering the urban microclimate (Steemers and Steane 2004). It is of great importance that the built and natural environments be balanced due to the dynamic interaction between them (Pearlmutter 2007). Studies have shown the relevance of the dynamic interaction between climates and built environment which emphasize that climatic analysis is important for the effective design of energy-efficient buildings.

2.7. Passive design strategies in tropical Nigeria

Passive design considers the building as an interconnected whole. Holistic concepts are applicable to the developmental process of a building. Nigeria is in the warm climates where cooling demands are high, the adoption of passive design strategies in the Nigerian building industry is not commonly placed yet. To raise this awareness, major passive design strategies can easily be adopted such as building orientation, natural ventilation, daylighting, thermal mass. The establishment of passive design standards for tropical Nigeria provides a benchmark for developers' regulation.

Building orientation is a major consideration in any building as it sets the foundation or basis for other considerations. According to CIBSE (2018), "North-facing windows suffer very little solar gain and benefits are often gained by having the major building axis pointing east/west" (CIBSE 2018). The acceptable orientation for Nigeria is solar north, with orientations of up to 20° west of north and 30° east of north, excluding direct sun by using trees and adjoining structures to shade every façade while capturing desired cooling breezes (McGee et al. 2013).

Naturally, ventilated buildings can generate the driving force for air movement required to remove stale air. Natural ventilation has the tendency of maximizing the potential of the stack effect, using air passages and wind effects (CIBSE 2018). This strategy can save a quantifiable amount of energy and help cut down CO_2 emissions from buildings. Aside from windows and fenestrations providing ingress and egress for air, they also help throw in light. Daylighting as a passive measure is beneficial in reducing the reliance on the power grid for lighting purposes. Maximizing daylighting is of paramount importance in Nigeria since power is currently inadequate.

In Nigeria, there is a constant need to reduce the temperature in buildings since it is in a warm climate region (Emmanuel 2005). Measures such as thermal massing are yet to be fully explored. Nigeria building materials constitute good thermal resistance and insulator if properly utilized. These passive design strategies are applicable in Nigeria and often requires no extra cost to include in designs.

A review of works of literature relating to the tropical climate of Nigeria and other general standards, or requirements has presented the expectations for the following passive design strategies: Thermal Mass, Daylighting, Building orientation, Natural ventilation. The recommendations for tropical or hot climates are presented according to research findings in the following below.

2.8. Passive Design Strategies

Passive design simply refers to the architectural design strategies used by designers to develop buildings that are responsive to the climatic requirements and other contextual necessities in their environment (Kroner 1997). Passive design is a concept of a self-sustainable building, especially in the area of energy economy, it entails the use of bioclimatic considerations to improve the performance of the building (Bhatt 2014). The strategies help to improve the interior comfort conditions, increasing the energy efficiency in buildings and reducing their energy consumption (Rodriguez-Ubinas et al. 2014). It is one of the most basic and effective means of attaining an energy-efficient and sustainable residential building, hence, it is the most recommended. In this approach, all design considerations are influenced by the natural environment of the proposed site for the best performance of the building (Bhatt 2014).

In passive design, a critical study of the location is conducted, and relevant information is obtained regarding climatic data of the site and environs for analysis. This may include the building's orientation, solstice, wind directions, topography, thermal mass, daylighting, natural ventilation, building material, natural ventilation, functionality, building insulation, building colouration, building elevation, etc. (James and Bahaj 2005). Passive design tends to provide high levels of comfort at a very low cost, thereby, promoting energy efficiency through natural ventilation systems, insulation, dry lining, solar panels, roof wind turbines, etc. (Alwan et al. 2017). Passive design strategies can easily be integrated at the design stages of a building. All major building attributes are usually better decided at the design stage. Therefore, the building benefits from a wide range of passive strategies which are cheaper and most efficient.

Low-energy building can be achieved through effective design decisions of a passive design approach that is suitable for a climate considering indoor comfort (Akande 2010). Below are some passive design strategies and recommendations for Nigerian tropical buildings.

2.8.1. Building Geometry

The shape, size, form, and design of a building play an active role in the performance of a building and can be used as a passive design strategy to achieve optimum comfort and energy savings (Akande 2010). CIBSE (2018) stated that the indoor environment of any building determines the health, productivity, and comfort of its occupants as buildings are used to provide the microclimate required for human existence (CIBSE 2018). Building shape and structure play an important role in improving the performance of the building. For example, a building shape can help improve airflow around the building, surface area exposure to heat gain or loss, solar gain, self-shading, etc. (Premrov et al. 2017). Aflaki et al. (1980) and Tombazis (2001) recommended that the Longitudinal ends of a building should be along the west-east axis which should also be narrow as possible (Tombazis and Preuss 2001; Aflaki et al. 2012).

The building form can make it easier to achieve an energy-efficient building as heat loss is minimised in relation to the building's volume (Oral and Yilmaz 2003). Buildings are designed into different forms and patterns, which affect the airflow, solar radiation, and other environmental influences around them. Building responses and performance is highly influenced by their morphology, hence should be taken into consideration.

2.8.2. Building Orientation

In the tropical region, the Southern elevation of a building receives more solar radiation while the Northern side receives the minimum amounts of radiation (Omrany and Marsono 2016). According to Tang (2002), the amount of direct radiation on the building facade is dependent on the azimuth in the wall, and the building's angle (Tang 2002). Hence, a proper building orientation can be useful in positioning the building on site performance as regards shading, wind flow and ventilation, solar radiation, and daylighting (Chiras 2002; James and Bahaj 2005).

<u>Ideal Building Orientation for West Africa</u>

The orientation of a building is a major determinant of the building's performance in passive design. It has a strong influence on what and how many design strategies are to be adopted. In reviewing pieces of literature on the ideal orientation of residential buildings in the study area, CIBSE (2018) established that the North-facing windows receive very little solar gain and benefits are usually gained by orienting the major building axis pointing east/west (CIBSE 2018). It is recommended that buildings be oriented in the direction of prevailing angles of wind and sun (Thomas and Garnham 2007). The acceptable orientation is solar north, orientations of up to 20° west of north and 30° east of north, therefore, exclude direct sun by using trees and adjoining buildings to shade every façade all year-round while capturing and funnelling cooling breezes (McGee et al. 2013). The acceptable orientation is solar north, orientations of up to 20° west of north and 30° east of North. It is also important that living areas are oriented 20°W–30°E of true North (Anumah and Anumah 2017). Efforts should also be made to exclude direct sun by using trees and adjoining buildings to shade every façade all year-round while capturing and funnelling cooling breezes. The living zones should be oriented towards the South and sleeping areas oriented towards

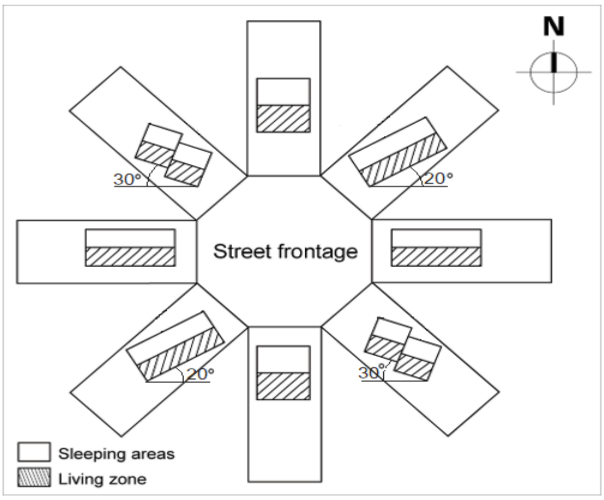


Figure 25: Ideal building orientation in tropical climates; Source: Noah Akhimien adapted from (ABCD, 2019)

North, East and West Façades have the smallest area and should be properly shaded (Tzempelikos and Athienitis 2007; Anumah and Anumah 2017).

2.8.3. Natural ventilation

It is essential that passive ventilation strategies use naturally occurring air flow patterns around and, in a building, to allow outdoor air into the interior space (Akande 2010). One major passive design principle for tropical climatic buildings is avoiding heat gain through proper orientation, wall and window shading, thermal mass, and the use of light and heat reflective surfaces (Tang 2002; Abbakyari and Taki 2017). Buildings can be designed to enhance these natural air flows and take advantage of them rather than work against them (Bhatt 2014; Aflaki et al. 2015). Passive ventilation can be optimised through cross ventilation, operable windows, building shape, orientation etc. Also, strategic architectural features such as structural fins, buttress, canopies and wind catchers, can help direct desirable air in and out of buildings (Hughes et al. 2012).

Natural Ventilation requirements for passive design

Natural ventilation in passive design is an essential consideration that can enhance cooling significantly especially when attention has been paid in the primary stages (Aflaki et al. 2015). Passive designs should benefit from proper access to natural ventilation for stale air replacement with fresh air naturally (Aflaki et al. 2015). Air movement is a key requirement for natural ventilation by designing the building facades, apertures and other responsive elements to maximize the natural airflow (Almeida et al. 2005). Natural ventilation inside buildings can generally be categorised into air pressure ventilation or wind force and stack effect ventilation or thermal force (Ghiaus et al. 2005).

However, it is important for rooms to have more than one opening (opposite or adjacent to each other) for good air exchange (Ghiaus et al. 2005). Buildings should be oriented to benefit from desired winds (Givoni 1994). Hence, it is necessary to provide openings facing the direction of desired winds either opposite or angularly where the formal is not possible (ABCB 2016).

According to CIBSE, naturally ventilated buildings create the driving force for wind movement by using a range of techniques that maximises the potential of stack effect, using air passages at different heights and wind effects, usually by ventilating from at least two facades (CIBSE Guild F & AM10 2012; CIBSE 2018). CIBSE provides guides on the following basic forms of ventilation strategy in relation to the form and layout of the building for which they are best suited (CIBSE 2018).

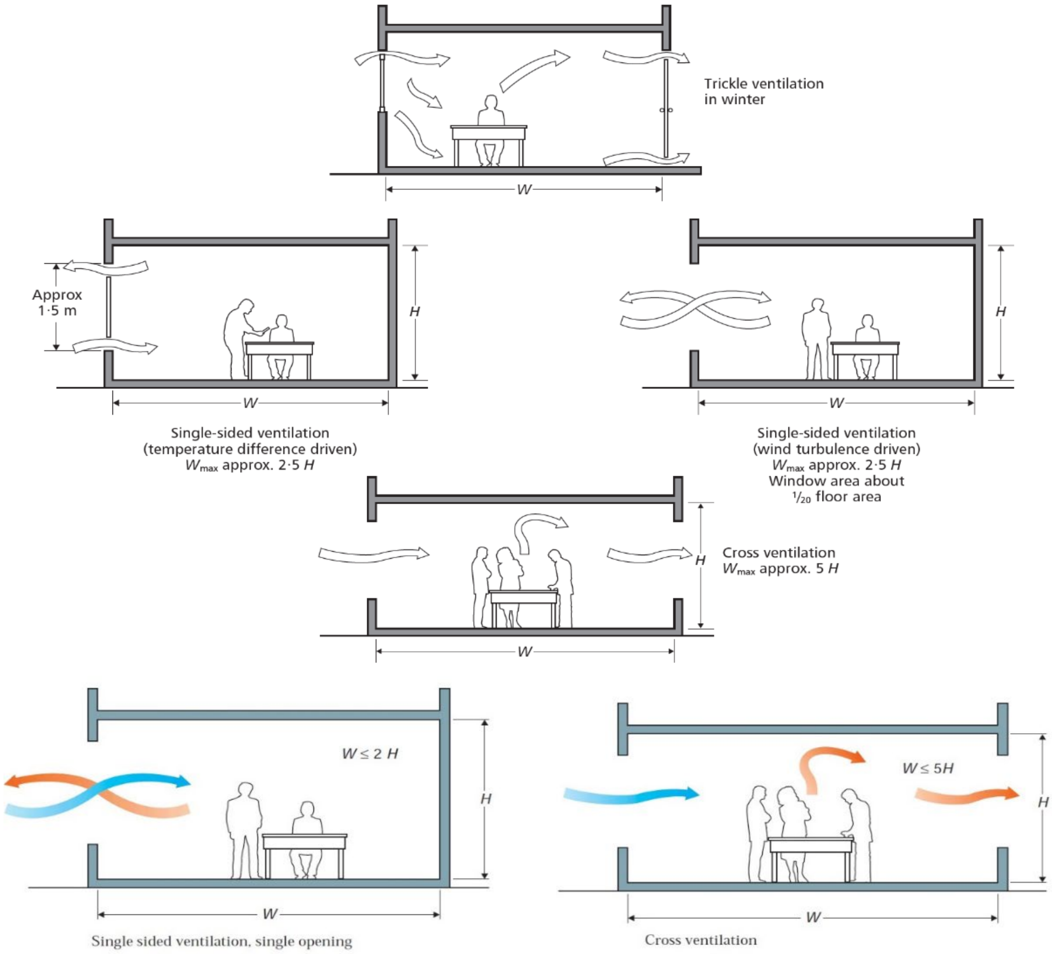


Figure 26: Basic forms of ventilation strategy (CIBSE 2018)

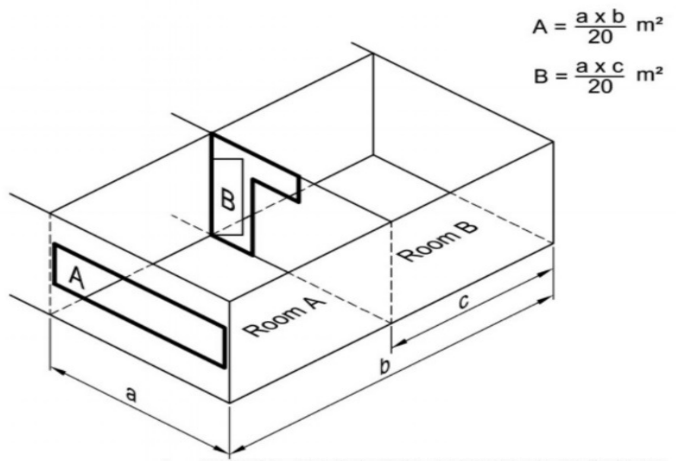


Figure 27: Natural ventilation requirement (ABCB 2016)

According to the Australian Building Codes Board, the minimum size of the opening must be 5% of the floor area of the room in warm climates (ABCB 2016). Concession applies for rooms adjoining another room with access to natural ventilation of 5%.

CIBSE recommends the following for habitable spaces, it specifies that room depths should be two times the ceiling height for single-sided ventilation (W ≤ 2H) and 5 times the ceiling height for cross ventilation (W ≤ 5H) (CIBSE 2018).

The above passive design recommendations (for thermal Mass, daylighting, building orientation, natural ventilation) obtained from literature reviews are guides that can be used to model residential buildings depending on specified requirements and simulated to determine their efficacy.

2.8.4. Daylighting

Maximising daylighting most especially in places where power is absent, inadequate or expensive is an efficient strategy in passive design. The design explores the best building configuration and solstice for natural lighting (Tzempelikos and Athienitis 2007). Daylighting maximizes the use of natural lighting by the distribution of naturally diffused daylight throughout a building's interior to reduce the need for artificial lighting (Bhatt 2014). The Daylight Autonomy is the measurement of the minimum illuminance frequency maintained by daylight alone on a work plane, usually a minimum threshold of 300 lux. It is often expressed as the percentage of the occupied period during a maintained illuminance threshold of 300lux by daylighting alone in a year. In other words, it establishes the extent to which a space is sufficiently daylighted. Hence, allowing for the recommended activity to be undertaken without electric lighting. Therefore, the zonal summary daylight autonomy (sDA) outputs represent the percentage of zone area that is at least 300lux or specific zone recommended lux for a minimum of 50%-time duration. The lighting can be highly influenced by strategic openings/windows, good space planning, large windows, transparent or translucent partitions, light shelves, skylights and light tubes, etc. (Zaki et al. 2012; Rodriguez-Ubinas et al. 2014).

Recommended Daylighting requirement

Illuminance is the measure of the amount of light received on a surface expressed in lux (lm/m^2). It is the measure of light used to determine daylight availability in the interior (Velux 2019). Luminance, a similar phenomenon is the measure of the amount of light reflected or emitted from a surface expressed in cd/m^2. It is the measure of light used to evaluate visual comfort and glare in the interior (Velux 2019). BREEAM states that an average daylight factor of 2% or more is for at least 80% of floor area in occupied spaces (BREEAM 2014). In residential buildings, it states kitchens should achieve a minimum daylight factor of at least 2%; living rooms, dining rooms and studies should achieve a minimum average daylight factor of at least 1.5%, and 80% of the working plane should receive direct light from the sky".

The Daylight availability ratio (DAR) which is also known as daylight autonomy can be computed as a function of orientation and window-to-wall ratio (Tzempelikos and Athienitis 2007). The daylight availability ratio is defined as a fraction of working time in a year during which enough daylight, more than the required lux value is available on a work plane ratio (Tzempelikos and Athienitis 2007). The annual daylight availability ratio (DAR) for each orientation can be calculated as follows:

$$\overline{\mathrm{DAR}}_{\mathrm{annual}} = \frac{\sum_{\mathrm{January}}^{\mathrm{December}} \overline{\mathrm{DAR}}_{\mathrm{month}}}{12}$$

Where: DAR is Daylight availability ratio.

Equation 1: Annual daylight availability ratio (Tzempelikos and Athienitis 2007; DEFRA 2011; Østergård et al. 2017)

In order to assess the daylighting requirement for the residential buildings, it is necessary to establish the minimum requirement for natural light in a habitable room. Window opening providing daylight is required to have a minimum area of 10% of the floor area of the room (ABCB 2018). This is calculated based on the floor area of a liveable room. Daylight may also be borrowed from adjoining rooms or spaces. In this case, the area of the two rooms is combined, and openings provided must equal 10% of the total floor area for compliance (ABCB 2018). It should be noted that South-facing facades receive more daylight than other facades which makes daylight availability for south facades higher for window sizes (Tzempelikos and Athienitis 2007). A concession is given when using a roof light in a room or in addition to the windows provided. Consequently, the ratio of opening to floor area is reduced from 10% to 3% or a combination of the two when both are provided (ABCB 2018). The concession is based on the exposure provided by the roof light. In comparison to a window, a roof light affords a greater level of lighting to a space.

The following are Daylighting recommendations from works of literature.

1. A window opening providing daylight is required to have a minimum area of 10% of the floor area of the room (ABCB 2018).
2. According to Velux daylight visualization, the recommended minimum levels of illuminance are 300 lux for most of the room area and 500 lux for areas where productive work is performed (Velux 2019).
3. CIBSE Guide A illuminance recommendations for dwellings are as follows (CIBSE 2018):

Bathrooms	-	150lux
Bedrooms	-	100lux
Hall/stairs/landings	-	100lux
Kitchen	-	150-300lux
Living rooms	-	50-300lux
Toilets	-	100lux

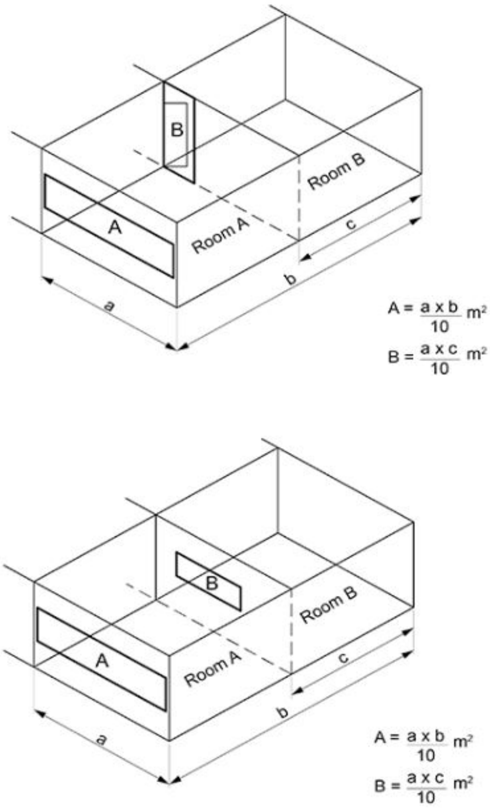


Figure 28: Daylighting requirement (ABCB 2018)

2.8.5. Thermal Mass

In climates where the primary concern is cooling, thermal mass can be used to reduce energy consumption by reducing the heat transmittance through its mass by slowing dissipating it during evening hours or during its idle period (Balaras 1996). In tropical regions where overheating in buildings is high, passive strategies such as thermal mass can prevent buildings from overheating as heat flows from the heavy walls inside can be removed with good ventilation (Shaviv et al. 2001). In hot climates it is imperative that heat is excluded, relative humidity controlled, while the thermal mass is cooled through natural ventilation during the night (Ochoa and Capeluto 2008).

The thermal mass of a material is the mass of the material multiplied by the specific heat capacity.

$$C_{th}=mc_p$$ Equation 2: Thermal mass

where is the mass of the body and is the isobaric specific heat capacity of the material. The ideal thermal mass material is that with high density and high specific heat capacity (Reardon et al. 2013). The volumetric heat capacity(kJ/m3.K) of a material is a function of the material density (kg/m3) multiplied by the heat capacity (kJ/kg.K).

Thermal Mass properties for tropical climates

The thermal mass of materials can be used to slowly diffuse the temperature difference of both the exterior and interior environment of a building (Reardon et al. 2013). This is done by absorbing heat and slowly releasing it as the temperature drops. The Kappa value or thermal mass value is used to quantify the thermal mass of building elements. It refers to the heat capacity of a material per square metre which is measured in kJ/m^2K.

Therefore, the higher the k-value, the higher the thermal mass performance, hence, the more heat the material component is able to store. Thermal mass is usually described as the ability of a material to absorb heat and store heat energy. It also provides inertia against fluctuating temperatures. A good material for thermal mass are materials with: (Reardon et al. 2013)

- high specific heat capacity
- high density

The typical K-values of some common building materials are as follows: (DesigningBuildings 2020)

- Dense concrete block wall with a plaster finish: 190 kJ/m2K.
- Timber frame wall has a K-value of 9 kJ/m^2K.
- Concrete floor/Ceiling has a K-value of 120/160 kJ/m2K.
- Timber floor/ceiling has a K-value of 9/18 kJ/m2K.

The kappa value (k) of a material can be calculated with the equation below: (DesigningBuildings 2020)

$k = 10^{-6} \times \Sigma (dj\ rj\ cj)$

Where:

- dj is the thickness of a layer (mm)
- rj is density of a layer (kg/m^3)
- cj is specific heat capacity of a layer (J/kg·K)

Materials such as rammed earth or adobe are known to have excellent thermal mass performance, especially in tropical regions due to their high density and specific heat capacity.

It is also important to understand the behaviour of thermal insulators in buildings as they play a significant role in maintaining indoor temperature. Research findings revealed that building materials are characterised by specific performance ratings. These ratings determine their performance. The table below shows the lambda values (λ), also known as the conductivity of common building materials.

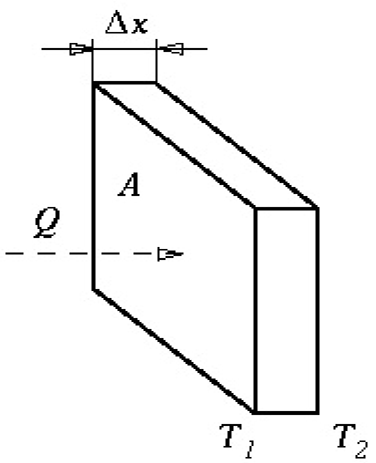
Table 11: Thermal conductivity of common building materials (Gyoh 2017)

Material	λ-value	Material	λ-value
Air, atmosphere (gas)	0.024	Gypsum board	0.17
Aluminum	205	Iron	80
Aluminum Brass	121	Krypton (gas, i.e. for windows)	0.0088
Argon (gas, i.e. for windows)	0.016	Leather, dry	0.14
Asbestos-cement board	0.744	Limestone	1. 26 – 1.33
Asbestos-cement	2.07	Marble	2. 08 – 2.94
Bitumen	0.17	Mineral wool insulation materials	0. 035 – 0.045
Brass	109	Paper	0.05
Brickwork, common (building brick)	0. 6 – 1.0	Plaster light	0.2
Brickwork, dense	1.6	Polycarbonate	0.19
Brick, insulating	0. 15 – 0.4	Polyethylene low density, PEL	0.33
Cast iron	58	Polystyrene, expanded styrofoam	0.03
Clay, dry to moist	0. 15 – 1.8	Polystyrol	0.043
Concrete, lightweight	0. 1 – 0.3	Polyurethane foam	0.03
Concrete, medium	0.4 – 0.7	PVC	0.19
Concrete, dense (structures)	1. 0 – 2.0	Sand, moist	0.25 - 2
Copper	401	Sandstone	1.7

According to Moran et al. (2010), Thermal transmittance (U) is a property of an actual layer with a certain thickness. It is the rate of heat transfer through a specific thickness of material when there is a temperature difference (ΔT) of 1 Kelvin across it (Moran et al. 2010). This is called U-value and it is measured in W/(m^2.K)

Equation 3: Thermal transmittance, Fundamentals of Engineering Thermodynamics (Moran et al. 2010)

$$U = \frac{Q\Delta x}{A(T_2 - T_1)}$$



Where:

$A(T_2$-$T_1)$ = Temperature change through 1m^2 surface area of a specific material thickness

Q/W = Number of watts through thermal mass

Thermal transmittance = W/m^{2}K

Q = (U.A.ΔT)/Δx

Thermal Resistance (R) has also been defined as the reciprocal of transmittance (Gyoh 2017). It is the resistance of a specific thickness of material to heat transfer for every change in temperature (ΔT) of 1K across it. This is called the R-Value and it is measured in (m^2.K)/W Transmittance is the rate of heat flow through typical materials with standard thickness such as insulation, wood, brick, concrete, etc. and non-homogenous material (Gyoh 2017).

Recall, Transmittance (U) is the number of Joules that flow through $1m^2$ surface area of a specific material thickness per 1Kelvin (K) change of temperature difference in unit time (Gyoh 2017).

Transmittance can be calculated by dividing the conductivity (λ) in W/m^2K by the thickness (d) in meters (m):

Equation 4: Transmittance (Gyoh 2017)

U = $\lambda/_d$ where: U is Transmittance; λ is Conductivity; d is material thickness.

Resistance (m^2K/W) can also be calculated by dividing the thickness (d) in meters by the conductivity

Equation 5: Resistance (Gyoh 2017)

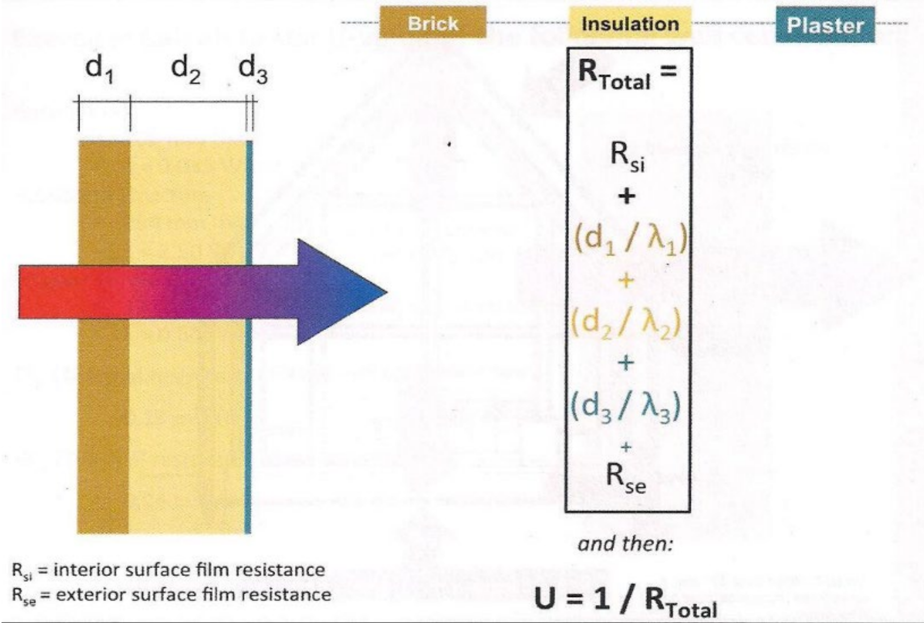
(λ) in W/mK: R = $d/_\lambda$ where: R is Resistance; d is material thickness; λ is Conductivity.

Therefore, the U-values (transmittance) for homogenous assemblies can be calculated as presented in the figure below considering the interior and exterior surface film resistance R_{si} & R_{se} (Straube and Finch 2009; Gyoh 2017).

Heat Loss = Area x U-value x Temperature change

= Watts

Equation 6: Calculating U-values - Homogeneous assembly (Gyoh 2017)



When calculating heat transmittance through a medium, it is important to take into consideration the surface film resistance (R_{si} & R_{se}) of the materials. The interior surface film resistance (R_{si} & R_{se}) have values of +0.10,+0.13,+0.17 for interior ceiling, wall and floor film resistance (R_{si}) respectively while the exterior film resistance has values of +0.04, +0.04, 0.0 for exterior roof, wall and below ground surface film resistance (R_{se}) respectively (Straube and Finch 2009). This is necessary to account for both the radiative and convective heat transfer modes at the exterior and interior surfaces of building components, the radiative and convective heat transfer coefficients act either as an equivalent conductance (also called surface film coefficients), alternatively, equivalent resistances (Straube and Finch 2009).

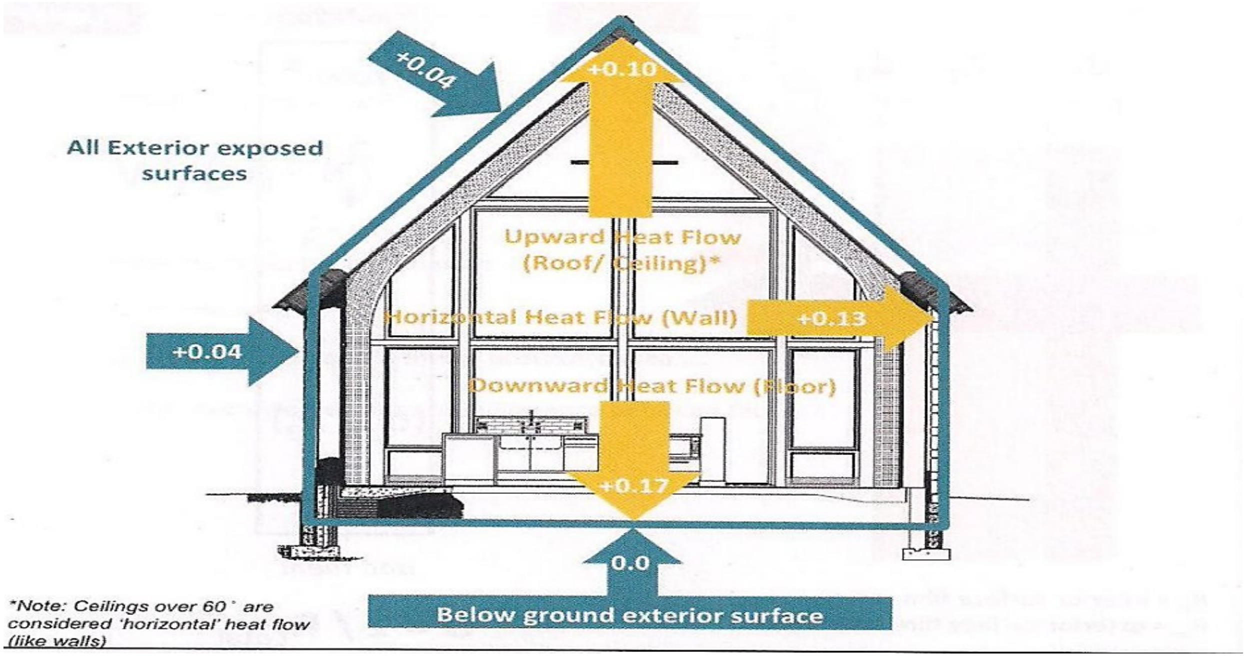


Figure 29: Surface film Resistances; Source: EEB workshop, (Gyoh L. 2017)

Surface film resistance lowers the thermal transmittance of material (this also implies the lower the U-value), they lower the rate of heat transfer through the mass. After a careful review of the thermal conductivity of a range of building materials in hot climates. The following U-values are considered.

1. Build energy (2018) recommends a U-value of 0.18 W/(m².K) or less for walls if using a partial fill cavity (usually with a 50mm clear residual cavity). Hence 0.18 W/m2K is achievable using: 125mm cavity with 75mm Kingspan Kooltherm K108; 150mm cavity with 100mm insulation at conductivity 0.022 W/mK (Build Energy 2018).

2. Arup (2018) U-values guide recommends a U-value of 0.25W/(m².K) to achieve a reduction in thermal conductivity (Arup 2016; Arup (Madrid & Lagos offices) and Design Genre 2016).

3. GreenAge (2013) recommends a U-value of 0.3W/m^{2}K for Warm Climates regions (GreenAge 2013).

4. According to House-Energy (2013) a U-value between 0.28 to 0.19W/m^{2}K which is equivalent to an R-value of (3.57-5.26) m^{2}K/W is ideal for warm climates (House-Energy 2013).

From the above recommendations for a hot climate, it was observed that the optimal transmittance (U-value) of a material for thermal massing should have a total resistance (R-value) between (3.57-5.26)m^{2}K/W which is equivalent to R-20 to R-30, and a U-value with the range of 0.28 to 0.19 (House-Energy 2013). It is important to consider the thermal Insulation, in terms of their respective U-value as well as solar control – WWR, Shading devices, G-value of glass, and shading devices.

2.8.6. Thermal Insulation

Thermal insulation is an important aspect of passive design, the provision of thermal insulation in buildings can greatly improve the energy efficiency of buildings and reduce operational energy (Hyde 2013). The U-value and thermal conductivity of thermal insulators are important parameters to consider while considering materials for thermal insulation (Gyoh 2017). Thermal insulators with low thermal transmittance and low thermal conductivity are recommended for thermal insulation as they help prevent heat loss and heat gain (House-Energy 2013). The reusability and recyclability of thermal insulation materials are important considerations in circular economy.

2.9. Circular Economy

2.9.1. Circular economy for buildings

Circular economy can be described as a regenerative system in which resources and waste are reduced by narrowing material loops (Bocken et al. 2016). This can be achieved through a circular design that accommodates maintenance, repair, reuse, remanufacturing and recycling of products (EMF 2013; Geissdoerfer et al. 2017). The programme of circular economy is focused on prolonging the longevity of products and cutting down waste. The circular economy which is a regenerative approach varies with the traditional linear economy, also known as 'take, make, use, dispose' model of production (EMF 2013; WRAP 2019). In a circular economy, the model of production is ‘take, make, use, recycle’. In the linear concept, resources are processed and at the end of life, they are disposed of. Instead, the circular economy concepts process for use, reuse and later recycling (Korhonen et al. 2018). This concept makes products to be continually exploited for a longer period and subsequently recycled. Thus, maximizing the economic benefit of the product and reducing waste. The linear concept and circular economy concept are described below.

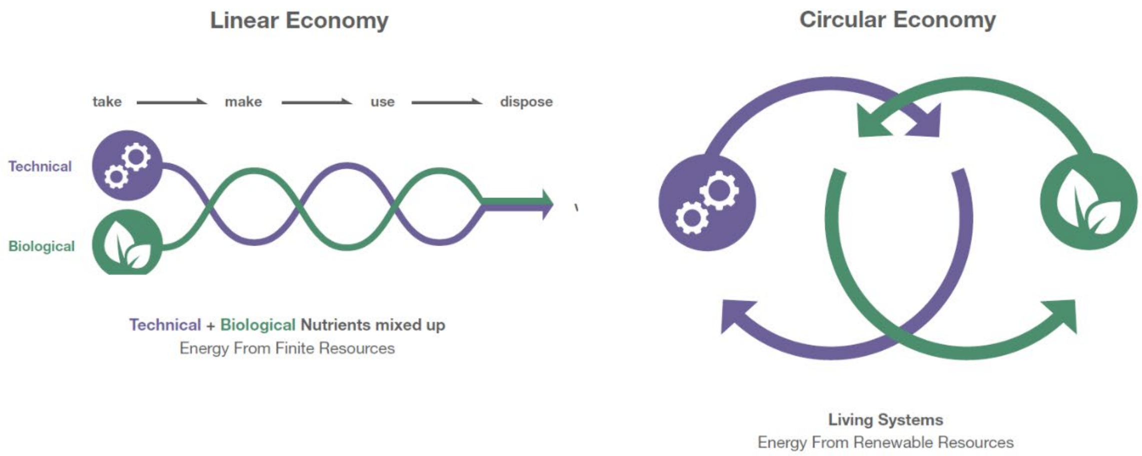


Figure 30: Linear and Circular Economy (EMF 2015)

Geissdoerfer et al. (2017) defined circular economy as a regenerative model that reduces waste and emission (Geissdoerfer et al. 2017). Some of the major benefits in the use of circular economy system cuts across Economics, Environmental and Social sustainability. One of the social perspectives of circular economy lies in the provision of job opportunities (Su et al. 2013; Morgan and Mitchell 2015).

Circular economy seeks to maintain building components and resources at their highest intrinsic value for as long as possible in which building components are kept in a continuous loop of use, reuse, repair and then recycled thereby reducing waste and preventing negative externalities such as CO_2 emissions (Jabbour et al. 2019). Circular economy is important in ensuring material sustainability in any building (Eberhardt et al. 2019a; Eberhardt et al. 2019b). Ellen MacArthur Foundation described circular economy as a regenerative system in which resource input, emission, waste, and energy leakage are reduced by closing and narrowing energy and material loops (EMF 2012).

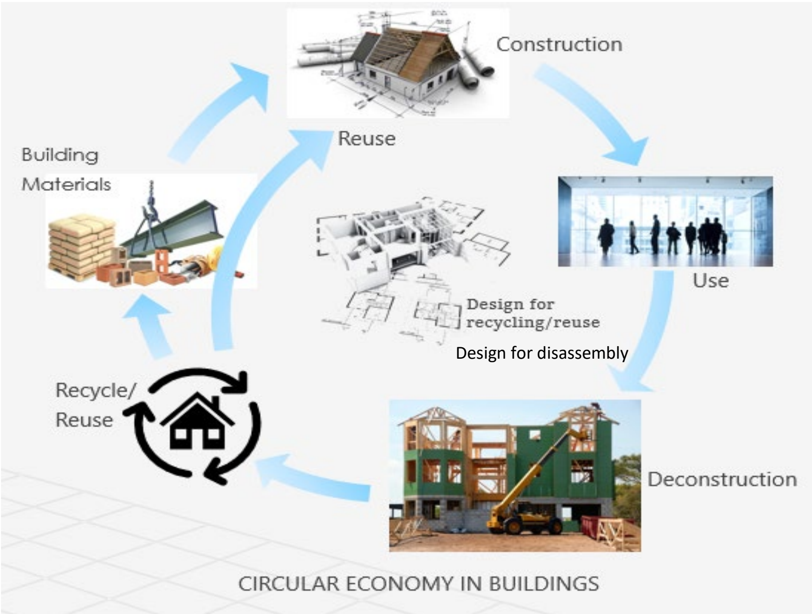


Figure 31: Circular economy in Buildings

The application of circular economy in buildings would involve Building materials to undergo construction, use, deconstruction, reuse or recycle and back to material for construction (Bullen 2007). There is an abundance of cheap natural resources for circular economy. The increase in world population is a clear signal for resources to become more difficult and expensive to access. According to Ellen MacArthur Foundation, the adoption of circular economy will preserve and enhance natural capital, optimise renewable resources, prevent waste by design (EMF 2012). The strategy allows materials, products and components to be held in repetitive loops, maintaining them at their highest possible intrinsic value (EMF 2012).

2.9.2. Resource sustainability

According to the European economic and social committee, “circular economy systems keep the added value in products for as long as possible and eliminate waste” (European Commission 2019). This implies that they keep resources within the economy even when a product has reached the end of its life, in order to be productively used again and possibly create further value. Waste reduction is a major goal in circular economy. The UK generates an average of 45.8 million tons of Construction and Demolition Waste annually (DEFRA 2015). The amount of construction and demolition waste annually is about 534 million tons in the United States while Australia generates about 19 million tons of construction and demolition waste annually (Hyder Consulting 2011; USEPA 2016). The adoption of circular economy principles can recover about 80-90% of building waste (Resource-deutschland 2014). This transition to a circular economy requires changes from the product manufacturers and consumers (European Commission 2019).

There seems to be a wide range of proven measures to promote resource efficiency and the potential to be applied on a more systematic basis. Ranta et al. (2018) claim that circular economy can cover a broad scope, findings show that researchers have focused on different areas such as industrial applications in terms of both products and services (Ranta et al. 2018). According to Letsrecycle (2019), protecting human health and the environment is the primary objective of waste management (Letsrecycle 2019). In the EU and many other states, the reclamation of wastes through their recycling and recovery of the energy contained in them with emphasis on re-utilisation of the resource value of wastes is on the increase (European Commission 2019).

Circular economy in buildings means that buildings will be designed for a lifecycle and not simply an end-use, performance-based contracts will see tenants and landowners benefit from recycling services, circularity will be embedded in all parts of a structure (Letsrecycle 2019). This will ensure that individual assets are flexible, interchangeable and highly customisable, and will enhance users’ experience of the environment. Design decisions such as optimising disassembly and reuse from the beginning of the programme have implications for the operation, renewal and repurposing of the building for recycling (Arup 2016).

Nuñez-Cacho et al. (2018) state that, “the main causes of construction's environmental impact are found in the consumption of non-renewable resources and the generation of contaminant residues, both of which are increasing at an accelerating pace” (Nunez-Cacho et al. 2018). In Nigeria, most products are not recycled or reused at the end of life because provisions haven’t been made for this process (Alonge 2018).

Construction companies impact greatly the economic, social and environmental aspects of sustainability, this has greatly affected the productive rate of different establishments, as well as the provision of employment (Gencel et al. 2012; Akanbi et al. 2018). The European Union parliament has adopted a zero-waste policy through the employment of circular economy (COM 2016). Several studies have shown that in order to ensure an efficient circular economy system, it is expedient that a high percentage of materials used for building should be recyclable and recoverable (Smol et al. 2015).

Moreover, the preferred method of preventing wasted materials and economic loss is through the adoption of preventive measures. It is required that all materials and resources needed for the construction of a building should be calculated and the resource should be reusable and recyclable materials (Bilal et al. 2015). The preparation of materials for reuse is the second step in the waste hierarchy (Liu et al. 2015).

Mark Walport – UK Government Chief Scientific Adviser (2017), saw waste as resources for other processes; manufacturing, reuse and recycling in ensuring that materials and products continue to circulate in the economy. Circular economy offers an alternative approach, as it is the general principle for the reworking of an economy on ecological lines, by closing material loops (UK Government Chief Scientific Adviser 2017).

Buildings are constructed with different material compositions which could be fit into the circular economy if well considered at the design and construction stages. An abundance of cheap natural resources would enable this approach to endure. As the world’s population grows and resources become harder and more expensive to access, it is becoming ever more critical to find alternative means of sourcing and using materials (EMF 2012). Therefore, it is necessary to ensure the recycling of already used materials in the construction of new ones. This will preserve the natural capital is preserved and enhanced, renewable resources are optimised, waste is prevented, and negative externalities are designed out (EMF 2015; Akanbi et al. 2018). This process encourages materials, products and components to be held in repetitive loops, maintaining them at their highest possible intrinsic value (EMF 2015).

2.9.3. The concept of circular economy in buildings

The circular economy concept offers a chance to make the change resource sustainability needs. The concept aims to decouple economic growth from resource consumption (Arup 2016). This means products and assets are designed and built to be more durable, and to be repaired, refurbished, reused and disassembled (Webster and Costello 2006; Tukker 2015). Hence, maintaining components and their materials at the highest useful purpose if feasible to minimise resource waste. The modular construction of buildings ensures the ease of deconstruction, hence buildings are easily disassembled and recycled into reusable products (Akanbi et al. 2018). Minimising negative externalities is a core aim of the circular economy (Arup 2016). The externalities apply to both the operation of assets, sourcing, manufacturing, transporting, installation of components and disassembly (Lacy et al. 2014; Arup 2016; Stahel 2016). Preventing or minimising these impacts is critical to enhancing natural capital and maximising the use and value of resources.

2.9.3.1. Circular economy as a concept for prolonging an asset's life

Residential buildings enjoy a variety of potential resilient features such as adaptability for sustainability. Design for disassembly is an easy way of having buildings in modules for such future recovery (Crowther 2018). In modules, means it can be deconstructed and deteriorated components replaced and recycled (Merrild et al. 2016). Designing for longevity ensures the long-term durability, utilisation and value of assets. Durable materials and good construction can reduce maintenance costs and extend the economic viability of a building (Arup 2016).

Also, standardised components manufactured off-site to higher quality control standards can reduce the risk of structural faults and minimise long-term maintenance requirements (Eberhardt et al. 2019a). Designing for longer lifespans can help reduce waste and ensure assets are used optimally throughout their Lifecycles (EMF 2012). Integrated smart services including concrete core cooling, passive systems that maximise natural daylighting and ventilation, and power and service systems in raised access floors which may include raised floors and suspended ceilings also help with repairs, maintenance and longevity (Del Borghi et al. 2014).

2.9.3.2. Circular economy as a concept decreasing resource usage

Principles such as off-site construction and modular components can help reduce the amount of waste generated on-site and enable reuse and recycling (Arup 2016). Components and materials from recycled buildings can be reused for the construction of new buildings, repurposed for buildings or in industrial sectors eliminating primary material use (EMF 2012; Minunno et al. 2018). This means there is a chance to reuse and reduce waste.

Waste reduction can also be considered at the design stage (Arup 2016). A good process flow from design, through construction, deconstruction and waste management can enable circular resource and material connection between industries of the built environment (Nussholz and Milios 2017). Integrated design and construction such as manufacturing technology, also known as 3D printing, can reduce material use (Arup 2016).

2.9.3.3. Products and materials in cycles/loops

Keeping resources in loops is decided at the design stage. Provision for in-take of used products back into the production cycle is major design consideration most especially in circular economy (Minunno et al. 2018). Looping of materials and components takes place usually in two phases first, creating new uses for materials through remanufacturing and recycling which include remanufacturing and recycling of machinery and equipment. Regular maintenance, refurbishment and repair help to maintain assets and products at their maximum utility (EMF 2012).

Focusing on disassembly during the design and in-service phase increases the chance of effective second use and reuse pathways for components and materials (Stahel 2016). This also enables greater integration of recycled materials and components from other industries. It helps increase monitoring and tracking the performance of assets, hence, creating looping opportunities further down the line. It is also important to speculate for required optimisation, repair, upgrade and maintenance during the life span of the building (Hossain and Ng 2018). Aside from the ability of passive designs to be responsive to climatic conditions, they should also be able to respond to circular economy and recycling demands. This means during the service period of a passive building, it can be repaired, deconstructed, upgraded, components regenerated, shared, optimised, looped, virtualised and exchanged for better ones (EMF 2012). Hence, passive buildings should be designed flexible and dynamic to accommodate circular economy demands.

However, in ensuring an effective circular economic system, it is expedient that materials required for building are recyclable materials and can be recovered for reuse. This can cause a great reduction in environmental landfills. Also, the use of recyclable materials is economical, thus reducing the cost of heating and cooling.

2.9.3.4. Circular economy for Remanufacturing and refurbishing products and components

In order to achieve a resource-efficient residential building, it is important that the built environment maximises the use of recyclable materials, components and structures to support their circulation within the industry and minimises the need for new materials (Guy et al. 2006). Remanufacturing helps to keep materials, components and structural members in use for a longer period, helping to reduce waste (Hazen et al. 2017). The integration of circular economy to different construction technics which are compatible with deconstruction programmes enables materials and structures to be transformed or repurposed. Coupled with modularity, disassembly allows for the structure to be changed easily and reduces construction waste (Stahel 2016).

Caterpillar, a remanufacturing company since the 1970s has been identified as a world leader in reducing, reusing, recycling, and reclaiming materials (EMF 2012; Arup 2016). This practice helps the company to benefit from its products at the end of their lives. The product is recycled and returns products to the same as-new condition and quality for a fraction of the cost of producing new ones. This model has reduced Caterpillar's costs for producing new products as well as the number of materials (Arup 2016).

2.9.3.5. Buildings as Material Banks

The engineering and construction industry is the world's largest consumer of raw materials (Eurostat 2014). It accounts for 50% of global steel production and consumes more than three billion tonnes of raw materials, buildings have been described as material banks, BAMB - Buildings as Material Banks (CE100 2016). BAMB an EU funded programme brings 16 parties within Europe together for the sole purpose of enabling a systemic shift in the building sector by creating circular solutions (CE100 2016).

The project is geared towards developing and integrating tools that will enable the shift of materials passports and reversible building design which can be supported by new business models, policy propositions and management and decision-making models. The BAMB project started in September 2015 and was expected to progress for three and half years as an innovation action within the EU funded Horizon 2020 programme (CE100 2016). The main objective of BAMB is to facilitate the reuse of building materials, products and components across multiple building applications. One of the benefits of reusing building products in a circular economy is the significant reduction of environmental impact.

Buildings are storages of vast compositions of materials that can be reused, recycled, upgraded or replaced (Wang et al. 2017). Building components can be deconstructed and materials extracted by adopting the circular economy concept. In this way, buildings would need to be designed to fit into circular economy principles. Hence, the building design and construction should be done considering the possible recycling of materials which may include reuse. Global demographic and lifestyle changes are increasing the demand for these resources, many of which are becoming scarcer and harder to extract (DEFRA 2016).

According to Ellen MacArthur Foundation, natural resources are currently being consumed at twice the rate they are produced (EMF 2013). By 2050, this could be three times. Growth in the world's population and its middle classes which will expand from two to five billion by 2030, adding to existing demand for homes and services is putting unprecedented pressure on natural resources (EMF 2012). Competition for resources and disruptions of supply are contributing to volatile materials prices already, hence, creating uncertainty in the short term and increasing costs overall (Arup 2016), stricter global environmental regulations aimed at protecting fragile ecosystems are also making it harder and more costly to extract and use certain resources (Lieder and Rashid 2016). The built environment is under increasing pressure to minimise this impact. A circular approach as proposed by Ellen MacArthur Foundation could help the sector to reduce its environmental footprint, and to avoid rising costs, delays, and other consequences of volatile commodity markets.

2.10. Models of Circular Economy

In order to successfully execute a successful circular economy, it is important to have a model or framework. This is a step by step process or strategy in engaging the concept of circular economy. In order to accelerate the transition into a circular economy, Ellen MacArthur Foundation, McKinsey & Co., and SUN introduced the ReSOLVE framework. The framework explores recycling options in maximizing a product's potential with increased longevity. The term "ReSOLVE" is an acronym for Regenerate, Share, Optimize, Loop, Virtualize, and Exchange which can be employed in "Designing for recycling" (EMF 2015).

Another model is the 7S model, which represents building in layers, the model was first proposed by Architect Frank Duffy in the 1970s, and was further developed by Stuart Brand in the 1900s (De and Eden 2019). The 7S model identifies different layers of a building that can be employed in "design for disassembly". Another study on "design for disassembly" in the design process state of the art" was based on the sustainability of embodied energy, through the reuse of construction materials that have elapsed their lifespan (Pan et al. 2015). The study termed "design for deconstruction" focused on the materials used for construction (reusable materials), the design patterns, the process of construction as well as deconstruction phase (Pan et al. 2015).

The ReSOLVE framework and 7S model are global concepts, usable in any part of the world and they both complement each other (EMF 2014). Together, they can be integrated into passive design for a resource and energy-efficient residential building in Nigeria. A combination of innovations and advanced processing in material science, information technology, product design and business models will raise hopes of decoupling resource consumption from economic growth (Walport and Boyd 2017). For a circular economy to function correctly, investors would have to adopt a systematic approach in which assets, processes and systems operate both singularly and as part of an integrated whole. An effective technique for the recovery of building materials that have lived their lifespan is by recovering waste resources through the process of recycling materials such as metals and fibre materials (Kanters 2018).

2.10.1. The ReSOLVE Framework (Design for Recycling)

The ReSOLVE framework identifies six different ways that developers, organisations and governments can think about applying circularity to Regenerate, Share, Optimise, Loop, Virtualise, and Exchange, for recycling in the built environment (CE100 2016; Manninen et al. 2018). In the concept of design for recycling, building components could be up-cycled, down-cycled, optimised or reused as demonstrated in the ReSOLVE framework. The six elements can be applied to products, buildings, neighbourhoods, cities, regions, or even to entire economies (Lewandowski 2016). Ellen MacArthur Foundation described how the framework can be applied to the built environment. it is an intervention to revitalise or naturalise existing infrastructure, this may include greening of existing infrastructure like parks, streets, outdoor spaces for a more naturally integrated built environment (EMF 2015). Thus, making cities cleaner, more attractive and more liveable.

The ReSOLVE framework is unique in its design for waste prevention. It can be integrated into the design of residential buildings in tropical Nigeria as it consists of processes or methods that help preserve resources irrespective of prevailing conditions. This is made possible by maximizing the potential of materials and components. The framework can easily be incorporated into passive design strategies. Merging the ReSOLVE framework to the 7S Model gives a practicable passive design solution - a categorised approach to achieving energy and resource-efficient buildings in Nigeria.

The ReSOLVE framework tries to demonstrate that elements of circularity is evident in buildings and inspires new projects to pick up on these elements and create a built environment that is holistically circular. It also provides a clear definition of elements of the framework for the built environment through the conception, construction, use, deconstruction/recycling stages.

Table 12: ReSOLVE framework (EMF 2015)

Regenerate	Regenerating and restoring natural capital	Safeguarding, restoring and increasing the resilience of ecosystems Returning valuable biological nutrients safely to the biosphere
Share	Maximising asset utilisation	Pooling the usage of assets Reusing assets
Optimise	Optimising system performance	Prolonging an asset's life Decreasing resource usage Implementing reverse logistics
Loop	Keeping products and materials in cycles, prioritising inner loops	Remanufacturing and refurbishing products and components Recycling materials
Virtualise	Displacing resource use with virtual use	Replacing physical products and services with virtual services Replacing physical with virtual locations Delivering services remotely
Exchange	Selecting resources and technology wisely	Replacing with renewable energy and material sources Using alternative material inputs Replacing traditional solutions with advanced technology Replacing product-centric delivery models with new service-centric ones

2.10.1.1. Regenerate

Integrating the regenerating approach to the built environment cuts across the use of renewable energy to power buildings (Solar, Wind, Geothermal, Biomass, Tidal, Wave) – including buildings as “energy generators” e.g. solar panels on roofs (CE100 2016). Other Regeneration programmes include recycling (upcycling or/and downcycling), restoration, resource recovery, and renewable production systems (Manninen et al. 2018). Vegetation in the built environment is a measure toward regeneration.

2.10.1.2. Share

Creating a broader opportunity for product utilisation by mutualising the usage of assets. A proper sharing scheme in reusing assets will create a great turnover (Ellen Mac Arthur Foundation, 2015). This is an effective way to maximise product usage, residential sharing such as peer to peer renting, infrastructure sharing such as parking space, storage, living spaces, etc. (Manninen et al. 2018). Other sharing may include Services, utilities and appliances. The approach can also provide additional revenue and cost savings for owners and operators. Shared living or Co-living is becoming very popular, most especially in low-cost housing. It features low-cost homes with private bedroom spaces and flexible, communal kitchens, dining rooms and libraries, which can be converted to bars, mailrooms and event spaces. The sharing strategy is also employable in residential buildings. Undesired building material can be shared among developers in the desire for components or products. That way, presumably wasted material or components are put to proper use or possibly recycled (CE100 2016).

2.10.1.3. Optimise

Increasing products’ performance and durability will prolong their longevity. This could be done through repair/maintenance, design for durability and upgradability (Kraaijenhagen et al. 2016), thus decreasing resource usage and increasing efficiency, designing out waste. This is a viable process in passive design as building components can be optimised for best performance. This framework also gives room for energy efficiency integration in the environment and Building envelop (EMF 2015).

2.10.1.4. Loop

The looping mechanism helps in remanufacturing and refurbishing products and components. In this process components or materials could be recycled through an approach usually by “designing for disassembly”. Thus, optimisation of the end of life of the building and materials. This framework will save money and nuisance in the case of the rubble in buildings. The modularity of the building is important for flexibility in maintenance, repair, upgrades, removal, deconstruction, re-use and recycling (Manninen et al. 2018). Designing for reuse makes it easy to either, upgrade and downgrade, recycle and reuse building components depending on the conditions. A sustainable comprehensive solution, combining a product designed according to cradle-to-cradle principles is a sure loop process for sustainability (EMF 2015).

2.10.1.5. Virtualise

The virtual approach in circular economy cuts virtually all material components and ensure no physical waste, like in the production of e-books instead of books, smart home systems, efficient lighting (Spring and Araujo 2017). This element usually gives users improved control and flexibility in utilisation. Designing out waste should be the first step to reducing waste in construction in order to reduce the amount of waste that is generated. Waste can completely be avoided by virtualising products and services that can be served in digital formats. It also has the potential to reduce material costs and costs associated with onsite waste management and processing (CE100 2016). Some examples of virtualisation of materials in buildings include wallpapers or three-dimension wall panels.

2.10.1.6. Exchange

Shifting to renewable energy and material sources. Swapping products for more efficient ones. This could include services, technologies, building components, e.g. deconstructed materials are taken to sites where they are needed in exchange for desired ones. The exchange of information in a standardised format could help facilitate the adoption of best practices (Jabbour et al. 2019). This practice encourages the adoption of associated principles such as modular construction, design for disassembly, and the use of sustainable and circular materials. Community-driven modifications and improvements to designs and software can increase the lifespan of designs, maximise their use and support the standardisation of components across multiple applications (Despeisse et al. 2017).

2.10.2. 7S Model (Design for Disassembling)

Frank Duffy and Stewart Brand developed this model on the shearing layers of buildings (Pomponi and Moncaster 2017). The model includes six layers: Site, Structure, Skin, Services, Space, and Stuff. It conforms to Building construction technics as buildings are usually made separate and with interlinking layers, however, these layers may have different life spans (EMF 2012).

Table 13: 7S Model (EMF 2012)

System	System includes the structures and services that facilitate the overall functioning of the system, e.g. roads, railways, electricity, water and waste water systems, telecommunications, parks, schools, digital infrastructure
Site	Site is the fixed location of the building
Structure	Structure is the building's skeleton including the foundation and load-bearing elements
Skin	Skin is the façade and exterior
Services	Services are the pipes, wires, energy and heating systems
Space	Space is the solid internal fit-out including walls and floors
Stuff	Stuff is the rest of the internal fit-out including the furniture, lighting, and ICT.

7s model, illustrating how the model layers would function in the built environment context. The building in layers means that building components could be separated, repaired, replaced, moved or adapted at different times without affecting the wider entity, e.g. the building or infrastructure asset which gives room for a circular economy. The parts can easily be fitted into the RESOLVE framework. Therefore, large wastage of assets is reduced, reduction of resource use and other environmental impacts, and obviates the need to construct entirely new buildings and assets (EMF 2012). This increases the longevity of the building and increases the flexibility of use, upgrade, downgrade and reuse of components.

Table 14: ReSOLVE framework and the 7S Model (EMF 2012)

	Regenerate	Share	Optimize
System	Extraction and reuse of biological resources via anaerobic digestion to create and supply energy onto the grid	Sale of energy back to the grid	Optimisation of transport links between built assets. Integration of low carbon systems. Designing out waste strategies (HS2)
Site	Detoxify and regenerate brownfield land to revive the biosphere (Old Oak and Park Royal Development, London)	Online platforms to facilitate space sharing. (The Collective) Open source data platforms for sharing designs (WikiHouse)	Use of localised renewable energy sources and distributed networks.
Structure	Nature-based design solutions. Low impact materials, design and construction (Madrid + Natural)	Reuse of structural elements of buildings, e.g. reclaimed timber or steel beams	Design for longevity and adaptability (White Collar Factory)
Skin	Integration of green walls and surfaces. Extraction of green walls for composting and reuse	Pool or share assets, equipment and personnel. Design for disassembly (Globechain)	Leasing of façade in performance based contracts (Frener & Reifer façade)
Services	AD recycling biological nutrients and biogas (Nestlé AD plant)	Reuse of building components e.g. pipes, metals, electronics	Leasing of lighting and energy. Sensor-based lighting (Phillips pay per lux)
Space	Use biodegradable and compostable materials (Ecovative)	Maximising space utilisation (HeadBox)	Design for flexible use. Maximise use of daylight and natural ventilation
Stuff	Use biodegradable and compostable materials (Ecovative)	Maximising space utilisation (HeadBox)	Design for flexible use. Maximise use of daylight and natural ventilation

7S model shows possible interventions in a circular economy that could be employed to the layers. They include regenerate, share, optimise, loop, virtualise and exchange. The circular economy model offers an alternative approach to infrastructural development by using fewer resources, lowering environmental impacts and relying on less volatile markets for natural

Table 15: ReSOLVE framework and the 7S Model (EMF 2012)

Loop	Virtualise	Exchange	
Renewables and circular resource flows (energy, water, waste etc). Adapt use over time, e.g. commercial to residential	Virtual/digital storage via cloud systems. Smart systems to improve systems integration	Integrated circular city design approach (Regen Villages)	System
Retrofit and reuse existing buildings and assets for different uses (Tata Steel)	Open source design via openly accessible online platforms (WikiHouse)	Construction using alternative sustainable and low impact materials (Hi-Fi mycelium tower)	Site
Design for disassembly. Regeneration of buildings for mixed use	Internet of Things / ICT / BIM to monitor performance and facilitate maintenance and repair	Use sustainable materials and approaches (Sky Believe in Better Building)	Structure
Modular design and off-site prefabrication (Sky Believe in Better Building)	BIM to monitor performance and facilitate repair (Hong Kong sludge treatment plant)	Integration of bio-façades (SolarLeaf House)	Skin
Open design and operating standards. Rainwater harvesting, grey water recycling, battery storage on-site	Smart sensors. Monitor and deliver maintenance services remotely (Forth Replacement Crossing)	Shift to services over ownership. Internet of Things. LED light replacement	Services
Remanufacturing of products and components (Cat Reman)	Video and virtual conferencing	Natural lighting and ventilation solutions	Space
Remanufacturing of products and components (Cat Reman)	Video and virtual conferencing	Natural lighting and ventilation solutions	Stuff

resources making it more sustainable. A circular economy can enhance resilience, it can create flexibility and additional capacity at a range of scales — individual assets, communities, cities or even whole economies (Arup 2016).

2.11. Review of Arup model in circular economy.

Arup – an independent firm of professionals in the built environment established a circular economy model of the commercial property development cycle to identify where circular approaches offer the greatest opportunity to increase efficiencies and reduce costs and environmental impacts (Arup 2016). This model can also be adopted in residential buildings. Residential building components can easily be fitted into circular economy as described by Arup. The usage of building components after their life span is an incremental resource for new buildings, whether the renewed component is to be used in the same building or for a new building.

1. Ecosystem

This strategy encourages buildings to be designed for a whole lifecycle and not simply an end-use. It is thought to encourage clients to issue full lifecycle contracts from design to operation and disassembly as well as to achieve a holistic lifecycle certification and awards (Song et al. 2015). The model encourages commercialisation strategies of building components. It states that components and structures will often be leased rather than purchased (Song et al. 2015). Also, Performance-based contracts will see tenants and landowners pay for a service such as lighting rather than individual fittings or materials. The economy model is an envelope for all other models. Circularity will be embedded in all parts of an ecosystem. In operation of this model, the building is designed to use renewable sources and, where possible, locally available used material streams (Arup 2016). This means there is a possibility of getting cheap material for construction.

2. Design

This model emphasized the need for a building to be more than just a structure providing space and shelter. It recommended that it should be designed to accommodate future changes such as remodelling, expansion or disassembly (Yasin and Rjoub 2017). The incorporation of this model to circular economy will change the approach of building designers which would translate to how structures and buildings will be reused and retrofitted where possible before new structures are considered (Wang et al. 2014). Hence, the design will be more than just form, structure and space. This consideration will enable operation and performance to be embedded into design processes in order to incorporate energy-efficient and circular economy principles such as passive design and minimised externalities (Arup 2016).

3. Sourcing

Material usage and availability is usually major consideration in building development. The extraction of materials may be dramatically curtailed in future, as resources become scarce (Arup 2016). The model suggests that modularity and adaptability will be key components of design in a circular built environment, it also added that buildings will be constructed from flexible, durable, and reused (Tazi et al. 2021). This would ensure the use of highly sustainable biomaterials and non-standardised materials and components left out of this circle.

4. Construction

The mode of construction in a circular world is used in the context of assembly. The physical casting of bespoke elements, such as concrete casts or steel components, may no longer be standard practice as the industry moves to increased flexibility. However, 3D printing could challenge this trend with the introduction of resins and substrates made from renewable or reusable materials (Woollaston and Steadman 2017). San Francisco-based 3D-printing start up, Apis Cor, recently showed it can 3D-print concrete walls for a small house in less than 24 hours. Using a 3D printer to lay down concrete walls on a test site in Russia, the firm was able to "print" a 400 square feet house (Woollaston and Steadman 2017). The printer like a small crane, places layers of concrete mixture which can last for 175 years, the printer is then removed and windows, appliances, insulation and a roof is added (Woollaston and Steadman 2017). Off-site manufacturing and prefabrication will help to eliminate waste from construction sites. Designs and detailing will be done to minimise material use.

5. Operation

Arup's operation model recommended that all buildings and structures will be designed to high-efficiency standards, minimising externalities and environmental impacts. Therefore, buildings are to be environmentally friendly as much as possible which will include structures with internal circular resource cycles such as water capture and filtering (Tseng et al. 2020). Buildings will be designed to be net producers of energy with battery storage and low-impact fit-out components such as LED lights and strategies that eliminate wastage of energy and materials. This model will enable the structure and components to be regularly managed with preventative maintenance techniques (Arup 2016).

6. Renewal

Building renewal is a sustainable strategy to either extend the lifespan of the building or replace existing components with new ones. The functions and demands on buildings and structures are constantly changing. Therefore, the need to adopt a flexible design technology rather than static and rigid by design. The approach intends to make buildings dynamic in circular economy platforms enabling greater adaptation and flexibility. This will allow buildings for easy access to building services or include demountable and reconfigurable façade systems, a feature that enhances the adaptability of buildings to adapt to a range of conditions (Vieira and Pereira 2015). Circular buildings will be retrofit and upgrade ready. Consequently, minimising the time and cost for renewal and eliminating waste and other outputs as policies. Industry standards will ensure components from different manufacturers and providers are interchangeable (Vieira and Pereira 2015).

7. Disassembly

Disassembly enables buildings to be a combination of movable parts and components elimination demolition up to 80%. Demolition will be minimised in a circular world and buildings would become flexible and adaptable to different work conditions paving way for novel building designs while allowing for change and disassembly (Sanchez et al. 2020). Lifecycle Building Information Modelling (BIM) models allow stakeholders to take buildings apart, redesign them using the same components. Structural pieces may be transported using standard vehicles and containers. As a result, buildings will be highly mobile, versatile and flexible – lengthening their useful lifespans (Arup 2016).

8. Repurpose

The circular built environment makes it easy to make necessary adjustments to the functional requirements of a building by making maximum use of components and materials, circulating them between buildings and projects and maintaining them at the highest possible value and performance. Some building components have tendencies to deteriorate at certain periods, components will no longer be suitable for use in the same context. At this stage, they are expected to be recycled and remanufactured into other less structural parts or other products for other industries. Arup proposed that every material part and component be carefully tracked through its lifecycle and recorded in lifecycle BIM models (Arup 2016). Established value networks and second-use strategies will ensure all components are adequately used in other industries, minimising the value lost and ensuring numerous repurpose cycles (Wang et al. 2014).

2.12. The Waste Hierarchy

The *"waste hierarchy"* ranks the options of managing waste according to what is best for the environment. This it does by giving top priority to preventing waste in the first instance. The generation of waste has been orchestrated by mass production and consumption. Recently, EU policy emphasis has shifted up the waste hierarchy to waste prevention, requiring that member states move in the same direction (Walport and Boyd 2017).

The waste hierarchy gives priority to waste prevention, to preparing it for re-use, then recycling, then recovery, and last of all disposal (e.g. landfill). Waste reduction it's an important feature of circular economy, according to Arup, a transition to a circular economy could save London city £5bn in waste management services alone by 2050 (Arup 2016).

However, reducing the amount of waste material going to landfills meant diverting waste materials into different routes, higher up the waste hierarchy. Wastes, therefore, had to be considered not as wastes, but as potential secondary resources for manufacturing and energy generation.

Recovering building materials from wastes is an approach to resource efficiency that aims to maximise the utility in a given unit of material while some materials (e.g. many metals) can be recycled indefinitely, there are limits on the number of times other materials, such as fibre-based matter (e.g. paper and textiles) can be reprocessed (Norris 2012).

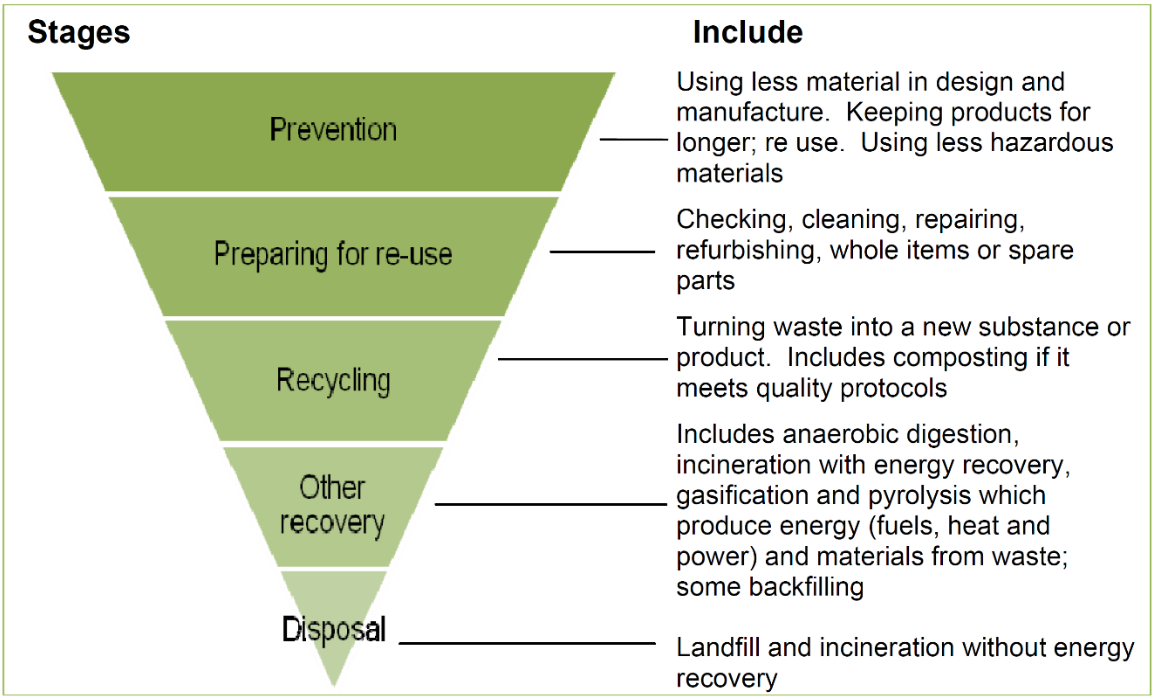


Figure 32:Waste hierarchy (DEFRA 2011,2012; Sun et al. 2018)

Waste management options have been ranked based on current scientific research on how the options impact environmentally in terms of climate change, water quality, air quality, and resource depletion. The Department of Communications, Climate Action and Environment gave a concise explanation for the waste hierarchy.

1. Prevention

The first is prevention which is described as most preferred to minimize the amount of waste through various means of control. It stated that the avoidance of the initial use of resources, then avoidance of wasting the resource. There is no need to buy what is not needed. A calculative purchase of products with less waste is required. Therefore, select the products that use the least hazardous materials and reusable to the greatest extent possible through substitution and postponing. Substitution is when no new materials are needed to fulfil the need while postponing is when the life of the goods is extended through good maintenance practices, repair, cleaning and refurbishment (DCCAE 2019). The goods only become waste until it gets to the last stage.

2. Preparing for re-use

Preparing for reuse relates to checking, cleaning or repairing activities that allow material or substance, product or component to be re-used without any other pre-processing (WRAP 2014). This is the easiest approach in the waste hierarchy which simply entails cleaning, checking, or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing (Adewuyi and Odesola 2016).

3. Recycling

Recycling consists of different phases – upcycling, downcycling depending on the condition of the product. When products or components are recycled major resources are saved and the environment preserved (Altamura and Baiani 2019). Recycling is usually when the material is returned to a state that can be used for something else.

4. Recovery

Recovery is ideal when there is little or no options for recycling or reusing. In this case, it is profitable to get back usable resources before considering disposal. Combustible waste is a resource for energy extraction (Arora et al. 2020). Although this step destroys the resource it is preferred to dispose of it by landfill or combustion without gaining the benefit of energy extraction. There are many different energy recovery technologies – including combustion with energy recovery, anaerobic digestion, processes including gasification and pyrolysis, advanced biorefinery technologies (Ajayabi et al. 2019).

5. Disposal

Described as least preferred, even as a final step, care must be taken for proper disposal. Deposit at a registered landfill or incineration without energy recovery. There are useful disposal methods, Incineration creates bottom ash which ends up in landfills (Li et al. 2015). It is vital to acknowledge that enhancing resource efficiency does not spell the end of disposal routes. Landfills must be carefully managed; it takes decades before full remediation of the land is reached (Esa et al. 2017). Following the waste hierarchy during construction can also be very useful in reducing waste. It can be seen from the waste hierarchy chart that waste prevention is most recommended. At this stage, developers are trying to prevent waste and making provisions for reuse of waste which is the second item on the chart (preparation for use). Where the waste is usable it then goes through the recycling process or composting depending of material type. Where applicable other recovery options are explored before inevitable disposal which is usually a small quantity (Te Dorsthorst et al. 2007; Song et al. 2015). Waste is reduced as it goes down the waste hierarchy.

Using recycled materials or reusing waste material can save costs to a large extent and reduce the consumption of virgin materials. The reduction of waste and higher volume of site-based work helps reduce carbon emissions associated with transportation as fewer journeys need to be made (CE100 2016). The reuse of building materials reduces CO_2 emissions and save the cost of combustion. Plastic PVC allows reducing CO_2 emissions up to 124 kg of CO_2 eq/m2 compared with the use of virgin PVC material.

A lot of money can be saved by applying good environmental practices: This can be done by planning how to apply the waste hierarchy by monitoring performance regularly and knowing the waste being generated. This is usually followed by making efforts to produce less, sort and segregate the waste not produced to help others recover value from it.

Other factors often influence the decisions producers make about waste generation and management, such as what options are technically feasible, which are economically viable, and which best protect natural resources or human health (DEFRA 2011).

The way waste is sorted can have a direct effect on how it can be recycled. The Report of the UK Government Chief Scientific Adviser (From waste to resource productivity, Evidence and Case Studies, 2017) says “Increasing resource efficiency requires products to be designed with their end-of-life in mind; this will also aid recyclers” (UK Government Chief Scientific Adviser 2017).

The reports provided ways by which policy might encourage this further (UK Government Chief Scientific Adviser 2017):

- **In education.** Building on innovations in higher degree programmes in design, architecture and fashion, sustainable design principles might be mainstreamed in teaching.
- **In research and innovation.** Policies could support further research into resource recovery by extending the research done with some materials to consider all materials as part of a resource chain. It would be useful to pay more attention to recovery processes for new and emerging materials and technologies.
- **In manufacturing.** There is a clear need on the part of all recycling businesses to know what materials, where, and in what quantities. A product passport system comprising such information should accompany all goods manufactured and should be updated on repair. Better resource efficiency can also be achieved through increasing levels of reuse. This form of resource efficiency is often in cohesion with enhanced recycling.

There are a lot of benefits from reusing or recycling building products after their usable periods. These range from climate protection to profit generation.

Mark Walport & Ian Boyd (2017) categorised waste (Walport and Boyd 2017):

1. By its origin, for example, household waste, industrial waste etc. Although this assumes that waste produced from the same source may be similar as people can easily comprehend the waste type.
2. By the type of original product such as packaging waste, waste electrical and electronic equipment (WEEE) etc. This categorisation allows waste streams to be easily identified and understood by a wide range of people.
3. By the material, it consists of. For example, paper, glass, plastics etc. This provides simple, accessible descriptions of waste, but it hides the complexity associated with different materials, such as the range of types of plastic; and the ability to return material to a production process.
4. By its physical and chemical properties, that is the material components within a waste, as well as the nature of any hazards they pose.

The data about these wastes can be used for measuring and reporting against policy measures and targets, recovery and management of waste, environmental protection, and the prevention of harm to human health.

In order to respond to the problem of waste, solutions from the natural and social sciences should be adopted in technology and engineering to achieve sustainable growth without over-exploiting resources (Walport and Boyd 2017). The manufacturing sector needs all the information required by the commercial sector to drive a circular economy. It also needs information about the potential availability of secondary raw materials, the quantity and quality of those materials. Therefore, an understanding of the types and quantities of waste generated is required, where they are generated and their physical and chemical properties. This level of detail help to make informed decisions about potential material substitution, availability and security of supply, and investment in handling or processing equipment. Hence, contributing to the cost-benefit analysis of using a secondary raw material when looking for industrial symbiosis opportunities (Walport and Boyd 2017).

Ekins and Hughes asserted that "despite considerable resource efficiency savings in recent years, global resource extraction is projected to reach 183 billion tonnes by 2050 under business-as-usual scenarios, a rise of almost 100 billion tonnes (Ekins et al. 2016). Consequently, it is necessary to find new ways to enhance resource productivity which play a critical role in achieving the UN Sustainable Development Goals agreed in 2015 (WRAP 2014).

Despite the potential for resource efficiency measures of the Paris agreement to cut greenhouse gas emissions by 60% by 2050, comparatively few advances have been made on resource-related innovation (Walport and Boyd 2017). Circular economy in buildings has the potential to make building resources endless and cheaper. A balanced approach between energy and resource efficiency is needed to accelerate the shift towards a more resource productive economy. The Royal Institute of British Architects (2013) described circular economy as a tool 'designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (RIBA 2013). Hence, buildings are expected to have ambitious circular economy strategies after the lifetime of the building. Circular economy must be seen not only as a sustainability consideration but also as a business strategy for economic opportunities to be realised (Prasad 2019). Prasad saw circular economy as a fast-growing business and political agenda (Prasad 2019). Research suggests a circular economy could add €0.6 trillion to the EU economy by 2030 by increasing resource productivity. According to Prasad S. (2019) "Circular economy offers the opportunity to de-risk project pipelines, generate reliable lower-risk cash flow and create stronger, longer-lasting relationships with clients" (Prasad 2019).

Annual global extraction of primary materials is set to triple by 2050, global waste to triple by 2100, 60% of total UK waste is generated from the construction industry, demolition and excavation (DEFRA 2016; World Bank 2018; Defra and Government Statistical Service 2019). The Ellen MacArthur Foundation defines four building blocks for achieving a circular economy: Circular business models, Circular design, Reverse logistics, Enablers and favourable conditions (i.e. public policy). In 2014, 120Mt of waste was generated from construction, demolition and excavation – equivalent to 59% of total UK waste and 30% of construction firms' pre-tax profit (Prasad 2019). In 2015, the UK economy used 576Mt of materials, and as far back as 1998 construction accounted for roughly half of our national material consumption (Prasad 2019).

2.13. Benefits of Circular Economy

In a circular economy, buildings are designed for a lifecycle and not simply an end-use (Bullen 2007). Performance-based contracts will see tenants and landowners benefit from recycling services (Akanbi et al. 2018). Circularity will be embedded in all parts of a structure. This will ensure that individual assets are flexible, interchangeable and highly customisable, and will enhance users' experience of the environment (Manninen et al. 2018). Design decisions such as optimising disassembly and reuse from the beginning of the programme have implications for the operation, renewal and repurposing of the building for recycling (Arup 2016).

In the model of circular economy, there is an integration of construction and reuse cycles of other industries (EMF 2015). This allows for the building to use renewable material sources and locally sourced materials (Korhonen et al. 2018). Hence, making the building more resilient and lowering the risk for investors. The value chain is upgraded, and the ecosystem is safeguarded. Designs are repurposed and the building's end of life is factored at the design and construction stage (Bocken et al. 2016). Therefore, designers and investors are to make long term plans for residential buildings to be recycled after the expiration of their life span (Geissdoerfer et al. 2017). This often requires collaboration and information exchange between developers and recycling establishments.

Greater London Authority (GLA)'s London Infrastructure Plan 2050 identified circular economy as a cross-cutting theme, as it encourages integration across the city's energy, water, waste, mobility, green and blue infrastructure, housing, and digital connectivity sectors (Arup 2016). Circular infrastructure can help to achieve holistic integration of circular economy principles at the same time minimising negative externalities, increasing longevity and maximising circular resource and material flow (WRAP 2016).

Circular economy offers a compelling opportunity to provide solutions to the complex and multi-dimensional nature of the built environment. It is an opportunity to enable a shift towards more sustainable forms of economic growth, urban life and value creation (Su et al. 2013). Capitalising on this opportunity requires a structuring towards a systems-based approach which can be applied at the scale of buildings, neighbourhoods, cities, regions and entire economies (Morgan and Mitchell 2015). This may include a new approach in financing, procurement, design, construction, operation, maintenance, repurpose and recycling, thereby maximising efficiency, encouraging flexibility and cutting down waste.

This needs to be a collaborative effort and an encompassing framework that is defined not by the delivery of individual components, but by the circular functionality of the entire value chain (Arup 2016). The UK construction industry has made significant progress in reducing the amount of waste sent to landfills since 2008 (DEFRA 2015). Arup asserted that waste management and disposal cost the industry the equivalent of 30% of pre-tax profits (WRAP

2013,2014). The cost of landfill tax will continue to increase (set to rise to £80/tonne of active waste in 2014), it is, therefore, necessary to reduce waste in a sustainable way by employing opportunities to improve profitability (Arup 2016).
A proactive approach to waste management can help to (WRAP 2013):

- Reduce costs/increase profit – The cost of waste can be over £1,000/skip when the cost of wasted materials and labour are included.
- Enhance reputation – Reducing waste and effectively tidying and safeguarding the work environment. This improves the reliability and safety of the establishment.
- Meet sustainability targets – Reducing site waste will help achieve BREEAM/LEED targets as most UK local authorities have adopted planning policies requiring the achievement of minimum requirements for sustainable home standards.
- Reduce environmental impact – An effective reduction and management programme, can save up to 58% of the carbon associated with waste.

2.14. Building Simulation

2.14.1. Calibrating Building Model with Real Building Data and Information in Terms Energy Use

The use of computer-simulated model to mimic the operation of a building means that the performance of the building over an extended time can be observed and documented quickly under several different scenarios (Greasley 2008). Usually, simulation method refers to the process of acquiring data, building a model and conducting experiments on models. An experiment consists of replicated scenarios and running the simulation for a period in order to provide data for analysis. Therefore, an experiment is conducted to understand the behaviour of a model and to evaluate the effect of different input levels on specified performance measures (Greasley 2008).

Pidd (1996) characterised systems best suited to simulation as: *Dynamic* - their behaviour varies over time, *Interactive* - consisting of several components which interact with each other, *Complicated* – a system consisting of many interacting and dynamic objects (Pidd 1996).

Gucyeter (2018) considered energy performance gap as one of the most significant issues associated with the assessment of energy consumption in the built environment (Gucyeter 2018). To narrow this gap, simulation approach for energy performance assessment requires comprehensive calibration procedures. The calibration of models for energy performance can aid to facilitate a base-case representation of existing building performance patterns which can enable further accuracy in the operation, diagnosis and energy conservation measures (ECMs) using calibrated models (Gucyeter 2018).

2.14.2. Importance of building simulation for energy optimization in buildings

Building simulation over the years has been used as a prediction tool for evaluating the performance of buildings thereby providing projections for futuristic operations which are backed up by relevant data for proper decision making. Simulation as a research tool saves time, resources and practical risk of undertaking a study or research as models are set up to deliver accurate and realistic results. In practice, simulation is most widely used and appropriate for applications that involve queuing – of people, materials or information (Greasley 2008).

Laine et al. (2007) appraised building simulation as an integral process of building design since it contains both the energy and condition analysis process description and the requirements for information exchange throughout the building process. They considered energy analysis throughout the design stages of a project into two key parts: (Laine et al. 2007).

1. Speculative: The analysis work that is undertaken during the programming stage of the project entails providing advice on the potential energy performance of a building and its

systems to other design roles. This serves as an advisory role to impact the overall building design, determine the feasibility of concepts in an energy context and establish energy targets.

2. Analytical: The analysis work undertaken during the sketch, full concept and coordinated design stages of the project which assumes the availability of geometric information about the building layout.

2.14.3. Approaches in building energy simulation

To facilitate pre-occupancy evaluation for buildings to bridge the performance gap, simulation modelling is well designated as an assessment methodology that requires a certain degree of confidence. Hence, to holistically resolve the whole-building energy performance assessment through the utilization of a simulation model, it is important to implement a calibrated building energy simulation approach (Østergård et al. 2016). Østergård, Jensen, and Maagaard (2016) identified the following building simulation methods (Østergård et al. 2016):

- Proactive building simulations refer to an anticipatory exploration of the design space in order to guide the design rather than evaluate the design.
- Statistical methods usually include running large numbers of simulations and applying statistical measures as well as coping with uncertainties, this approach may facilitate exploration of a large design space and identify important inputs and favourable input domains.
- Holistic design entails the calculation of many interdependent performance objectives and combining the results to support decision making. Such important interdependent objectives are energy demand, thermal mass, daylight, natural ventilation, etc.
- Optimisation of performance objectives in order to automate the exploration of a large design space and help guide the design towards high performance.
- Computer-aided design (CAD) - Building Performance Simulation (BPS) interoperability may be achieved by the integration of models, shared schemas, and run-time coupling.
- Knowledge-based methods aim to share knowledge in reducing the time spent modelling by seeking to improve consistency and validity.

2.14.4. Relevant modelling and simulation information

In the building modelling process, a large quantity of input data is always involved. The quantity of data may vary depending on the level of detail pursued in the model definition and the available data.

Uncertainty in building models.
During manual calibration, a deterministic approach is usually adopted. However, it is not all input data that affect the investigated energy consumption in the same way. it is important to identify, throughout a screening analysis, the parameters that influence the building model, and establish their level of uncertainty (Fabrizio and Monetti 2015).

Measured data are sometimes used for providing the model with further information (e.g., building occupancy, temperature setpoint, etc.) during validation of the calibrated model based on statistical indices (Fabrizio and Monetti 2015).

To achieve the best and most accurate simulation results, it is necessary to have all relevant information about a given task to undertake simulation operations.
Harish and Kumar (2016) stated that 'the forward approach in modelling and simulation briefly emphasizes the importance of acquiring (Harish and Kumar 2016):
(1) climate data for the case building
(2) building design
(3) geographical data (location, orientation, obstructions etc.)
(3) construction data
(4) building installation characteristics
(5) building operations, occupancy and schedules

2.14.5. Calibrated Simulation

A calibrated simulation can simply be described as the process of fine-tuning the simulation parameters so that the actual measured values closely match those predicted by the simulation program (Kishore and Rekha 2018). As a result of the complexity of the built environment and other prevailing large numbers of independent interacting variables, it is often difficult to achieve an accurate representation of real-world building operations (Coakley et al. 2014). Consequently, by reconciling model outputs with measured data/base case data, it is possible to achieve more accurate and realistic results. Coakley et al. (2014) described this reconciliation of model outputs with measured data as calibration (Coakley et al. 2014). Calibration is usually in a building simulation model to assess how well the simulated parameters match with the actual in-situ monitored parameters. Hence, this comparison is used to ascertain the 'goodness-of-fit' between the simulated and measured parameters.

A calibrated simulation is an appropriate method to measure and determine the energy and savings of ECMs (Energy Conservation Measures) under certain conditions. Simulation models are calibrated in order to decrease the effect of modelling errors, insufficient inputs, imprecise assumptions, and uncertainty related to design and operation on the simulation outcomes.

The purpose of calibration is to ensure that the energy model can generate energy use results close to the expected or measured values using actual inputs, including occupancy schedule, weather, lighting, equipment schedules, densities, HVAC system parameters and controls. It is essential to specify the level of calibration to work on and to verify if the data collected are adequate for carrying out the calibration. Hence, to compare optimised performance with based case energy performance, the base case building information such as dimensions of building, materiality, thermal performance, area, the volume of a building, etc. needs to be obtained which also require consistency while simulating with the optimised case where applicable (Fabrizio and Monetti 2015). Building energy models are usually calibrated based on monitoring data of the existing buildings and from research data from various field studies for new designs which could facilitate performance predictions with high accuracy (Zhao and Magoulès 2012; Coakley et al. 2014).

Yoon et al. (2003) consider calibration of simulation models via monitoring data as a time-consuming and difficult process in building energy performance studies (Yoon et al. 2003). Present research assesses the significance of such a calibration approach in terms of controlling different parameters correspondingly and evaluating their sensitivities on the gross consumption prediction of an accurate simulation model. Therefore, to evaluate the effects of energy conservation measures (ECMs) on building energy performance, it is necessary to obtain a base case simulation model that represents the existing behaviour of the building as closely as possible (Gucyeter 2018). In this respect, the findings of the present study suggest that concise data monitoring could facilitate an accurately calibrated building energy simulation model through a manual iterative method. Such an approach could be very influential in reducing the energy performance gap and the discrepancy between simulated and monitored energy performances of buildings.

In addition, current research could help to underscore the fact that energy performance modelling and calibration for existing buildings are detailed, yet convenient since the base case model could be developed through a meticulous audit and realistic process (Gucyeter 2018). However, it is common to use a "trial and error" method to calibrate a building model as this kind of approach driven by experience assumptions, may bring inexperienced users to time consuming and unsolved problems (Fabrizio and Monetti 2015).

2.14.6. Steps for Calibrated Simulation (U.S. DOE, 2000)

The top priority of any simulation operation is to deliver accurate results for the best decision to be taken. The United States Department of Energy recommends the following steps for calibrated simulation approach (DOE 2000):

1. Develop a Calibrated Simulation Plan

In the preparation of a calibrated simulation plan, the baseline scenario and post-retrofit scenario must be specified, selection of the simulation software, and the tolerances of calibration indices must be checked.

2. Data collection

The data may include building plans, geometry and construction materials, historical utility data where possible, necessary information of building system components such as lighting systems, plug loads, HVAC systems, building envelope and thermal mass, building occupants if needed, other major energy loads and weather data. On-site surveys, spot, and short-term measurements, etc may be appropriate methods to collect data and information.

3. Imputation data and model run

One good way for inputting data into a model is the manual of the simulation software which is selected by the simulator. In order to minimize possible simulation error, the following data should be checked as input or output:

a) Building orientation

b) HVAC system zoning

c) External surface characteristics

d) Power densities and operating schedules of lighting and plug load

e) HVAC system characteristics and operating schedules

f) Plant equipment characteristics, etc.

4. Calibration of a simulation model

Comparing model hourly usage predictions with best/recommended energy standards and practices.

5. Refine model

If the statistical indices calculated during the previous step indicate that the model is not sufficiently calibrated, revise the model inputs, run the model, and compare its prediction to the measured data again. In the of calibration for best design for energy performance, it becomes imperative to refine model parameters for best building energy performances to meet obtainable standards.

6. Calculate energy and demand savings

The baseline model and post-retrofit model are done to calculate the energy and demand savings of each ECM. Calibrating energy models to measured data can be used to identify and estimate savings, as well as support investments, grade energy conservation measures by analysing retrofit options (Raftery et al. 2011).

2.14.7. Model Calibration Criteria

Model calibration is usually adjustments or comparisons in simulation operations to meet certain accuracy, standards or requirements. This process begins with the design of the measuring instrument that needs to be calibrated. The design must be able to maintain a calibration through its calibration interval. This implies that design must be capable of measurements that are within certain engineering tolerance when used within the stated environmental conditions over some reasonable period (Haider and Asif 2016). The main purpose of calibration is for maintaining the quality/standard of measurement.

Building energy models are usually complex. There are many assumptions on the building characterisation, with a direct impact on the simulation results. The process of modelling acquires a higher degree of difficulty during calibration. Therefore, to handle properly the model complexity during calibration, the tuning process of the model parameters requires domain experts' knowledge (Fabrizio and Monetti 2015).

Reddy, T.A. (2006) examined a range of tools, approaches, techniques, and procedures commonly used to calibrate simulated building energy models to measure data in developing a more systematic approach to model calibration.

Reddy classified the most used calibration methods as fellows (Reddy 2006).

- Manual iterative calibration which is based on the user's experience consists of an adjustment of inputs and parameters on a trial-and-error basis until the program output matches the expected data.
- Graphical and statistical methods – This calibration is based on specific graphical representations and comparative displays of the results to orient the calibration process.
- Automated calibrated methods – This calibration is based on special tests and analytical procedures involving specific intrusive tests and measurements.

The above methods are not exclusive and could be coupled. For example, the use of graphical and statistical analysis methods to support iterative manual calibration, semi-automatic procedures coupling mathematical and heuristic manual methods (Reddy 2006).

2.14.7.1. Typical energy simulation procedure

Typical energy simulation procedure by Østergård, T. et al (2016) in a building performance simulation process (Østergård et al. 2016).

1. A baseline model is created in building performance software that can calculate the objectives of interest.

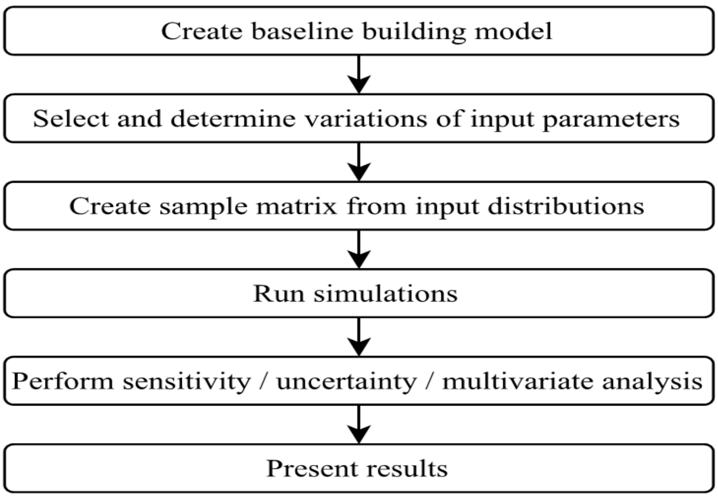
2. Several input parameters, ranging from very few to hundreds, are selected depending on the scope of the analysis. Parameters assigned have a probability density function that reflects the parameter uncertainty related to the numerical model, boundary condition, physical property, or design variability.

3. A sample matrix is constructed from the probability density functions as various sampling procedures exist, and their applicability depends on the analysis to be performed. However, sampling procedures include random, stratified, factorial, Latin hypercube, and quasi-random with low-discrepancy sequences (Saltelli et al. 2008).

4. For each sample a building simulation is performed, and relevant outputs are collected.

5. Results are finally analysed using uncertainty analysis, sensitivity analysis, multivariate analysis, or combinations of these which may be used to create meta-models as described below (Østergård et al. 2017).

Table 16: A typical energy simulation procedure by Østergård, T. et al (2016) in a building performance simulation process(Østergård et al. 2016)



Reddy (2006) and Bertagnolio (2012) both defined different levels of calibration based on building information available shown in the table below (Reddy 2006; Bertagnolio 2012).

Table 17: Different levels of calibration based on building information available (Reddy 2006; Bertagnolio 2012)

	Building input data available						
Calibration levels	Building model design	Building orientation	Natural ventilation	Natural lighting	Building Fabrics and thermal properties	Window to Wall ratio	Building components (shading devices)
Level 1	✓						
Level 2	✓	✓					
Level 3	✓	✓	✓				
Level 4	✓	✓	✓	✓			
Level 5	✓	✓	✓	✓	✓		
Level 6	✓	✓	✓	✓	✓	✓	
Level 7	✓	✓	✓	✓	✓	✓	✓

The above table shows 7 levels of calibration that could be applied in demonstrating energy performance in buildings. The above calibration methodology consists of 7 building input data for energy calibration in a passive design. The procedure involves one at a time simulation (from level 1 to level 7) or all at a time simulation (level 7). This operation can be performed using building energy simulation software like DesignBuilder, etc. (Fabrizio and Monetti 2015).

Modelling base case building

Building energy models are complex and composed of many input data. During modelling a building within a simulation program, the accuracy especially relies on the ability of the user to input the parameters that result in a good model of the actual building energy use (Liu et al. 2003; Saltelli et al. 2008). According to Škrjanc, Zupančič, Furlan, and Krainer (2001) models are developed to simulate the building energy systems and components (Škrjanc et al. 2001). Škrjanc et al. (2001), further classified models into three types, physical, symbolic and mental models. Symbolic models are less comparatively complex, models can be mathematical or non-mathematical, and mathematical models involve mapping the physical laws governing the dynamics of the system's process into mathematical relations using variables and constants (Škrjanc et al. 2001).

The stepwise procedure, a method of modelling identified by Harish and Kumar (2016) for forwarding approach modelling is given below (Harish and Kumar 2016). Although the procedure is not universal but instead, followed by most development engineers.

Step 1: Acquire Climate data as per the location of the building under study.

Step 2: Acquire building design data.

Step 2.1: Acquire building geographical characteristics: location, orientation, etc.

Step 2.2: Acquire building construction data: Thermophysical properties of the building materials, etc.

Step 3: Heat plant characteristics

Step 3.1: Type of HVAC system

Step 3.2: Type and characteristics of the HVAC subsystems: AHU, Coil units, etc.

Step 4: Building operating schedules

Step 5: Simulate the model as per the desired simulation periods

Step 6: Predict the net energy (peak or average values) consumption patterns.

Building modelling for simulation usually starts by inputting parameter values for the building shape, building rotation, WWR, Wall insulation, Thermal mass, Glass type, Window shading, plug loads as listed (Samuelson et al. 2016).

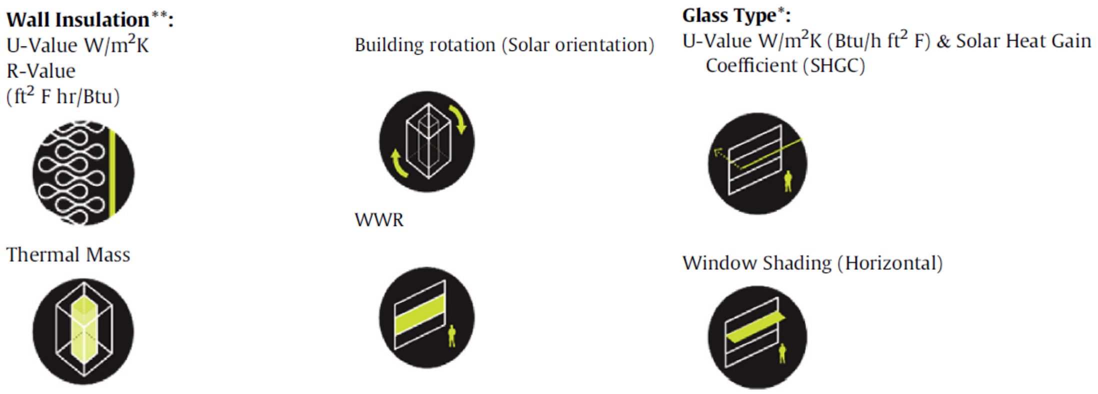


Figure 33: Some input parameters for simulation (Samuelson et al. 2016)

2.14.7.2. Calibration Methodologies and procedures for Building Simulation Models

Clarke et al. (1993) proposed four main categories of calibration methodologies which were also revised by Reddy et al. (2007) as presented below (Clarke et al. 1993; Reddy 2006):

(1) Manual calibration methods based on an iterative approach.

(2) Graphical calibration methods.

(3) Special tests and analysis procedures-based calibration.

(4) Automated techniques for calibration, based on analytical, mathematical approaches.

The different methods from the four main categories above can be used during the same calibration process. That is both graphical and mathematical/statistical methods can be used in synergy to improve the calibration of a building model. Also, both manual and automated calibration can be based on analytical procedures.

1. Manual Calibration

This first category includes all calibrated simulation (CS) applications without a systematic or an automated procedure. It is highly based on users' experience and judgment and it is the most used in simulation applications (Pedrini et al. 2002; Pan et al. 2007; Hassan et al. 2011). It may also include "trial and error" approaches, which are based on an iterative manual tuning of the model input parameters. Input data could be altered based on the users' experience and knowledge about the building. Manual calibration corresponds thus to subjective and ad-hoc approaches.

2. Graphical Techniques

Techniques based on graphical representations and comparative displays of the results are included within the manual calibration methodologies. They are generally consisted of time-series and scatter plots apart from classical and time-series plots still used for calibration purposes, innovative methods have also been employed (Pedrini et al. 2002; Hassan et al. 2011).

Two main techniques are listed for their wide application:

- 3D comparative plots
- Calibration and Characteristic signature.

3D Comparative Plots

The 3D plot approach was developed to analyse hourly differences, during the whole simulation period, between simulated and measured data (Haberl and Bou-Saada 1998). This method is used for calibrating time-dependent parameters, such as schedule loads. Hourly values are computed and compared in the plot. The authenticity of this method relies on the increased ease of identifying even small differences in the measured and simulation data comparison. For example, the 3D plot, created and represented below shows daily three different dimension graphical plots, representing measured data, simulated data and the difference between simulated and measured data, respectively.

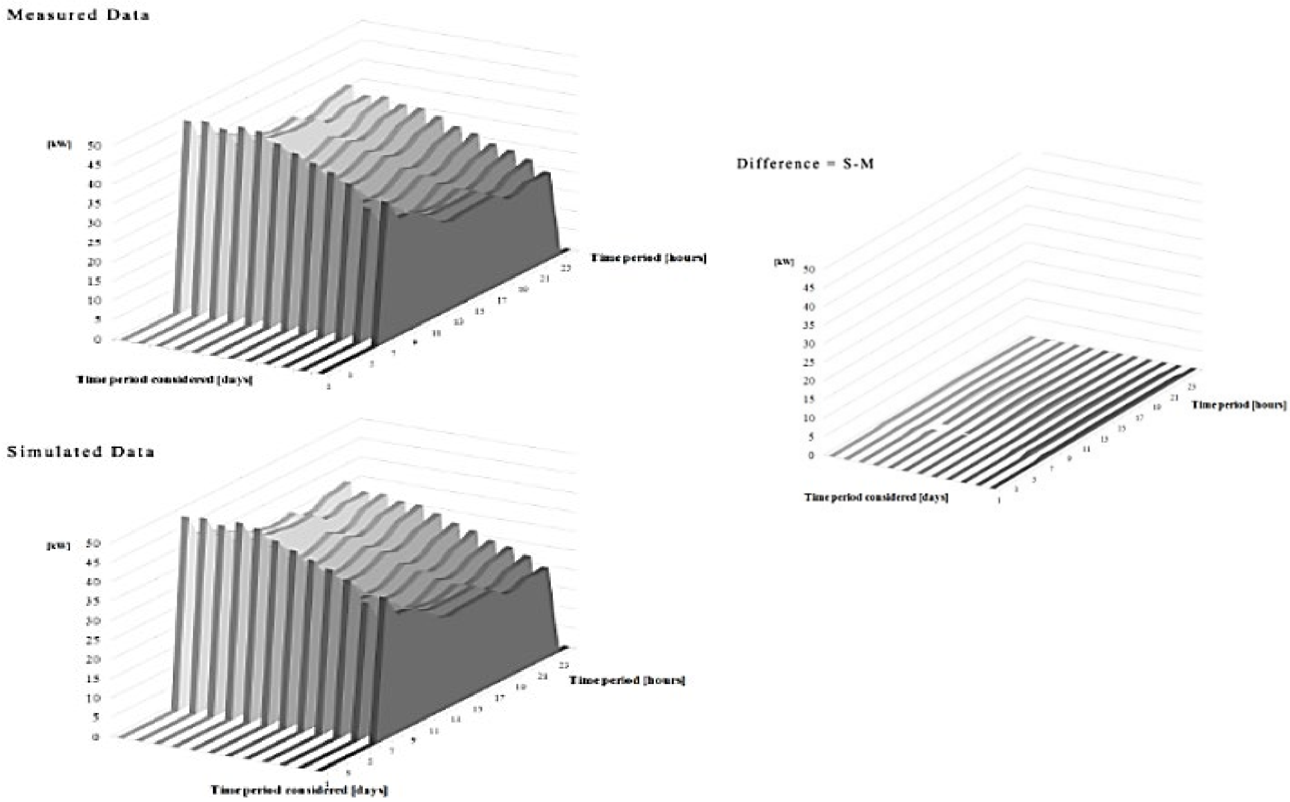


Figure 34: 3D plot (Fabrizio and Monetti 2015)

2.2. Calibration Signature

Signature is used to describe a graphical representation which refers to the difference between the simulated and the measured energy performance of a case study (Liu et al. 2015). A characteristic signature, another signature is defined for comparing values from two distinguished simulations, instead of values from measured and simulated data. This signature should be taken as a reference or baseline for the measured values. Characteristic signatures are usually calculated based on a daily average basis and are represented by a characteristic shape due to the climate and the system type considered (Fabrizio and Monetti 2015).

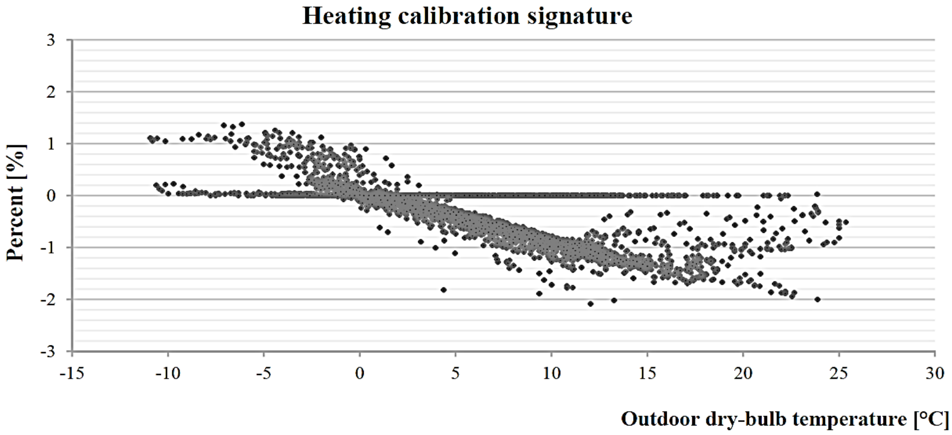


Figure 35: Example of Calibration signature (Fabrizio and Monetti 2015).

3. Calibration Based on Analytical Procedures

This category is solely based on analytical and test procedures which could be a short or long-term monitoring period. It can easily be distinguished from the automated methodologies as it does not employ mathematical or statistical procedures for the calibration process. Measurement tests such as blower door tests or wall thermal transmittance measures are considered among the special tests that can be used for calibrating the building models. This is so because they could be invasive and they cannot always be performed especially when buildings are constantly occupied (Fabrizio and Monetti 2015).

4. Calibration Based on Analytical and Mathematical Approaches using Automated Techniques

Automated techniques are approaches that cannot be considered user-driven and are built on sort of automated procedures (Coakley et al. 2014). They can also be based on mathematical procedures such as Bayesian calibration or analytical approaches.

4.1. Bayesian Calibration

Bayesian analysis is a statistical method that uses probability theory to compute a posterior distribution for unknown parameters (θ) given the observed data (y). According to Booth et al. (2012) and Heo (2011), it is used for calibration purposes for incorporating direct uncertainties in the process (Heo 2011; Booth et al. 2012). Typically, the Bayesian technique was used for the model predictions in other domains such as geochemistry or geology rather than in building physics simulation (Zhang and Arhonditsis 2008; Rahn et al. 2011; Tierney and Tingley 2014). According to Heo et al. (2012) and Gregory et al. (2014), different studies have focused on the application of this technique to the building simulation domain (Heo 2011; Gregory et al. 2014).

4.2. Meta-Modelling

Van Gelder et al. (2014), described a meta-model as a mathematical function in which coefficients are determined based on a limited number of input/output combinations (Van Gelder et al. 2014). It can also be defined as a "model of a model" or a surrogate model that is commonly used for reducing the model complexity which is a simpler and computationally faster version of the model (Eisenhower et al. 2012).

4.3. Optimization-Based Methods

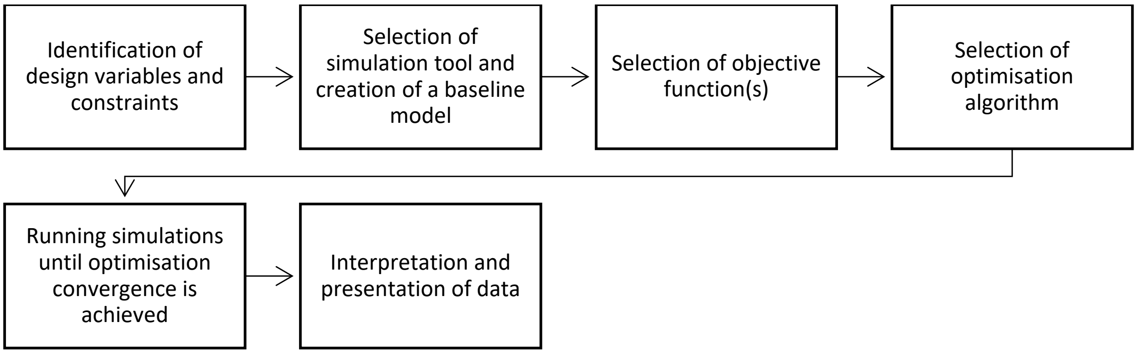
Optimization is used in building simulation to refer to an automated approach based on numerical simulation and mathematical optimization (Evins 2013; Nguyen et al. 2014). The methods are usually based on the coupling between a building simulation software such as EnergyPlus, TRNSYS, etc. and an optimization program like GenOpt which employs optimization algorithms (Attia 2012; Evins 2013; Machairas et al. 2014). To perform optimization, an objective function must be set within the optimization programme. In calibration application, the objective function is defined as a function of the difference between measured and simulated data which is based on the matching between a set of measured data and simulated data (Fabrizio and Monetti 2015).

2.14.7.3. Optimisation

In simulation operations, optimisation refers to the automated use of mathematical optimisation in combination with building performance simulations (Fabrizio and Monetti 2015). Machairas et al. (2014) and Nguyen et al. (2014) in their works asserted that a building optimisation analysis typically consists of the following steps that may be repeated in an iterative design process (Machairas et al. 2014; Nguyen et al. 2014).

1. Identification of design variables and constraints.
2. Simulation tool and creation of a baseline model selection.
3. Selection of objective function(s).
4. Selection of optimisation algorithm.
5. Running simulations until optimisation convergence is achieved.
6. Interpretation and presentation of data.

Table 18: Optimisation Analysis (Machairas et al. 2014; Nguyen et al. 2014)



2.15. Application of Circular Economy Principles in Buildings: A systematic review

Aspects of this section (2.15) are published in a peer-review Journal – 'Journal of Building Engineering' as referenced below.

Akhimien, N. G., Latif, E. and Hou, S. S. 2021. Application of circular economy principles in buildings: A systematic review. Journal of Building Engineering 38, p. 102041. doi: https://doi.org/10.1016/j.jobe.2020.102041

To help understand the works done in the field of the application of circular economy in buildings, it is important to conduct a systematic review with regards to its application in buildings. This is to explore studies and research, their concepts, research gaps, contributions, etc. Thereby, enabling this research to craft an up to date circular economy interventions for buildings.

The transition from a linear economy into a circular economy is not realisable until circular economy principles are applied into the life-cycle stages of buildings which is a proactive design approach to manage buildings from cradle to cradle (Minunno et al. 2018). Resources are depleted without any effective programme for recovering materials (Rahman et al. 2017).

In this systematic review, the study is aimed at identifying suggested advancements for the application of circular economy principles in buildings as well as considering the Nigerian context. The study objectives are to systematically review/analyse proposed circular economy interventions in buildings and finally conclude on findings whilst identifying research gaps.

2.15.1. Research objectives for systematic review

1. To systematically review proposed circular economy interventions in buildings by analysing selected and relevant kinds of literature towards the application of circular economy in buildings.
2. To identify major research gaps in the application of circular economy in buildings through the categorisation of works of literature under various circular economy themes.

2.15.2. Methodology for Systematic review

To explore circular economy interventions in the construction industry with special emphasis on the application of its principles in buildings, it is imperative that a systematic review is conducted. This is a practical approach to account for and evaluate the quantity and quality of studies/research that has been undertaken in the application of circular economy principles in buildings through a systematic review as an essential method for this kind of study (Esa et al. 2017). This method is set to provide a critical overview of previous studies as it relates to the subject matter as well as identify research gaps in the various works (Webster and Watson 2002). To accomplish the aim of this review, it is recommended by Briner and Denyer (2012) that the following adapted steps are adhered to:

1. Set a method for systematic review

2. Present method transparently
3. The method should be a repeatable process of arriving at the same conclusion
4. Develop a general summary and connection to the subject of discussion

(Briner et al. 2012).

Table 19: Stages for Systematic review (adapted from Higgins and Green, 2008)

	Stages	Investigation
1	Study Focus	Exploring the application of circular economy principles in buildings as well as considerations for the Nigerian context.
2	Research objective	Conduct a systematic review of works of literature focused on the application of circular economy in buildings.
3	Selection Criteria	Strictly pieces of literature on circular economy application in the built environment. related abstracts; related full articles; literature with supplementary information.
4	Strategies for material acquisition	Extraction of high-quality pieces of literature from databases, Ranging searches from the last 10 and 5 years (Science Direct, Web of Science and Scopus)
5	Filters and Eligibility	Publications from peer reviews and proceedings
6	Data collection	Use of marking matrix for the inclusion and exclusion of works of literature. search steps: title search, abstract search, keywords search, full-text search, data extraction, bibliometric network.
7	Quality assessment and accuracy	Special releases and documentaries on circular economy principles and applications, the inclusion of other relevant studies in a circular economy that may be inferred in the building sector, exclusion of generic articles, exclusion of irrelevant kinds of literature to the aim of this review.
8	A systematic review, Synthetization, results, and conclusion	Analysis, summary, and submission of findings.

Following the above steps, it is essential to define the aim of the review and evaluate targeted research in the subject area. The study is to explore and analyse literature materials on the application of circular economy principles in buildings. Hence, the main objective of the review is to identify and systematically review studies on the application of circular economy in buildings. Therefore, studies and research papers in the context of this discussion are collected and analysed. This included the creation of a bibliometric network of all related abstracts to find the most related topics with a focus on this research.

This strategy started with a preliminary investigation of articles by creating a bibliometric network. According to Van Eck and Waltman (2014), a bibliometric network is a constituent of nodes and edges showing the correlation of words and the strength of their connection through the edges (Van Eck and Waltman 2014). These keywords are obtained from the abstract/pieces of literature and the network of the words is networked to the most researched areas under the theme and topic. To do this, a software called VOSviewer, developed by Nees Jan van Eck and Ludo Waltman is used to analyse the studies. The objective of creating this network for this review is to draw searches from the theme of circular economy and focus the review on the subject area of this investigation.

The VOS Viewer can reveal the most used keywords as it relates to the topic which it visualizes by the size of the nodes, therefore, the bigger the nodes, the higher the number of citations of the word. It also shows how closely related keywords in the fields of study by distance-based networks in which the network distance between two nodes indicates their correlation (Van Eck and Waltman 2014).

The software is programmed to delimit the use of a specific database for bibliometric networking. Consequently, this research is carried out in three major databases (Web of Science, Science Direct, and Scopus). The search keywords chosen included.
(TITLE-ABS-KEY ("circular economy") AND TITLE-ABS-KEY (buildings) AND TITLE-ABS-KEY (recycle)) They are decisively chosen to focus on the aim of this systematic review. Using these keywords in the preliminary search and limiting by date range within the last ten years, 32 document results were discovered in the Scopus database, 59 results are found in Science Direct, and 125 are found in Web of Science. The search done in the month of April 2020 had a total of 216 papers.

2.15.3. Results

The results of this review are presented in two categories, it started by providing a descriptive analysis of the central focus of obtained articles and giving a brief description of publications. The articles are further divided into seven major research themes of circular economy for content analysis.

2.15.3.1. Analysis of literature material according to circular economy research theme

Furthermore, the review analysed each article according to the seven research themes discovered in this review. These themes form a comprehensive approach towards the application of circular economy principles in buildings. However, many of the pieces of literature focused on certain themes. Therefore, to facilitate the discussion and understanding of the recent developments on the application of circular economy in buildings and analyse articles in similar areas of research, it is necessary to conduct this review in a systematic manner following these different aspects or themes.

The analysis went on to reveal basic circular economy concepts and principles found in the obtained literature for this review. This was done by listing the found concepts and principles in the 64 articles. In this systematic review, each concept and principle are attached to their life cycle stage. This gives a very realistic approach toward the application of circular economy in buildings. Hence, this analysis provides not only a holistic approach but also steps toward the implementation of circular economy in the buildings as well as identification of insufficiently covered areas for further research in this field.

2.15.4. Discussions

The discussions are divided into sub-headings based on the collected literature materials. The descriptive analysis is based on the bibliometric results. The discussion later progressed to a critical review of literature content on the seven aspects of circular economy. The discussion is concluded with the identification of research gaps found in this literature review.

2.15.4.1. Descriptive discussion

According to the bibliometric data in this review, studies on Circular Economy in buildings are increasing. This is evident in the bibliometric data reported in this research. Moreover, the statistical exponentiation of articles has doubled over the last three years. There are research groups hosting events such as BAMB (Building as Material Banks), which is based on pathways for a circular future. This has contributed greatly to the increase in circular economy research in buildings. However, a great consideration of life cycle stages, as well as the reusability and transformation of buildings was the focal point of the event (BAMB 2017). It is however noticed that some of the publications had a specific interest in circular economy in buildings, while some tried to base their research on a holistic approach towards the application of circular economy principles in buildings as buildings are seen as material bank for material extraction during use and at end of life (Akanbi et al. 2018).

2.15.4.2. Content discussion

The discussion for this review is based on seven found aspects of circular economy in buildings. (1) Design for disassembly (2) Design for recycling (3) Building materiality (4) Building construction (5) Building operation (6) Building optimization (7) Building end of life.

2.15.4.2.1. Design for disassembly

According to some of the obtained studies (from a total of 10 works of literature), the concept of design for disassembly arose from the need for buildings to easily be deconstructed, which in turn increased components adaptability and flexibility to different configurations. Building components are usually prefabricated and later site assembled (Minunno et al. 2018).

The research into the standardisation of material sizes and types may be useful to complement the seven strategies of circular economy since the construction industry is increasingly moving towards a closed-loop supply chain (Minunno et al. 2018). Other scholars lamented that the concept is being introduced slowly in the built environment as many stakeholders are yet to fully understand the practicality of applying the concept in the building sector (Adams et al. 2017; Eberhardt et al. 2019b).

2.15.4.2.2. Design for recycling

Firstly, the review analysed pieces of literature that considered the reduction of material consumption through the design of reusable components. Secondly, works of literature that considered products adaptability to different recycling phases (up-cycling and down-cycling). In addition, studies are also analysed with respect to the 3Rs hierarchy (reduce, reuse, and recycle) of the circular economy. A total of 28 pieces of literature carried out research in this area (design for recycling), 8 studies in this review had published on the reduction of material consumption through the design of reusable components, notably the following works of literature (Sansom and Avery 2014; Kreilis and Zeltins 2017; Akanbi et al. 2018; Migliore et al. 2018; Cruz Rios et al. 2019; Saint et al. 2019; Milios and Dalhammar 2020). 12 works of literature had a special interest in the adaptability of materials to recycling, studies such as (Huang et al. 2018) which focused on the 3Rs hierarchy was also reviewed.

Minunno et al. (2018) recommend that whilst following the 3Rs (reduce, reuse, and recycle) hierarchy of circular economy, the building components that are not reusable or adaptable should be designed with preference to their recyclability potential (Minunno et al. 2018; Rossetti et al. 2018). Therefore, the recycling phase for each material component (whether reuse, upcycling or downcycling) should be considered at the early stages of the project design (Campioli et al. 2018).

2.15.4.2.3. Materiality

Papers reviewed under this heading had a special focus on building materials in a circular economy. Most of the studies are channelled towards building material specifications and how this can possibly be fitted into the 3Rs hierarchy. Hence, this section is reviewed in two parts based on the focus of obtained pieces of literature. The first part focuses on, waste reduction through material design and specification. Pioneering papers gathered in this area include (Eberhardt et al. 2019b; Giama et al. 2019; Hertwich et al. 2019; Honic et al. 2019; Kerdlap et al. 2019). The second part focuses on, Material storage using buildings as material banks (BAMB), major works of literature of focus are (Cai and Waldmann 2019; Eberhardt et al. 2019b; Hopkinson et al. 2019). A total of 22 collected pieces of literature explore focus on materiality as one of the key drivers of circular economy.

2.15.4.2.4. Construction

Nine articles in the systematic review have explored 'construction'. The construction phase is an important stage of a building's life cycle as it is a major determinant of the reusability, and recyclability of the building (Akanbi et al. 2018; Ghaffar et al. 2020). Ghaffar et al. (2020) emphasise the need to sustain building materials through the use of smart design, construction and circular value chains where buildings would function as banks for valuable materials and products (Ghaffar et al. 2020). The construction method of a building has been proven to be a major enabler of circularity, this is evident in the work of Ruiz et al. (2018), they state that a resource-efficient construction approach is aimed at encouraging construction practices that reduce cost, waste and atmospheric emissions (Ruiz et al. 2020). However, Mangialardo and Micelli (2018) express concern that although other sectors are improving their efficiency through the adoption of a more circular pattern, the construction industry seems to be left behind (Mangialardo and Micelli 2018).

2.15.4.2.5. Operation

This aspect received very little attention from researchers in this systematic review, with 5 papers discussing critical issues. Some researchers recommend the minimisation of recuperative maintenance with preventive maintenance (Adams et al. 2017; Giama et al. 2019), which is a proactive approach to ensure buildings are in their best condition for as long as possible (Esposito et al. 2018). Buildings and infrastructure have been said to possess lifespans of decades or centuries but require an ongoing input of materials and energy for their smooth operation and maintenance (Hertwich et al. 2019). Heisel and Rau-Oberhuber (2020) also emphasise the need to keep products in use for as long as possible, such as the re-use or redistribution of material components during building use (Heisel and Rau-Oberhuber 2020). A very few available pieces of literature on this aspect indicates insufficient awareness and knowledge in the preposition of strategies towards the operational stage of a building.

2.15.4.2.6. Optimisation

Saint et al. (2019) classify the following operational activities: use, maintenance, repair, replacement and refurbishment under the use stage of a building (Saint et al. 2019). These activities usually form parts of a building's maintenance regime and they form an integral part of the circular economy concept of Optimisation (Arup 2016; Zimmann et al. 2016). Optimization in buildings may include component upgrades or enhancements to increase the building's longevity (Baiani and Altamura 2018; Migliore 2019). A total of 6 relevant papers are collected which indicates the lack of adequate studies in the area. However, the studies reveal that building optimisation is geared towards making products and systems operate at maximum efficiency (Arup 2016; Baiani and Altamura 2018; Antoniol and Barucco 2019; Eberhardt et al.

2019b; Giama et al. 2019; Saint et al. 2019). Arup (2016) states that it is essential to maintain materials and components at their highest possible value during the employment of design and construction processes to eliminate waste, maximise efficiency, thereby promoting reuse and repurposing (Arup 2016). They also add that the design of durable components for longevity is another optimisation strategy used in buildings (Arup 2016). This is necessary as it prolongs the useful period of the building whilst giving opportunities for component parts to be upgraded, renewed, repaired and exchanged in a circular economy (Minunno et al. 2018; Cruz Rios et al. 2019).

2.15.4.2.7. End of Life

This aspect receives one of the highest focus from researchers in this systematic review. The total number of reviewed works of literature are 24. From the studies, it is observed that the end of life phase is a major consideration for circular economy in buildings as material components are either reused directly, upcycled, or downcycled (Kreilis and Zeltins 2017; Esposito et al. 2018; Minunno et al. 2018; Tomic and Schneider 2018; Wong et al. 2018; Cai and Waldmann 2019; Honic et al. 2019; Hopkinson et al. 2019; Migliore 2019; Williams 2019; Moreno-Juez et al. 2020). Hopkinson et al. (2019) conclude that to create a circular economy building system, it is required for the building system to employ both recovery and reuse of building components from the end of life to stock replacement and maintenance (Hopkinson et al. 2019). They add that a larger percentage of construction and demolition waste are downcycled at the end of a building service life (Hopkinson et al. 2019). This is true due to low awareness of circular economy in buildings, consequently, buildings are not designed for recycling (Huang et al. 2018; Rossetti et al. 2018; Cruz Rios et al. 2019; Mihai 2019; Ghaffar et al. 2020). Ruiz et al. (2020) identify an end-of-life strategy which is termed as ‘selective deconstruction’, meaning that the building components that have reached their end of life are selectively dismounted off from in-service components (Ruiz et al. 2020).

2.15.5. Summary

This systematic review explores the existing knowledge and the knowledge gaps in the published research work focusing on circular economy interventions in buildings. The objectives conducted a systematic review of relevant studies on the subject area and reviewed pieces of literature that conducted substantial research in the area. A total of 64 publications were gathered for this study, with which a bibliometric network was created revealing the two most discussed areas of circular economy in buildings in this review. Following the initial review of the articles, seven major circularity aspects were identified, and the articles were divided into these aspects for further analysis and discussion.

While reviewing the works of literature, it was observed that most studies are articulated around two major aspects namely: recycling of waste components and disassembly of building components and end of life.

The studies emphasized the need to shift from a linear economy to a circular economy. However, some studies had identified some barriers to this progression. Some of these barriers included inadequate guidance for the effective acquisition and categorization of construction and demolition waste in addition to the undeveloped market for the reuse of building products and lack of standardisation for the reuse and recycling of construction and demolition waste.

There were areas that did not receive enough attention from researchers such as construction, mainly optimisation, and operation. It is observed that both optimisation and operation shared some common modalities such as they were both under the use stage of the building. Optimisation was found to be more associated with building maintenance while operation was related to building use for longevity. Twenty-four articles attempted to uncover the end of life interventions, most of the researchers agreed that material looping at the end of life to a great extent would help to increase resource efficiency and reduce waste.

The studies on building construction and materiality also had their fair share of research attention. The studies on materiality suggested waste reduction through material design, calculation, and specification. Another study proposed that designing out waste or design for waste prevention stood as one of the best opportunities in the reduction of waste generation while others recommended the use of buildings as material banks. In circular construction, studies supported the use of bolt and nut joints during construction instead of nails or/and glue, welding, or any other permanent assembling technic that may negatively affect the reusability of recoverable materials.

A major deficiency of research identified from the analysis of the articles is that there is a lack of a holistic approach towards a systematic application of circular economy in buildings. Although, the studies on major circularity interventions have demonstrated the possibility for the application of circular economy in buildings and the potentials that lie ahead, however, the knowledge of circular economy in buildings is low and it is yet to be commonly placed. Furthermore, the growing number of publications is a positive indication of growing awareness. The research gaps identified above would foster a holistic solution for resource and energy efficiency in buildings. The interventions explored and analysed in this systematic review are found to be global and applicable in the Nigerian context as they are strategic in repurposing building waste and improving the availability of building materials which is a much-needed intervention in Nigeria. This systematic review has also been able to put together and analyse major recommended circular economy interventions for a holistic application of circular economy in Nigerian buildings which is a major novelty of this research.

2.16. Factors influencing Circular Economy in Buildings

The following are factors to consider in building circularity. Akanbi et al. (2018) highlighted factors that must be considered and factors that may be considered for the reuse and recycling of buildings as seen in the table below (Akanbi et al. 2018). These factors also influence the reusability and recyclability of building materials. The study also evaluated a number of circular economy considerations such as reusability, recyclability, toxicity, material requiring secondary finish, etc. It is established that steel is highly reusable and recyclable, followed by timber and concrete.

Table 20: Factors influencing the reusability and recyclability of building materials

No.	Factors	Reference	Material reusability	Material recyclability
1.	Specification of reusable materials during design	(Guy et al. 2006; Webster and Costello 2006)	o	□
2.	Specification of recyclable materials during design	(Guy et al. 2006; Webster and Costello 2006)	□	o
3.	Use of nut/bolt joints instead of nails and gluing	(Crowther 2005; Guy et al. 2006; Webster and Costello 2006)	o	□
4.	Use of prefabricated assemblies	(Crowther 2005; Guy and Ciarimboli 2008)	o	□
5.	Minimisation of types of building components	(Chini and Balachandran 2002; Guy et al. 2006)	o	□
6.	Avoidance of toxic and hazardous materials	(Crowther 2005; Guy et al. 2006)	□	o
7.	The layering of building elements according to anticipated life span	(Brand 1995)	o	o
8.	Avoidance of secondary finishes	(Crowther 2005; Guy et al. 2006; Tingley 2013)	o	□

o – key factors that must be considered. □ – factors that may be considered.

The study also helped identify the building components/materials that are reusable, recyclable, toxic and those needing secondary finish as seen in the table below (Akanbi et al. 2018).

Table 21: Reusable, and recyclable building components/materials

Systems and options	Recyclable	Reusable	Toxic	Secondary Finish
1. Structural Foundations				
H-Pile foundation	✓	✓	×	×
Concrete ground beam	✓	×	×	×
Concrete with mastic tanking	✓	×	×	×
2. Floor system				
In situ Concrete floor with ceramic tiles	✓	×	×	×
Precast Concrete slab with carpet	✓	×	×	×
Timber floor with ceramic tiles	✓	✓	×	×
3. Structural frame system				
Exposed Steel with fixed connections				
Concrete Encased Steel with fixed connections	✓	✓	×	×
Exposed Steel with bolted connections	✓	×	×	×
Concrete Encased Steel with bolted connections	✓	✓	×	×
Timber with bolted connections	✓	✓	×	×
Timber with nailed connections	✓	×	×	×
Reinforced Concrete with bolted connections	✓	✓	×	✓
4. Wall system				
Demountable dry internal wall – Steel				
Curtain wall	✓	✓	✓	✓
Brick/block cavity wall	✓	✓	×	×
Cladded timber cavity wall	✓	×	×	✓
Steel framed wall	✓	×	×	✓
5. Doors and windows				
Glass with aluminium frame				
Timber with timber frame – Softwood	✓	✓	×	×
Timber with timber frame – Hardwood	✓	✓	×	✓
6. Ceiling system				
Aluminium strips with steel frame	✓	×	×	✓

Soffit plaster and paint	✓	✓	×	×
Timber planks with timber frame	✓	✓	×	✓
Ceiling tiles with metal frame	✓	✓	×	✓
7. Roof system				
Flat galvanised steel on Z profile beams	✓	✓	×	×
Reinforced concrete roof with sand/cement screed	✓	✓	×	×
Pitched roof timber structure	✓	×	×	✓
Tiles covering on a pitched roof	✓	✓	×	×

A study conducted by study Tazi et al. (2021) reported the end of life scenarios for construction and demolition wastes in the dwelling sector, the report analysed the treatment of major building materials at their end of life, it was revealed that a large amount of the materials were recyclable and a little amount went into landfills as presented in the table below (Tazi et al. 2021).

Table 22: End of life scenarios for construction and demolition wastes from the residential building sector

Materials	Treatment	Materials	Treatment
Stone (Asakura 2013)	88% recycled + 12% landfilled	Concrete and block concrete (Asakura 2013)	88% recycled + 12% landfilled
Solid and hollow bricks from baked clay (Asakura 2013)	88% recycled + 12% landfilled	Tiles from baked clay	100% recycled
Gypsum (GtoG 2016)	100% recycled	Mortar and mineral plaster	100% recycled
Glass (Tam and Tam 2006)	85% recycled + 15% landfilled	Mineral wool (BRE/Eurobond 2008)	100% recycled
Wood and conglomerated wood	61% recycled + 28% incinerated + 11% landfilled	Metals (steel, aluminium and zinc)	98% recycled + 2% landfilled
Polymers (PVC + PS + PU) (Tam and Tam 2006)	70% recycled + 30% incinerated	Asphalt + Sand (Tam and Tam 2006)	100% recycled

Another study by O'Grady et al. (2021), aimed at developing a method (3DR – Design for disassembly, deconstruction and Resilience) to assess the design, disassemblability and deconstructability of buildings in addition to the resilience of building materials and other building components (O'Grady et al. 2021). In the study, they experimented with four building scenarios, the first designed using circular principles, the second designed business as usual (linear version) without consideration of the circular economy principles, the third was a double brick version and the last was a timber structure building. The table below shows some of the parameters used in the assessment (to calculate the level of disassemblability of deconstructability of a building (O'Grady et al. 2021).

Table 23: Parameters to calculate the level of disassemblability of deconstruct-ability of a building

Variable	Description	Operation and tools required	Value
DIt, DEt	Availability, dimensions, and types of tools required to deconstruct a building (DEt) or disassemble components (DIt)	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic equipment	0.2
DIm, DEm	Equipment or People required to move components to another building (DIm) or transport components following deconstruction (DEm)	One person: < 20 kg	1
		Two people: < 42kg	0.9
		Hand trolley: < 50kg	0.7
		Forklift: < 2,000kg	0.4
		Crane: > 2,000kg	0.1

O'Grady et al. (2021) also evaluated the degree of resilience of a part, material or component of buildings. The table below shows the measurement values of the reusability and recyclability of building materials.

Table 24: Degree of the resilience of a part, component or material

Description	Re value
Reusable an infinite number of times	1
Reusable up to three times	0.9
Reusable only once	0.7
Recyclable	0.6
Downcyclable	0.2
Disposable	0
Re = resilience of component	

The tables below show the experimented four-building scenarios, (building designed with circular principles, business as usual - linear version without consideration of the circular economy principles, double brick version and timber structure building). The tables were used to assess the tools required to disassemble, move building components in addition to the resilience of building materials which helped determine the reusability and recyclability of the various building components/materials (O'Grady et al. 2021).

Table 25: Building designed using circular economy principles

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Steel chassis and load-bearing structure	16,138.9	Gas/pneumatic tool	0.5	Forklift	0.4	Infinitely reusable	1
Stairway steel structure	422.8	Gas/pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls	3,590.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Bolts and nuts	97.7	Power tool	0.8	One person	1	Recyclable	0.6
Pressed fibre particle board used as floor structure	4,102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool is used in all external walls and ceiling	2,325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Screw pile lightweight steel foundations	735	Hydraulic plant	0.2	One person	1	Recyclable	0.6

Finishes							
Carpet covering 193 m^2 of internal floors	183.4	No tool	1	One person	1	Reusable 3 times	0.9
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Reusable once	0.7
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Reusable 3 times	0.9
Magnetic felt ceiling	333.7	No tool	1	One person	1	Reusable 3 times	0.9
Plasterboard cladding used in kitchen/bathroom and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber for ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Reusable 3 times	0.9
Steel sheets for first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Aluminium windows and glazed doors	744.0	Hand tool	0.9	Two people	0.9	Reusable 3 times	0.9
Internal timber doors	138.0	Power tool	0.8	One person	1	Infinitely reusable	1

Note: DIt = the tool(s) required to disassemble components; DIm = equipment required to move components; Ri = resilience of components.

Table 26: Business as usual building - Linear version

Description	**Mass (kg)**	**Tools needed**	***DIt***	**Transport tool**	***DIm***	**Resilience**	***Ri***
Structural materials							
Steel chassis and load-bearing components (including nuts and bolts)	16,236.6	Gas/pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Stairway steel structure	422.8	Gas/pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls	3,590.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Pressed fibre particle board used as floor structure	4,102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool is used in all external walls and ceiling	2,325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Concrete foundations	19,848.0	Hydraulic plant	0.2	Forklift	0.4	Downcyclable	0.2
Finishes							

Carpet covering 193 m^2 of internal floors	183.4	Hand tool	0.9	One person	1	Downcyclable	0.2
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Downcyclable	0.2
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glued felt ceiling	333.7	Hand tool	0.9	One person	1	Recyclable	0.6
Plasterboard cladding used in kitchen/bathroom areas and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber used as ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Downcyclable	0.2
Steel sheets used as first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Recyclable	0.6
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Aluminium windows and glazed doors	744.0	Power tool	0.8	Two people	0.9	Disposable	0
Internal timber doors	138.0	Power tool	0.8	One person	1	Disposable	0

Note: DIt = the tool(s) required to disassemble components; DIm = equipment required to move components; Ri = resilience of components

Table 27: Double brick building.

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Brick walls	122,058.0	Hydraulic plant	0.2	Crane/excavator	0.1	Downcyclable	0.2
Timber load-bearing roof structure	3,143.9	Power tool	0.8	Forklift	0.4	Reusable once	0.7
Concrete floor structure, ground and first floors	81,005.07	Hydraulic plant	0.2	Excavator	0.1	Downcyclable	0.2
Steel reinforcement bars	875	Hydraulic plant	0.2	Excavator	0.1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	Hand tool	0.9	One person	1	Downcyclable	0.2
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Downcyclable	0.2
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glued felt ceiling	333.7	Hand tool	0.9	One person	1	Recyclable	0.6
Plasterboard cladding used in kitchen/bathroom areas and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber used as ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Downcyclable	0.2
Steel sheets used as first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Recyclable	0.6
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Aluminium windows and glazed doors	744.0	Power tool	0.8	Two people	0.9	Disposable	0
Internal timber doors	138.0	Power tool	0.8	One person	1	Disposable	0

Note: DIt = the tool(s) required to disassemble components; DIm = equipment required to move components; Ri = resilience of components

Table 28: Timber structure building

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Timber load-bearing wall structure	3,237.4	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Timber load-bearing floor structure	14,553.8	Power tool	0.8	Two people	0.9	Reusable once	0.7
Timber load-bearing roof structure	3,143.9	Power tool	0.8	Crane	0.4	Reusable once	0.7
Pressed fibre particle board used as floor structure	4,102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool used in all external walls and ceiling	2,325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Bricks supporting the timber structure	793.6	Power tool	0.8	Hand trolley	0.7	Downcyclable	0.2
Concrete foundations	15,735.6	Hydraulic plant	0.2	Excavator	0.1	Downcyclable	0.2
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	Hand tool	0.9	One person	1	Downcyclable	0.2
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Downcyclable	0.2
Salvaged timber composing stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glued felt ceiling	333.7	Hand tool	0.9	One person	1	Recyclable	0.6
Plasterboard cladding used in kitchen/bathroom areas and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber used as ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Downcyclable	0.2
Steel sheets used as first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Recyclable	0.6
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Aluminium windows and glazed doors	744.0	Power tool	0.8	Two people	0.9	Disposable	0
Internal timber doors	138.0	Power tool	0.8	One person	1	Disposable	0

Note: DIt = the tool(s) required to disassemble components; DIm = equipment required to move components; Ri = resilience of components

The experiment was able to identify reusable, recyclable and disposable building materials. It also established the building technology (i.e. the building designed with circular principles, business as usual - linear version without consideration of the circular economy principles, double brick version and timber structure building) with the most reusable, recyclable and deconstruct able building materials. The building designed with circular principles were found to be more reusable, recyclable and easy to disassemble, while the double brick building was the least reusable and recyclable (O'Grady et al. 2021). The study also presented the number of materials in weights (kg) for the major building components – structure, foundation, roof, floor, external cladding, floor covering, insulation, walls, windows, doors and glazing for the four building types, it was observed that the floors and walls had the highest quantity of materials, followed by the foundations, then the structural frame system, roof system, finishes and windows and doors (O'Grady et al. 2021). This phenomenon agrees with the study conducted by Atmaca and Atmaca (2016), the study established a similar hierarchy of building material quantities (Atmaca and Atmaca 2016). This material quantity hierarchy can be related to the 7S model (Structure, Skin, Stuff, Services, System, Space, Site). Therefore, Space (including walls and floors) has the highest quantity, followed by Structure (foundation, frame system), then Skin (including roof, external cladding and finishes), followed by Stuff (such as lighting, fixtures, furniture, doors and windows), Services (pipes, wires, building services), Site (building's location), and System (support infrastructure for the building).

Chapter Three
3.0. Research Methodology
3.1. Research

The research concept is centred on establishing a framework that will serve as a guide for incorporating circular economy in the design of energy-efficient residential buildings in Nigeria. Therefore, the research seeks to combine both passive design strategies and circular economy principles in the design of energy and resource-efficient residential buildings in Nigeria. Dynamic energy building optimisation-simulation results, based on passive design interventions for the tropical savannah climate of Nigeria were compared against the typical residential building design practices in Nigeria as regards energy consumption through the use of simulation interventions. This was done by the selection of a typical Nigerian base case model to determine the energy consumption of the residential building using energy simulation tools. The typical residential building (base case) was later optimised one at a time, and all at a time. The optimised case simulation results were compared with the base case simulation results with regard to energy consumption to identify the best case. The specific design parameters for each design variable to achieve energy efficiency in the tropical savannah climate of Nigeria were also identified. The best case from the comparison was further optimised in a multivariate Pareto simulation with circular economy strategies incorporated to achieve optimal efficiency of the building in terms of energy and resource.

In circular economy, the research evaluated the circular principles of "Design for disassembly" using the 7S model and "Design for recycling" using the ReSOLVE framework. These two models were explored and analysed which led to the development of a material selection matrix. The principles of circular economy based on this research and matrix were incorporated into the optimised case towards achieving energy and resource-efficiency in Nigerian residential buildings. This implies whilst designing and optimising using passive design strategies such as building orientation, thermal mass, daylighting, natural ventilation, Window to Wall Ratio (WWR), g-value, etc. circular economy principles were considered in terms of modularity, reusability, recyclability, and materiality. For example, whilst considering components for daylighting such as windows, glazing properties in passive design, in circular economy, the modularity and materiality for disassembly and recyclability of these components were as well considered. In the case of thermal mass, the thermal performance and materiality of each thermal responsive component were also considered for later disassembly, reuse and recycling in a circular economy. Therefore, energy performance and resource efficiency were considered simultaneously. Reusable and recyclable building materials were categorised into major building components (using the 7S model) whilst considering passive design strategies and circular economy principles in the Nigerian context. Based on the research findings, analysis and discussions, a framework was developed for incorporating circular economy in the design of energy-efficient residential buildings in Nigeria.

3.2. Research objectives and methods

1. To conduct literature reviews to identify the components for passive design and circular economy in Nigeria. – Literature review, and Quantitative analysis
    a) Review of the Nigerian tropical savannah climate. – *(Literature review, and quantitative analysis)*
    b) Analysis of the Nigerian weather data. – *(Literature review, and quantitative analysis)*
    c) Study of the residential building typology in Nigeria. – *(Literature review, and quantitative analysis)*
    d) An overview of energy efficiency in residential buildings. – *(Literature review, qualitative and quantitative analysis)*
    e) Study of Passive design strategies in Nigerian residential buildings. – *(Literature review, and quantitative analysis)*
    f) Study of circular economy principles. – *(Literature review, and quantitative analysis)*

2. To assess and optimise these passive design components (i.e., building orientation, thermal mass, daylighting, local shading, natural ventilation, thermal insulation, WWR, g-value) towards achieving optimal energy performance in Nigerian residential buildings. – *Numerical simulation and Quantitative analysis.*
    a) Identification of typical base case of Nigerian residential building typology for simulation. – *(Literature review)*
    b) Model, calibration and validation of base case building with respect to the Nigerian Federal Ministry of Power report and the obtained weather data. – *(numerical simulation)*
    c) Simulation preparations. – *(numerical simulation)*
    d) Setup for the base case and optimised case. – *(numerical simulation)*
    e) Optimisation Simulation (one at a time, all at a time). – *(numerical simulation)*
    f) Assessment of passive design strategies and optimisation of building. – *(numerical simulation)*

3. To compare, select, and recommend the best passive design case based on simulation results. – quantitative analysis
    a) Comparison of results between the base case and optimised case. – *(quantitative analysis)*
    b) Selection of best case based on performance. – *(quantitative analysis)*

4. To adopt circular economy interventions. – Literature review, Numerical simulation and Quantitative analysis
   a) Design for disassembly.
      (i) Classification of building components into the 7S model. – *(Literature review)*
      (ii) Identification of "Design for disassembly" methods. – *(Literature review)*
      (iii) Analysis of assembly and disassembly methods. – *(Literature review)*
      (iv) Process for Design for Disassembly *(Literature review)*

   b) Design for recycling.

      (i) Selection of recommended recyclable materials. – *(quantitative analysis)*

      (ii) Categorisation of materials according to building components into the 7S model. – *(quantitative analysis)*

      (iii) Development of the material selection Matrix *(Literature review, Numerical simulation and Quantitative analysis)*

      (iv) Sorting reusable and recyclable building materials into the ReSOLVE framework using the material selection matrix. – *(Literature review and quantitative analysis)*

      (v) Energy dynamic simulation with circular economy materials incorporated to building model – *(Numerical simulation and Quantitative analysis)*

5. To establish an approach for the application of circular economy principles in Nigerian residential buildings - *Literature review, Numerical simulation and Quantitative analysis.*
   a) Design to passive design recommendations. – *(Literature review and Quantitative analysis)*
   b) Design for disassembly by splitting building components into the 7S model. – *(Literature review and quantitative analysis)*
   c) Design for recycling by using the material selection matrix and Sorting of (reusable and recyclable) materials into building components and ReSOLVE framework. – *(Literature review and quantitative analysis)*
   e) Design for end of life – deconstruction, reuse, and recycling. – *(Literature review and quantitative analysis)*

6. To develop a framework for the incorporation of circular economy in the design of energy and resource-efficient residential buildings in Nigeria. - *Literature review and Quantitative analysis*

   a) Requirements for energy and resource-efficient residential building in Nigeria based on research. – *(quantitative analysis)*

b) Guidance on attaining set recommendations from research findings. – *(quantitative analysis)*

c) Recommendations and Conclusion. – *(quantitative analysis)*

3.3. Research Structure

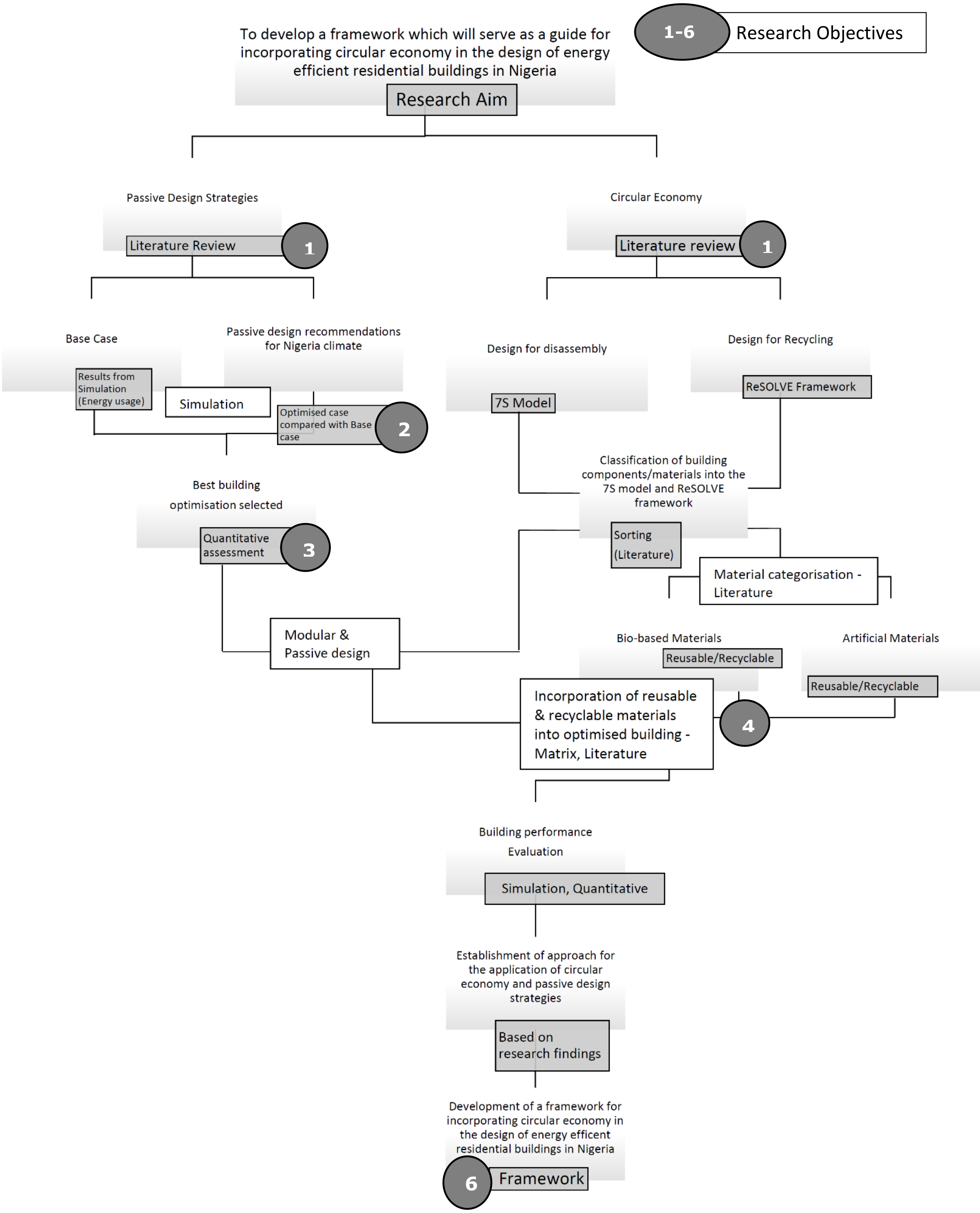


Figure 36: Research Structure

3.4. Methods for data collection

3.4.1 Literature materials:

A review of literature on residential buildings and circular economy principles in Nigeria. The review provided relevant information such as residential building typologies in the Nigerian building stock, old and modern building materials in Nigeria, passive design recommendations (for building orientation, thermal mass, thermal insulation, daylighting, local shading, WWR, g-value and natural ventilation) in Nigeria. Other information gathered included the Nigerian climatic data from the reports of the Federal Ministry of Power, weather data files, circular economy principles and interventions in the Nigerian context, typical building attributes, building materials, and building design characteristics.

3.4.2 Documents and Records:

A study of The Nigerian National Building Energy Efficiency Code (BEEC) based on its studies on residential buildings in Nigeria. This provided relevant information regarding the Nigerian residential building base case and previous interventions by Edge and GIZ in Nigeria (Arup (Madrid & Lagos offices) and Design Genre 2016; Federal Ministry of Power 2017; GIZ 2020). It also provided insights on previous research done in the country and the base case model used in addition to the final results, recommendations and conclusions. The documents also revealed typical building design features, building components and dimensions, building design strategies and commonly built building types.

3.4.3 Simulation results:

Results from simulations provided the energy consumption of the base case model and the optimised case model for comparison. The simulation results also revealed the parameters that had the highest impact on energy demand. Therefore, highlighting the various design variables that require optimisation for the specific parameters. The simulations also gave indications of the effectiveness and efficiency of various strategies and how they could possibly be improved. This is necessary to assess and optimise the building energy consumption.

3.4.4 Observation:

A practical overview of Nigerian residential building attributes through physical observations. This includes typical building dimensions, building materials, building design characteristics. However, previous researchers have already obtained the information which is available from works of literature (Isinkaye (Isinkaye and Agbi 2013; Akanni et al. 2014; Aminu and Peterside 2014; Abbakyari and Taki 2017; Guardian contractors 2017; Geissler et al. 2018; Ogunmakinde 2019; Ogunmakinde et al. 2019).

3.5. Research Method

3.5.1. Stage 1

Methodology for conducting energy simulation for passive residential building (base case and optimised case).

Building data for typical residential buildings in Nigeria were collected in the course of this research and from reputable previous studies in Nigeria such as the Federal Ministry of Power and the Nigerian Building Energy Efficiency Code (BEEC). Dimeji-Ajayi (2018) listed popular and common building materials in Nigeria, they include cement, granite, sand, laterite, blocks, nails, steel rods, wire mesh, binding wire, roofing sheets, water closet seats, windows, doors, burglar-proof, timber, plywood, floor tiles (Dimeji-Ajayi 2018). These listings were also matched by other researchers (Isinkaye and Agbi 2013; Adeleye 2014; Akanni et al. 2014; Guardian contractors 2017). Relevant building information obtained was used to model the base case in DesignBuilder and the base case was simulated to determine its energy demand. In turn, the building was optimised (one-at-a-time, and all-at-a-time simulation) to achieve optimal performance with regard to energy consumption. The aspects of passive design strategy optimisation include building orientation, window to wall ratio, local shading, g-value, thermal mass, thermal insulation, natural ventilation, and daylighting. The following includes modelling parameters for the base case and optimised case.

Table 29: Modelling parameters for the base and optimised cases

Base case Parameters	**Simulations**	**Optimized case parameters**
Base case building orientation	**Building orientation**	Best Building orientation base on simulation results
Base case building design	**Building form**	Same building design with base case to maintain consistency
Base case building fabrics	**Thermal mass**	Optimised thermal mass based on simulation
Base case thermal insulation	**Thermal insulation**	Optimised thermal insulation based on simulation
Base case windows and opening characteristics	**Daylighting**	Recommended daylighting requirements for residential buildings
Base case ventilation characteristics	**Natural ventilation**	Ideal natural ventilation requirements
Base case window to wall ratio	**WWR**	Optimised window to wall ratio based on simulation results
Base case g-value	**g-value**	Optimised g-value based on simulation

Base case shading devices	**Local shading**	Optimized local shading devices based on simulation results
Evaluation of energy consumption in both base and optimised cases		

Methodology for the calibration and validation of the base case model:

The base case model is a typical representation of the Nigerian residential building stock (Federal Ministry of Power 2017; Solid Green Consulting 2017). It was used as the base case for a study conducted in Nigeria to improve by 20% the efficiency (in energy, water, and embodied energy in materials) of buildings in Nigeria (Arup (Madrid & Lagos offices) and Design Genre 2016; Federal Ministry of Power 2017; GIZ 2020). The weather data file obtained for the base case provides information about the air temperature, air velocity, relative humidity, operative temperature. The methodology for checking that the model readings (in terms of air temperature, air velocity, relative humidity, operative temperature) are consistent with the actual construction and the report of the Nigerian Energy Efficient Code (BEEC) includes the use of measuring devices such as anemometer for measuring air velocity, thermometers for air temperature, operative temperature, and hygrometer for relative humidity. The measurements of the building were done at specific times of the day for 12 months. The specific times for measurements were at 9:00 am in the morning and 6:00 pm in the evening, every day.

3.5.2. Stage 2

<u>Methodology for the adoption of circular economy principles in Nigerian residential buildings</u>

The research explored the principles of “Design for disassembly” using the 7S model and “Design for recycling” using the ReSOLVE framework. The process of design for disassembly, reusability, and recyclability was analysed with respect to component design, material documentation, assemblage method, connection type, standardisation, component annotation, accessible connectors, the program for selective and volumetric deconstruction and reconstruction. These models were considered with regard to design for disassembly. Circular economy principles were adopted in terms of modularity, recyclability, reusability, and materiality based on the research findings and as recommended by works of literature. This paved way for the development of the material selection matrix to aid the selection of reusable and recyclable building materials based on their viability, effectiveness and efficiency for energy and resource efficiency. The materials were categorised into major building components of the 7S model for the ease of disassembly and reuse/recyclability potentials of the ReSOLVE framework while considering compatibility with passive design strategies and circular economy principles in the Nigerian climate. The selected material was further incorporated into the optimised case and finally simulated in a multivariate Pareto optimisation mode to obtain the results of the energy building performance in the Nigerian tropical savannah climate.

3.5.3. Stage 3

Development of the framework for incorporating circular economy in the design of energy-efficient residential buildings in the tropical savannah climate of Nigeria

The requirements for new energy and resource-efficient residential buildings in Nigeria as identified from the experiments based on simulation results and literature were used as a basis for the development of the framework. This provides a detailed design guideline on the steps for the application of passive design and circular economy principles as it relates to the Nigerian climate. The framework was informed by various variables experimented with based on this research (which includes building orientation, thermal mass, thermal insulation, natural ventilation, daylighting, WWR, g-value and local shading) in addition to drawing from the best results obtained during the simulation as well as from literature review.

3.6. Methodology for building energy optimisation

The optimisation priority is geared towards reducing the total primary (source) energy demand of the building whilst using passive design strategies. The process started by determining the total primary energy consumption of the base case building. To conduct an effective optimisation, it is important to identify the parameters that have the most impact on energy demand, then those parameters were enhanced for best performance which was followed by a multivariate Pareto simulation. The optimisation operation began by engaging one-at-a-time optimisation to see the effect of each design parameter and variable to gradually cut down the primary energy demand. Passive design strategies (such as building orientation, thermal mass, thermal insulation, natural ventilation, daylighting, WWR, g-value and local shading) were optimised by simulating the model using DesignBuilder. Reusable and recyclable materials were also incorporated into the model. The optimisation process consisted of one-at-a-time and all-at-a-time simulation of the various parameters which was followed by multivariate simulation with circular economy interventions incorporated.

The methodology of optimising the building started with determining the best building orientation, followed by the WWR of each facade, Local shading, g-value, thermal insulation, thermal mass, etc. Below is a chart of the optimisation process.

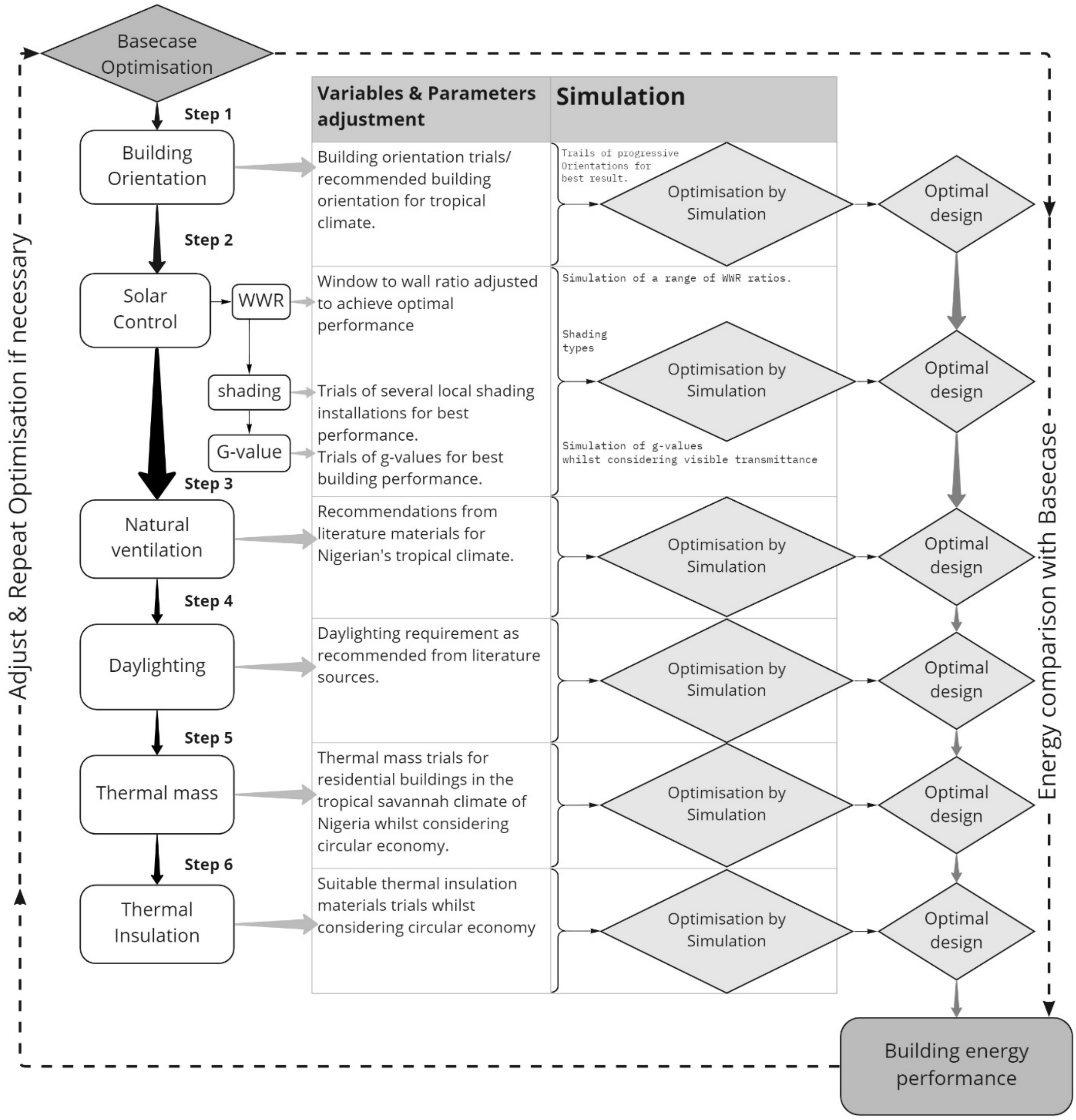
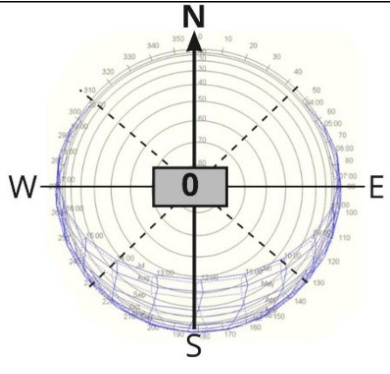
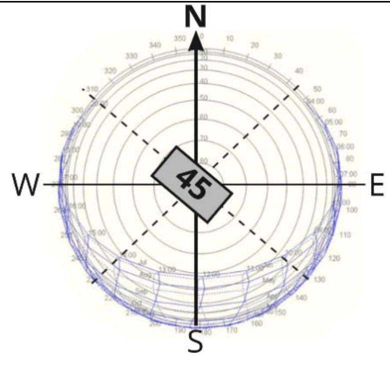
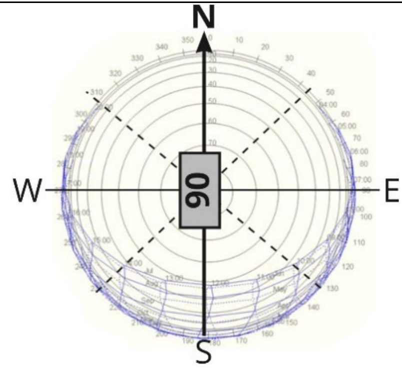
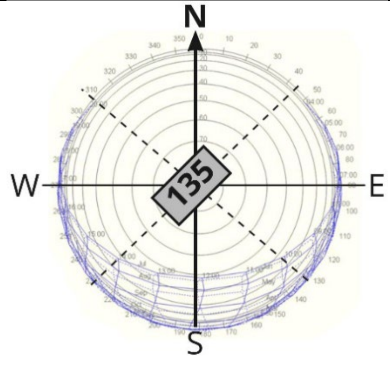
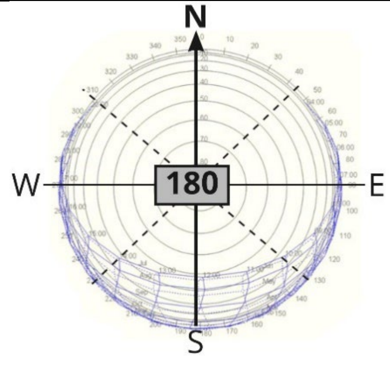
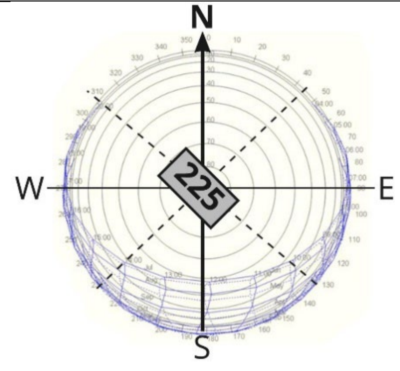
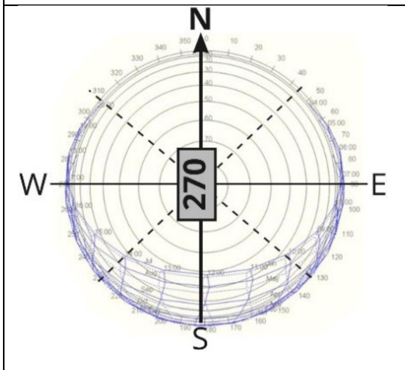
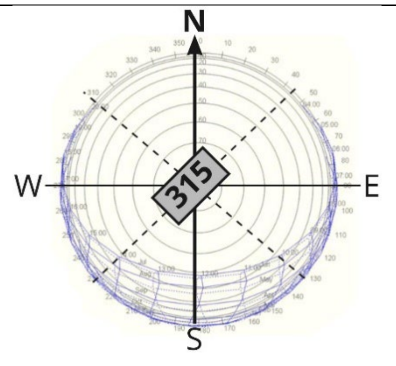
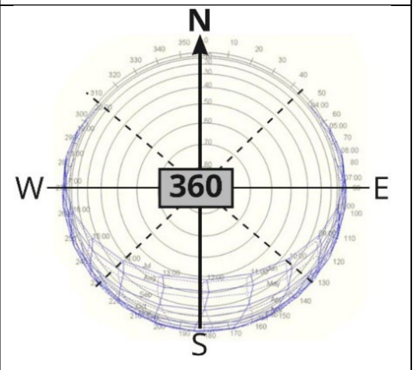


Figure 37: Building Optimisation Process

3.6.1. Optimisation for Building Orientation

To achieve the optimal orientation for the building, the building was orientated from 0 degrees through a range of degree variations to 360 degrees (0, 45, 90, 135, 180, 225, 270, 315, 360).

Table 30: Optimisation for building orientation

Simulation of different building orientations to check for the most optimised orientation with regards to energy efficiency.		
		
		
		

The orientation with the best energy performance was selected.

According to McGee C. et al 2013; Anumah, J.J. and Anumah, L., 2017, the acceptable building orientation is solar north for tropical hot climates, therefore orientations of up to 20° west of north and 30° east of north. It is also important that living areas are oriented 20°W–30°E of true North. Therefore, sleeping zones were oriented Northwards while living zones were oriented Southwards (McGee et al. 2013; Anumah and Anumah 2017).

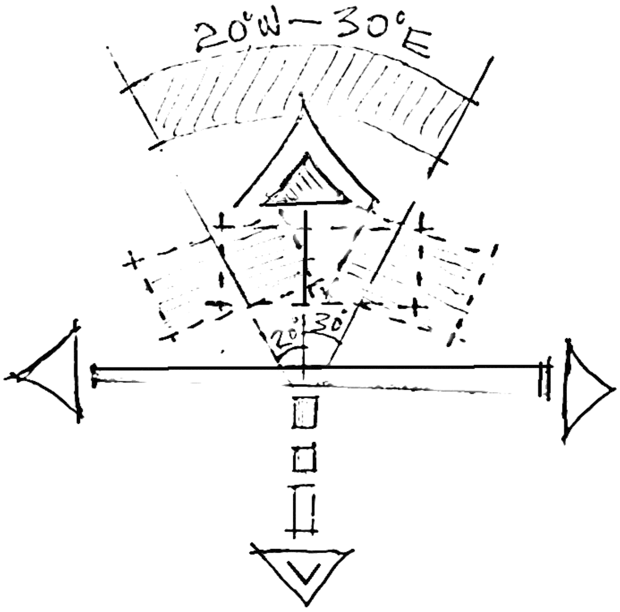


Figure 38: Optimal Building orientation range for Tropical West Africa

The results of the building orientation are compared with this recommendation to see its validity.

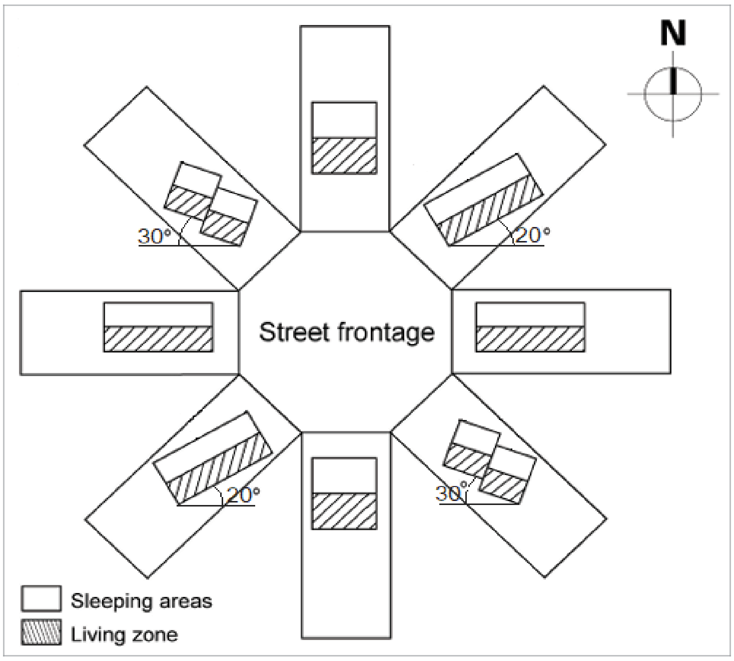


Figure 39: Ideal building orientation in tropical climates; adapted from (McGee et al. 2013; ABCB 2018)

Also, it is recommended that sleeping zones should be positioned on the Northwards of the building and Living zones on the Southwards of the building thereby providing a buffer for the sleeping areas (McGee et al. 2013; Adunola and Ajibola 2019). This recommendation is also checked with the building orientation simulation results.

3.6.2. Optimisation for Solar Control

The optimisation for solar control is carried out in three categories:

1. Window to wall ratio
2. Local shading
3. g-value

3.6.2.1. Wall to Window Ratio (WWR)

To determine the effect of changes in the window to wall ratio of the building as it relates to energy demand, the window to wall ratio was adjusted progressively from 6% to 95% for each façade independently to see the effect it has on energy demand.

The window to wall ratio of the base case building is 12.49% while the window to wall ratio of each façade is as shown in the table below. At this stage, the various window to wall ratio is presented in the table below.

Table 31: Original Window and Wall Ratio (WWR) of each Facade

Facades	South Façade	East Façade	West Façade	North Façade
WWR (Base case)	15.49%	6.92%	13.85%	13.71%

A total of 104 simulations were conducted to optimise the window to wall ratio of the building.

The table below shows the various WWR simulated for each façade of the building.

Table 32: Simulation results for WWR optimisation

WWR (%)	**Total primary (source) energy demand - KWh/(m²a)**			
	South Façade	**East Façade**	**West Façade**	**North Façade**
6.00	-	-	-	-
6.92 (Base case)	-	-	-	-
10.00	-	-	-	-
12.00	-	-	-	-
13.71 (Base case)	-	-	-	-
13.85 (Base case)	-	-	-	-
14.00	-	-	-	-
15.00	-	-	-	-
15.49 (Base case)	-	-	-	-
16.00	-	-	-	-
20.00	-	-	-	-
25.00	-	-	-	-
30.00	-	-	-	-
35.00	-	-	-	-
40.00	-	-	-	-
45.00	-	-	-	-
50.00	-	-	-	-

55.00	-	-	-	-
60.00	-	-	-	-
65.00	-	-	-	-
70.00	-	-	-	-
75.00	-	-	-	-
80.00	-	-	-	-
85.00	-	-	-	-
90.00	-	-	-	-
95.00	-	-	-	-

The best Window to Wall Ratio simulation result for each façade was then selected and all-at-a-time simulations were conducted to see the combined result of each unique WWR of each façade.

3.6.3. Local Shading

The local shading optimisation was carried out for the four elevations (North, East, West, South) of the building one at a time. Each unique elevation are simulated with different types of shading devices to see the efficiency of each strategy as each elevation may have a unique shading design. The design varies from louvres, overhang, and side fins with different arrangements.

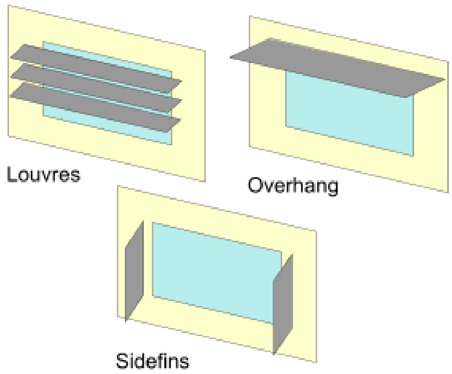


Figure 40: Shading design variations (DesignBuilder)

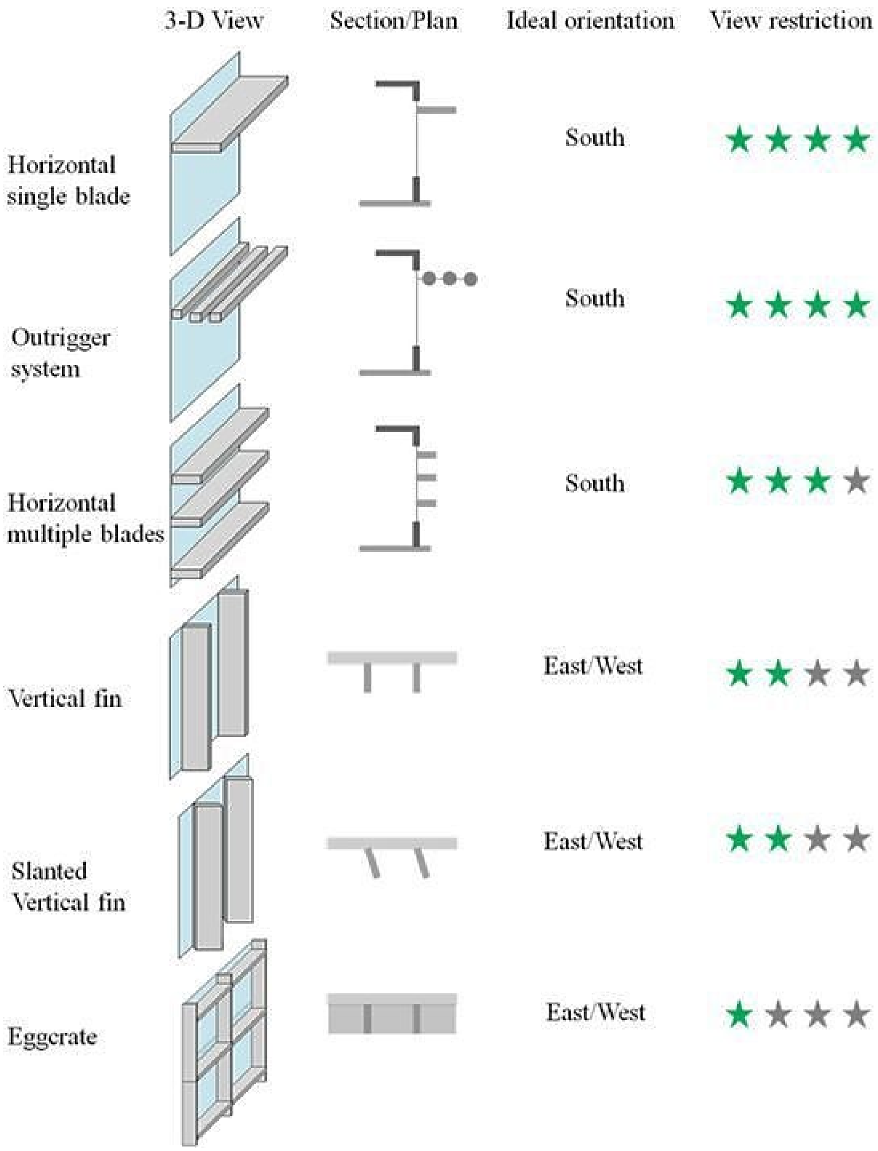


Figure 41: Local shading variations with regards to elevations and view restrictions

3.6.3.1. South Elevation

To achieve the best shading strategy for the south elevation of the building, the optimisations were done using different strategies with variations to identify the best solution, whilst taking into consideration the location of the building in the southern hemisphere. A total of 105 simulations were carried out to determine the best strategy for the south elevation.

These strategies include:

A. Single horizontal overhang
B. Horizontal multiple blades
C. Box shading or egg-crate

A. Single horizontal overhang

The simulation started by using a horizontal shading device to optimise the south elevation. The Standard horizontal shading in Nigeria is 365mm wide and 75mm thick (Adunola and Ajibola 2016; Abdulkareem et al. 2018). Therefore, the study proceeded by increasing and decreasing 365mm to check for the best-optimised case.
For this experiment, the overhang projection was in the following variations of 200, 365, 400, 600, and 800mm. The vertical offset from the overhang to the top of the window was kept at 200mm in all the cases. The height of the window was kept at 1.5m which is the standard window in Nigeria (Abatan et al. 2018; Awosusi 2018; Bankole 2019). The horizontal window overlap of the overhang was kept at 200mm for consistency.

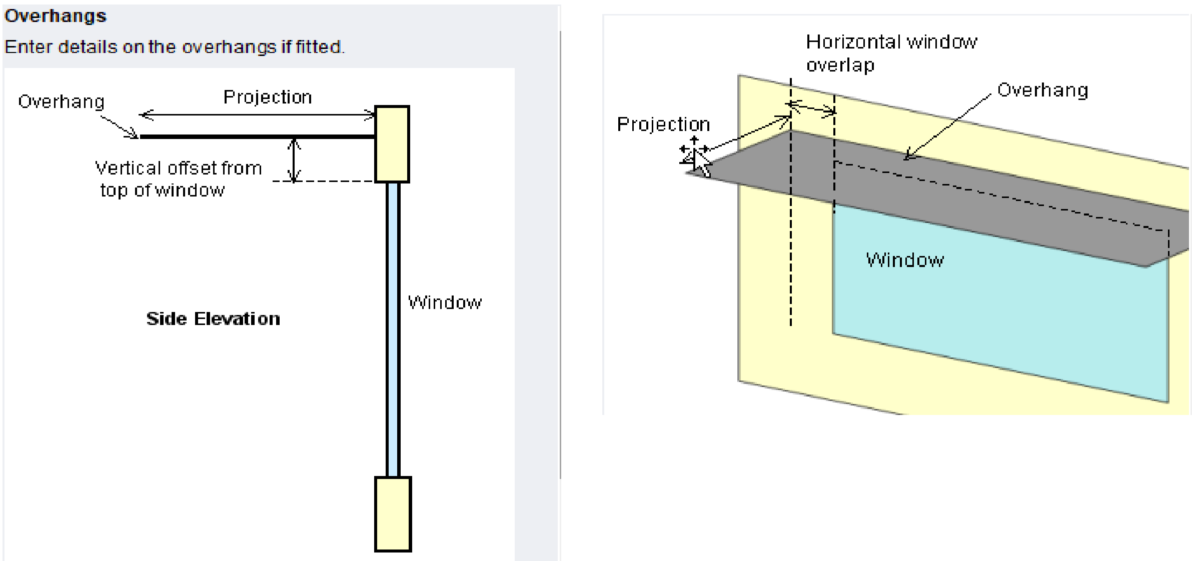
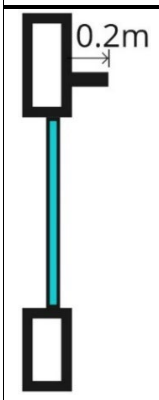
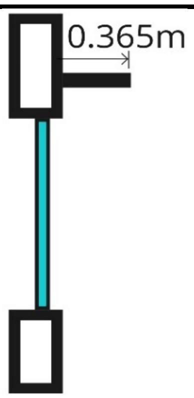
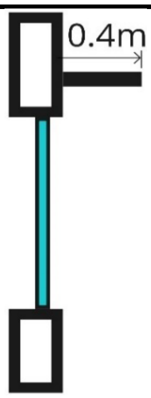
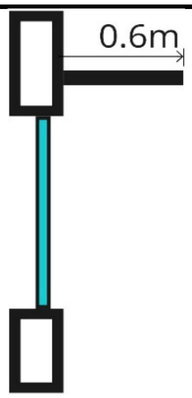
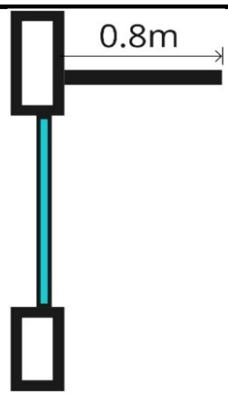


Figure 42: Overhangs (DesignBuilder)

Table 33: Energy Simulation of horizontal overhang shading variations

Energy Simulation of horizontal overhang shading variations (section view) **200, 365, 400, 600, 800 (mm) –** Primary (source) energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

The results for the horizontal overhang shading for the south elevation were recorded and the optimisation process proceeded to experiment with other strategies.

B. Horizontal multiple blades

The next strategy to experiment with was the horizontal multiple blades.

To determine the arrangement that works better, the horizontal multiple blade simulation was done in three categories, the variations are as follows.

1. Different depths of blades and Number of blades.
2. Number of blades and angle of blades.
3. Different angles of blades and variations in blade depths

Throughout the simulation, the variations shown in the figure below were constantly changed for each simulation. However, the distance of the louvres from the window was kept at 50mm for consistency. The vertical offset from the top of the window was kept the same with the spacing between louvres for each case. The horizontal window overlap was kept at 200mm all through the simulations.

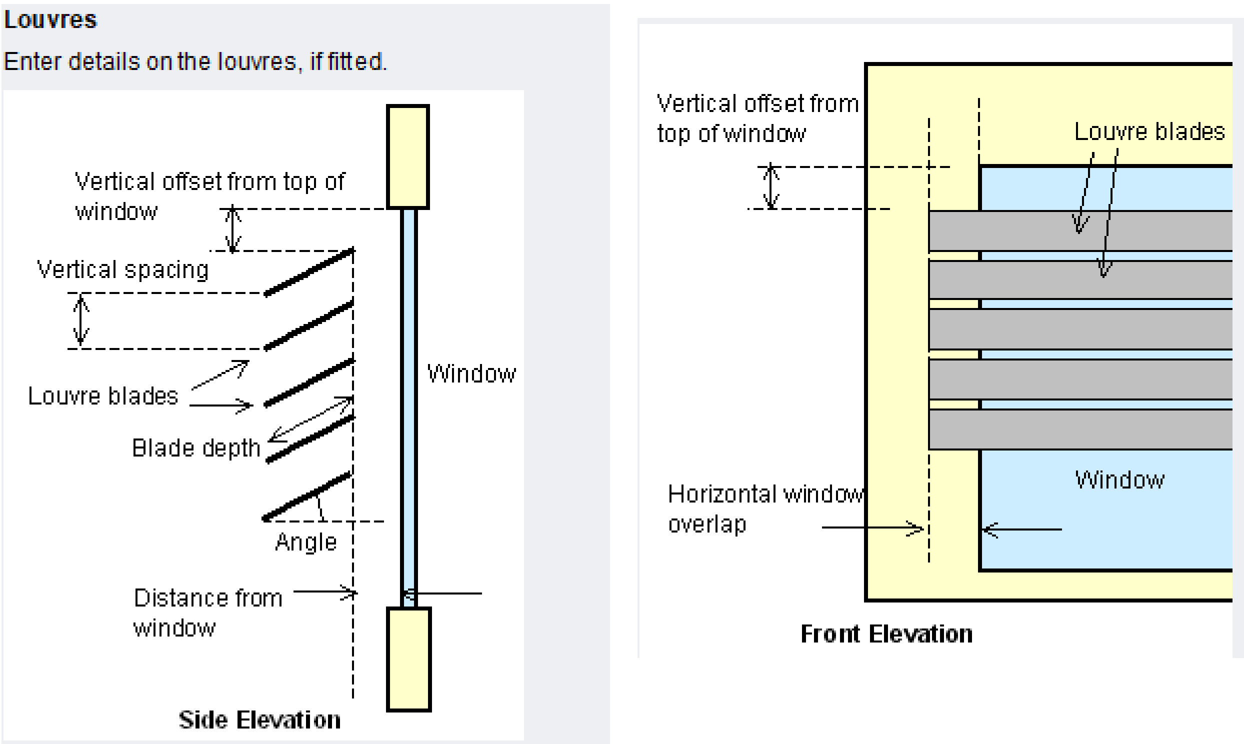
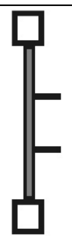
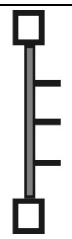
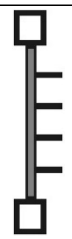
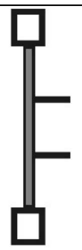
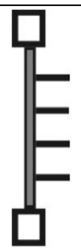


Figure 43: Louvres (DesignBuilder)

1. <u>Category one simulations: Different Depths of blades and Number of blades</u>

The first phase of simulations is between variable blade/louvre sizes and the number of blades. A total number of 25 simulations were done in this category. The best size was selected for simulation two.

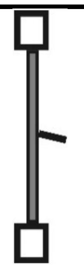
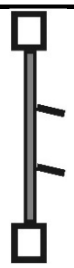
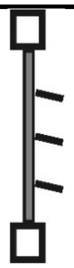
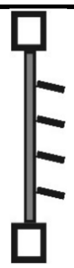
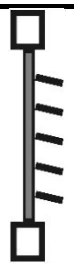
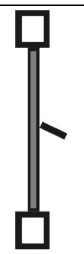
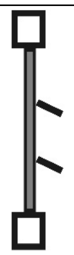
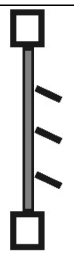
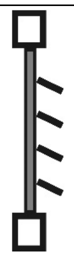
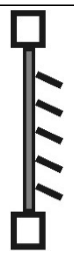
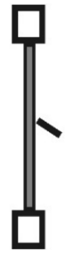
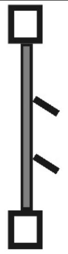
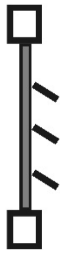
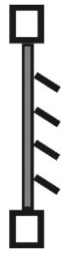
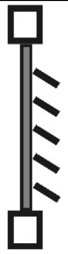
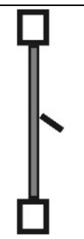
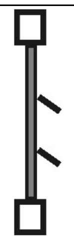
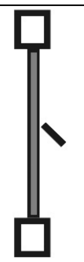
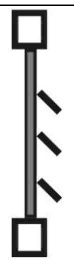
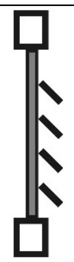
Table 34: Different sizes of blades and Number of blades

Simulations		Number of blades				
		1	2	3	4	5
Blade Depths	100	 Case 1	 Case 2	 Case 3	 Case 4	 Case 5
	200	 Case 6	 Case 7	 Case 8	 Case 9	 Case 10
	300	 Case 11	 Case 12	 Case 13	 Case 14	 Case 15
	400	 Case 16	 Case 17	 Case 18	 Case 19	 Case 20
	500	 Case 21	 Case 22	 Case 23	 Case 24	 Case 25

2. <u>Category two simulations: Number of blades and angle of blades</u>

The second simulation was between the angles of blades and the number of blades. This is to determine the best combination of blade angles and the number of blades for optimisation. The best case (depth of blades) in category one was selected for simulation two and kept constant.

Table 35: Category two simulations

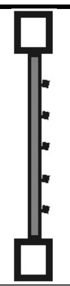
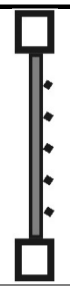
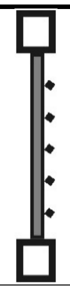
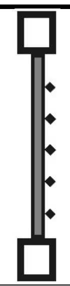
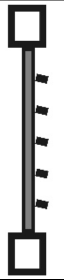
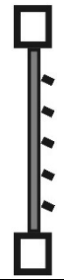
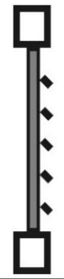
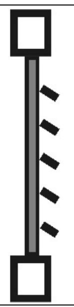
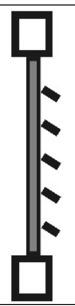
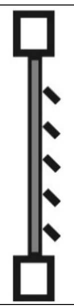
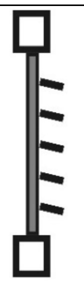
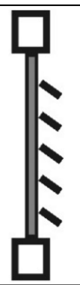
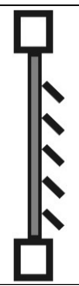
Simulations		Number of Blades				
		1	2	3	4	5
Angles of Blades (degrees)^0	10^0	 Case 1	 Case 2	 Case 3	 Case 4	 Case 5
	20^0	 Case 6	 Case 7	 Case 8	 Case 9	 Case 10
	30^0	 Case 11	 Case 12	 Case 13	 Case 14	 Case 15
	40^0	 Case 16	 Case 17	 Case 18	 Case 19	 Case 20
	50^0					

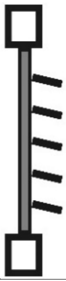
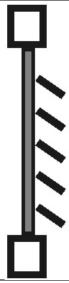
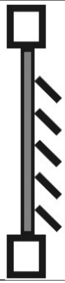
		Case 21	Case 22	Case 23	Case 24	Case 25

3. <u>Category three simulations: Different angles of blades and variation in blade depths</u>

The third simulation was between the angles of blades and Variation in blade depths. This is to determine the best combination of blade angles and blade depths for optimisation. The best case (number of blades) in category two was selected for simulation three and kept constant. Therefore, this is to validate/determine a suitable angle or depth of the blade with five-blade louvres.

Table 36: Category three simulations

Simulations		**Angles of Blades (degrees)^0**				
		10^0	20^0	30^0	40^0	50^0
Depth of Blades (mm)	100	 Case 1	 Case 2	 Case 3	 Case 4	 Case 5
	200	 Case 6	 Case 7	 Case 8	 Case 9	 Case 10
	300	 Case 11	 Case 12	 Case 13	 Case 14	 Case 15
	400	 Case 16	 Case 17	 Case 18	 Case 19	 Case 20

	500					
		Case 21	Case 22	Case 23	Case 24	Case 25

C. Box shading or egg-crate

The research also experimented with the box shading or the egg-crate. To do this effectively, the box shading considered both the number of installed fins and the depth of fins.

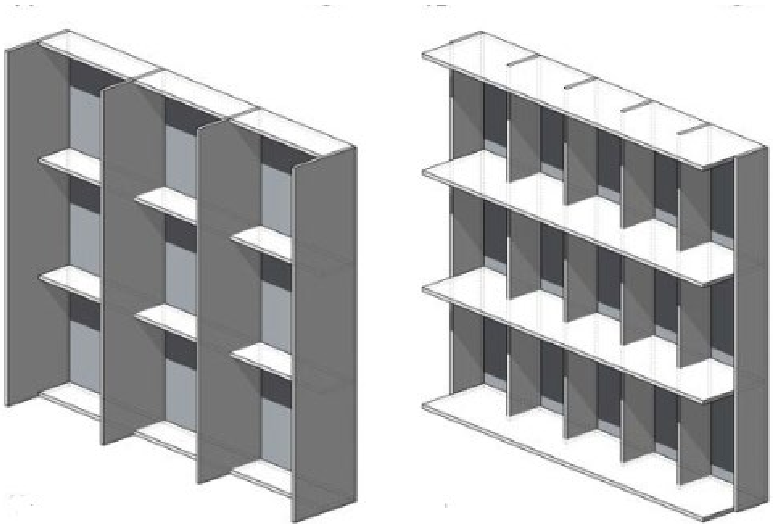


Figure 44: Egg crate or box shading

The best strategy was adopted for the South façade based on the series of simulations conducted.

3.6.3.2. West Elevation

To optimise the west elevation, the optimisation is done in three categories:

A. Side fins
    1. Left side fin with variable projections.
    2. Right side fin with variable projections.
    3. Left and right side fins with variable projections.
B. Selected Left and right side fins with variable overhang.
C. Number of vertical fins and depth of fins
D. Number of vertical fins and angles of fins
E. Selected number of vertical fins and selected angles of fins with variable overhang

For consistency, the gap between the side fin from the window is maintained at 200mm, the bottom overlap kept at 0mm, top overlap kept at 200mm.

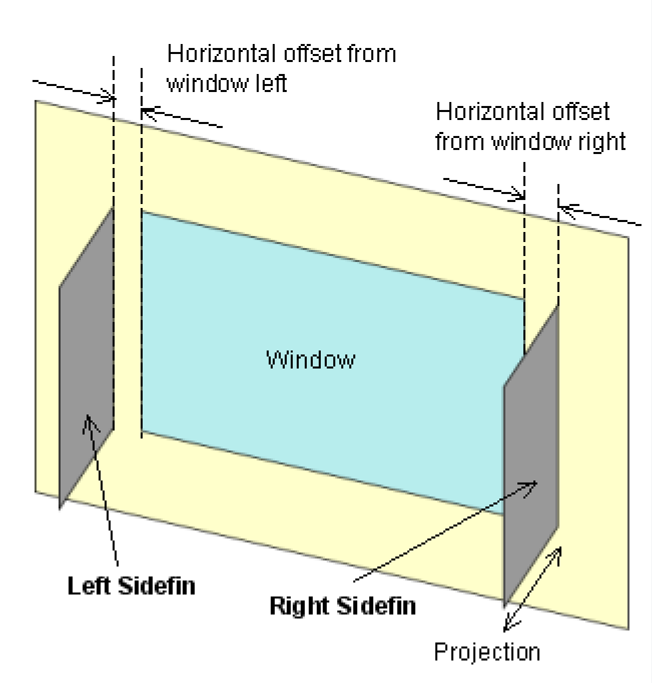


Figure 45: West elevation Sidefins (DesignBuilder)

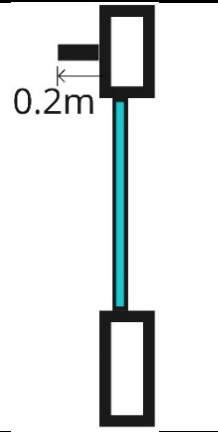
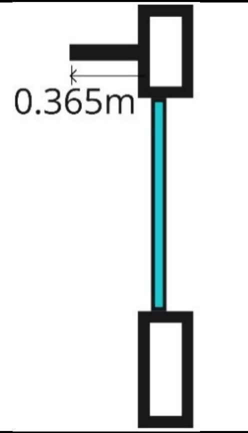
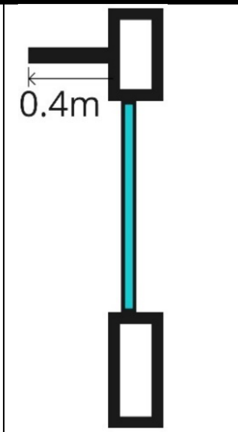
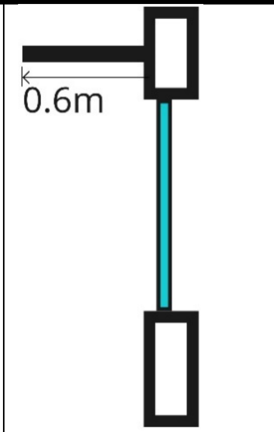
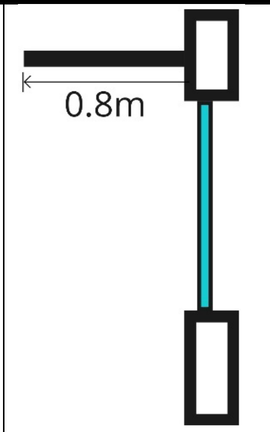
It is important to note that the standard projection length of side fins in Nigeria is 365mm (Adunola and Ajibola 2016; Abdulkareem et al. 2018), hence variations were made below and above this standard to determine the most optimised projection in the Nigerian context.

The optimisation process tried the following optimisation trials to see which performs better in terms of energy demand and built upon the potentially positive results for best performance.

A. Side fins

1. Simulation - Left sidefin with variable projections

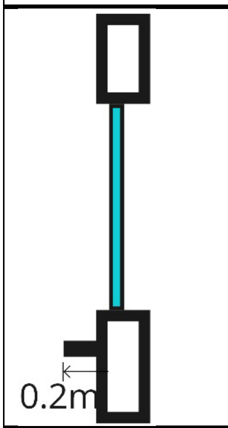
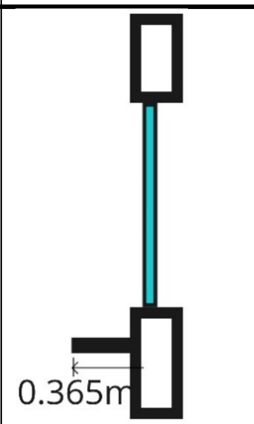
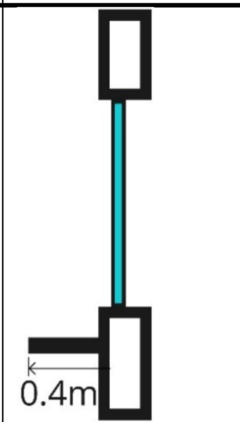
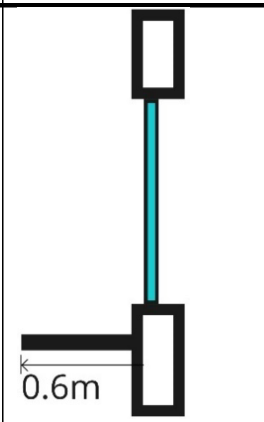
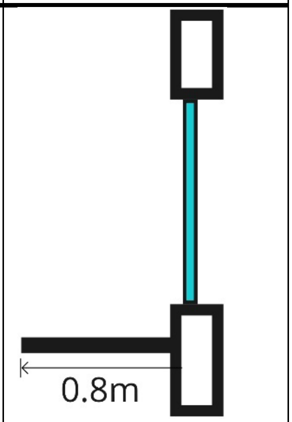
Table 37: Left sidefin with variable projections (Simulation)

Energy Simulation of left sidefin variations (plan view) **200, 365, 400, 600, 800 (mm)**				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total primary (source) energy demand - KWh/(m²a)	Total primary (source) energy demand - KWh/(m²a)	Total primary (source) energy demand - KWh/(m²a)	Total primary (source) energy demand - KWh/(m²a)	Total primary (source) energy demand - KWh/(m²a)

After the above optimisation trial, the simulation would proceed to the next setup below.

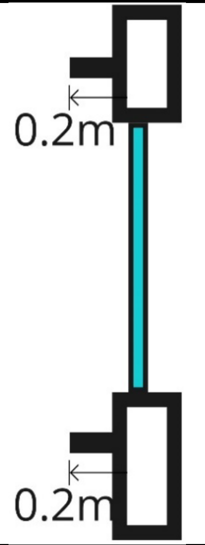
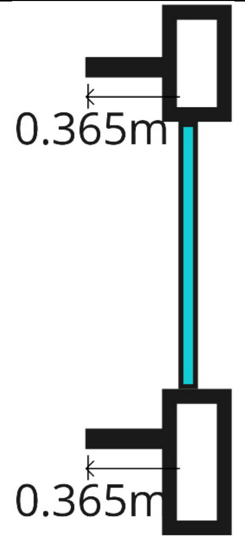
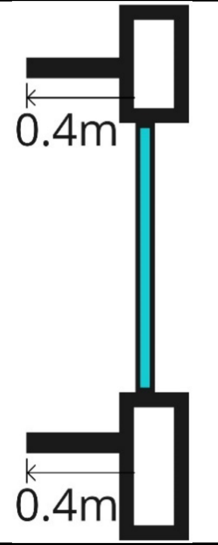
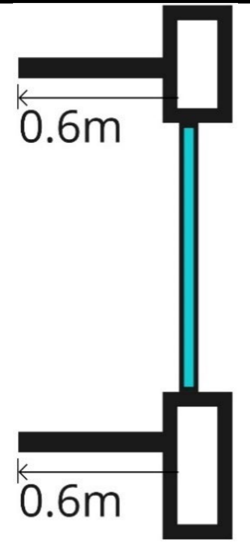
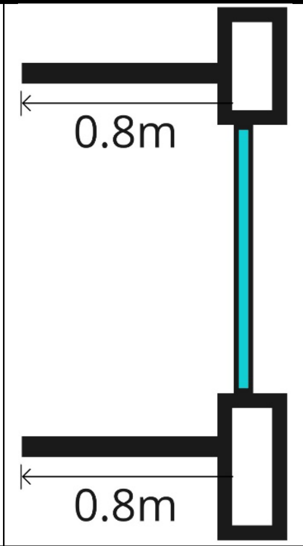
2. Simulation - Right fin with variable projections

Table 38: Right fin with variable projections (Simulation)

Energy Simulation of right sidefin variations (Plan view) **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

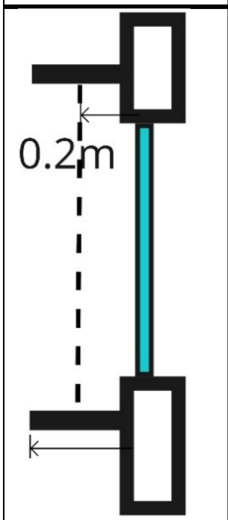
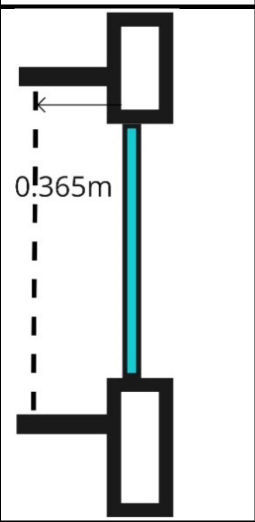
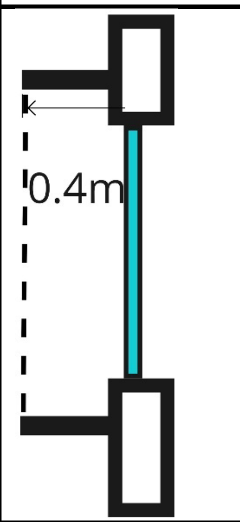
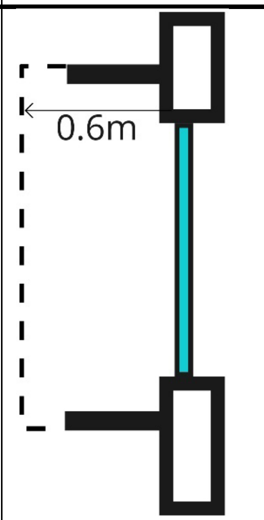
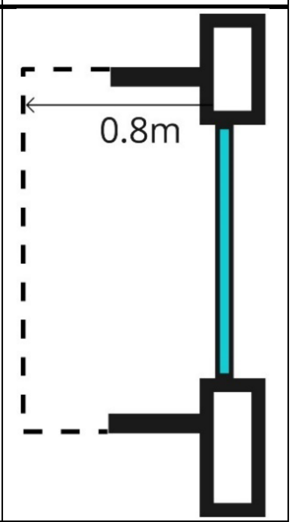
3. Simulation - Left and right sidefins with variable projections

Table 39: Left and right sidefins with variable projections (Simulations)

Energy Simulation of left and right side fin variations (Plan view) **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

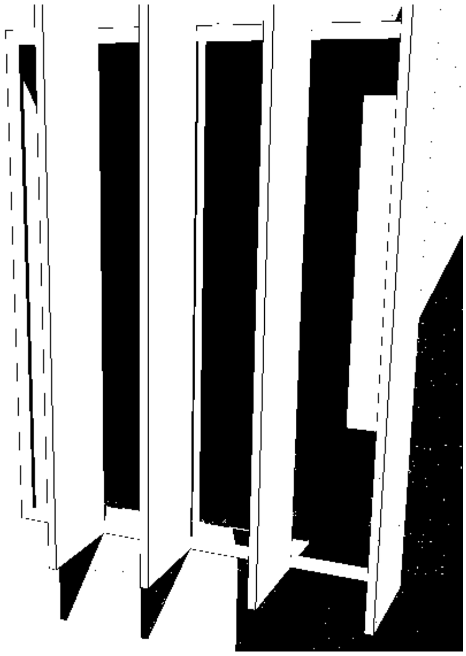
B. Selected Left and right sidefins with variable overhang

Table 40: Selected Left and right sidefins with variable overhang (Simulations)

Energy Simulation of selected Left and right sidefins with variable overhang **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

C. Number of vertical fins and depth of fins

This optimisation process started by installing variable vertical shading fins. This was done while changing the depth of fins.



For consistency, the bottom overlap was kept at 0mm, while the top overlap was kept at 200mm. The thickness of fins was maintained at 20mm.

A total number of 30 simulations were done under this category to determine the best optimisation strategy for the west elevation.

.

Figure 46: Vertical fins

Table 41: Number of vertical fins and depth of fins

Simulation Results		Number of vertical fins				
		1	2	3	4	5
Depth of Fins (mm)	100	Case 1	Case 2	Case 3	Case 4	Case 5
	200	Case 6	Case 7	Case 8	Case 9	Case 10
	300	Case 11	Case 12	Case 13	Case 14	Case 15
	400	Case 16	Case 17	Case 18	Case 19	Case 20
	500	Case 21	Case 22	Case 23	Case 24	Case 25
	600	Case 26	Case 27	Case 28	Case 29	Case 30

D. Number of vertical fins and angles of fins

In this stage of the experiment for best optimisation, the building adopts the best result from category C simulation (Number of vertical fins and depth of fins).

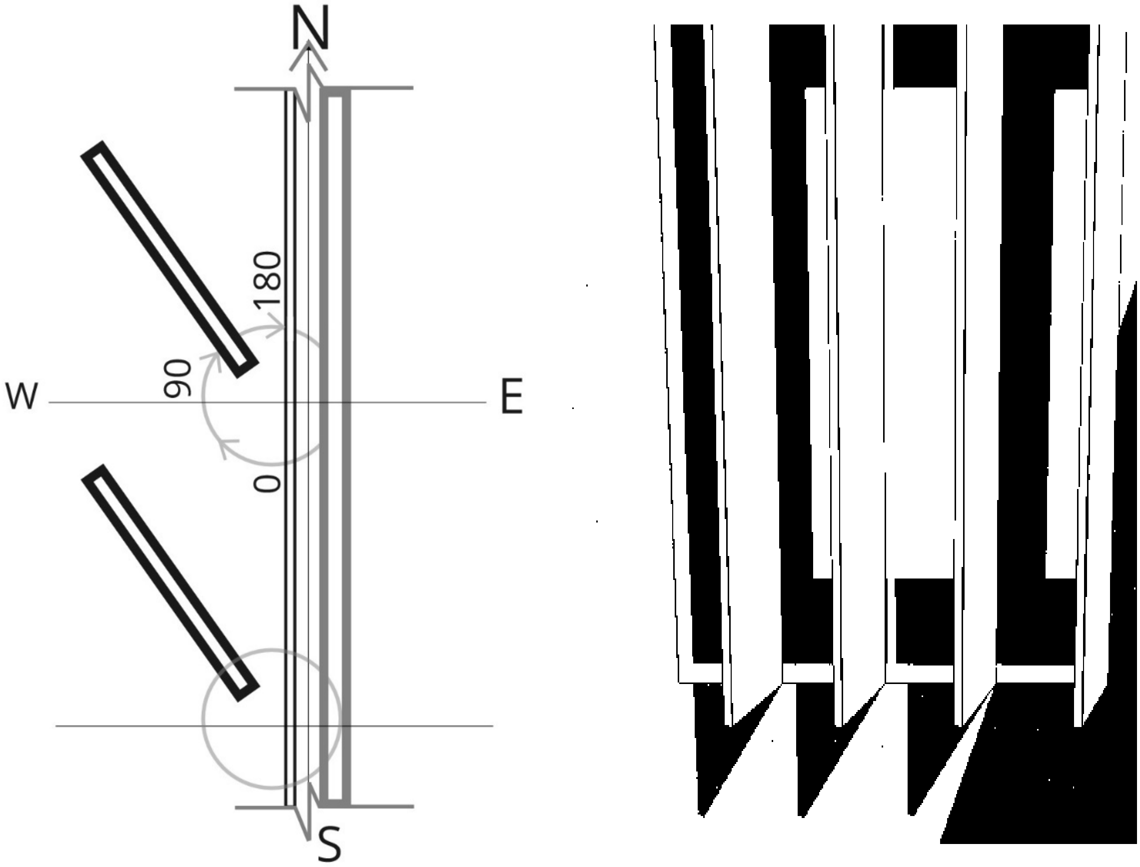


Figure 47: Vertical fins

The vertical fins were progressively adjusted from 0 degrees to 180 degrees from the South to the North.

A total of 90 simulations were executed in this category.

Table 42: Number of vertical fins and angles of fins

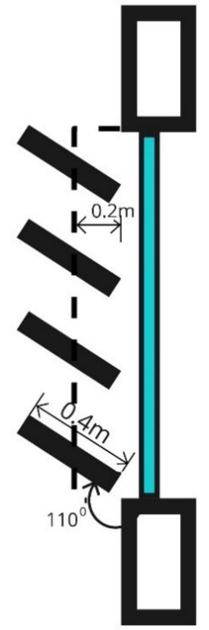
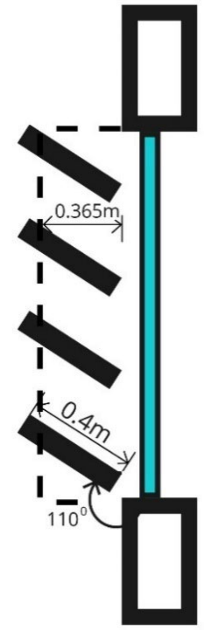
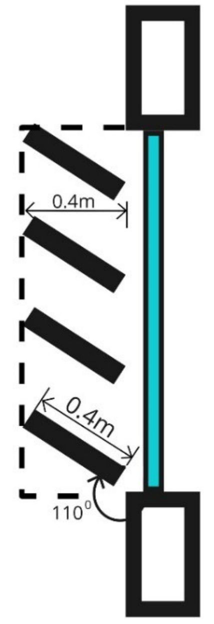
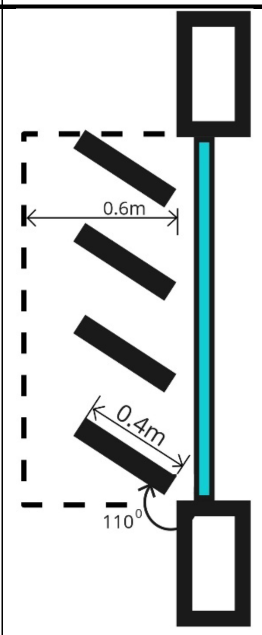
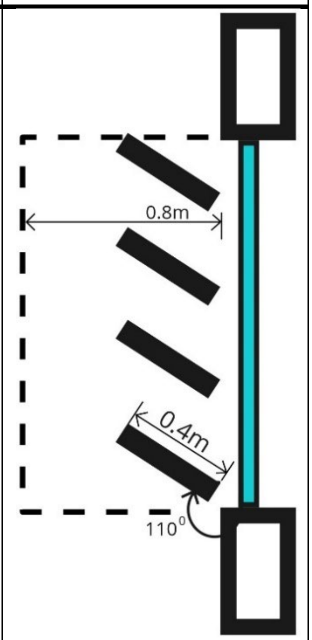
Simulation		Number of vertical fins				
		1	2	3	4	5
Angle of blades (⁰)	10	Case 1	Case 2	Case 3	Case 4	Case 5
	20	Case 6	Case 7	Case 8	Case 9	Case 10
	30	Case 11	Case 12	Case 13	Case 14	Case 15
	40					

		Case 16	Case 17	Case 18	Case 19	Case 20
	50					
		Case 21	Case 22	Case 23	Case 24	Case 25
	60					
		Case 26	Case 27	Case 28	Case 29	Case 30
	70					
		Case 31	Case 32	Case 33	Case 34	Case 35
	80					
		Case 36	Case 37	Case 38	Case 39	Case 40
	90					
		Case 41	Case 42	Case 43	Case 44	Case 45
	100					
		Case 46	Case 47	Case 48	Case 49	Case 50
	110					
		Case 51	Case 52	Case 53	Case 54	Case 55
	120					
		Case 56	Case 57	Case 58	Case 59	Case 60
	130					
		Case 61	Case 62	Case 63	Case 64	Case 65
	140					
		Case 66	Case 67	Case 68	Case 69	Case 70
	150					
		Case 71	Case 72	Case 73	Case 74	Case 75
	160					
		Case 76	Case 77	Case 78	Case 79	Case 80
	170					
		Case 81	Case 82	Case 83	Case 84	Case 85
	180					
		Case 86	Case 87	Case 88	Case 89	Case 90

E. The selected number of vertical fins and selected angles of fins with variable overhang

The simulation was done with the adoption of the best cases from category C and D simulations.

Table 43: Category E energy Simulations

Energy Simulation of Category E Simulation (Plan view) **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

The best strategy is adopted for the west façade based on the series of simulations conducted.

3.6.3.3. East Elevation

To optimise the East elevation, the optimisation simulation is done in five categories:

A. Side fins
   1. Left side fin with variable projections.
   2. Right side fin with variable projections.
   3. Left and right sidefins with variable projections.
B. Selected Left and right sidefins with variable overhang.
C. Number of vertical fins and depth of fins
D. Number of vertical fins and angles of fins
E. Selected number of vertical fins and selected angles of fins with variable overhang

For consistency, the gap between the side fin from the window was maintained at 200mm, the bottom overlap kept at 0mm, top overlap kept at 200mm.

As stated before, the typical projection length of side fins in Nigeria is 365mm. Therefore variations are made below and above this size to determine the most optimised projection in the Nigerian context (Adunola and Ajibola 2016; Abdulkareem et al. 2018; Bankole 2019).

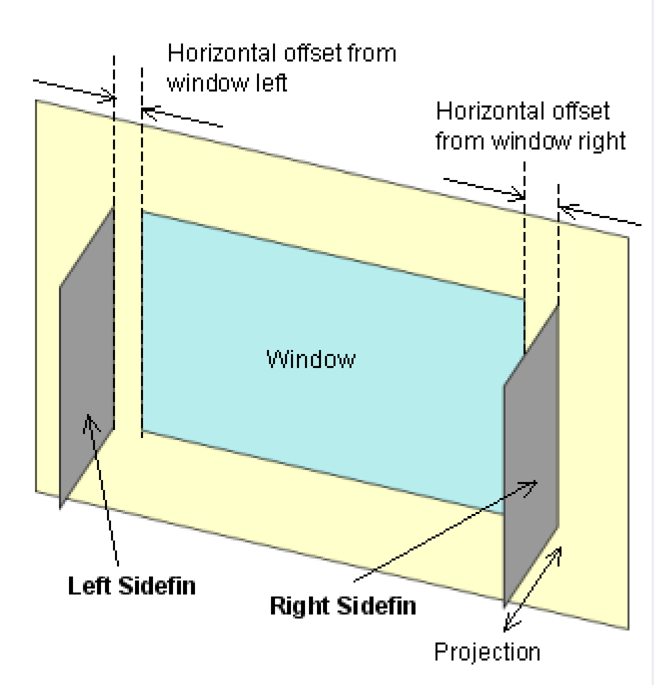
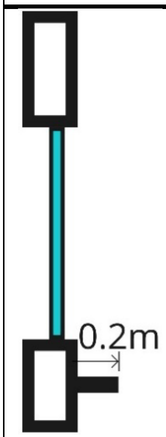
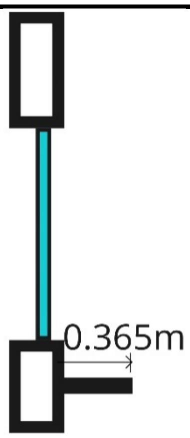
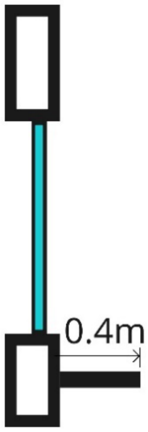
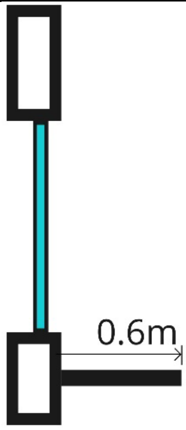
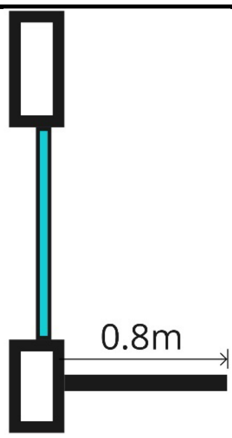


Figure 48: East Sidefins (DesignBuilder)

A. Side fins

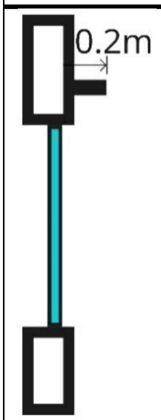
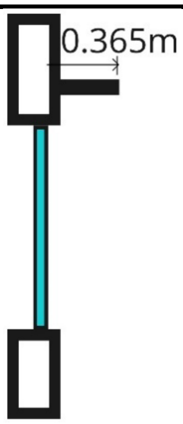
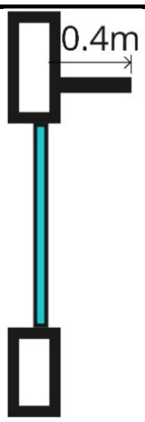
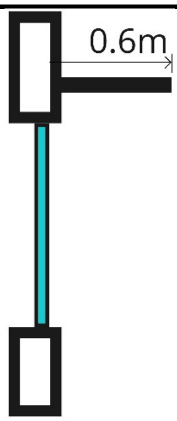
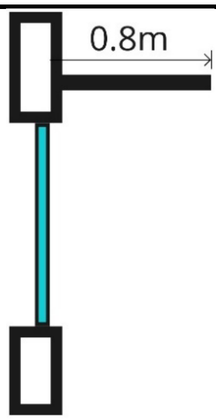
1. Simulation - Left sidefin with variable projections

Table 44: Left sidefin with variable projections (Simulations)

Energy Simulation of left sidefin variations (plan view) **200, 365, 400, 600, 800 (mm)** - Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

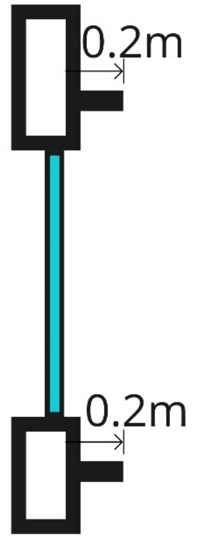
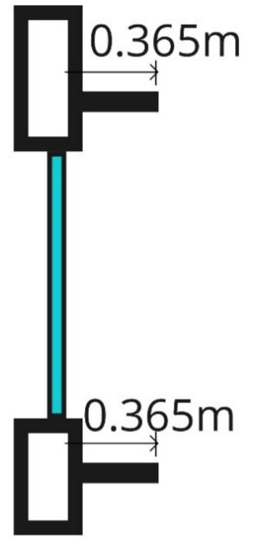
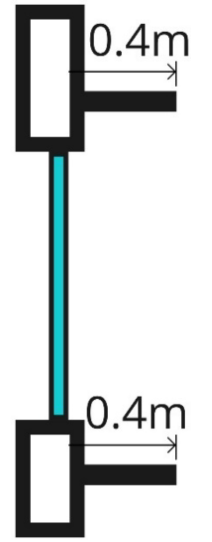
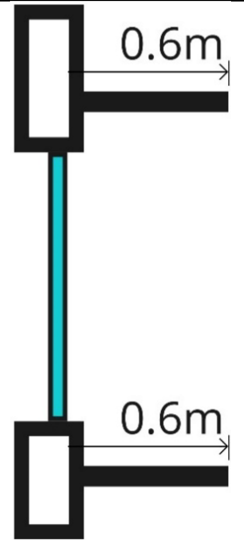
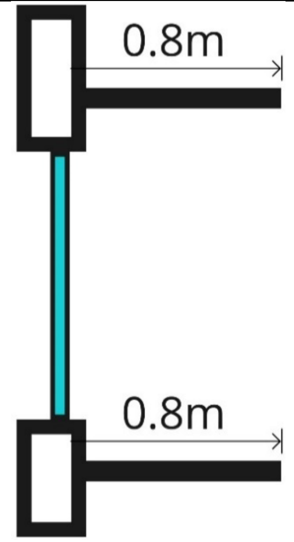
2. Simulation - Right fin with variable projections

Table 45: Right fin with variable projections (Simulations)

Energy Simulation of right sidefin variations (Plan view) **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

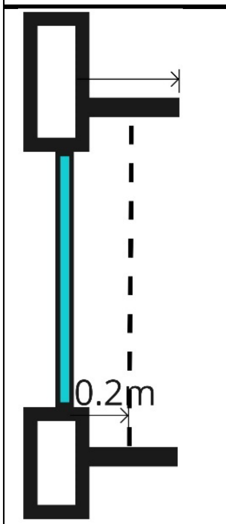
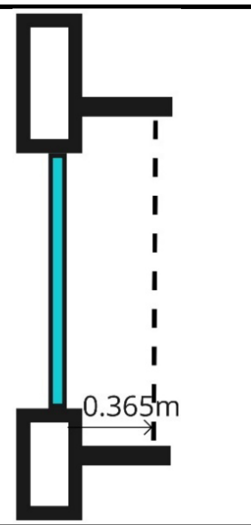
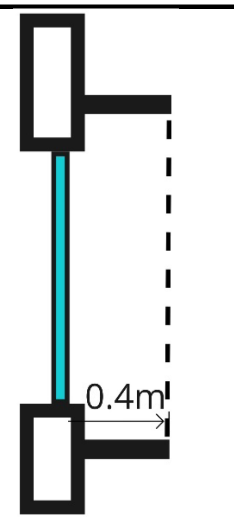
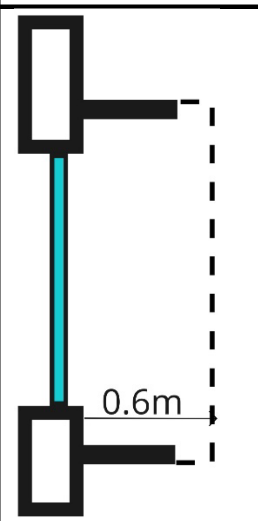
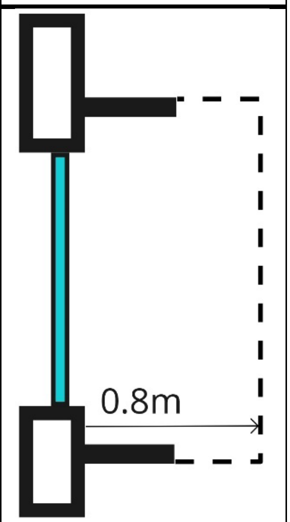
3. Simulation - Left and right sidefins with variable projections

Table 46: Left and right sidefins with variable projections (Simulations)

Energy Simulation of left and right side fin variations (Plan view) **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

B. Selected left and right sidefins with variable overhang

Table 47: Selected left and right sidefins with variable overhang (Simulations)

Energy Simulation of selected left and right sidefins with variable overhang **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

C. Number of vertical fins and depth of fins

The next shading strategy was the use of vertical fins. This optimisation was done by installing variable depths of vertical shading fins.

For consistency, the bottom overlap was kept at 0mm, while the top overlap was kept at 200mm. The thickness of fins was maintained at 20mm.

A total number of 30 simulations were done under this category to determine the best optimisation strategy for the East elevation.

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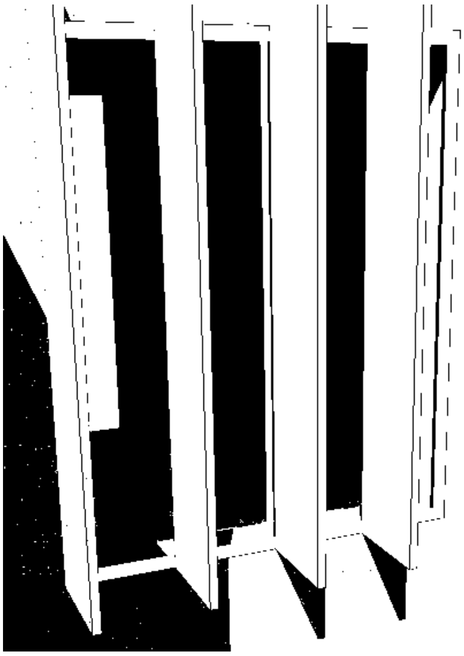


Figure 49: East elevation vertical fins

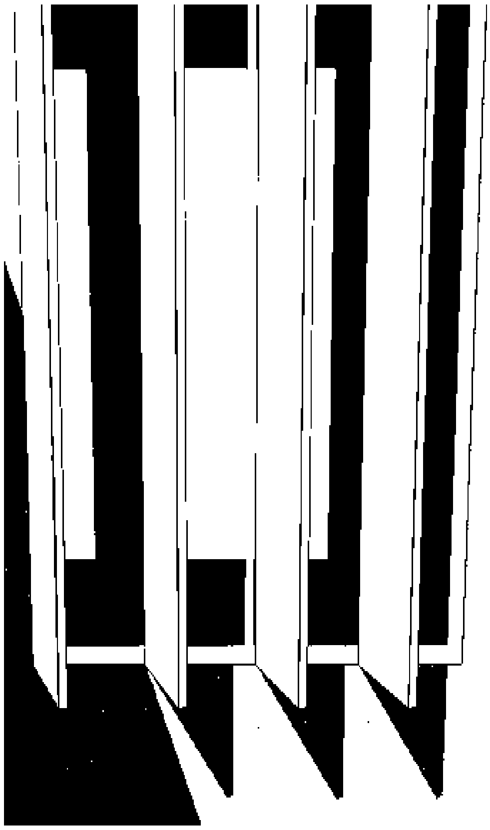
Table 48: Number of vertical fins and depth of fins

Simulation Results		Number of vertical fins				
		1	2	3	4	5
Depth of Fins (mm)	100	-	-	-	-	-
		Case 1	Case 2	Case 3	Case 4	Case 5
	200	-	-	-	-	-
		Case 6	Case 7	Case 8	Case 9	Case 10
	300	-	-	-	-	-
		Case 11	Case 12	Case 13	Case 14	Case 15
	400	-	-	-	-	-
		Case 16	Case 17	Case 18	Case 19	Case 20
	500	-	-	-	-	-
		Case 21	Case 22	Case 23	Case 24	Case 25
	600	-	-	-	-	-
		Case 26	Case 27	Case 28	Case 29	Case 30

D. Number of vertical fins and angles of fins

The building adopted the best result from category C simulation (Number of vertical fins and depth of fins).

The vertical fins were progressively adjusted from 0 degrees to 180 degrees from the South to the North.



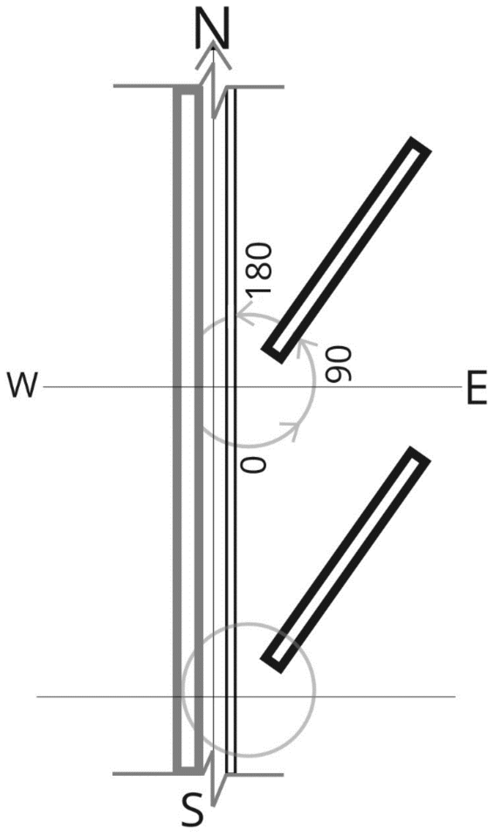


Figure 50: East elevation vertical fins

A total of 90 simulations were executed in this category.

Table 49: Category D simulations

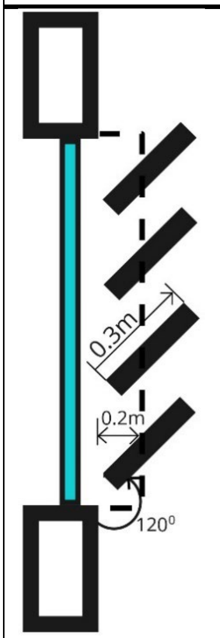
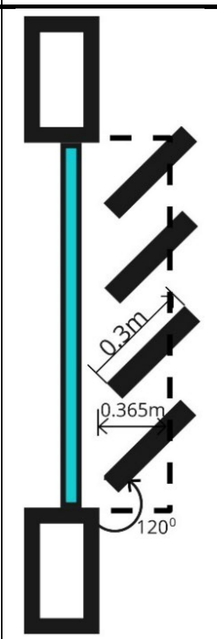
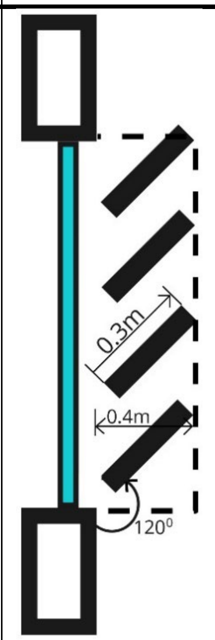
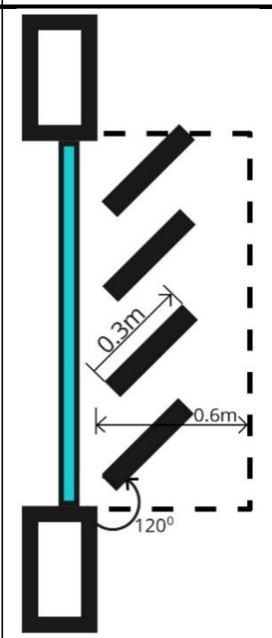
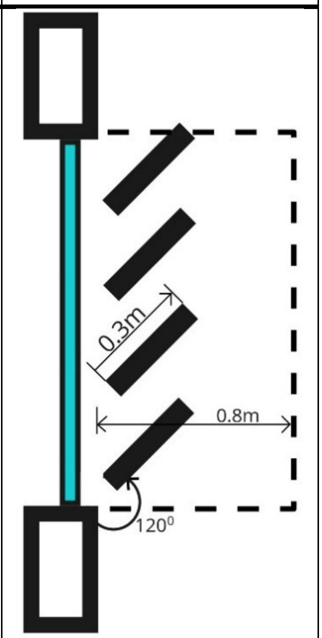
Simulation Results		Number of vertical fins 1	2	3	4	5
Angle of blades (⁰)	10	-	-	-	-	-
		Case 1	Case 2	Case 3	Case 4	Case 5
	20	-	-	-	-	-
		Case 6	Case 7	Case 8	Case 9	Case 10
	30	-	-	-	-	-
		Case 11	Case 12	Case 13	Case 14	Case 15
	40	-	-	-	-	-

		Case 16	Case 17	Case 18	Case 19	Case 20
	50	-	-	-	-	-
		Case 21	Case 22	Case 23	Case 24	Case 25
	60	-	-	-	-	-
		Case 26	Case 27	Case 28	Case 29	Case 30
	70	-	-	-	-	-
		Case 31	Case 32	Case 33	Case 34	Case 35
	80	-	-	-	-	-
		Case 36	Case 37	Case 38	Case 39	Case 40
	90	-	-	-	-	-
		Case 41	Case 42	Case 43	Case 44	Case 45
	100	-	-	-	-	-
		Case 46	Case 47	Case 48	Case 49	Case 50
	110	-	-	-	-	-
		Case 51	Case 52	Case 53	Case 54	Case 55
	120	-	-	-	-	-
		Case 56	Case 57	Case 58	Case 59	Case 60
	130	-	-	-	-	-
		Case 61	Case 62	Case 63	Case 64	Case 65
	140	-	-	-	-	-
		Case 66	Case 67	Case 68	Case 69	Case 70
	150	-	-	-	-	-
		Case 71	Case 72	Case 73	Case 74	Case 75
	160	-	-	-	-	-
		Case 76	Case 77	Case 78	Case 79	Case 80
	170	-	-	-	-	-
		Case 81	Case 82	Case 83	Case 84	Case 85
	180	-	-	-	-	-
		Case 86	Case 87	Case 88	Case 89	Case 90

E. Selected number of vertical fins and selected angles of fins with variable overhang

The simulation was carried out by selecting the best cases from category C and D simulations.

Table 50: Selected number of vertical fins and selected angles of fins with variable overhang

Energy Simulation of Category E Simulation (Plan view) **200, 365, 400, 600, 800 (mm) -** Total primary (source) energy demand				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)

3.6.3.4. North Elevation

The North façade of the building was observed in the month of June when the sun is at its highest peak. These observations were recorded at the times when the sun gradually rises through its hottest levels and when it begins to set and cool off in the West. The times of the day simulated were as follows: 8:00, 10:00, 12:00, 14:00, 16:00 and 17:00. Although, the North façade did not necessarily require shading due to the geographical location of the site. According to literature studies, since the geographical location of the building is in the Northern hemisphere, therefore, the North façade experiences little or no sunshine, which means that shading devices are not necessarily required in the North façade of the building (Bhatt 2014; Anumah and Anumah 2017).

The sun path study below was used to further determine if the North façade required shading devices.

Table 51: Building Sun path study for 8:00, 10:00, 12:00, 14:00, 16:00 and 17:00

Sun path diagram simulated during the sun's highest peak of the year	
June 15, 8:00	June 15, 10:00
June 15, 12:00	June 15, 14:00
June 15, 16:00	June 15, 17:00

3.6.4. Optimisation for Windows (g-value)

Methodology to optimise the g-value of the windows

The optimisation of the g-value of the glazing is done using two strategies.

The first optimisation strategy is to gradually decrease the g-value of the glass on the windows with a decremental factor of -0.20. That is, from the original value of 0.69 to 0.42 to 0.22.

To conduct this experiment, glazing types with g-values of 0.42 and 0.22 were selected to check their sensitivity and their effect on the building solar heat gains through the windows and the total energy consumption of the building.

The second optimisation strategy involved the use of a glazing material with a low g-value, u-value and high visible light transmittance.

This would ensure that the daylight is not greatly reduced by selecting glazing with a low g-value.

First optimisation strategy (Step 1)

In the first stage of the experiment, the g-value of the glazing was reduced from 0.69 of the base case to 0.42.

Original properties of glazing

Total solar transmittance:	69.10%
Glaze type:	Bronze glazing
Thickness:	5.72mm

Adjusted properties of glazing

Total solar transmittance:	42%
Glaze type:	Bronze glazing
Thickness:	5.72mm

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption.

Solar heat gain simulation (Step 2)

In the second step of the experiment, the g-value of the glazing was reduced to 0.22, amounting to a total reduction of 64.5%.

Original properties of glazing

Total solar transmittance:	69.10%
Glaze type:	Bronze glazing
Thickness:	5.72mm

Adjusted properties of glazing

Total solar transmittance:	22%

Glaze type: Bronze glazing

Thickness: 5.72mm

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption.

Second Optimisation Strategy (g-value)

In this case, a new glazing material with a low g-value, u-value and high visible light transmittance is selected. This is to ensure that light visibility transmittance is not significantly affected. The results of this simulation were also compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption.

3.6.5. Thermal insulation optimisation

Since the base case model did not have thermal insulators on the exterior walls, thermal insulators were introduced by incorporating thermal insulation material into the wall construction in an attempt to optimise the building and reduce energy consumption.

To do this, a thermal insulating biobased material for the exterior walls is selected. To assess the best thickness of the thermal insulator, several applicable thermal insulation thicknesses are used and simulated to see the most effective one with regards to energy efficiency in buildings.

The experiment used several insulation thicknesses, 50, 75, 100, 125, 150 of hemp fibre with thermal conductivity of 0.04W/m-K, specific heat capacity of 2150J/Kg-K. The following were kept constant throughout the trial optimisation simulations - the composition of the exterior wall consists of 150mm brick wall of the base case, 50mm spacing between insulation and brick wall, 100mm autoclaved aerated concrete (AAC) block, and 25mm sandcrete wall plaster.

Table 52: Thermal Insulation simulation trials

Selected thermal Insulation	Benefits	Material thickness (mm)	Primary (source) energy consumption
Hemp fibre	Hemp is completely recyclable and has no irritation to skin or lungs, it is protected against moulds and bacteria, it is sustainable with no harmful substance (Latif et al. 2014).	50	- KWh/(m²a)
		75	- KWh/(m²a)
		100	- KWh/(m²a)
Material properties		125	- KWh/(m²a)
Thermal Conductivity: 0.04W/m-K Specific Heat: 2150J/Kg-K Density: 35Kg/m^3		150	- KWh/(m²a)

The results of the simulation are further compared with that of the base case to check for changes in temperatures, heat gain, and energy consumption.

3.6.6. Thermal mass optimisation

To optimise the thermal mass of the building, a thermal mass material was selected considering its volumetric heat capacity and an appropriate thermal conductivity that can absorb and release heat in sync with the natural heat flow of the building (LHedlund 2016). The u-value of the material was kept constant at 2.20W/m^2-K. The thickness of the material was gradually adjusted to determine the most effective thickness with regard to the energy consumption of the building. The construction material of the external walls which has a composition of 150mm sandcrete solid block wall and 25mm sand-cement plaster on both sides were replaced with hydra form bricks. The sandscrete blocks had a thermal conductivity of 1.00W/m-K. An exterior wall material with a high volumetric heat capacity (high density and specific capacity) was selected. Thus, improving the thermal mass performance. Outer leaf bricks are used instead which have a lower thermal conductivity of 0.79W/m-K, a specific capacity of 840J/Kg-K and a density of 1950Kg/m^3. As seen from the DesignBuilder settings extract below, the U-value of the brick was kept constant at 2.20W/m^2-K (or R-value of 0.46m^2-K/W) in all instances of the brick thickness change to see the effect of thermal mass.

Figure 51: Extract from DesignBuilder

Table 53: Properties of thermal mass material for exterior wall Outer leaf

Wall Material (Exterior)	Thermal conductivity	Specific Capacity	Density
Masonry - heavyweight Dry	0.79W/m-K	840J/Kg-K	1950Kg/m^3

To determine the most appropriate thickness of the thermal mass for optimisation, several wall thicknesses are simulated with the selected material. The following were also kept constant throughout the trial optimisation simulations - the composition of the selected exterior wall is maintained, 50mm spacing between exterior wall and 100mm autoclaved aerated concrete (AAC) block, and 25mm sandcrete wall plaster as shown in the table below.

Table 54: Optimisation of thermal mass (thickness of material)

Selected thermal mass material	Material thickness (mm)	Total energy consumption
Masonry - heavyweight Dry	75	- KWh/(m^{2}a)
	100	- KWh/(m^{2}a)

	125	- KWh/(m²a)
	150	- KWh/(m²a)
	175	- KWh/(m²a)
	200	- KWh/(m²a)
	225	- KWh/(m²a)

To check the effect of combining thermal mass and insulation, the optimisation operation went on to combine both the best optimisation results of the thermal mass and thermal insulation.

To do this, the best optimisation for the thermal mass with regards to material type and thickness is used as constants and the thickness of the best thermal insulation was adjusted to determine the best case for the combined optimisation of the thermal mass and insulation.

Table 55: Optimisation simulation trials for thermal mass.

Selected thermal mass material	Material thickness (mm)	Primary (source) energy consumption
Masonry - heavyweight Dry	75, 100, 125, 150, 175, 200, 225	- KWh/(m²a)
Hemp fibre	50	-
	75	-
	100	-
	125	-
	150	-
	175	-
	200	-
	225	-

3.6.7. Optimisation for Natural ventilation

For natural ventilation optimisation, the optimisation also adopted the following passive design strategies as recommended in the literature to improve the natural ventilation. Firstly, orienting the building 20°W–30°E of true North to benefit from the desired south-west monsoon winds (Givoni 1994; Daemei et al. 2019) which were done in DesignBuilder by orienting the building zero ‘0’ degree North. Secondly, changing the sliding windows (which only open 50%) to projected windows to open 100% by adjusting the free aperture to open 100% on DesignBuilder (ABCB 2016; Roslan et al. 2016; Ochedi 2018). The Nigerian energy efficiency building design guide and the Australian Building Codes Board (ABCB) recommendation for tropical climates states that the minimum size of the opening must be 5% of the floor area of the room (ABCB 2016; Federal Ministry of Power 2017). It is important to note that Australia and Nigeria shares relatively similar climatic conditions as they both come under the hot, tropical savannah climate regions (Arnfield 2020). The above ABCB recommendations are specific to West African tropical climate of which Nigeria comes under (ABCB 2016; Federal Ministry of Power 2017).

Figure 52: Glazing area opening percentage

3.6.8. Optimisation for Daylighting

For daylighting optimisation, the windows were adjusted to adhere to the minimum requirement of the passive design guide stating that a window providing daylight is required to have a minimum opening area of 10% of the floor area of the room (ABCB 2018). This was done in DesignBuilder by ensuring the window area has a minimum of 10% of the floor area of the room.

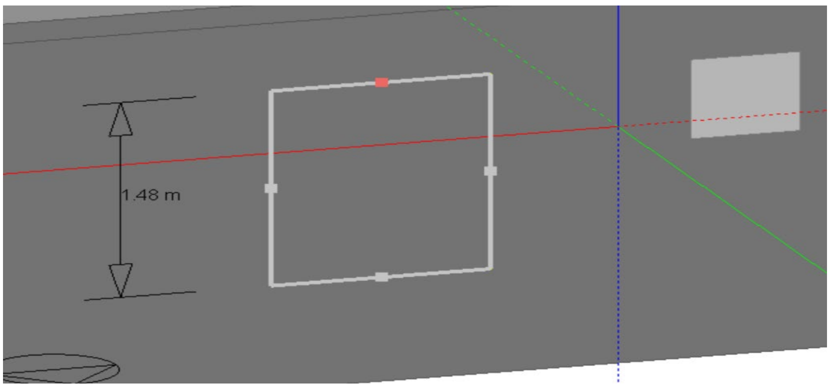


Figure 53: Window model on DesignBuilder

It is important to note that Australia and Nigeria shares relatively similar climatic conditions as they both come under the hot, tropical savannah climate regions (Arnfield 2020). The above ABCB recommendations are specific to West African tropical climate of which Nigeria comes under (Federal Ministry of Power 2017; ABCB 2018).

3.6.9. Optimisation of the roof material

The roof material optimisation was conducted by replacing the aluminium roofing sheets with a low thermal conductivity roof material (roof tiles) in DesignBuilder. Several gauges or thicknesses were tried to identify the best roof gauge or thickness for the roof tiles in order to reduce the heat transmission into the building.

Table 56: Optimisation trials for roof material based on simulations.

Selected roof material		Material thickness (mm)	Total energy consumption KWh/(m²a)
Roof tile		4.00	-
Thermal Conductivity:	0.84W/m-K	5.00	-
Specific Heat:	800J/Kg-K	6.00	-
Density:	1900Kg/m^3	9.00	-
		10.00	-

Also, the roof was previously not insulated leading to the ease of heat transfer into the building. To optimise and see the effect of insulation, the roof was insulated with hemp fibre and several thicknesses were tried to obtain the optimal thickness for the insulation in DesignBuilder. The best roof tile thickness was used in conjunction with varied insulation thicknesses.

Table 57: Optimisation trials for roof material and insulation

Selected material		**Material thickness (mm)**	**Total energy consumption KWh/(m²a)**
Roof tile Thermal Conductivity: Specific Heat: Density:	 0.84W/m-K 800J/Kg-K 1900Kg/m^3	4.00, 5.00, 6.00, 9.00, 10.00	-
Hemp fibre		50	-
		75	-
Thermal Conductivity:	0.038W/m-K	100	-
Specific Heat:	2150J/Kg-K	125	-
Density:	35Kg/m^3	150	-
		175	-
		200	-
		225	-

The best case is adopted and used after the optimisation of the roof material.

After identifying the best passive design strategies for the base case Nigerian residential building, circular economy principles are explored in terms of the principles for design for disassembly and design for recycling, these principles are further developed and applied to the passively designed building (optimised case). This is done with special emphasis and consideration on the materiality of the passive design. Based on the research findings, a material selection matrix is developed. The matrix is to aid the selection of energy and resource efficient materials for the building. The research progressed to the incorporation of circular economy principles into the optimised case. Therefore, the building took into consideration the material composition of the building for a circular economy. This cuts across the reusability and recyclability of the thermal mass material, insulations, optimised glazing materials, window shading devices, façades/elevations' components based on the building's orientation, aperture, and vent materials, etc. Consequently, these passive components are designed for disassembly, reuse, and recycling.

The incorporation of circular economy into the building is done using two major principles of circular economy. The 7S model is used as a Design for Disassembly guide and the ReSOLVE framework is used as a Design for Recycling guide. Therefore, while adopting passive design strategies in the building, the reusability and recyclability of the building components are considered alongside. Consequently, these passive design components are designed for disassembly, reuse, and recycling. After the incorporation of circular economy principles into the optimised case in conjunction with the material selection matrix, the building is further optimised using multivariate Pareto simulation to determine the overall energy performance of the building.

3.6.10. Multivariate Pareto Simulation

The multivariate Pareto optimisation was done in DesignBuilder. The objectives of the optimisations were to minimise the total site energy consumption and minimise thermal discomfort whilst considering circular economy principles. The variables for the optimisation include building orientation, local shading, g-value, thermal mass, thermal insulation, natural ventilation, natural ventilation, roof vent area, roof material and daylighting. The analysis type was set to optimisation. For window to wall ratio, the variable type was set as window to wall ratio, the minimum value was set to 20% while the maximum value was set to 80%. The step optimisation was set as 2 and the target objects were set on the Building. For building orientation, the variable type was set as building rotation, the minimum value was set to 0 while the maximum value was set to 355. The step optimisation was set to 5 and the target objects were set on the Building. For local shading, the variable type was set as local shading type, the option list included a progression of overhangs from 0 to 1.5 meters, a progression of louvres from 0 to 1.5 meters and a general multivariate combination of both louvres and overhangs. The target objects were set on the Building. For Daylighting, the variable type was set as glazing type, the option list for glazing types includes – single, double and triple glazing with visible light transmittance of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100% and a general multivariate simulation of all combinations. The target objects were set on the Building. For thermal mass, the variable type was set as external wall construction, the option list included Masonry - heavyweight Dry brick wall, sand-cement block wall, autoclaved aerated concrete (AAC) and heavyweight concrete wall. The wall materials had a range of thickness from 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, and 400mm, and a volumetric heat capacity range of 500 to 3000kJ/m^3.K for a general multivariate simulation. The target objects were set on the Building. For thermal insulation, the variable type was set as external wall construction, the option list included hemp fibre, cellulose, denim or cotton and woodwool insulation. The insulation materials had a range of thicknesses from 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 400mm, and a thermal transmittance range of 0.00 to 0.45W/m^2-K for a general multivariate simulation. The target objects were set on the Building. For Roof material, the variable type was set as pitched roof construction, the option list included sandstone tile, clay tile, slate tile, and roof tile with a thickness range of 0-30mm, having a range of thermal transmittance between 0-7W/m^2-K. The insulation included hemp fibre, cellulose, denim or cotton and woodwool insulation. The insulation materials had a range of thickness from 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 400mm, and a thermal transmittance range of 0.00 to 0.45W/m^2-K for a general multivariate simulation. The target objects were set on the roof blocks. For g-value, the variable type was set as glazing type, the option list for glazing types includes – single, double and triple glazing with a thickness range of 0 – 12mm, air gap range of 5-15mm, a thermal transmittance range between 0-7W/m^2-K and a specific heat gain coefficient range of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100% for a general multivariate simulation/combinations. The target objects were set on the Building. For natural ventilation, the variable type was set as %external window opens, the minimum value was set to 0% while the maximum value was set to 100%. The step optimisation was set as 1 and the target objects were set on the Building. For roof vent area, the variable type was set as roof vent area, the minimum value was set at 0.00m^2 and a the maximum value of 10.00m^2. The step optimisation increment was set at 0.10. The two roof zones were targeted.

Chapter Four
4.0 Nigerian Building Information
4.1. General information

Akanni et al. (2014) in their study identified cement, high tensile bar, granite, sharp sand, soft sand, 225mm sandcrete hollow block, 150mm sandcrete hollow block, corrugated asbestos roofing sheet, galvanized iron roofing sheet, hardwood timber as Nigerian most common building materials (Akanni et al., 2014). In a similar study, Isinkaye and Agbi (2013) discussed commonly used building materials in Nigeria, they included sand, gravel, cement, ceramic tiles and bricks.

Typical residential buildings in Nigeria are predominantly bungalows and they are characterised by very similar morphology. These characteristics include building heights, room sizes, window height and sizes, construction type, door sizes, building materials, fixtures and components. Previous studies and field investigations stated that standard room sizes in Nigeria range between 10-13 square meters (Adeleye 2014; Guardian contractors 2017). Nigeria windows sizes in residential buildings are between (1.2 x 1.5) meters for bedrooms and (1.5 x 1.8) meters for sitting rooms or bigger rooms. A fieldwork conducted by Adeleye (2014) indicated that most window sizes in Nigeria were 1.8 square meters (Adeleye 2014). Model data of typical residential buildings in Nigeria is recorded from literature materials, investigations, site experience. The information recorded includes dimensions of typical residential buildings in Nigeria – room sizes, window sizes, door sizes, head room, building height, roof height; construction, design, building composition and components, etc. These information helped in the identification and modelling of the base case model.

It is also important to note the airtightness of residential buildings in Nigeria. The air infiltration rate also described as unintentional ventilation (DesignBuilder 2019), is the rate of air inflow into the building through unconventional openings. The air change rate (ac/h) of typical Nigerian residential buildings based on previous field studies is 0.68 air changes per hour at 50 Pascals pressure (ACH50) (Odunfa K. M. et al. 2018; Gyoh 2020). This is due to the fact that the differential vapour pressure between the exterior and interior environment is little as the temperature difference between the indoor and outdoor are about 2-3 degrees Celsius (Gyoh 2020).

4.2. Residential Building Typology in Nigeria

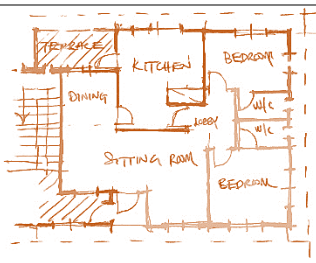
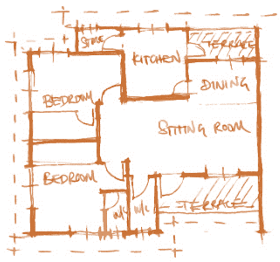
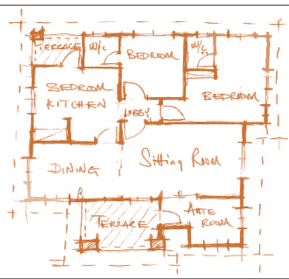
As a result of relatively similar weather conditions across the states of Nigeria, modern buildings typologies are similar and consistent in the country. According to the Executive Summary of the Nigerian National Building Energy Efficiency Code (BEEC), the research conducted primarily at the Federal Capital Territory of Abuja is adoptable by all states in Nigeria (Arup 2016; Arup (Madrid & Lagos offices) and Design Genre 2016).

The Nigerian National Building Energy Efficiency Code (BEEC) based on its studies of residential building projects in Nigeria puts forward three representative building typologies as identified from the Nigerian building stock (Solid Green Consulting 2017).

They include:

- Multi-unit apartments
- Bungalows duplexes
- Bungalows

Table 58: Typical residential building typology in Nigeria (BEEC)

Typology	Multi-unit apartment	Bungalow duplex	Detached Bungalow
Geometry			
Design			
Description	A multi-unit apartment is a combination of several residential accommodations usually separated by a party wall. They could share common facilities like stairs.	Bungalow duplex is a semi-detached storey building with two apartments separated usually with a party wall.	The detached bungalow in the Nigerian context is a one storey building usually with two to five bedrooms, living room(s), kitchen(s), bathrooms, and toilets.
	The bungalow is the most common and most built in Nigeria as identified in these studies		

The three residential building typologies are similar in terms of construction, material, and apartment organisation/design, building elements such as the size of rooms, doors, windows, etc. It is important to note that the detached residential bungalow is identified as the typical building typology by the Federal Ministry of Power, Edge and GIZ in a study done in Nigeria to improve by 20% the efficiency (in energy, water, and embodied energy in materials) of Nigerian Buildings (Federal Ministry of Power 2017; GIZ 2020). According to Arup (2016), the bungalow is a popular family home in Nigeria with three bedrooms, a living room, a kitchen, a bathroom, and a toilet. The bungalow house is the most popular residential building in Nigeria (Arup (Madrid & Lagos offices) and Design Genre 2016). According to a study conducted by Awosusi (2018), the report concluded that to a large extent, the bungalow building is the most popular residential and commercial house in Nigeria due to the fact that they are economical to build while maintaining luxury and durability (Awosusi 2018). According to Biobaku (2018), bungalows are largely affordable to maintain, and it is built across several neighbourhoods of Nigeria (Biobaku 2018). This is true because most residential developments are executed by private individuals with low income who can't afford larger buildings as a typical bungalow, it is also far cheaper and easier to build (Bankole 2019). Previous research done in Nigeria reports that most Nigerian residential buildings are low-rise structures (Aduwo et al. 2013). The study conducted in students' residences in Nigeria revealed that 75% of residents were low rise residential buildings. Another research by Jiboye (2014) through a questionnaire survey, employed a stratified systematic sampling method to select 406 (10%) households from three (3) major residential districts of Osogbo, Nigeria. The data were analysed using descriptive statistics and one-way analysis of variance (ANOVA). The study revealed that 80% and 14.8% of the respondents live in contemporary vernacular houses usually called "face-me-I-face-you" bungalows houses, and apartment houses (mostly detached bungalows), respectively, whereas, 2.5%, 1.5%, and 1.2% of the respondents live in duplexes, single-family houses, and traditional courtyard dwellings, respectively (Jiboye 2014).

4.3. Conventional Nigerian residential building construction method

The following construction method/process for Nigerian residential buildings is based on findings from literature, investigations and site experience. Buildings are mostly constructed in-situ in Nigeria. The foundation style are usually strips, a layer of about 25mm blinding is cast into the excavated strips of about 600mm depths and this is followed by casting of 100-150mm of concrete as foundation footing, reinforcement is placed where required and blocks are laid to the damp proof course (DPC) usually about 600mm above ground level.

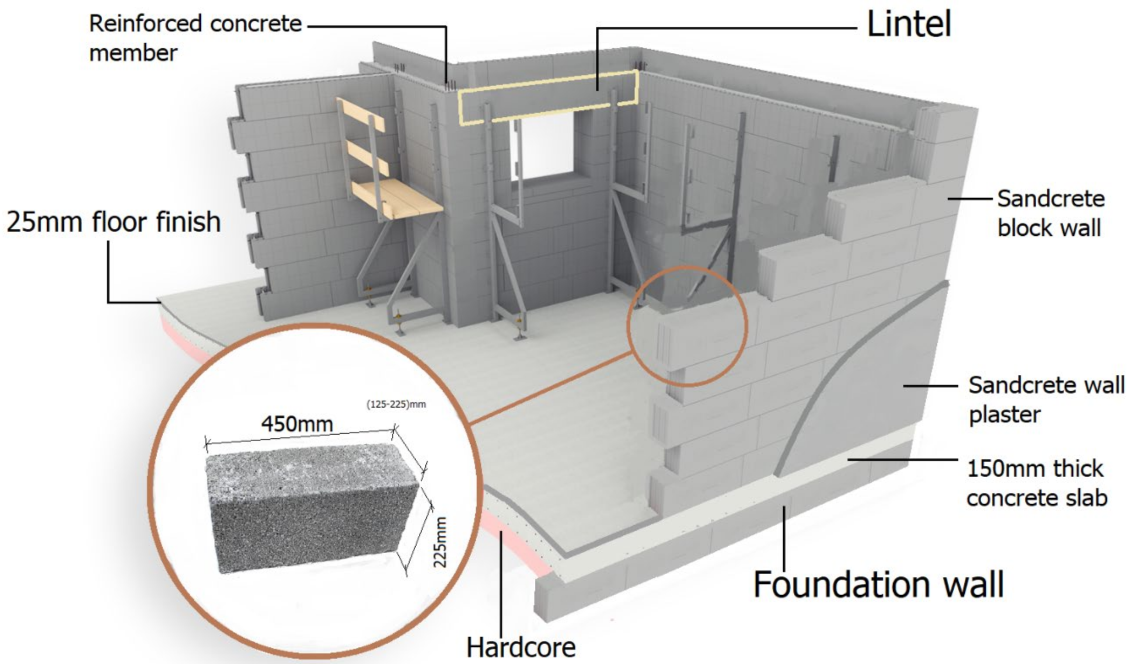


Figure 54: Model of building construction in Nigeria

The partitions are filled to DPC level and compacted with earth and hardcore before 150mm thick oversite concrete floor slab is cast. Laying of blocks is continued for perimeter and partition walls and other structural works predominantly cast with concrete are done alongside such as lintels, beams, columns, slabs, etc. Sandcrete blocks are usually used for laying. In Nigeria, sandcrete blocks are made from cement with a sand ratio of about 1:8, and water (Denis et al. 2002). They are compressed rectangular blocks which can either be hollow or solid with the most common measuring (150x225x450)mm. The blocks are joined with mortar. Windowsill levels are usually at 900mm from DPC and lintel height is typically 2100mm from DPC (Adeleye 2014; Guardian contractors 2017). The ceiling is done at 3 meters from DPC and timber roofing is done at about 500mm from lintel level. Roof pitch could be as high as 6 meters. The roofs are usually not ventilated and insulated and often roofed with dark colour aluminium roofing sheets. The walls are plastered with sandcrete of a higher mix ratio of cement and the floors are usually 25mm thick finished with tiles, sandcrete, plaster, terrazzo, carpet or rug. Windows are usually protected by burglar-proofs and single glazed tinted or clear windows are installed with fabric blinds or curtains on windows. The ceiling is usually done using asbestos ceiling boards, PVC (Polyvinyl Chloride) or POP (Plaster of Paris) (Denis et al. 2002). Walls are painted and wooden or steel doors are installed.

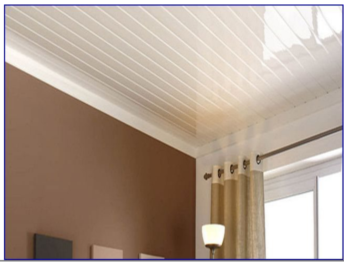
4.4. Typical Nigerian residential building design information/description from literature instigations and site experience

The properties of major Nigerian building materials are put below after a review of studies and field work to extract material data (Engineering ToolBox 2003; Olatunde 2011; Gyoh 2017; Ochang et al. 2018; Ogunrin 2019; Gyoh 2020).

Table 59: Typical Nigerian residential building design information/description

Building Structure	Building component	Typology of building components	Size/ Thickness	Material properties	Most used in Nigeria
Roof	Roofing sheets	Typical Nigerian roofing sheets include (Isinkaye and Agbi 2013; Akanni et al. 2014): Aluminium long spans, This is one of the most sought after in Nigeria, although not as strong as stone-coated roofing sheets. It is known for its durability and long-lasting nature. 	0.40mm, 0.45mm, 0.50mm, 0.55mm (gauges)	**Thermal Conductivity:** 205W/m-K **Specific Heat:** 880J/Kg-K **Density:** 2800Kg/m^3	Long span Aluminium, 0.45mm gauge 
		zinc, Zinc roofing sheets has been an old-time roofing material that is hardly used in present-day construction due to its poor durability and corrosive nature. 	0.40mm - 0.7mm	**Thermal Conductivity:** 110W/m-K **Specific Heat:** 388J/Kg-K **Density:** 7200Kg/m^3	
		Asbestos, Asbestos roofing is an aged material used in Nigeria due to its ability to absorb heat and resist corrosion. However, it is not environmentally friendly, consequently, asbestos is banned in many western countries due to health and environmental issues associated with it. 	4.50mm – 6.00mm	**Thermal Conductivity:** 0.85W/m-K **Specific Heat:** 837J/Kg-K **Density:** 2000Kg/m^3	
		Stone Coated sheets	0.40mm – 0.55mm	**Thermal Conductivity:** 810W/m-K **Specific Heat:** 840J/Kg-K **Density:**	

	This is popular roofing in Nigeria, it is durable and elegant and is regarded as the most lasting roofing sheet in Nigeria. The sheets are coated with chips of stones on acrylic film to strengthen, increase durability and beauty. 		$1700Kg/m^3$	
Roof trusses	<u>timber trusses</u> The most common roof trusses used in Nigeria for the construction of residential buildings are timber as it is cheaper and readily available (Akanni et al. 2014) 	50mm x 50mm, 50mm x 75mm, 50mm x 100mm, 75mm x 150mm (Akanni et al. 2014)	**Thermal Conductivity:** 0.17W/m-K **Specific Heat:** 2000J/Kg-K **Density:** $800Kg/m^3$	50mm x 50mm, 50mm x 75mm, 50mm x 100mm, (Akanni et al., 2014)
	<u>Steel trusses</u> Steel trusses are hardly used in residential buildings in Nigeria due to cost and technicality (Akanni et al. 2014). 	50mm x 50mm, 50mm x 75mm, 50mm x 100mm, 75mm x 150mm	**Thermal Conductivity:** 45W/m-K **Specific Heat:** 480J/Kg-K **Density:** $7800Kg/m^3$	
Roof ventilation	Most roofs of Nigerian residential buildings are not ventilated. 	-	-	Mostly not ventilated.
Ceiling	POP (Plaster of Paris)  	The sizes and thickness of POP vary depending on design and fixture.	**Thermal Conductivity:** 0.11-0.19W/m-K **Specific Heat:** 1800-2400J/Kg-K **Density:** $1525-1725Kg/m^3$	The most used is asbestos and PVC.

		PVC (Polyvinyl Chloride) 	PVC are usually 5mm thick laid on timber noggins.	**Thermal Conductivity:** 0.19W/m-K **Specific Heat:** 840 - 1170J/Kg-K **Density:** 1400Kg/m^3	
		The ceiling is usually done using  asbestos ceiling boards (Denis et al. 2002).	The asbestos is usually 3mm thick laid in 1200mm x 1200mm, 600 x 600mm.	**Thermal Conductivity:** 0.30-0.74W/m-K **Specific Heat:** 1000J/Kg-K **Density:** 1000-1900Kg/m^3	
	Roof height	Nigerian residential buildings are typically highly pitched due to heat transmission from the heated roof into the interior space by convection. 	4m – 8m roof height	-	5m
	Roof Shading	Roof shading is usually provided by eaves and porches.	450mm - 600mm width	-	-
	Terrace and balcony	Nigerian residential buildings are generally characterised by terraces and balconies 	-	-	-
	Roof Colour	Residential buildings are typically dark in colour. These colours vary from red, blue, green, off-white with Black and Brown as the most common. 	-	-	Black and Brown
Super-structure	Headroom	Head rooms in Nigerian residential buildings are mostly 3 meters high (i.e. from floor to ceiling). 	Typically, 3 meters headroom	-	3 meters
	height	Residential buildings in Nigeria are usually between 3.3m to 4.0m high, that is from DPC (damp proof course to roof eave and 6.0m – 6.6m for one storey buildings with an incremental of about 3.0meters for multi-storey.	3.3m – 4.0m	-	3.5 meters

windows	Windows are usually single glazed with a dimension of 1200mm x 1500mm for standard rooms, 1800mm x 1500mm for sitting rooms, 600mm x 600mm for toilet windows and 1200mm x 900mm for kitchen windows.   	1200mm x 1500mm, 1500mm x 1500mm (Olufemi, 2014)	A single glazed bronze window between 5-6mm thick. **Thermal Conductivity:** 0.84W/m-K **Specific Heat:** 840J/Kg-K **Density:** 2500Kg/m^3	1200mm x 1500mm for rooms, 1200mm x 900mm for kitchen, 600mm x 600mm for toilet, 1800mm x 1500mm for sitting rooms. (Olufemi, 2014)
Openings/ Arches	Openings/Arches are done usually at terraces or balconies and they are usually a beam or arch overhead.	The width or height varies depending on the area to span, usually not more than 6 meters	-	-
Blinds	 Curtains or blinds in Nigeria are usually fabric material and may be thick, light or dark to prevent unwanted daylighting. They are also used for decoration and privacy.	They usually extend beyond the width and height of the windows	The fabric properties of blinds vary.	-
Glazing	 Single Glazing is the common type with aluminium frames and tinted or clear glass	The typical width of glass varies from 4mm – 6mm. Size of glazing is usually within window sizes of 1200mm x 1500mm, 1500mm x 1500mm (Adeleye 2014)	**Thermal Conductivity:** 0.84W/m-K **Specific Heat:** 840J/Kg-K **Density:** 2500Kg/m^3	1200mm x 1500mm, 1500mm x 1500mm
Doors	Doors are usually made of wood and steel. A few doors consist of aluminium and glass with curtains where necessary.	Basic door sizes are (900-1500)mm x 2100mm	**Thermal Conductivity:** 0.19W/m-K	900mm x 2100mm. The most used are wooden door

			Specific Heat: 2390J/Kg-K **Density:** 700Kg/m^3	
Wall Cladding	 Wall cladding is usually done using slate stones, sliced rocks, ledge stones, cobblestones, marble stones, granite stones, they are usually 600mm x 150mm and have a thickness of 15mm which could be laid in panels contractors (Guardian contractors 2017). They also give protection to the wall.	They are usually 600mm x 150mm and have a thickness of 15mm.	The property of wall cladding would vary greatly depending on the stone type. Below are the properties of granite stone. **Thermal Conductivity:** 3.49W/m-K **Specific Heat:** 840J/Kg-K **Density:** 2880Kg/m^3	Slate stones in panels are most used
3D wall panels	 3D wall panels are also used although not very common in usage.	The sizes and thickness of 3D wall panels vary greatly depending on design, material composition, etc.	The thermal properties also vary accordingly.	
Wall ceramic tiles	Wall ceramic tiles are laid with sand and cement with water. 	Wall tile thickness in Nigeria is approximately 9mm. While the combined thickness with mortar is about 25mm	**Thermal Conductivity:** 1.20W/m-K **Specific Heat:** 850J/Kg-K **Density:** 2000Kg/m^3	Wall ceramic tiles are mostly used in Bathrooms, Kitchens, and toilets.
Wall Types	Block: Block types include – solid block, hollow block. They are made from a mixture of either fine or coarse aggregate, cement, and water. 	(125x225x 450)mm (150x225x 450)mm	**Thermal Conductivity:** 1.00W/m-K **Specific Heat:** 840J/Kg-K **Density:** 1935Kg/m^3 Mix ratio of 1:8 (cement: aggregates)	(150x225x 450)mm

Hollow block		(225x225x 450)mm	**Thermal Conductivity:** 0.86W/m-K **Specific Heat:** 860J/Kg-K **Density:** 2085Kg/m^3 A mix ratio of 1:6 (cement: aggregates)	
Brick	Compressed earth 	(230x180x 115)mm (300x150x 100)mm	**Thermal Conductivity:** 0.72W/m-K **Specific Heat:** 840J/Kg-K **Density:** 1920Kg/m^3	(300x150x 100)mm
Concrete	: 	Width is usually about 125mm to 300mm	**Thermal Conductivity:** 1.40W/m-K **Specific Heat:** 840J/Kg-K **Density:** 2100Kg/m^3 Mix ratio: 1:2:4	They are rarely used for building wall construction.
Paint	Paint varies from flat, satin, semi-gloss, and gloss.	The coating is usually 001" inch or 1 mil.	-	-
Plastering	Sandcrete walls with cement consist of a mixture of sand, cement and water to form a paste for wall rendering. 	Rendering thicknesses are usually between (20-25)mm	**Thermal Conductivity:** 1.00W/m-K **Specific Heat:** 1000J/Kg-K **Density:** 1800Kg/m^3	25mm

Sub-structure	Floor finish	Floor finishes are done using tiles, sand Crete, sand Crete covered carpet or rug, terrazzo. Ceramic tiles 	Floor finish thicknesses are between 20mm-25mm	**Thermal Conductivity:** 0.80W/m-K **Specific Heat:** 850J/Kg-K **Density:** 1700Kg/m^3	Ceramic tiles are usually used
	Rubber Carpet	Rubber Carpet, although recently this floor finish is rarely used as ceramic tiles are preferred. 	They are usually very thin, about 0.5mm in thickness.	**Thermal Conductivity:** 0.40W/m-K **Specific Heat:** 1000J/Kg-K **Density:** 1380Kg/m^3	
	Concrete Floor Slab		The concrete floor slab is usually 150mm thick	**Thermal Conductivity:** 1.13W/m-K **Specific Heat:** 1000J/Kg-K **Density:** 2000Kg/m^3	
	Rug		This floor cover is gradually going out of common use in Nigeria. Thickness varies depending on the type. About 7mm	**Thermal Conductivity:** 0.06W/m-K **Specific Heat:** 1360J/Kg-K **Density:** 198.40Kg/m^3	

Floor Terrazzo		Terrazzo may get up to 25mm thickness.	**Thermal Conductivity:** 1.80W/m-K **Specific Heat:** 800J/Kg-K **Density:** 2560Kg/m^3	
Slab	Slabs in Nigerian residential buildings are usually concrete slabs. Suspended floors are reinforced with steel. 	Typical slab thickness is between 100mm – 150mm.	**Thermal Conductivity:** 1.13W/m-K **Specific Heat:** 1000J/Kg-K **Density:** 2000Kg/m^3	Most used is 150mm
Foundation Filling	Residential buildings in Nigeria are usually filled with earth to Damp proof course (DPC) and then compacted before slabbing. Earth Filling. 	Usually, Earth filling extends to DPC level from Natural ground level (NGL).	**Thermal Conductivity:** 1.30W/m-K **Specific Heat:** 713J/Kg-K **Density:** 2200Kg/m^3	Earth filling is mostly used with sandstone, earth, and debris as hardcore.
Hardcore filling		Large stones/hardcore, also known as boulders are hardly used in residential buildings in Nigeria. Sizes are about 300mm	**Thermal Conductivity:** 3.49W/m-K **Specific Heat:** 840J/Kg-K **Density:** 2880Kg/m^3	

Debris Filling	In some cases, foundations are filled with site debris. 	The debris is usually of unequal sizes and comprises mostly construction waste.	Mainly sandstone **Thermal Conductivity:** 1.30W/m-K **Specific Heat:** 712J/Kg-K **Density:** 2200Kg/m^3	
Foundation Wall	 Foundation walls in Nigerian residential buildings are made of block walls which are usually solid or hollow.	Foundation walls usually are 600mm deep and could extend up to 600mm from Natural ground level	**Thermal Conductivity:** 0.86W/m-K **Specific Heat:** 860J/Kg-K **Density:** 2085Kg/m^3 A mix ratio of 1:6 (cement: aggregates)	Solid block foundations are the most used.
Foundation footing	The most common foundation type in Nigeria is the strip foundation. 	Foundation footing is done with concrete and has a base of about 150mm thickness. Column bases may be reinforced.	**Thermal Conductivity:** 2.20W/m-K **Specific Heat:** 840J/Kg-K **Density:** 2400Kg/m^3 Mix ratio of 1:3:6 (cement: aggregates)	Strip foundation is the most used in residential buildings in Nigeria.
Foundation excavation	Foundation trenches are usually dug to a depth of about 600mm and 550mm wide strips. 	600mm deep and 550mm strips	Soil - earth, common **Thermal Conductivity:** 1.28W/m-K **Specific Heat:** 880J/Kg-K **Density:** 1460Kg/m^3	600mm deep and 550mm strips

Chapter Five

5.0. Dynamic energy building simulation for a typical Nigerian residential building.

5.1. Introduction

As part of the objective of assessing passive design strategies for buildings in Nigeria, a base case is selected which represents the typical buildings in Nigeria. The simulation of a residential bungalow building located in Abuja of Nigeria is carried out using DesignBuilder to measure its Energy efficiency with emphasis on the use of passive design strategies for its construction. Abuja is an important site in Nigeria, not only as of the Federal Capital Territory but also as it represents the climate of Nigeria (Arup 2016; Federal Ministry of Power 2017). Previous research conducted primarily in Abuja with respect to the Nigerian National Building Energy Efficiency Code (BEEC) is adoptable by all states in Nigeria due to the relatively similar weather condition across all states of Nigeria, hence modern building typologies are similar and consistent across the country in terms of design, material, and construction (Arup 2016; Federal Ministry of Power 2017).

Weather data file for the location is collected and read in Climate Consultant to gather useful information as regards temperature range, wind velocity, illumination, solar radiation, relative humidity, ground temperature, etc. The weather data file is also inputted into DesignBuilder and the building is modelled considering passive design strategies. The building is comprised of two bedrooms with toilets, an open plan sitting room with a dining section and kitchen, as well as a store and terrace. Below is a brief description of the building data, other information is available under the appropriate headings.

The study is aimed at evaluating the energy consumption of a two-bedroom bungalow building located in Abuja, Nigeria (Base case) and possibly optimising it for best performance based on passive design strategies. The evaluation started by obtaining the relevant weather data file and further proceeded to simulate/analyse them using Climate Consultant. The study building is modelled with DesignBuilder using the measured base case data. Simulations are conducted for major passive design interventions (including building orientation, natural ventilation, daylighting, and thermal mass) to assess their performance on the base case. The investigation finally established the primary energy demand of the building in comparison with existing benchmarks.

5.1.1 Simulation Objectives

The central aim of this simulation is to assess the primary energy demand of the building based on its adopted design strategies of which reducing energy consumption is a major consideration as the thermal comfort range in Nigeria is between 23^{0}C to 29^{0}C (Gyoh 2020). To effectively achieve this, the objective of the simulation includes the following:

i. Assessment of building orientation
ii. Assessment of window to wall ratio
iii. Assessment of local shading and g-value
iv. Assessment of thermal mass
v. Assessment of daylighting
vi. Assessment of thermal insulation
vii. Assessment of natural ventilation
viii. Finally, determination of the dynamic energy demand of the building.

5.1.2. Base case (Detached two-bedroom apartment)

The figure below shows a detached two-bedroom residential bungalow building. The two-bedroom apartment building is one of the medium-income housing interventions approved by the Federal Government of Nigeria (Project: Construction of Residential Housing Units under the Partnership & Business Development Programme). The building typology is approved for construction in designated Nigerian states by the Ministry of Housing & Urban Development. The project is geared towards providing accommodation for the residents in Nigeria.

Figure 55: Front and side elevations of base case

It is important to note that the building is a typical representation of the Nigerian building stock, it has been established as the base case for works of research conducted in Nigeria by the

Federal Ministry of Power, Arup, Edge, and GIZ in a study done to improve the efficiency (in energy, water, and embodied energy in materials) of Nigerian Buildings (Arup (Madrid & Lagos offices) and Design Genre 2016; Federal Ministry of Power 2017; GIZ 2020). As previously mentioned, the bungalow is the most common residential building type in Nigeria as a popular family home with about two bedrooms, a living room, a kitchen, a bathroom, and a toilet (Arup (Madrid & Lagos offices) and Design Genre 2016). According to Awosusi (2018), the bungalow house is the most popular residential building in Nigeria. Awosusi (2018), reported that to a large extent, the bungalow building is the most popular residential and commercial house in Nigeria due to the fact that they are economical to build while maintaining luxury, affordability to maintain, and durability, and they are built across several neighbourhoods of Nigeria (Awosusi 2018; Biobaku 2018).

The residential building is comprised of two bedrooms, a sitting room, a kitchen to a store, and one entrance terrace. The compounds are 80.31% interlocked (pavement), which is the same for the building type in the estate.

Figure 56: Front view of Base case Building

5.1.3. Building location context

According to Stewart and Oke (2012) Local Climate Zone classification, the local climate Zone (LCZ) of the building's location from its metadata (with Google Earth) falls mainly under the open low-rise of the built types. This is classed under the LCZ 5 and 6. This area has an open arrangement of low-rise buildings with an abundance of pervious land cover of low plants, scattered trees and construction materials consisting of wood, tile, stone, brick, concrete, steel and glass (Stewart and Oke 2012).

Figure 57: Street view of Existing base case bungalow building

The building location is in a sparsely populated urban context as the area is designated for development.

Figure 58: A section of Housing units in the Estate

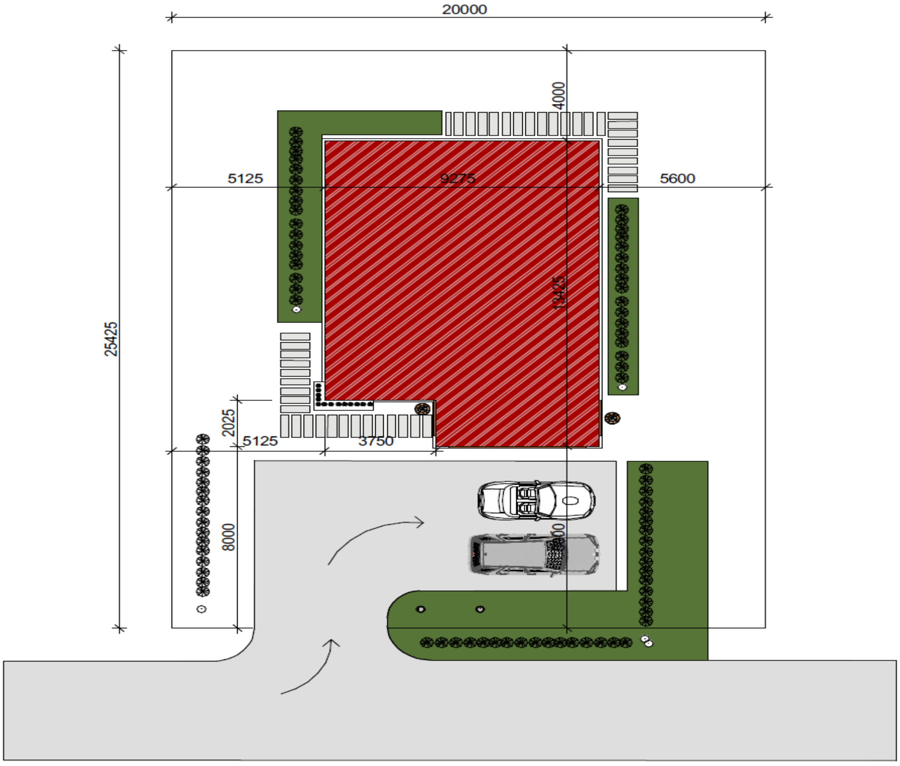


Figure 59: Site plan of Base case

Table 60: Site Usage	Area [m2]
Total Building Area	116.22
Net Conditioned Building Area	106.02
Unconditioned Building Area	10.20

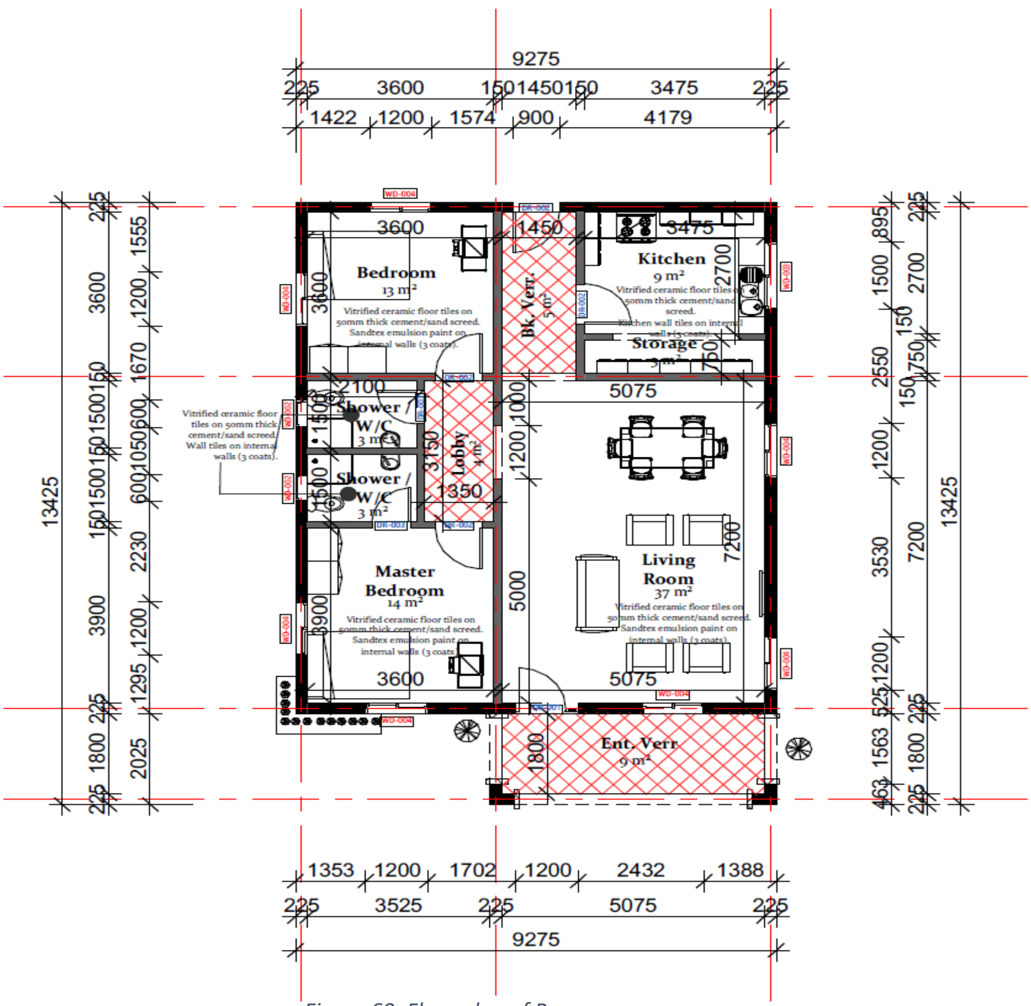


Figure 60: Floor plan of Base case

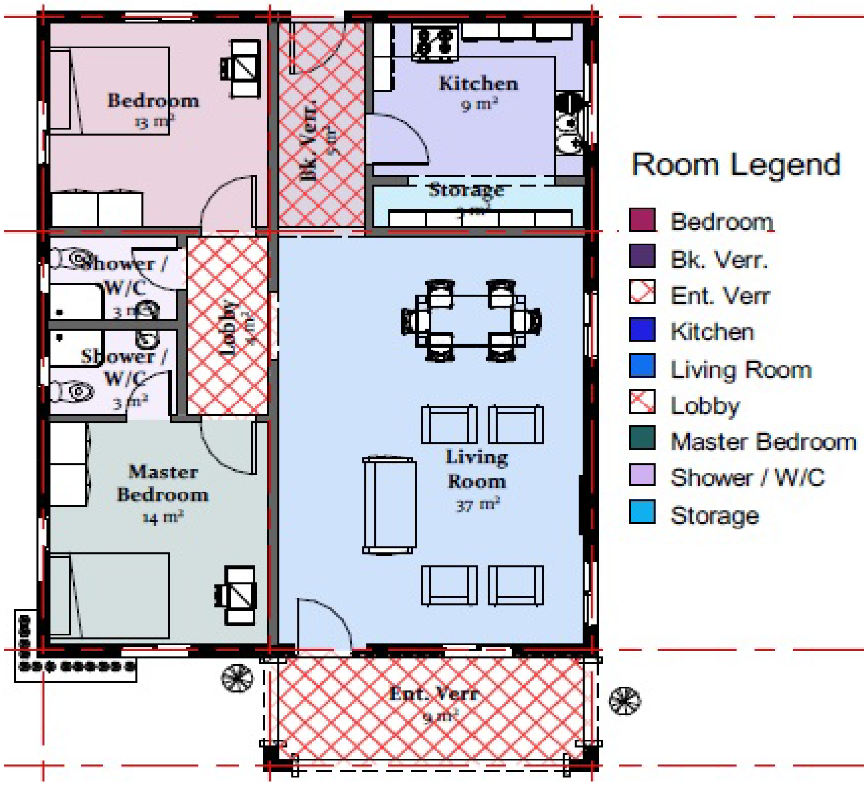


Figure 61: Presentation plan of Base case

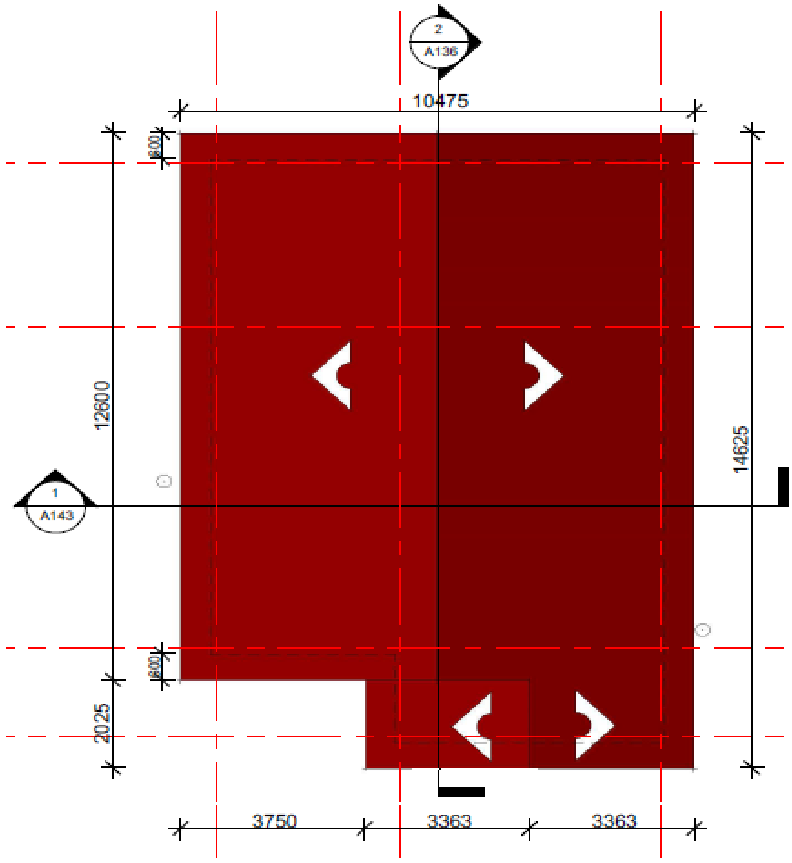


Figure 62: Roof plan of base case

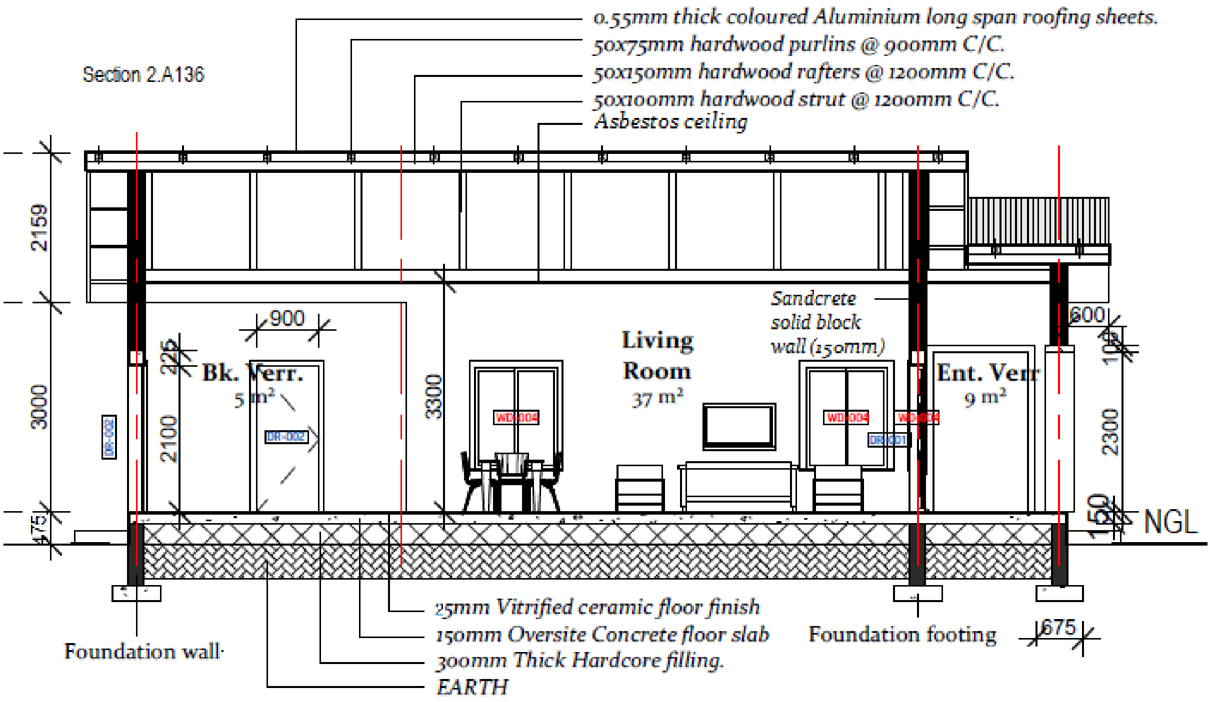


Figure 63: Longitudinal section of base case

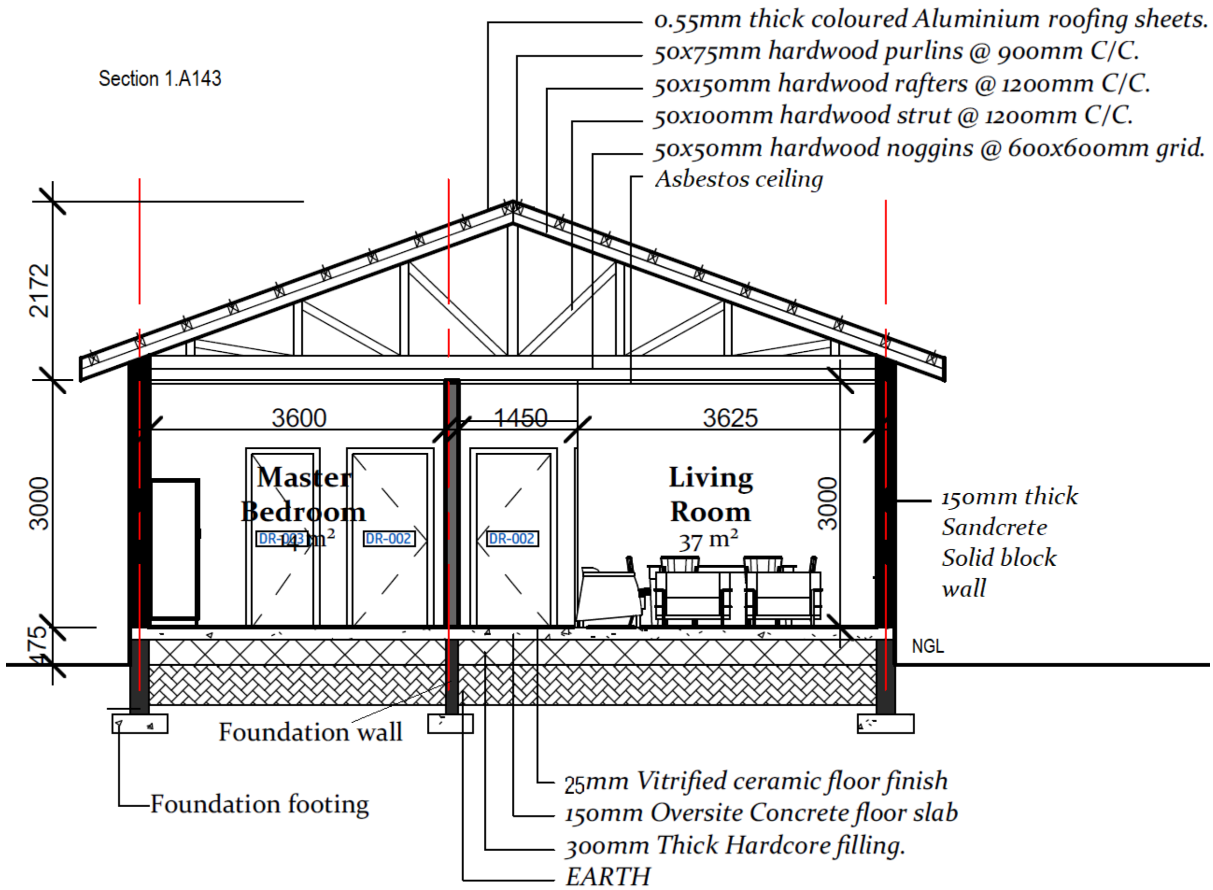


Figure 64: Transverse section of base case

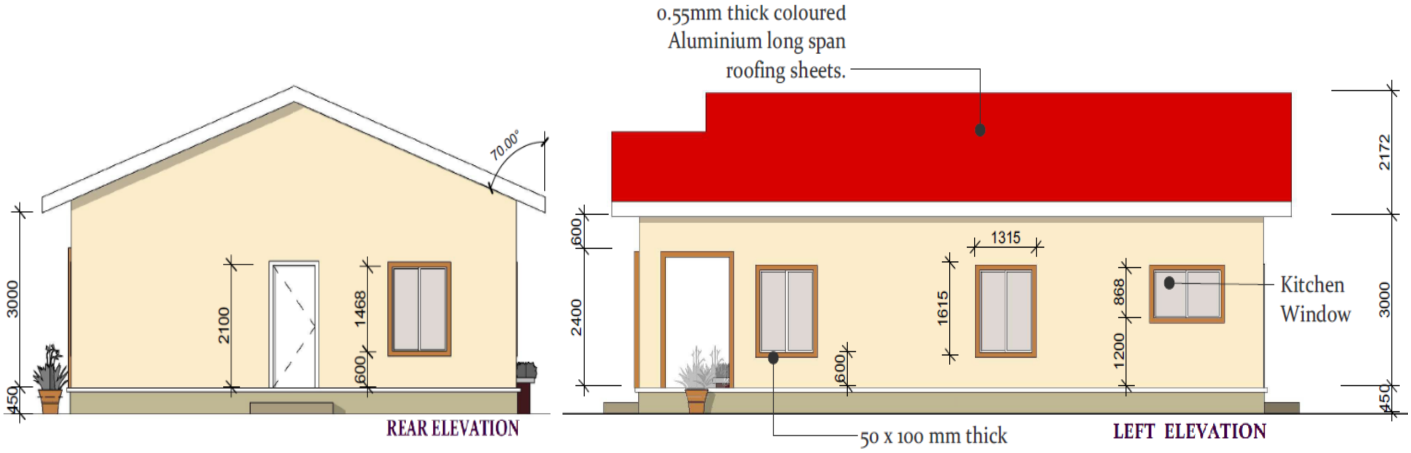


Figure 65: Rear and Left elevation of base case

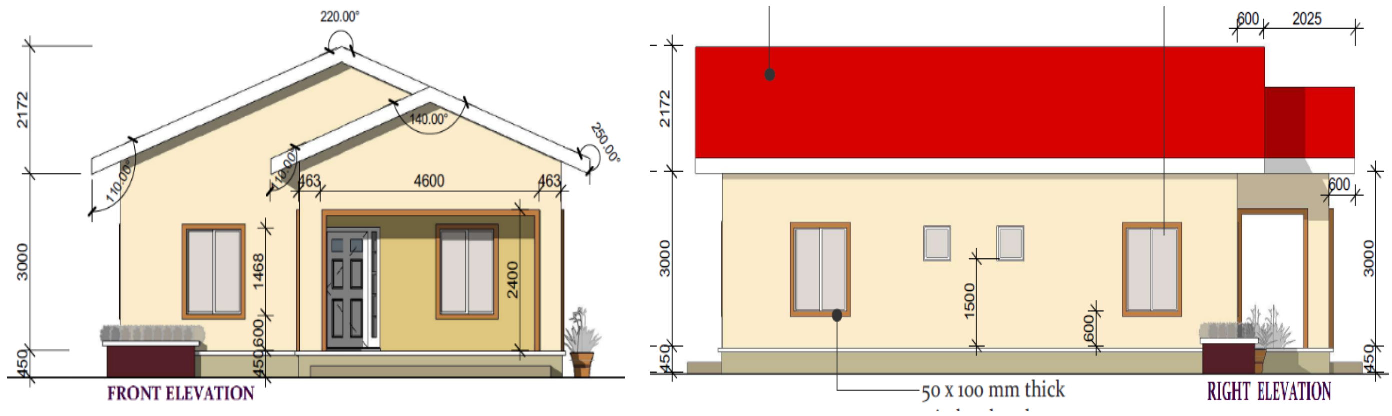


Figure 66: Front and Right elevation of base case

5.1.4. Building information

The building foundation is built on concrete strips with 150mm wide solid sand cement foundation block wall, the foundation height is 475mm from normal ground level to damp proof course. The internal and external walls of the building are constructed with 150mm solid sandcrete blocks with a thermal conductivity of 1.00W/m-K, Specific Heat of 840J/Kg-K, and Density of 1935Kg/m^3 (Coulibaly and Toguyeni 2014; Amstrong 2017; Gyoh 2017; SpecifiedBy 2018; GreenSpec 2020). These walls were then rendered or plastered with sand cement plaster of 25mm thickness given a total U-value of 1.48W/m^{2}K (DesignBuilder 2019). The interior walls are painted with white colour emulsion paint and exterior walls are painted with yellow. The window to wall ratio is 30%, all windows are glazed with aluminium sliding windows. The windows are also protected with burglar proofs by using metal grids, while curtains and mosquito nets are mounted on the windows. The main access door is made of steel while others are wooden doors. The ceiling material is asbestos ceiling boards painted with white emulsion paint. Using 50 x 50mm hardwood ceiling noggins the ceiling is fixed on spacings of 1.2 x 1.2 meters. The headroom of the building is 3 meters with an overall building height of 5.65 meters. The gable roof had a wooden fascia of 300mm wide and 25mm thick hardwood painted with blue emulsion paint. The entire roof is done with aluminium roofing sheets. The roof eaves are 600mm wide without any vents and the roof is not ventilated. The number of occupants is four in number.

5.1.5. Typical Construction information

The construction material properties were obtained from works of literature, codes, and standard of Nigerian building materials (such as thermal conductivity values, density, heat capacity, surface resistance coefficient, etc.), layers and calculations were done with DesignBuilder to obtain the U-values and other data for analysis.

Roof:

The roof is a gable of 2.17m in height. The roofing material comprises aluminium roofing sheets of gauge 0.55mm with a U-value of 7.14W/m^2- K. The roofing sheets are connected to timber purlins, purlins to timber rafters and timber ceiling noggins of 50mm x 50mm. Asbestos ceiling boards are then fixed to the noggins. The roof eaves are 600mm wide and the aluminium roofing sheet is red.

Exterior wall:

Exterior walls are constructed with sandcrete cement solid blocks of 150mm width, 225mm height, and 450mm length, which is laid with sand-cement mortar. The exterior walls are also rendered with 25mm sandcrete wall plaster bringing the total U-value to 2.70W/m^2- K.

Interior wall:

The Interior wall composition is the same as the exterior wall. 150mm width, 225mm height, 450mm length, laid with sand-cement mortar. The interior walls are also rendered with 25mm sandcrete wall plaster. However, the total U-value is 2.17W/m^2- K, due to convective heat transfer coefficient, radiative heat transfer coefficient and surface resistance differentials of both the inner surface and outer surface (DesignBuilder 2019).

Floor:

The substructure is constructed by filling the foundation with 300mm sandstone and debris up to damp-proof-course, thereafter, a 150mm thick oversite concrete slab was cast followed by ceramic floor tiles laid with sand-cement mortar to produce a combined thickness of 25mm. The total U-value of this installation is 1.68W/m^2- K (DesignBuilder 2019).

Windows:

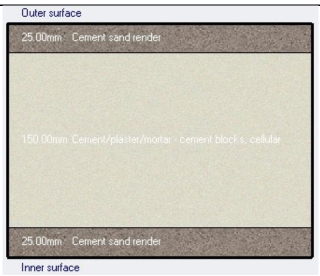
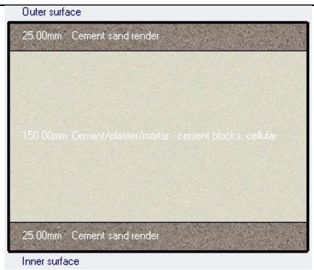
Windows were built with 40mm thick aluminum window frames and a single-glazed bronze glass of 6mm thickness. The glazing U-value is 6.12W/m^2- K. Window sizes varied which were divided by a vertical divider.

Doors:

Interior doors were constructed with timber measuring 50mm thick, 900mm wide and 2100mm in height with a U-value of 0.86 W/m^2- K. Exterior doors are made of steel measuring (50x1200x2100) mm having a U-value of 5.84 W/m^2- K (DesignBuilder 2019).

5.1.6. Construction Data

Table 61: Base Case construction data

Parameters	Representation	Total U-Value
Glazing		6.12W/m²- K
Roof	 	7.14W/m²- K Construction members: Aluminium roofing sheet of gauge 0.55mm
	 	7.06W/m²- K Ceiling asbestos 0.85W/m-K of thermal conductivity and thickness of 3mm.
Floor	 	1.68W/m²- K. Construction members: 10mm ceramic floor finish, 15mm thick cement floor screed, 150mm thick concrete floor slab, 300mm sandstone.
Exterior wall	 	2.70W/m²- K Construction members: 25mm thick sandcrete wall plaster, 150mm solid sandscrete block wall, 25mm thick sandcrete wall plaster.
Interior wall	 	2.17W/m²- K Construction members: 25mm thick sandcrete wall plaster, 150mm solid sandscrete block wall, 25mm thick sandcrete wall plaster.
Exterior Paving	 	3.41W/m²- K Exterior paving was done with sandscrete interlocking tiles of 80mm thick.
Exterior lawn	The green areas are about 5% of the unbuilt area.	Low grasses with few hedges.

5.1.7. Electrical installations and appliances in the building

The building had electrical installations which were taken into consideration for the purpose of accurate calibration. These electrical installations include electric light bulbs, standing fans, ceiling fans, electric cooker, television, and refrigerator. The type, number, and specification of appliances are given in the table below.

Table 62: Electrical appliances in Base case (specification)

S/N	Appliance type	Quantity	Specification
2	Ceiling fans	2	Power: 60W; Voltage: 240V
3	Standing fan	1	Power: 40W; Voltage: 230V; Frequency: 50Hz
4	Electric cooker	1	Voltage: 220V-240V; Frequency: 50Hz; Power: 1200W
5	Television	1	Voltage: 220V-240V; Power consumption (max): 60W.
6	Refrigerator	1	Voltage: 120V; Frequency: 60Hz; Power: 156W

Table 63: Electrical appliances in Base case (power density)

S/N	Appliance type	Quantity	Power density (W/m^2)
1	Ceiling fans	2	1.14
2	Standing fan	1	0.38
3	Electric cooker	1	11.32
4	Television	1	0.57
5	Refrigerator	1	1.47

5.1.7.1. Equipment Schedules

The use of equipment in the building were scheduled based on typical Nigerian domestic activity for residential buildings (Nairaland), Building Energy Efficiency Guideline for Nigeria - Federal Ministry of Power, Works, and Housing. The equipment schedules were done for the refrigerator, television, electric cooker, standing fan, and ceiling fans.

5.1.7.1.1. Electric cooker

Typically, in Nigerian residential/domestic homes, cooking is done approximately twice a day, however, electric cookers are usually used in the morning for light meals (breakfast) and gas cookers are used later (Nairaland 2014). This is due to the fact that people would prepare breakfast in the morning (around 6:30 to 7:30) and return after work in the evening to cook around 17:30 to 19:30 with gas cookers, gas cookers are also used predominantly during weekends (Nairaland 2014; Federal Ministry of Power 2017).

Therefore, cooking would normally start early in the morning for approximately 1hour on weekdays (WD) and in the evening for about 2 hours except for weekends (WE) and weekdays in the evening with gas cookers all through the day (Nairaland 2014).

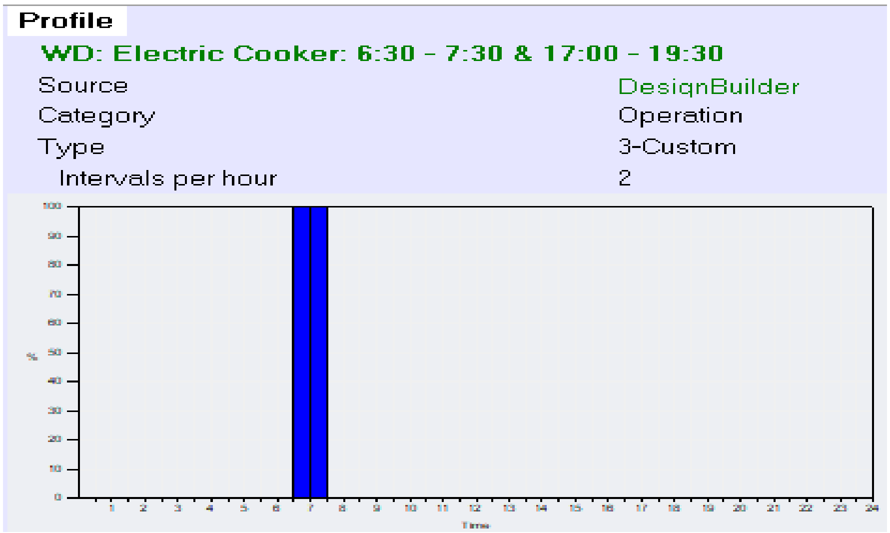


Figure 67: Weekday (WD) domestic cooking schedule

5.1.7.1.2. Refrigerator

The refrigerator is kept on constantly as indicated in the schedule below.

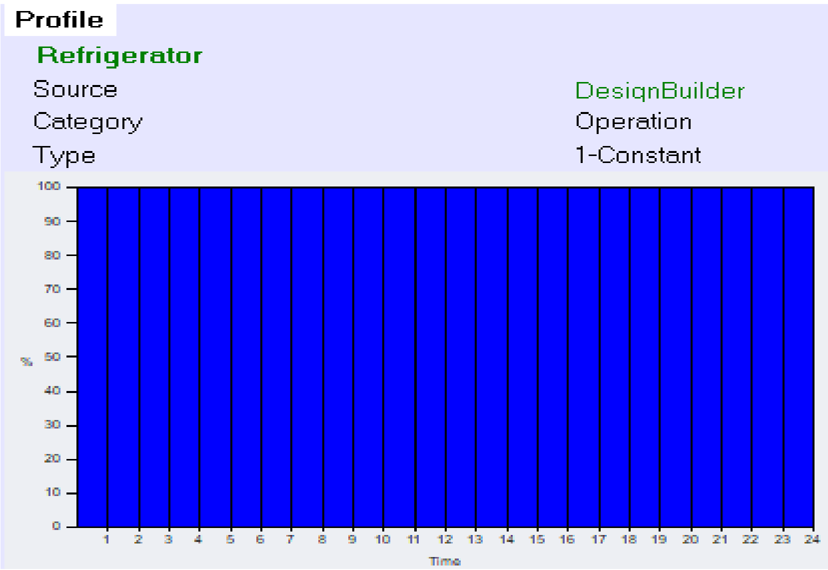


Figure 68: Refrigerator schedule

5.1.7.1.3. Television

The television schedule is broken into two categories as indicated by previous studies - Domestic, family weekday: 7:00 - 7:30 & 17:00 - 22:00 and Domestic, family weekend: 8:00 - 22:00 (Uyigue et al. 2009; Nairaland 2014; Solid Green Consulting 2017). This is due to the fact that working families would typically put the television on for about half an hour before going to work and turn it back on after returning from work in the evening, the television is usually turned on all day in the weekends as most occupants would be at home (Federal Ministry of Power 2017).

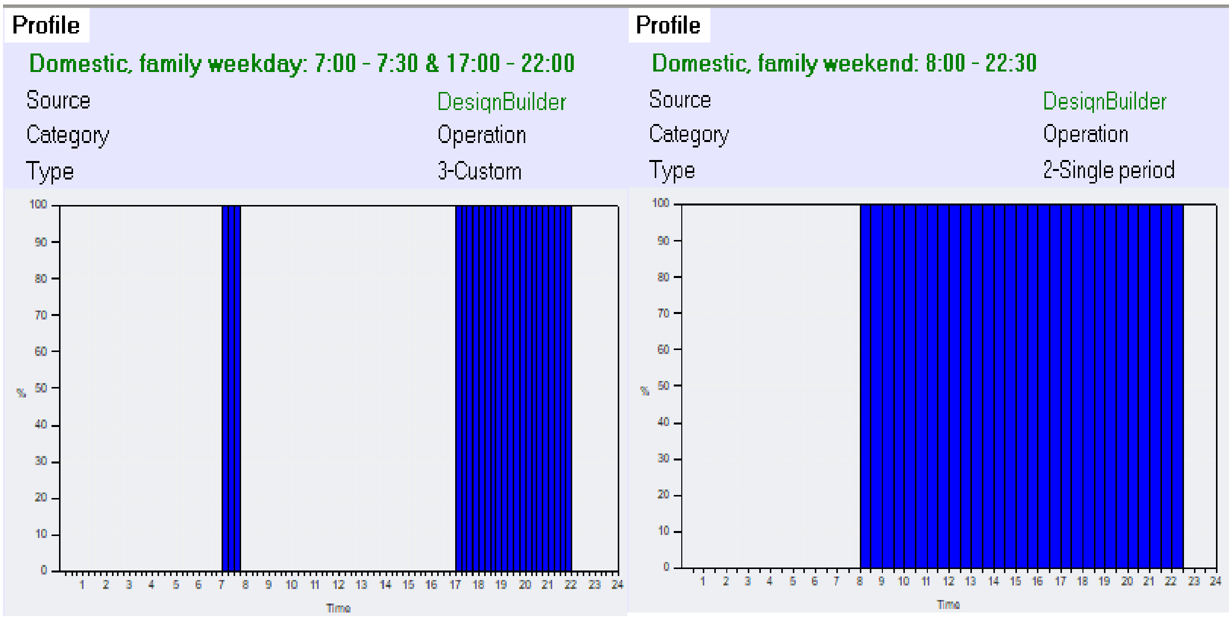


Figure 69: Television schedule for Domestic family weekday and weekend

Table 64: Television Schedule

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Feb	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Mar	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Apr	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
May	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30

Jun	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Jul	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Aug	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Sep	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Oct	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Nov	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30
Dec	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	7:00 - 7:30 & 17:00 - 22:00	8:00 - 22:30	8:00 - 22:30

5.1.7.1.4. Electric Fan

Typically, electric fans are usually turned in the evening from about 17:00 to 22:30 daily due to gradual heat build-up (Nairaland 2014; Federal Ministry of Power 2017; Ochedi 2018).

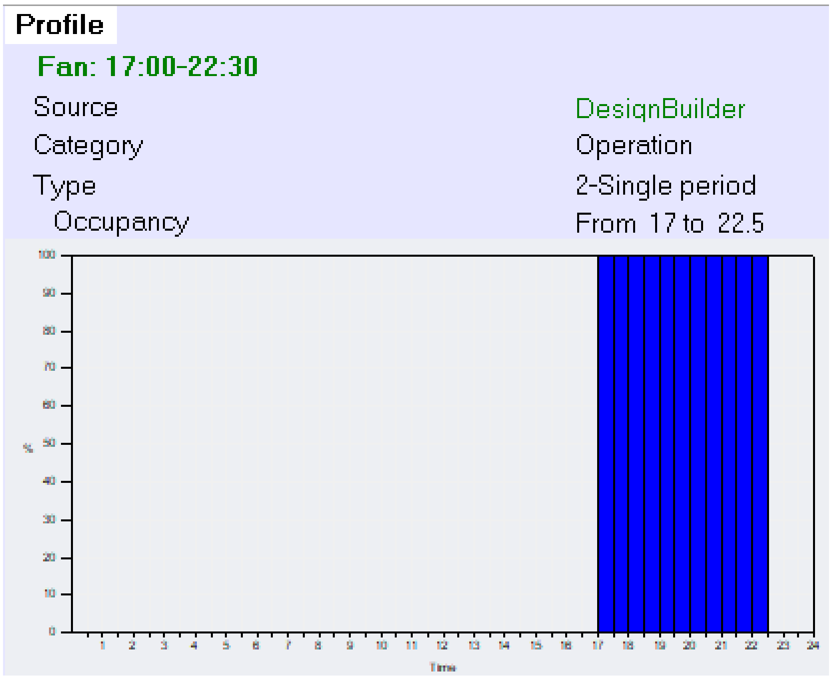


Figure 70: Electric fan schedule

5.1.8. Justification for Base case selection

The residential-detached bungalow is the most commonly built among the three popular building typologies in the Nigerian building stock as identified by the Nigerian National Building Energy Efficiency Code (BEEC) based on its studies of residential building projects in Nigeria (Solid Green Consulting 2017). The base case is identified as the typical building typology by the Federal Ministry of Power, Edge and GIZ in a study done in Nigeria to improve by 20% the efficiency (in energy, water, and embodied energy in materials) of Nigerian Buildings (Federal Ministry of Power 2017; GIZ 2020). Most Nigerian buildings are detached bungalows which is a popular family home in Nigeria with bedrooms, a living room, a kitchen, bathroom, and toilet (Arup (Madrid & Lagos offices) and Design Genre 2016). Detached two-bedroom bungalows are popular and cheaper to build usually by non-professionals, hence they are very many sub-standard, energy and resource inefficient residential-detached bungalows in Nigeria (Emmanuel et al. 2014; Amasuomo et al. 2017; Awosusi 2018; GIZ 2020). Therefore, the energy and resource-efficient strategies for this typology will mean that many Nigerian buildings would be more sustainable in terms of energy and resource whilst cutting CO_2 emissions (Bankole 2019).

5.1.9. Observations of the base case

1. The use of a dark coloured roof.
2. There is no roof ventilation or eave vents.
3. The windows are unshaded, exposed to East and West solar radiations.
4. The external and internal walling components are sandcrete solid block walls.
5. The windows are fitted with single sliding glazed windows which only opens 50% of the entire window, hence, reducing opening size by 50%.
6. The surrounding landscape is mostly paved without much lawn or trees.
7. There are no window shadings or other forms of shading aside from eaves on the building façade.
8. The longer façade of the building is exposed to the sun (East and West facing) with no shading.

5.2. Base-case building Modelling

The model was done on DesignBuilder using obtained building data from weather data files (.epw), site visits, building measurements and literature. The figure below shows the block plan of the two-bedroom apartment with each activity zone designated. All building data such as building height, room sizes, roof type, and component dimensions were used in the modelling. A measured architectural drawing of the base case was developed and all required parameters

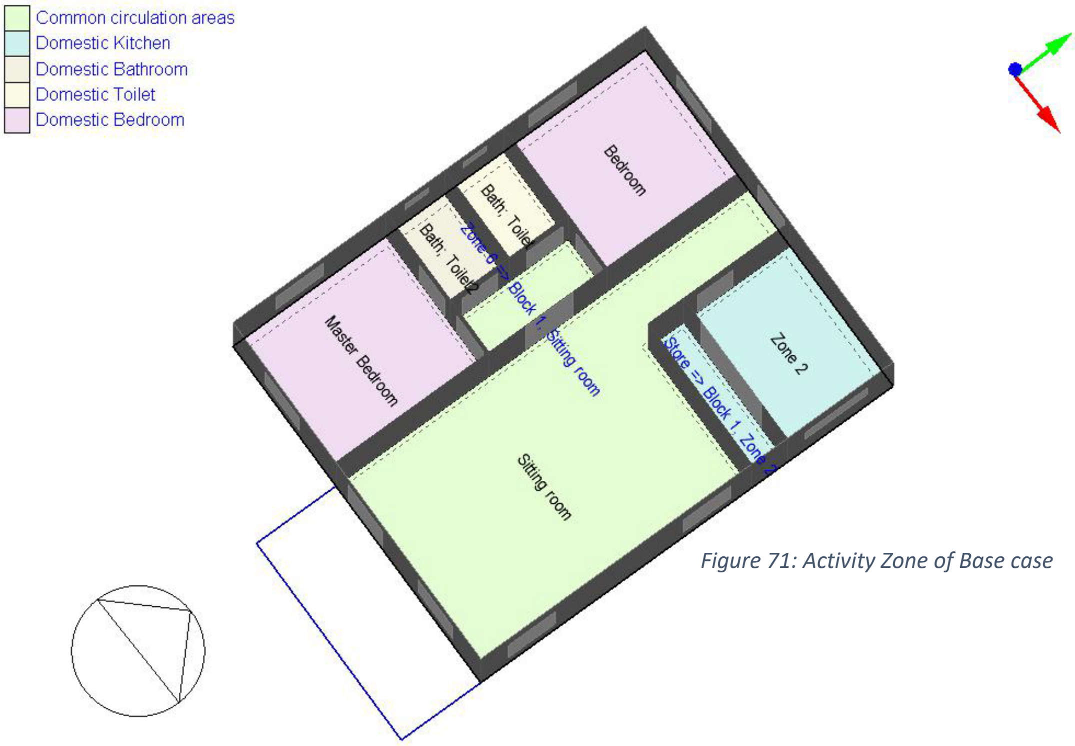


Figure 71: Activity Zone of Base case

were used to model the building with the appropriate construction materials. The material properties such as their various density, specific heat, thermal conductivity, and other relevant material properties were taken into consideration for the purpose of calibration. All electrical appliances in the study building were taken into consideration and represented in DesignBuilder. These included all-electric bulbs, refrigerator and freezer, television, electric cooker, standing fan and ceiling fan. An air change rate (ac/h) of 11.62 air changes per hour at 50 Pascals pressure (ACH50) was used which is typical for Nigerian residential buildings based on previous studies (Odunfa K. M. et al. 2018; Gyoh 2020). The occupancy density of 0.034pp/m^2 for 4 people living in the building was used (Federal Ministry of Power 2017). A metabolic factor of 1.00 was used with winter and summer clothing of 1.00 and 0.50 (clo) respectively. A minimum fresh air of 12litres/person was used, the power density calculated for general lighting was 6W/m^2 which is also recommended by BEEC for Nigerian buildings (Federal Ministry of Power 2017). This was followed by providing windows, doors, roof, etc. as in the existing building.

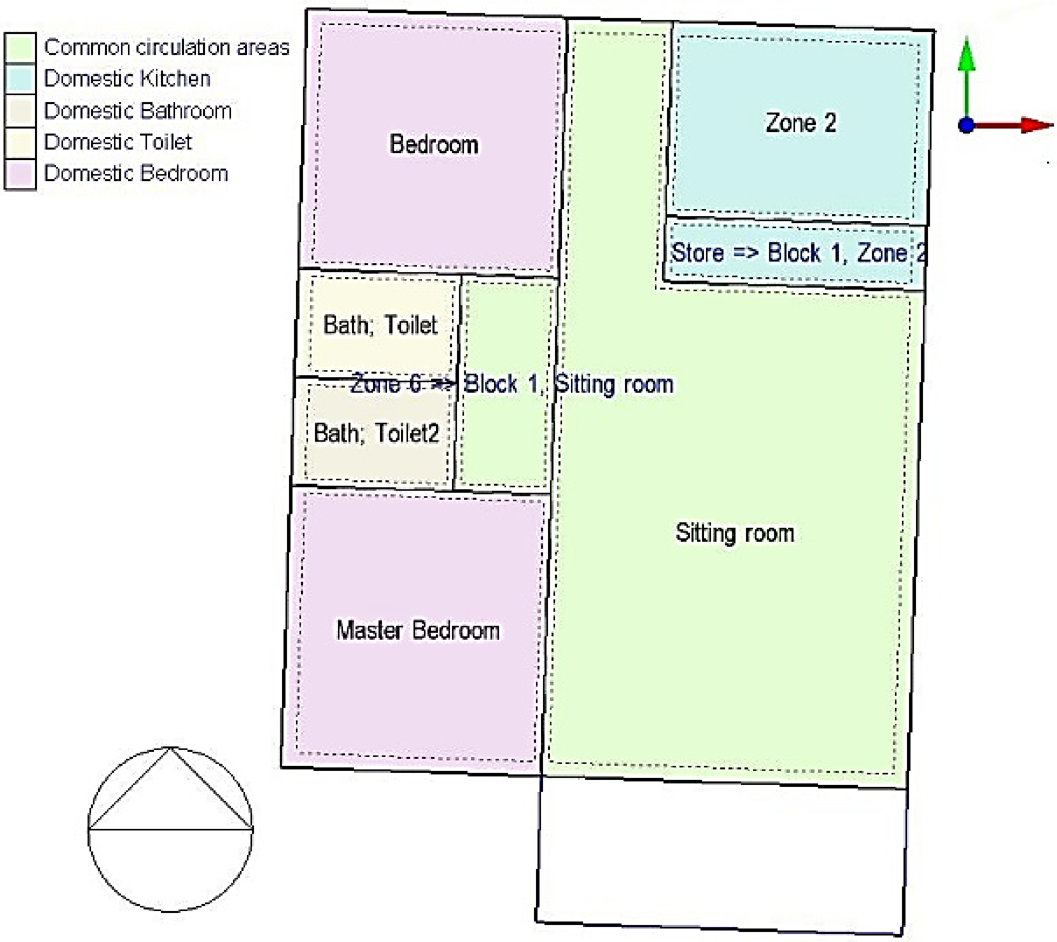


Figure 72: Building floor zone

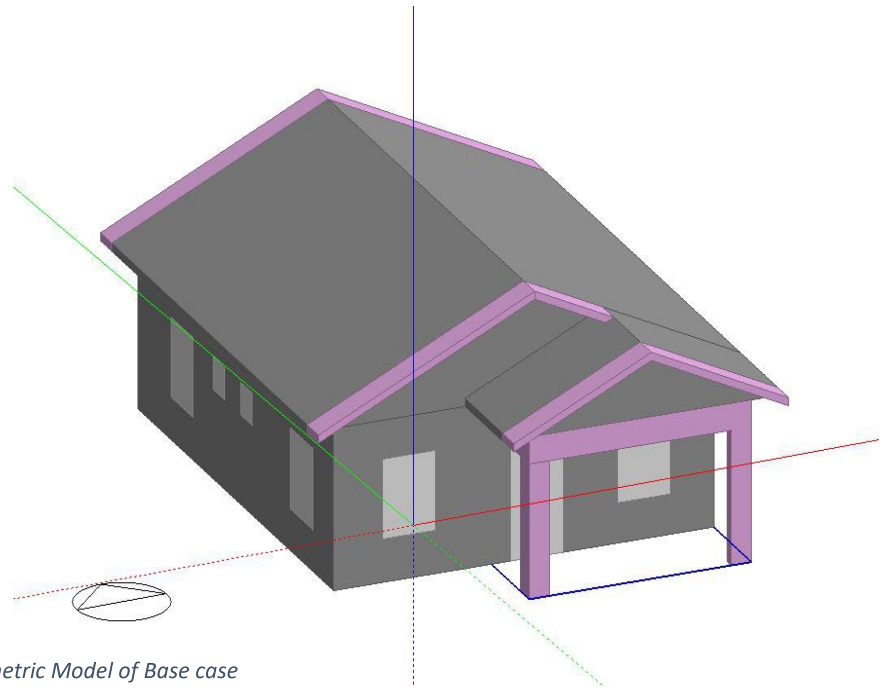


Figure 73: Axonometric Model of Base case

5.2.1. Calibration and Validation of Model

The building was modelled on Designbuilder and monitored to ensure that the site's air temperature, relative humidity, and wind speed were consistent with the model predictions. The data for the model simulation was obtained from a weather data site: (Climate.OneBuilding.Org) and read on Climate Consultant. The weather file for the study area was downloaded as an .epw file which consists of the climate data of the region. The file was uploaded into DesignBuilder in order to condition the building model with the real weather characteristics of the region. The quality of data downloaded from weather data sites such as OneBuilding, EnergyPlus, AccuWeather are known to be reliable and are widely used (Raftery et al. 2011; Coakley et al. 2014; Østergård et al. 2016).

The site data for comparison with the model predictions were obtained by taking measurements of the building's internal and external air temperature, and relative humidity, as well as measuring the site wind speed. This was done using measuring devices such as anemometer for measuring wind speed, thermometer for air temperature, and hygrometer for relative humidity. The measurements of the building were done at specific times of the day for 12 months. The specific times for measurements were 9:00 am in the morning and 6:00 pm in the evening, every day.

The readings revealed that temperatures are highest during the dry/wet seasons of February, March, April, and May with an annual average air temperature of 25.87^{0}C, an annual average operative temperature of 26.13^{0}C. It is important to note that the temperature of the building's location is highest in the month of March with a temperature mean of 31^{0}C and it is lowest in the month of August with a temperature mean of 24^{0}C. The average annual relative humidity was recorded at 84.5%.

Although the model predictions trace with the site measurements as a representation of reality. However, there were variances as can be seen in the graphs below, but overall the researcher found the data satisfactory. A comparison between the model predictions and site measurements is presented below.

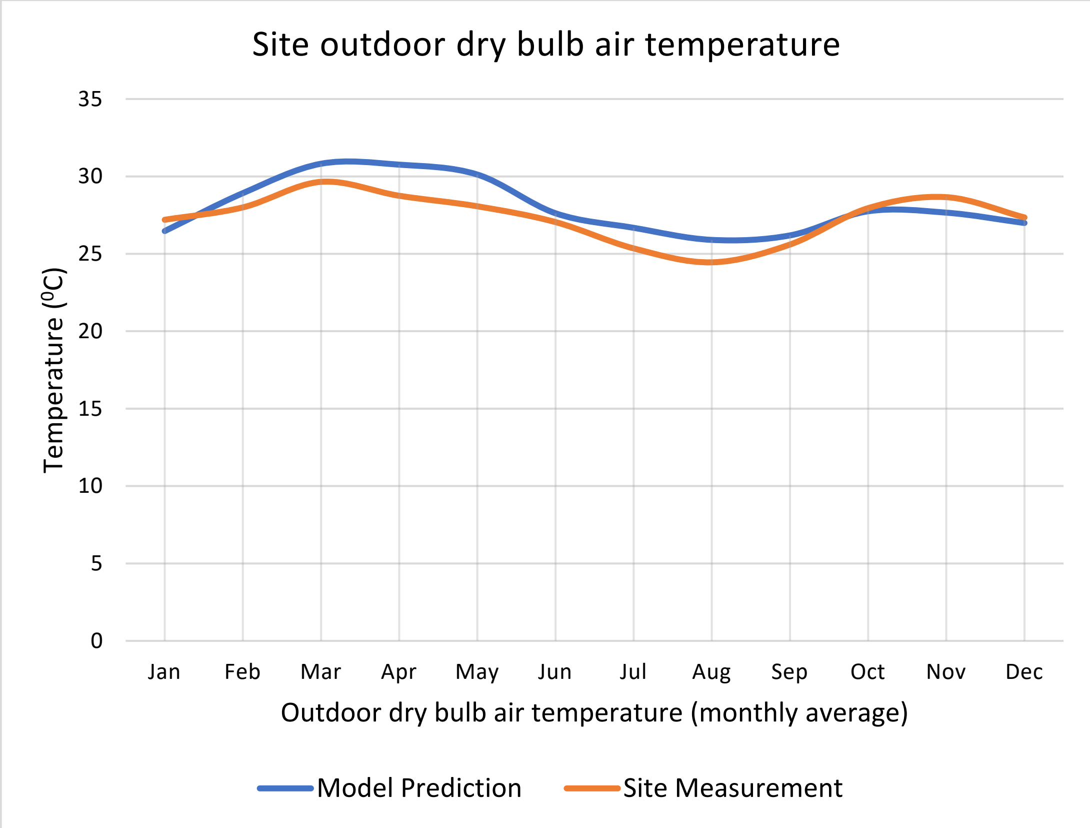


Figure 74: Outdoor air dry bulb temperature comparison between the model prediction and site measurement

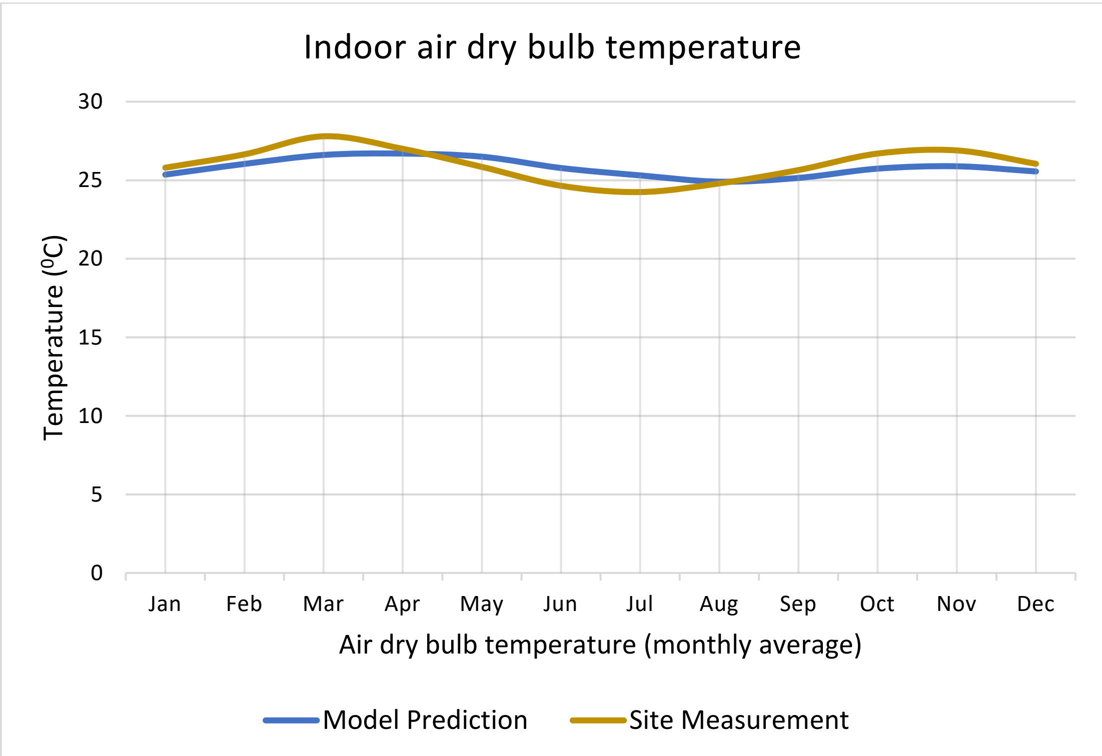


Figure 75: Indoor air dry bulb temperature comparison between the model prediction and site measurement

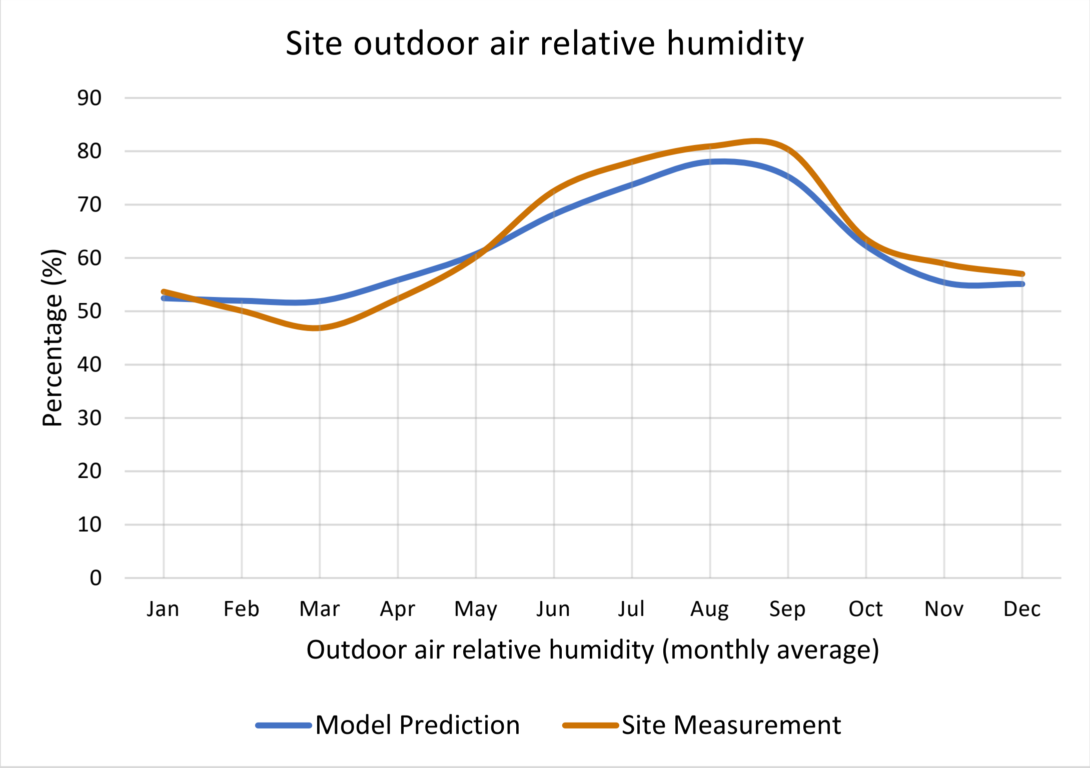


Figure 76: Outdoor relative humidity comparison between the model prediction and site measurement

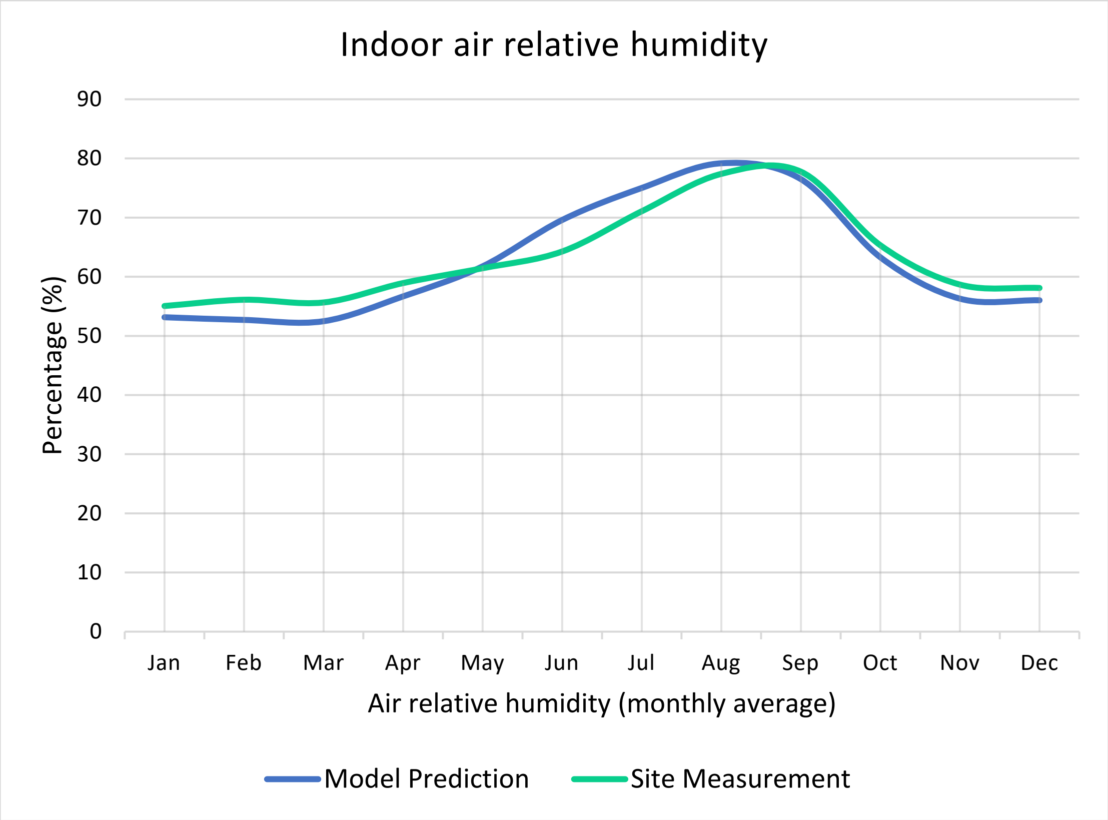


Figure 77: Indoor air relative humidity comparison between the model prediction and site measurement

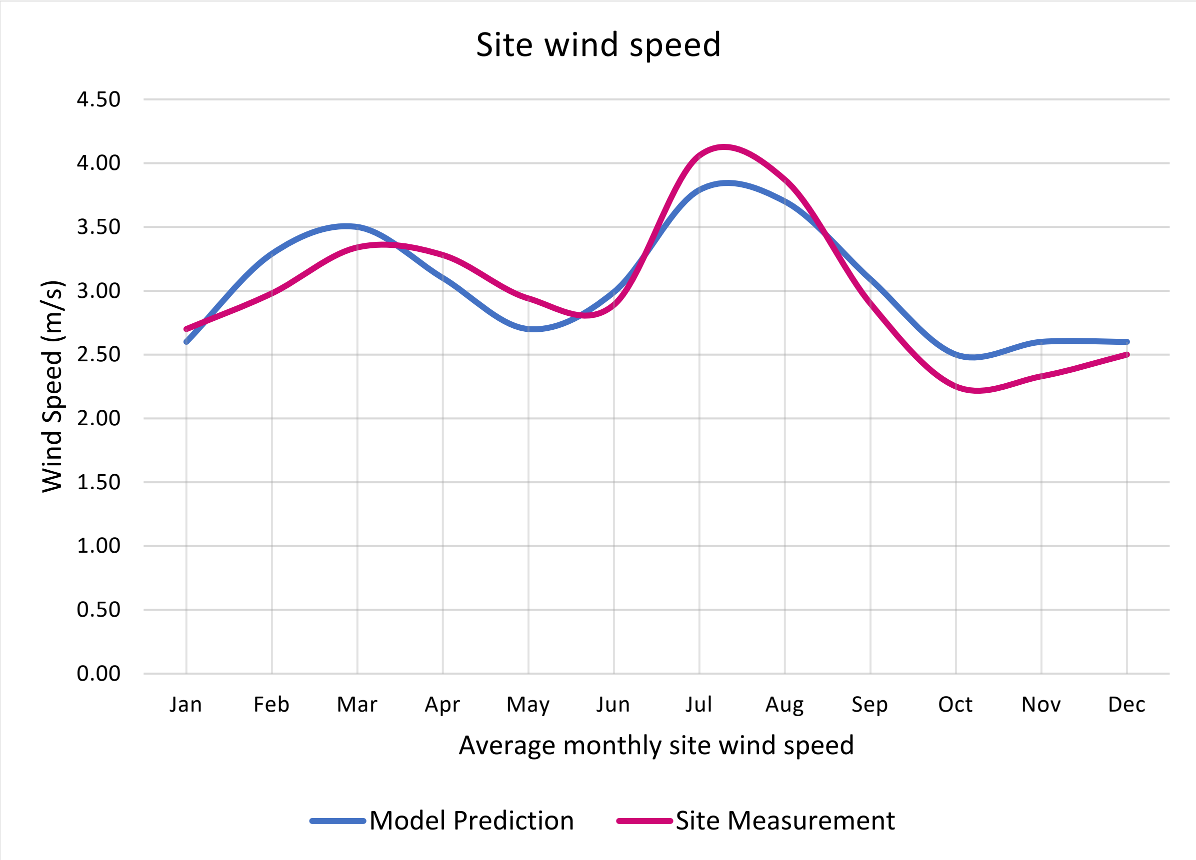


Figure 78: Site wind speed comparison between the model prediction and site measurement

5.3. Sun-path Study

The building was simulated to reveal the sun's path, light, and shade effects on the building all through the year. The figure below shows the sun path diagram of the base case building, its orientation with the North arrow and lights, shades, and shadow at 15:00 in March 2020. This revealed that most areas of the façades are exposed to the sun as the eaves can only provide little shading. It also reveals the exposure of the building to excessive sunshine without shading devices.

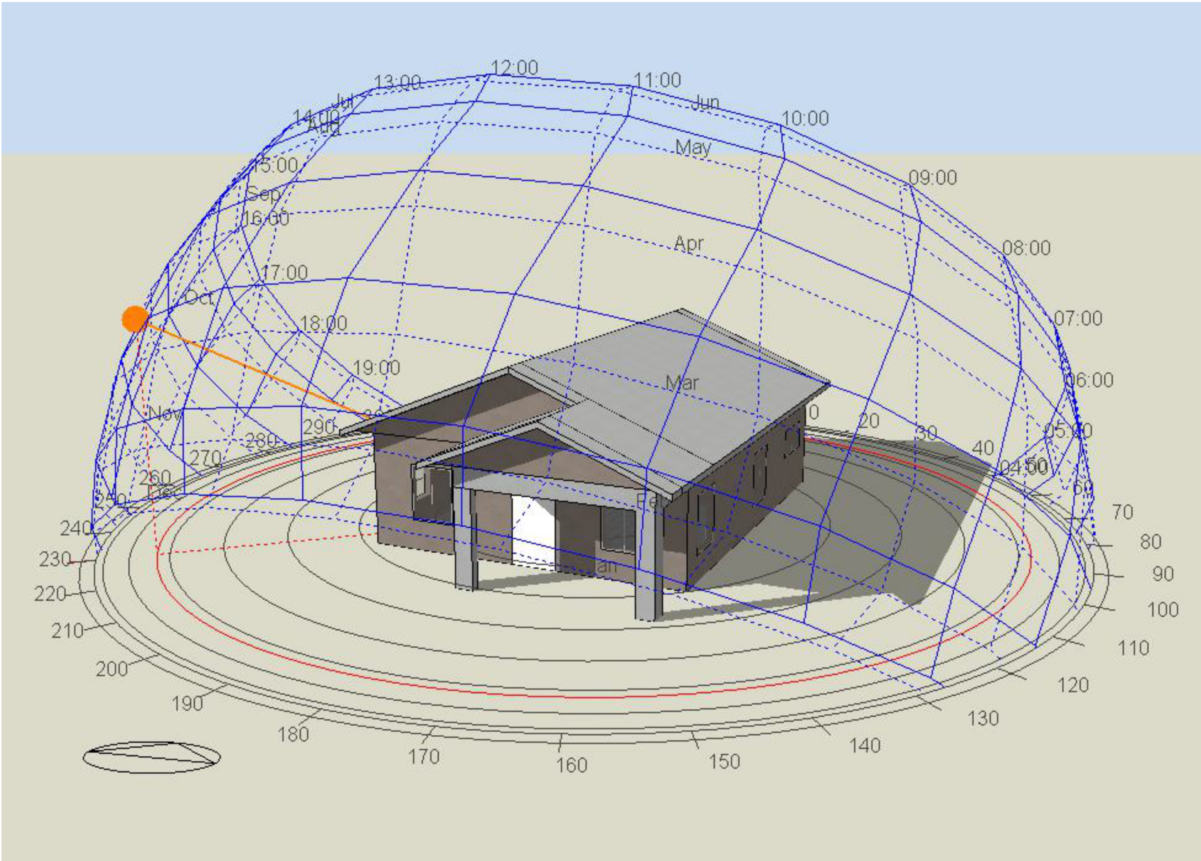
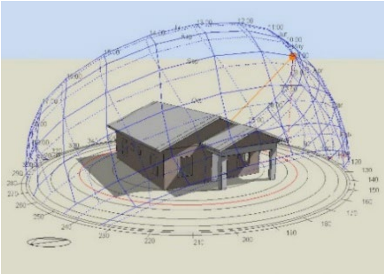
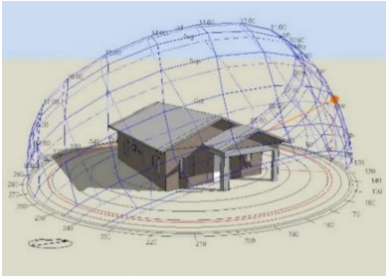
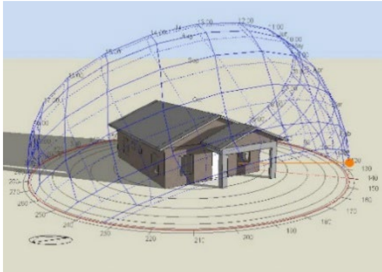
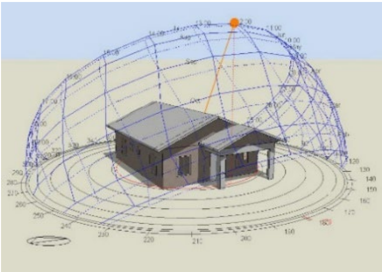
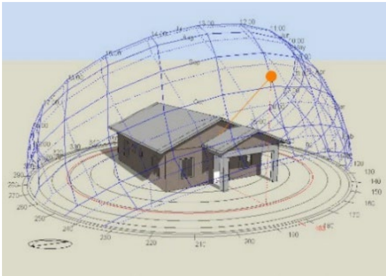
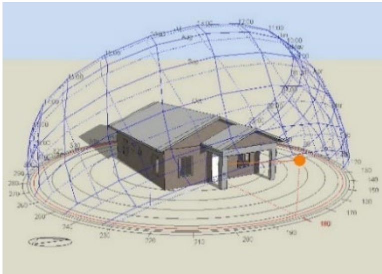
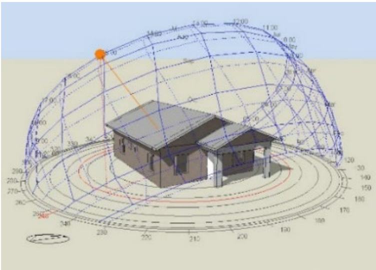
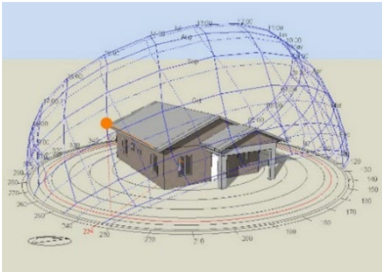
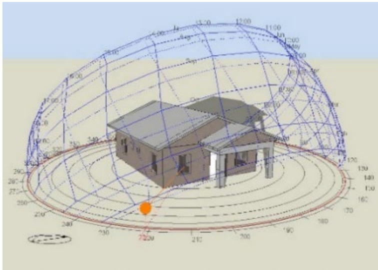


Figure 79: Sun Diagram at 15:00, 21st March 2020

The table below shows the sun path diagram of specific time periods. The simulation was done for the periods of 21st June; 21st December; 23rd September at 9:00, 12:00, and 15:00 (Hours). The simulation revealed that the building shading strategies are not effective almost all year round, most especially 21st of December when the sun would be at its lowest angle to the site. Thereby, causing intense solar heating to the fabrics which could result in overheating.

Table 65: Sun-path diagram (21st June; 21st December; 23rd September – 9:00, 12:00, 15:00Hrs)

	21st June	23rd September	21st December
9:00			
12:00			
15:00			

5.4. Base case energy consumption

It was necessary to determine the energy consumption of the building to establish the base-case energy demand for comparison. Using the modelled building in DesignBuilder with all the related data for the building inputted, the building was simulated to know its energy consumption.

The simulation results for daily temperature, heat gains and the energy consumption is as shown below.

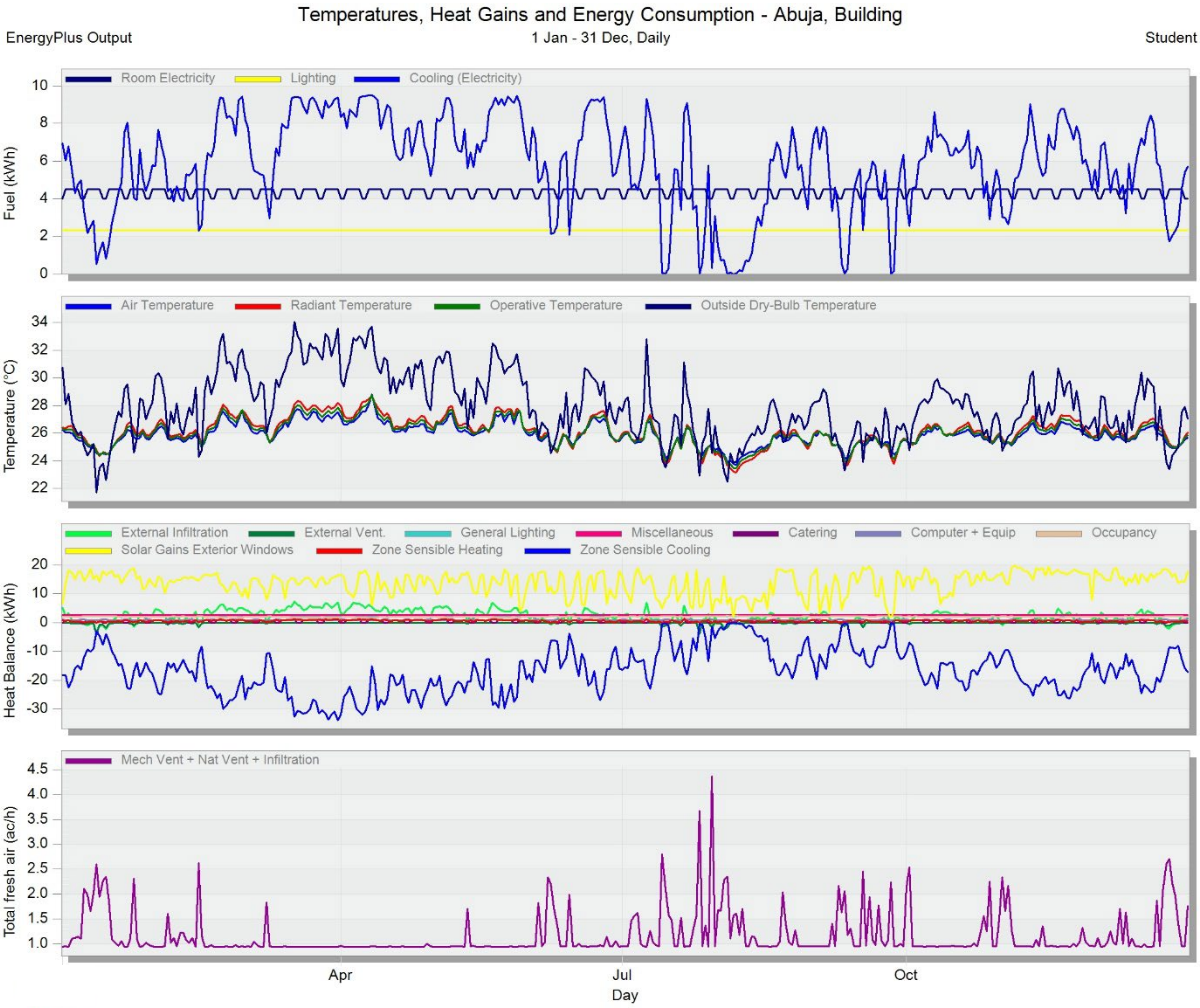


Figure 80: Graph showing Daily Temperature, Heat Gains and Energy Consumption of Simulation result (Base case)

5.5. Energy simulation report

The above simulation graphs are the readings of temperature, Heat gains, and energy consumption of the building (base case). The first observation was that a large amount of energy is used for cooling as indicated by the blue line (cooling - electricity). It is noted that much of the energy is used in cooling the building. The solar gains through exterior windows amounted to 5029.75KWh/year, which influenced the annual cooling electricity consumption to 2131.75KWh. It was also noticed that solar gains were highest during the dry/wet seasons of March, April, and May with gains up to 430.18KWh, 404.24KWh and 419.77KWh, respectively. During the dry season, the solar gains go up again in October – 450.26KWh, November – 514.22KWh, December – 500.22KWh and January – 483.10KWh. In Nigeria, there are only two seasons - the dry and wet seasons. The wet season begins from April to October with June as the wettest month. The dry season begins from November to March. The temperature in the study location is usually high as noticed on the graph above. The outside-dry-bulb temperature average is 27.98^{0}C, air temperature is 25.90^{0}C, the radiant temperature is 26.13^{0}C, and the operative temperature is 26.02^{0}C for the run period. There was also a bit of heat gain from external infiltration which had an input of 869.24KWh.

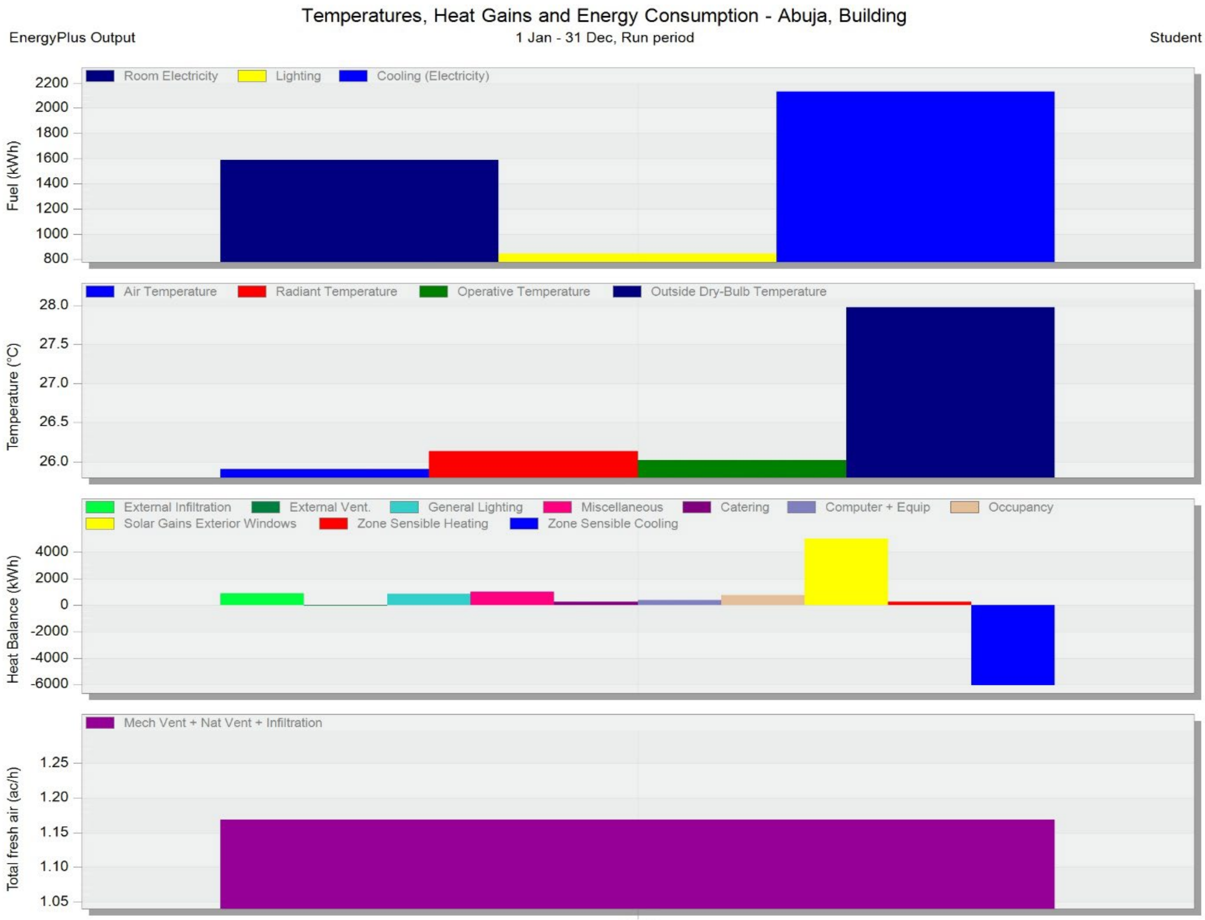


Figure 81: Graph showing Temperature, Heat Gains and Energy Consumption for the run period

The annual lighting is 845.68KWh, although the general lighting contributed to the building heat gain. The occupancy had a contributory heat gain of 759.88KWh. A combination of mechanical ventilation, natural ventilation and infiltration had a resultant air-change rate of 1.17ac/h.

Performing a monthly simulation run revealed that the cooling demand kicked off at 237.44KWh in the month of March which is usually the hottest month of the year and reached its peak of 246.28KWh in the month of May. The outside dry bulb temperature was also at its maximum in the month of March at 30.82^{0}C, a range maintained through the month of April and gradually declined to 30.12^{0}C in the month of May.

The building Heating, Ventilation and Air-conditioning (HVAC) systems have reportedly been the major consumer of energy in buildings, these demands were either to cool down or heat up building spaces (EIA 2006; Pérez-Lombard et al. 2008). As seen in this case study, the cooling need used 2131.75KWh/year which is largely influenced by the solar heat gains through the exterior windows, maintaining a heating range of 324.80KWh to 514.22KWh all through the year as seen on the heat balance graph below.

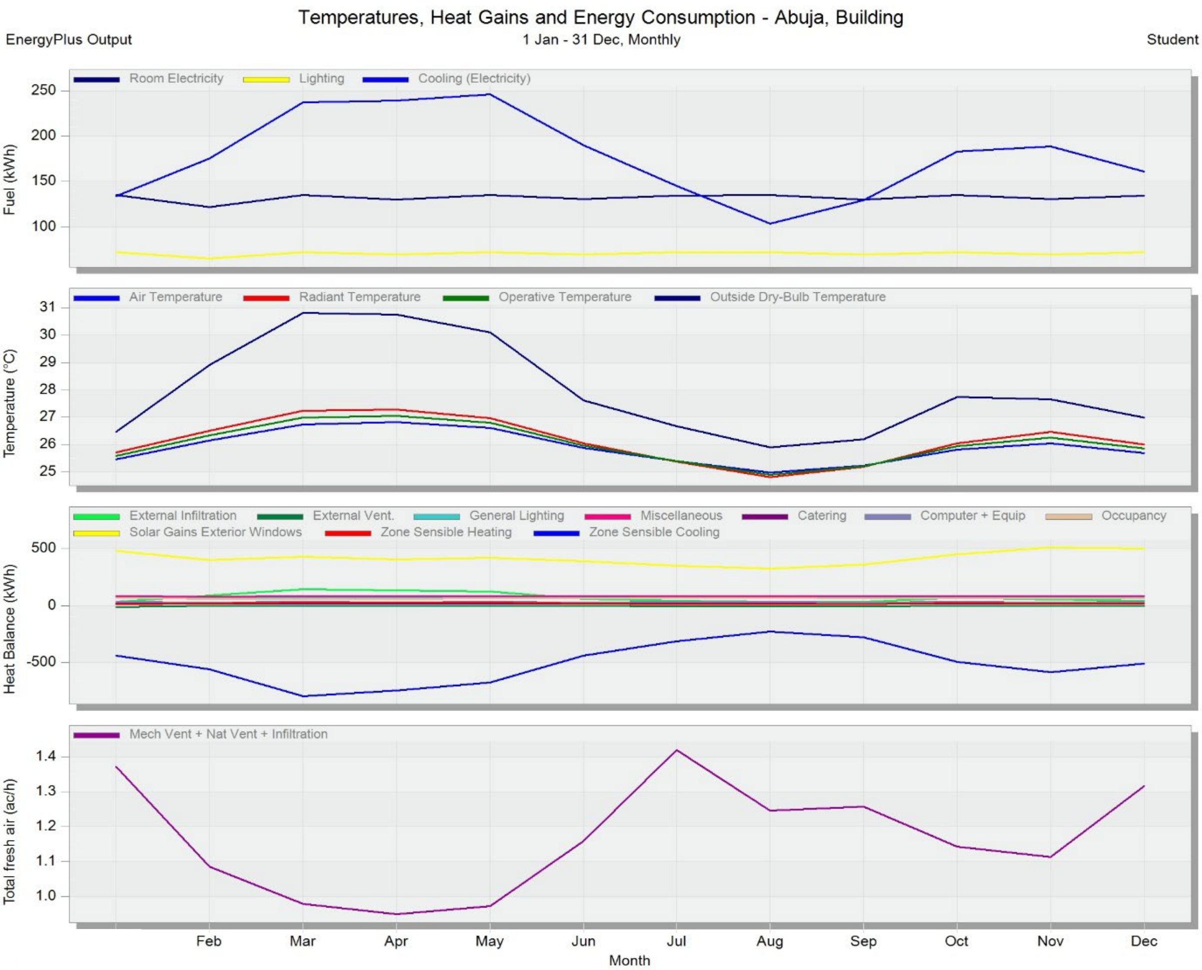


Figure 82: Monthly graph of Temperature, Heat Gains, and Energy Consumption (Base case)

The total primary energy demand of the base-case building was **230.90**KWh/(m²a).

Table 66: Energy consumption of base-case building (run period – 1 Jan - 31 Dec)

Parameters	Base case Energy report
Room Electricity (KWh)	1587.47
Lighting (KWh)	845.68
Cooling (Electricity) (KWh)	2131.75
Air temperature (^{0}C)	25.90
Radiant temperature (^{0}C)	26.13
Operative temperature (^{0}C)	26.02
Outside dry-bulb temperature (^{0}C)	27.98
External infiltration (KWh)	869.24
External ventilation (KWh)	-43.60
General Lighting (KWh)	845.68
Refrigerator (KWh)	994.52
Electric cooker (KWh)	227.31
Television + Equip (KWh)	365.64
Occupancy (KWh)	759.88
Solar gains exterior windows (KWh)	5029.75
Zone sensible heating (KWh)	232.35
Zone sensible cooling (KWh)	-6085.24
Mech vent + Nat vent + infiltration (ac/h)	1.17

5.6. Assessment of the base case building performance

The base case simulation results and studies were evaluated under passive design strategies using specific benchmarks and recommendations.

After reporting on the above information about the building, the study proceeded towards the base case assessment using the simulation results and works of literature.

5.6.1. Building orientation

The building is oriented 3 degrees East of North. Hence, the shorter façade of the building is facing the North and South while the longer façade is facing the East and West. The orientation of the building did not meet the acceptable building orientation according to McGee C. et al (2013) which states that the acceptable building orientations are those up to 20° west of north and 30° east of north which is suitable for countries close to the equator (McGee et al. 2013; Gyoh 2017). This was not the case as the base case orientation was 3° East of North. The building orientation also did not meet the recommendation according to CIBSE Guide F, as it is recommended that the North-facing windows which receive very little solar gains, and the major building axis should point east/west (CIBSE Guild F & AM10 2012). The building orientation had its sleeping areas on the West Wing of the building and living areas on the East wing. This arrangement would expose the sleeping areas to solar radiation since these zones have first contact with the sun. Hence, the building orientation of the base case did not also meet the Australian passive building design guide for buildings in tropical hot climates of West Africa (McGee et al. 2013).

5.6.2. Window to Wall Ratio (WWR)

The window to wall ratio of a building is the area of window(s) to the area of the wall(s) of a building. The WWR of the building was calculated to be 12.49% in total as the windows of the building measured approximately 1.2 x 1.5 meters.

The WWR of each façade of the base case is as presented in the table below.

Table 67: Window to wall ratio of each façade for Base case

Facades	South Façade	East Façade	West Façade	North Façade
WWR (Base case)	15.49%	6.92%	13.85%	13.71%

5.6.3. Local shading assessment of Nigerian typical shading device

Although the base case did not have local shading, some Nigerian residential buildings install window hoods with a typical projection of 365mm (Abdulkareem et al. 2018; Awosusi 2018; Biobaku 2018). To assess the efficacy of this strategy the base case building is simulated using this shading device measuring 365mm projection. The windows of the base-case building were fitted with overhang and side fins of 365mm projections. This experiment is to check the effect of installing local shading on temperatures, heat gain, and energy consumption. The investigation revealed that the solar gains through the exterior windows had decreased from 5029.75KWh of the base case to 3766.61KWh. The cooling electricity had also decreased from 2131.75KWh to 1958.31KWh. There was a general reduction in the air temperature from 25.90^{0}C to 25.83^{0}C, radiant temperature from 26.01^{0}C to 25.97^{0}C and the operative temperature from 26.02^{0}C to 25.90^{0}C. The external infiltration had also increased from 869.24KWh to 898.54KWh. The external ventilation experienced an increase, it went from -43.60^{0}C to -37.73^{0}C. Occupancy figures also went from 759.88(KWh) to 763.66(KWh). The zone sensible heating and cooling recorded decreases from 232.35(KWh) and -6085.24(KWh) to 247.01 (KWh) and -5460.85(KWh) respectively. The results of the simulation were further compared with that of the base case to check for changes in temperatures, heat gain, and energy consumption.

Table 68: Results showing the effect of local shading (365mm overhang and side fins) on the windows of base case (run period – 1 Jan - 31 Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	1958.31
Air temperature (^{0}C)	25.90	25.83
Radiant temperature (^{0}C)	26.01	25.97
Operative temperature (^{0}C)	26.02	25.90
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	898.54
External ventilation (KWh)	-43.60	-37.73
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	763.66
Solar gains exterior windows (KWh)	5029.75	3766.61
Zone sensible heating (KWh)	232.35	247.01
Zone sensible cooling (KWh)	-6085.24	-5460.85
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.15

The comparison of the base case result with the adjusted case results revealed that solar heat gain through the exterior windows had decreased which in turn reduced the cooling load. Thereby, resulting in a reduction in the total energy consumption of the building from 230.90KWh/(m²a) to 220.23KWh/(m²a).

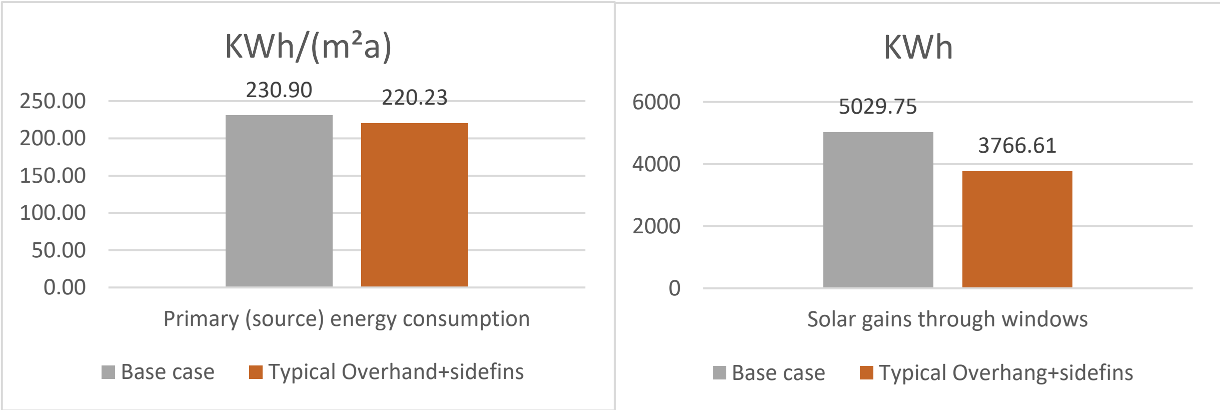


Figure 83: Energy consumption and solar gains comparison between basecase and typical overhang+sidefins

The installation of the overhang and side fins on the windows had a 4.62% impact on the primary energy demand of the building.

It is important to note that the temperature of the building's location is highest in the month of March with a temperature mean of 31^{0}C and it is lowest in the month of August with a temperature mean of 24^{0}C. Hence the building would experience high solar heat gain in March and would need to maintain a comfort range between 24-30^{0}C as seen in the temperature range chart below.

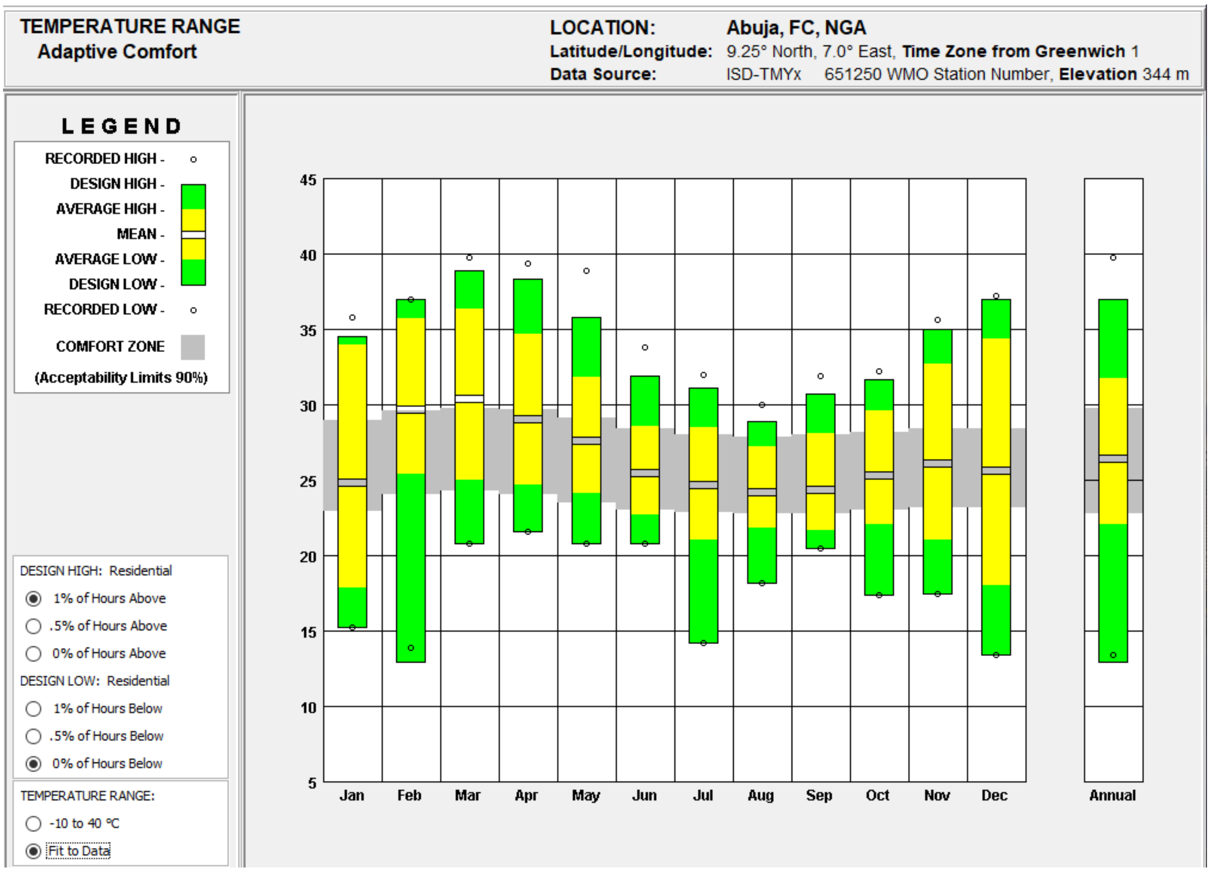


Figure 84: Temperature range of Base case location

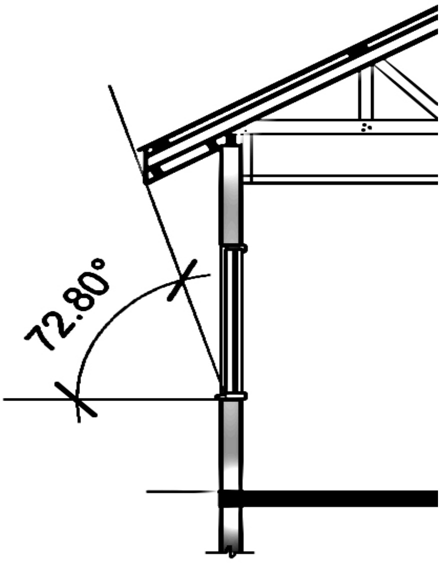


Figure 85: Base case Eave showing shading angle.

This figure is a measurement of the building and the shading angle to simulate the sun hours and shade with Climate consultant using the sun shading chart. Simulating the building parameters such as the eave width of 600mm, building model and weather data revealed that the building during the plot month (winter-spring/December 21 - June 21) would be exposed to a Warm/Hot temperature of at least 24^{0}C (Warm/Hot > 24^{0}C) for 745 hours of sunshine (see sun shading chart). The period range (December 21 – June 21) according to the weather data has March as the hottest month of the year in the study location. The period had 64 hours of exposure in the "Warm/Hot" category as seen in the Sun shading chart in the comfort temperature of at least

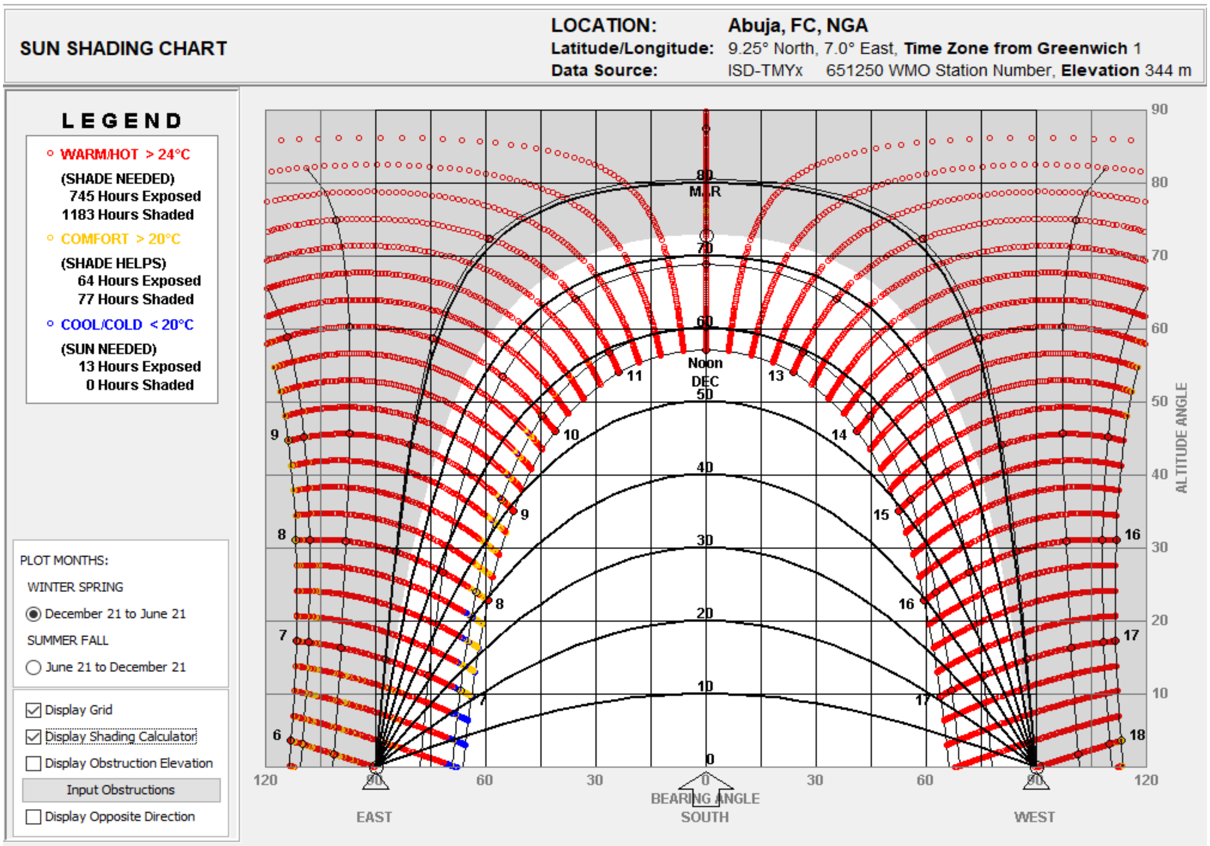


Figure 86: Sun shading chart with eave shading of 72.8 degrees

20^{0}C. The Cool/Cold (< 20^{0}C) period had just 13 hours of cold temperature less than 20^{0}C. The long hours of intense solar heating are due to inadequate shading as the building exterior fabrics are exposed to excessive solar heating which would significantly increase the heat gain of the building.

The windows were not also effectively shaded as the eaves of the building were 600mm wide. On the horizontal plane, this only provides 72.80 degrees of shading from the eave or overhang which is a very steep angle and may only be effective when the sun is almost directly or directly above the building (overhead). In addition, there were no vertical shading devices, thus, exposing the walls and windows to low solar radiation.

5.6.4. g-value assessment simulation

The simulation results indicated that most of the heat gain came through the windows and this had a negative effect on the building with regards to higher cooling demand. The base case windows are 5.72mm bronze glazed having a g-value of 0.62. The window to wall ratio is 12.49% and the aluminium sliding windows had a vertical divider. To conduct this experiment, the g-value of the glass was adjusted to check its sensitivity and its effect on the building solar heat gains through the windows and the total energy consumption of the building.

The geometric progression of the glass g-value was a decremental factor of -0.20 or -20%. Therefore, from the original 0.62 to 0.42 to 0.22, which resulted in a total reduction of 64.5%.

Step 1

The steps of the simulation to check the effect of the reduced g-value of the glazing to 0.42 on solar heat gain and total energy consumption of the base case is as presented below. In the first stage of the experiment, the g-value of the glazing was reduced from 0.62 of the base case to 0.42.

Original properties of glazing

Total solar transmittance:	62%
Glaze type:	Bronze glazing
Thickness:	5.72mm

Adjusted properties of glazing

Total solar transmittance:	42%
Glaze type:	Bronze glazing
Thickness:	5.72mm

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption.

Step 2

The steps of the simulation to check the effect of the reduced g-value of the glazing to 0.22 on solar heat gain and total energy consumption of the base case is as presented below. In the second step of the experiment, the g-value of the glazing was reduced to 0.22, amounting to a total reduction of 64.5%.

Original properties of glazing

Total solar transmittance:	62%
Glaze type:	Bronze glazing
Thickness:	5.72mm

Adjusted properties of glazing

Total solar transmittance:	22%
Glaze type:	Bronze glazing

Thickness: 5.72mm

Step 1

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption. The investigation revealed that the solar gains through the exterior windows had drastically decreased from 5029.75KWh of the base case to 2574.80KWh. The cooling electricity had also decreased from 2131.75KWh to 1846.78KWh. There was a general reduction in the air temperature from 25.90^{0}C to 25.75^{0}C, radiant temperature from 26.01^{0}C to 25.82^{0}C and the operative temperature from 26.02^{0}C to 25.79^{0}C. The external infiltration had also increased from 869.24KWh to 932.83KWh. The external ventilation experienced an increase, it went from -43.60^{0}C to -34.19^{0}C. Occupancy figures also went from 759.88(KWh) to 768.47(KWh). The zone sensible heating and cooling recorded decreases from 232.35(KWh) and -6085.24(KWh) to 260.49(KWh) and -5057.71(KWh) respectively. The results of the simulation of the comparison with that of the base case to check for changes in temperatures, heat gain, and the energy consumption is as presented below.

Table 69: Results showing the effect of g-value variation (0.42) in the base case glazing (run period – 1 Jan - 31 Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	1846.78
Air temperature (^{0}C)	25.90	25.75
Radiant temperature (^{0}C)	26.01	25.82
Operative temperature (^{0}C)	26.02	25.79
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	932.83
External ventilation (KWh)	-43.60	-34.19
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	768.47
Solar gains exterior windows (KWh)	5029.75	2574.80
Zone sensible heating (KWh)	232.35	260.49
Zone sensible cooling (KWh)	-6085.24	-5057.71
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.14

The results show that there was a significant decrease in the solar gains through the exterior windows from 5029.75KWh to 2574.80KWh, also the cooling load reduced from 2131.75KWh to 1846.78KWh, an indication that the reduced g-value of the glazing had caused a decrease in energy consumption in cooling down the building. The total primary energy demand also decreased from 230.90KWh/(m²a) to 213.37KWh/(m²a).

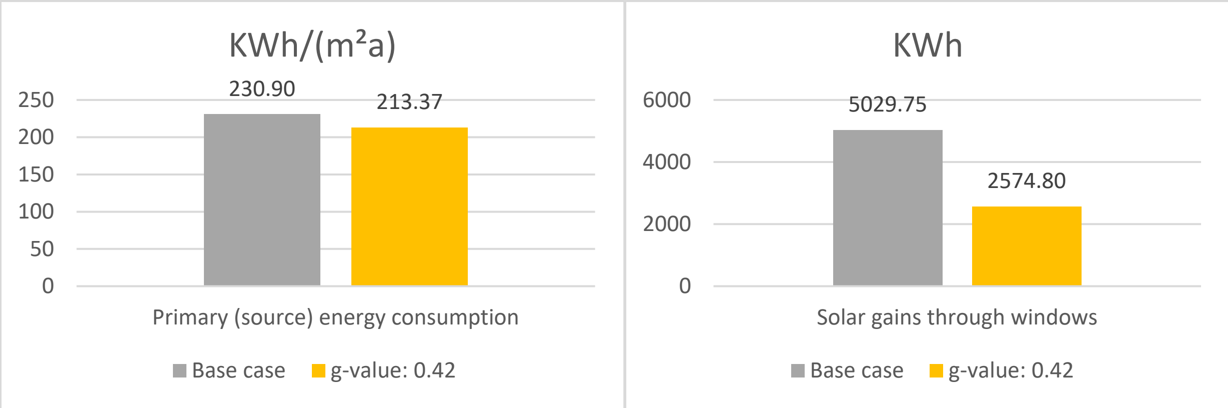


Figure 87: Energy consumption and solar gains comparison between the base case and change in g-value

The adjustment in the g-value of the exterior glazing had a 7.59% impact on the primary energy demand of the building.

Step 2

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption. The investigation revealed that the solar gains through the exterior windows had drastically decreased from 5029.75KWh of the base case to 1020.35KWh. The cooling electricity had also decreased from 2131.75KWh to 1719.89KWh. There was a general reduction in the air temperature from 25.90^{0}C to 25.68^{0}C, radiant temperature from 26.01^{0}C to 25.66^{0}C and the operative temperature from 26.02^{0}C to 25.67^{0}C. The external infiltration had also increased from 869.24KWh to 964.79KWh. The external ventilation experienced an increase, it went from -43.60^{0}C to -30.55^{0}C. Occupancy figures also went from 759.88(KWh) to 772.41(KWh). The zone sensible heating and cooling recorded decreases from 232.35(KWh) and -6085.24 (KWh) to 273.61(KWh) and -4609.20 (KWh) respectively. The results of the simulation were further compared with that of the base case to check for changes in temperatures, heat gain, and energy consumption.

Table 70: Results showing the effect of g-value variation (0.22) in the base case glazing (run period – 1 Jan - 31 Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	1719.89
Air temperature (^{0}C)	25.90	25.68
Radiant temperature (^{0}C)	26.01	25.66
Operative temperature (^{0}C)	26.02	25.67
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	964.79
External ventilation (KWh)	-43.60	-30.55
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	772.41
Solar gains exterior windows (KWh)	5029.75	1020.35

Zone sensible heating (KWh)	232.35	273.61
Zone sensible cooling (KWh)	-6085.24	-4609.20
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.12

The results show that there was a significant decrease in the solar gains through the exterior windows from 5029.75KWh to 1020.35KWh, also the cooling load reduced from 2131.75KWh to 1719.89KWh, an indication that the reduced g-value of the glazing had caused a decrease in energy consumption in cooling down the building. The total primary energy demand also decreased from 230.90KWh/(m²a) to 205.57KWh/(m²a).

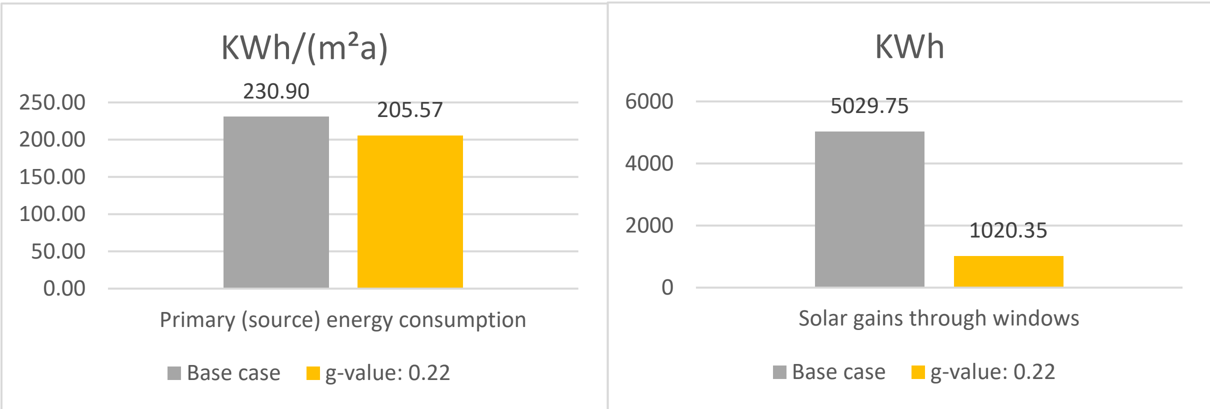


Figure 88: Energy consumption and solar gains comparison between the basecase and change in g-value

The adjustment in the g-value of the exterior glazing had a 10.97% impact on the primary energy demand of the building.

This experiment revealed that the g-value of the glass when reduced has a significant effect on the energy demand of the building. Although this reduction could also reduce visibility – light transmittance through the glass. However, this was considered during the optimisation process.

5.6.5. Thermal Mass

The Kappa value is used to quantify the effective thermal mass of building elements. It refers to the heat capacity of a material per square meter which is measured in kJ/m^{2}K. Therefore, the higher the k-value, the higher the thermal mass performance and the more heat the material component can store. It is also important to know that the higher the volumetric heat capacity of a material (which is a function of the density and specific heat capacity), the better the thermal mass performance of the material, thus, the material with high density and specific heat capacity performs better (Gyoh 2017). Aside from the thermal mass having the ability to absorb and store heat energy, it also provides inertia against fluctuating temperatures (DesigningBuildings 2020). A good material for thermal mass is those of high specific heat capacity, and high density (Reardon et al. 2013).

The assessment started by simulating different variables of the base case wall material to check which variable may have higher impacts on heat gain, cooling load and energy use. Hence, the first objective is to establish the variable with the highest impact on the thermal mass material of the base case wall material.

The variables for this simulation include:

Density and Thermal conductivity. The higher the density value of a material, the better the thermal mass performance while the lesser the value of the thermal conductivity the better the performance (Gyoh 2017). Hence, the incremental change for Density value was a multiplication by 1.5 for step 1 and multiplication by 2.0 for step 2. A decremental change for Thermal conductivity was a division by 1.5 for step 1 and a division by 2.0 for step 2. This is intended for uniformity. Hence, the original material properties (Density, and Thermal conductivity) of the sandcrete wall which is the wall material of the base case will be multiplied by 2.0.

Figure 89: DesignBuilder Sandcrete layers representation

For the experiments, all other parameters of the base case will remain constant.

Please Note: 25mm thickness of cement sand render maintained in all cases and 150mm of block thickness maintained as well.

Simulation 1

Simulation to check the effect of Density on Sandcrete solid block wall.

Original properties of Sandcrete solid block wall

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

Adjusted properties of Sandcrete solid block wall (first step)

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3 x 1.5 = 2902.5Kg/m^3

Adjusted properties of Sandcrete solid block wall (second step)

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3 x 2 = 3870Kg/m^3

The results from this simulation were compared with the base case result to check the effect of Density on Temperatures, heat gain, and energy consumption.

Simulation 2

Simulation to check the effect of thermal conductivity on Sandcrete solid block wall.

Original properties of Sandcrete solid block wall

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

Adjusted properties of Sandcrete solid block wall (step 1)

Thermal Conductivity: 1.00W/m-K ÷ 1.5 = 0.67W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

Adjusted properties of Sandcrete solid block wall (step 2)

Thermal Conductivity: 1.00W/m-K ÷ 2.0 = 0.50W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

A comparison of the simulation results was done against the base case to check the effect of thermal conductivity on temperatures, heat gain, and energy consumption.

Simulation 1 results

The simulation to check the effect of Density on Sandcrete solid block wall is as presented below. The experiment involved two steps increment simulations. Step 1 – multiply density value by 1.5, Step 2 – multiply density value by 2.0.

Step 1

Original properties of Sandcrete solid block wall

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

Adjusted properties of Sandcrete solid block wall (Step 1)

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3 x 1.5 = 2902.5Kg/m^3

The results from the step 1 simulation were compared with the base case result to check the effect of Density on Temperatures, heat gain, and energy consumption. The simulation results revealed that cooling (electricity) reduced from 4736.62KWh of the base case to 4521.96KWh, although there was a slight increase in the air temperature, radiant temperature and operative temperature from 25.70^{0}C, 26.01^{0}C and 25.85^{0}C to 25.78^{0}C, 26.06^{0}C and 25.92^{0}C respectively. The external infiltration had also decreased from 955.42KWh to 918.51KWh. There was a reduction in the external ventilation as it went from -30.92^{0}C to -36.13^{0}C. Occupancy figures also went from 767.34(KWh) down to 763.80(KWh). The zone sensible heating and cooling recorded decreases from 254.86(KWh) and -5159.50(KWh) to 249.99(KWh) and -4826.10(KWh) respectively.

Table 71: Results showing the effect of density variation in thermal mass (run period - 1Jan-31Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	2048.51
Air temperature (^{0}C)	25.90	25.98
Radiant temperature (^{0}C)	26.01	26.18
Operative temperature (^{0}C)	26.02	26.08
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	834.90
External ventilation (KWh)	-43.60	-48.66
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	756.44
Solar gains exterior windows (KWh)	5029.75	5029.75
Zone sensible heating (KWh)	232.35	227.92
Zone sensible cooling (KWh)	-6085.24	-5766.39
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.18

From the above results, it can be seen that there was a reduction in the cooling load (from 2131.75KWh to 2048.51KWh, an indication that the increased density of the thermal mass had caused a reduction in energy consumption in cooling the building. There was a general reduction of the total energy consumption which reduced from 230.90KWh/(m^2a) to 225.78KWh/(m^2a).

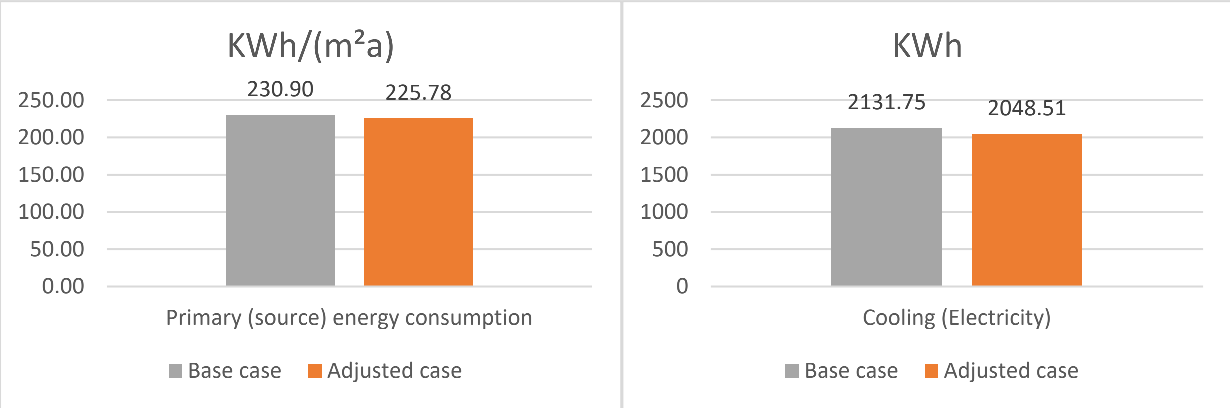


Figure 90: Thermal mass adjustment comparison between the basecase and adjusted case (Density: step 1)

The change in the density of the thermal mass had a 2.22% impact on the total energy consumption of the building.

Step 2

<u>Original properties of Sandcrete solid block wall</u>

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

<u>Adjusted properties of Sandcrete solid block wall</u>

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

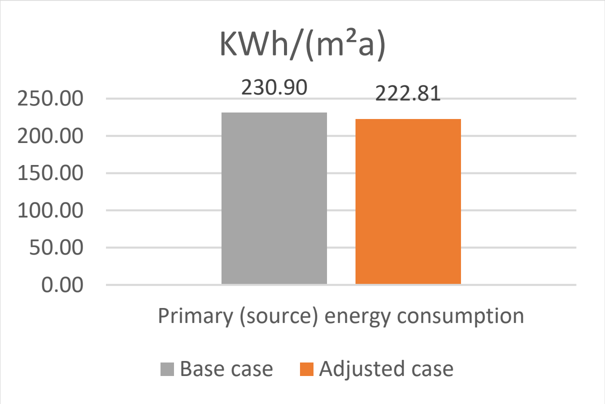
Density: 1935Kg/m^3 x 2 = <u>3870Kg/m^3</u>

The results from step 2 simulation were compared with the base case result to check the effect of Density on Temperatures, heat gain, and energy consumption. The simulation results revealed that cooling (electricity) reduced from 2131.75KWh of the base case to 4395.96KWh, although there was a slight increase in the air temperature, radiant temperature and operative temperature from 25.90^{0}C, 26.01^{0}C and 26.02^{0}C to 26.03^{0}C, 26.21^{0}C and 27.12^{0}C respectively. The external infiltration had also decreased from 869.24KWh to 816.00KWh. There was a reduction in the external ventilation as it went from -43.60^{0}C to -52.83^{0}C. Occupancy figures also went from 759.88(KWh) down to 754.03(KWh). The zone sensible heating and cooling recorded decreases from 232.35(KWh) and -6085.24(KWh) to 224.20(KWh) and -5578.82(KWh) respectively.

Table 72: Results showing effect of density variation in thermal mass (run period - 1Jan-31Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	2000.22
Air temperature (^{0}C)	25.90	26.03
Radiant temperature (^{0}C)	26.01	26.21
Operative temperature (^{0}C)	26.02	26.12
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	816.00
External ventilation (KWh)	-43.60	-52.83
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	754.03
Solar gains exterior windows (KWh)	5029.75	5029.75
Zone sensible heating (KWh)	232.35	224.20
Zone sensible cooling (KWh)	-6085.24	-5578.82
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.19

From the above results, it can be seen that there was a reduction in the cooling load (from 2131.75KWh to 2000.22KWh, an indication that the increased density of the thermal mass had caused a reduction in energy consumption in cooling the building. There was a general reduction of the total energy consumption which reduced from 230.90KWh/(m²a) to 222.81KWh/(m²a).



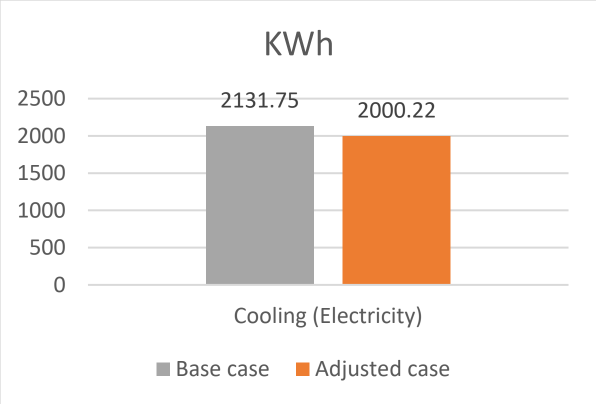


Figure 91: Thermal mass adjustment comparison between base case and adjusted case (Density: step 2)

The change in the density of the thermal mass had a 3.50% impact on the total energy consumption of the building.

Simulation 2 results

The results of the simulation to check the effect of thermal conductivity on the thermal mass performance of Sandcrete solid block wall is as presented below. The experiment involved a two-stage reduction of the thermal conductivity value of the base case sandcrete block wall by dividing the thermal conductivity value by a factor of 1.5 for step 1 and dividing by 2.0 in Step 2.

Step 1

Original properties of Sandcrete solid block wall

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

Adjusted properties of Sandcrete solid block wall (step 1)

Thermal Conductivity: 1.00W/m-K ÷ 1.5 = 0.67W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

A comparison of the simulation results was done against the base case to check the effect of thermal conductivity on temperatures, heat gain, and energy consumption. It was discovered from the simulation results that cooling (electricity) reduced from 2131.75KWh of the base case to 1938.88KWh. There was also a decrease in the air temperature from 25.90^{0}C to 25.86^{0}C, radiant temperature from 26.01^{0}C to 26.00^{0}C and operative temperature from 26.02^{0}C to 25.93^{0}C. The external infiltration had also increased from 869.24KWh to 887.08KWh. The external ventilation also experienced a slight increase, it went from -43.60^{0}C to -43.25^{0}C. Occupancy figures also went from 759.88(KWh) down to 761.59(KWh). The zone sensible heating and cooling recorded increases from 232.35(KWh) and -6085.24(KWh) to 239.87(KWh) and -5347.25(KWh) respectively.

Table 73: Results showing the effect of thermal conductivity variation in thermal mass (run period – 1 Jan - 31 Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	1938.88
Air temperature (^{0}C)	25.90	25.86
Radiant temperature (^{0}C)	26.01	26.00
Operative temperature (^{0}C)	26.02	25.93
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	887.08
External ventilation (KWh)	-43.60	-43.25
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	761.59

Solar gains exterior windows (KWh)	5029.75	5029.75
Zone sensible heating (KWh)	232.35	239.87
Zone sensible cooling (KWh)	-6085.24	-5347.25
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.16

The results show that there was a decrease in the cooling load from 2131.75KWh to 1938.88KWh, which indicated that the decreased thermal conductivity of the thermal mass material had caused a decrease in energy consumption in cooling down the building. The total primary energy demand also decreased from 230.90KWh/(m²a) to 219.04KWh/(m²a).

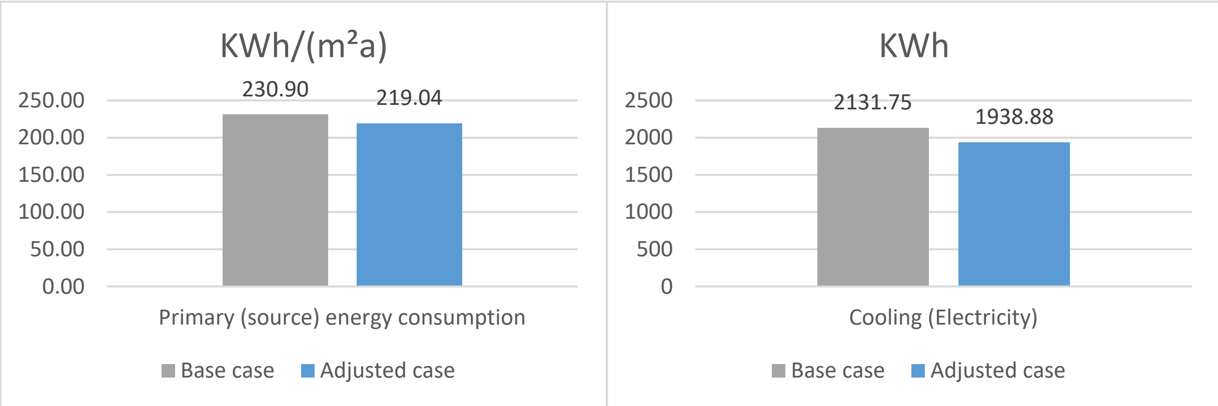


Figure 92: Thermal mass adjustment comparison between base case and adjusted case (thermal conductivity: step 1)

The adjustment in the thermal conductivity of the thermal mass material of the sandcrete solid block had a 9.49% impact on the primary energy demand of the building.

Step 2

<u>Original properties of Sandcrete solid block wall</u>

Thermal Conductivity: 1.00W/m-K

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

<u>Adjusted properties of Sandcrete solid block wall (step 2)</u>

Thermal Conductivity: 1.00W/m-K ÷ 2.0 = <u>0.50W/m-K</u>

Specific Heat: 840J/Kg-K

Density: 1935Kg/m^3

A comparison of the simulation results was done against the base case to check the effect of thermal conductivity on temperatures, heat gain, and energy consumption. It was discovered from the simulation results that cooling (electricity) decreased from 2131.75KWh of the base case to 1793.68KWh. There was also a decrease in the air temperature from 25.90^{0}C to 25.82^{0}C, radiant temperature from 26.01^{0}C to 25.89^{0}C and operative temperature from 26.02^{0}C to 25.86^{0}C. The external infiltration had also decreased from 869.24KWh to 903.63KWh. The external ventilation also experienced a slight decrease, it went from -43.60^{0}C to -42.74^{0}C. Occupancy figures also went from 759.88(KWh) down to 762.70(KWh). The zone sensible heating and cooling recorded decreases from 232.35(KWh) and -6085.24(KWh) to 245.67(KWh) and -4797.32(KWh) respectively.

Table 74: Results showing the effect of thermal conductivity variation in thermal mass (run period – 1 Jan - 31 Dec)

	Base case results	Adjusted case results
Lighting (KWh)	845.68	845.68
Cooling (Electricity) (KWh)	2131.75	1793.68
Air temperature (^{0}C)	25.90	25.82
Radiant temperature (^{0}C)	26.01	25.89
Operative temperature (^{0}C)	26.02	25.86
Outside dry-bulb temperature (^{0}C)	27.98	27.98
External infiltration (KWh)	869.24	903.63
External ventilation (KWh)	-43.60	-42.74
General lighting (KWh)	845.68	845.68
Occupancy (KWh)	759.88	762.70
Solar gains exterior windows (KWh)	5029.75	5029.75
Zone sensible heating (KWh)	232.35	245.67
Zone sensible cooling (KWh)	-6085.24	-4797.32
Mech vent + Nat vent + infiltration (ac/h)	1.17	1.16

The results show that there was a significant decrease in the cooling load from 2131.75KWh to 1793.68KWh, which indicated that the decreased thermal conductivity of the thermal mass material had caused a decrease in energy consumption in cooling down the building. The total primary (source) energy demand also decreased from 230.90KWh/(m²a) to 210.11KWh/(m²a).

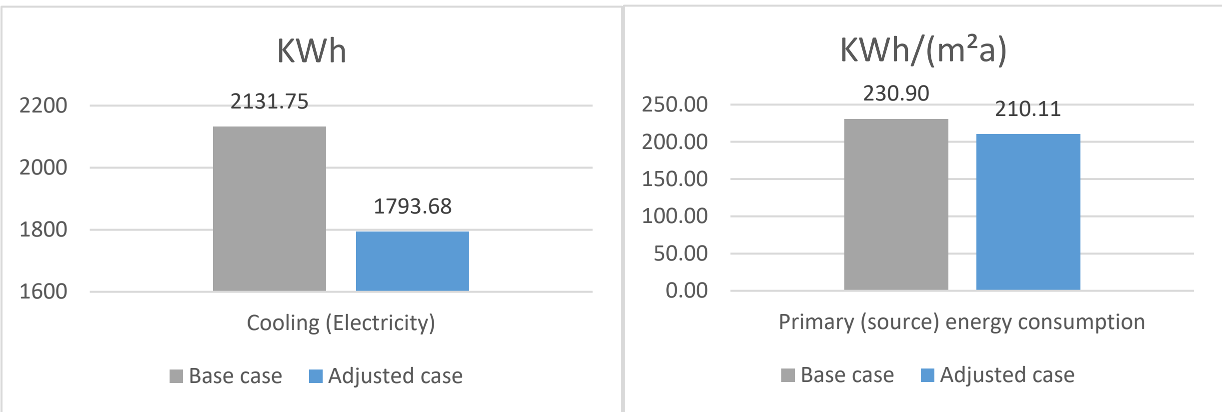


Figure 93: Thermal mass adjustment comparison between base case and adjusted case (thermal conductivity: step 2)

The adjustment in the thermal conductivity of the thermal mass material of the sandcrete solid block had a 9.00% impact on the primary energy demand of the building.

From the above simulations, the impact of the variables was calculated. The percentage impact each of the variable had on the base case overall energy consumption were as follows. Density: 3.50%, Thermal conductivity: 9.00%. The thermal conductivity variable of the thermal mass had the highest impact on cooling and the total energy consumption.

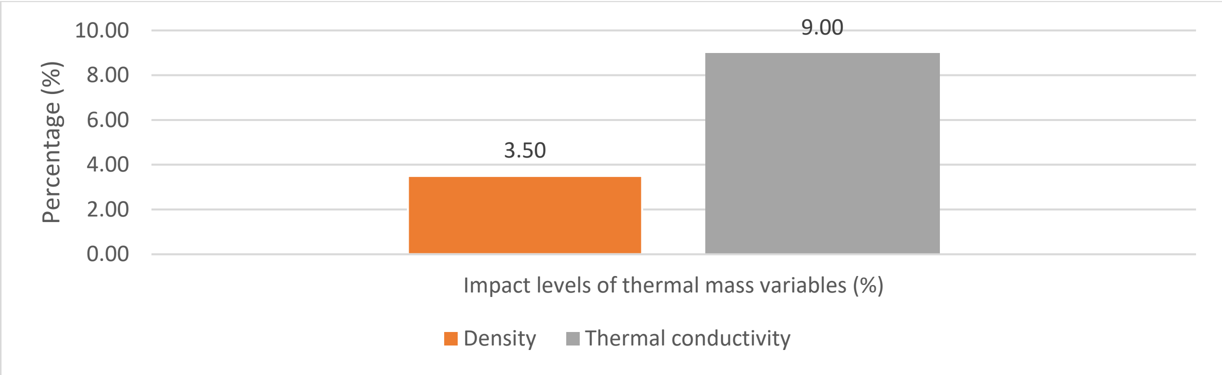


Figure 94: Percentage impact of thermal mass variables

From the above results, thermal conductivity had the highest impact on building performance. Hence, the thermal conductivity of a thermal mass component or material plays a significant role in influencing the thermal mass of the building and the overall energy consumption. Therefore, the selection of a thermal mass material for optimisation was one with low thermal conductivity for a positive outcome in terms of reducing temperatures, heat gain, and energy consumption. According to Gyoh (2020), the lower the thermal conductivity of a material, the better the thermal mass performance, the study classed thermal conductivity values with their "whole numbers" to be "zero(0.)" as better fit materials for thermal mass construction (Gyoh 2020). The base case had a thermal conductivity value to be 1.00W/m-K which did not meet the range of Gyoh's thermal conductivity classification. The simulation results revealed that the base case thermal mass component would have performed better with a material with a lower thermal conductivity or a material with high density and specific heat capacity which will be considered during the optimisation. It is important to note that the higher the volumetric heat capacity of the thermal mass, which is a function of the density and specific heat capacity of the material. Therefore, the higher these parameters (density and specific heat capacity), the more effective the thermal mass.

5.6.6. Daylighting

According to the Nigerian energy efficiency building design guide and the Australian Building Codes Board (ABCB) for tropical climates, a window opening providing daylight is required to have a minimum area of 10% of the floor area of the room (Arup (Madrid & Lagos offices) and Design Genre 2016; Federal Ministry of Power 2017; ABCB 2018). It is important to note that Australia and Nigeria share relatively similar climatic conditions as they both come under the hot, tropical savannah climate regions (Arnfield 2020). The above ABCB recommendations are specific to West African tropical climate of which Nigeria comes under (Federal Ministry of Power 2017; ABCB 2018).

The building zones of the base case met this passive design recommendation of the Nigerian energy efficiency building design guide and the Australian Building Codes Board by having a minimum opening area of 10% of the floor area of the room.

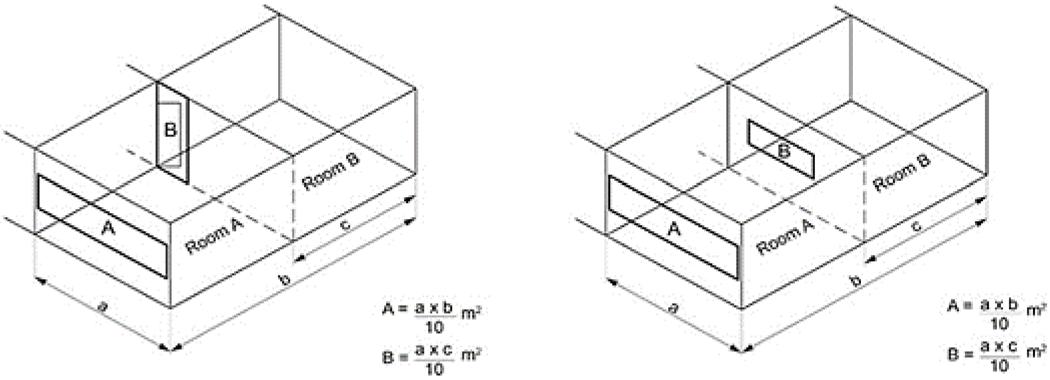


Figure 95: Daylighting requirement for West African buildings (Source: Australian Building Codes Board - ABCB, 2018)

The table below shows the zones that met the minimum daylight recommendations.

Table 75: Daylighting assessment

Zone	Room area (m^2)	Zones with a minimum of 10% threshold
Sitting room/ circulation area	39.07	15.00%
Master Bedroom	11.88	25.62%
Bedroom	10.93	25.64%
Kitchen	10.30	12.83%
Store	2.33	12.32%
Toilet/Bathroom	2.54	38.10%
Toilet/Bathroom 2	2.54	38.10%
Lobby	3.22	13.12%

The table above shows the daylight calculations of the base case. It shows the room areas and the percentage of floor areas above 10% daylight opening.

5.6.7. Thermal Insulation

There are no thermal insulation components installed in the building. Therefore, heat transfer from outside the building is conducted through the sandcrete block wall without any resistance from a thermally insulating material. Most of the heat transferred inward by the lean thermal mass, such as the exterior walls would be retained since there are inadequate means of quick heat removal as lightweight construction responds quickly to cooling breezes (Reardon et al. 2013).

In the tropical region, there is a great need to constantly keep the heat out or slowly release the heat during the cold period, for instance at night as this has an impact on the building's energy consumption (Cao et al. 2016).

5.6.8. Natural Ventilation

The natural ventilation of the building met the Nigerian energy efficiency building design guide and the Australian Building Codes Board (ABCB) recommendation for tropical climates, which states that the minimum size of the opening must be 5% of the floor area of the room (ABCB 2016; Federal Ministry of Power 2017). It is important to note that Australia and Nigeria shares relatively similar climatic conditions as they both come under the hot, tropical savannah climate regions (Arnfield 2020). The above ABCB recommendations are specific to West African tropical climate of which Nigeria comes under (ABCB 2016; Federal Ministry of Power 2017).

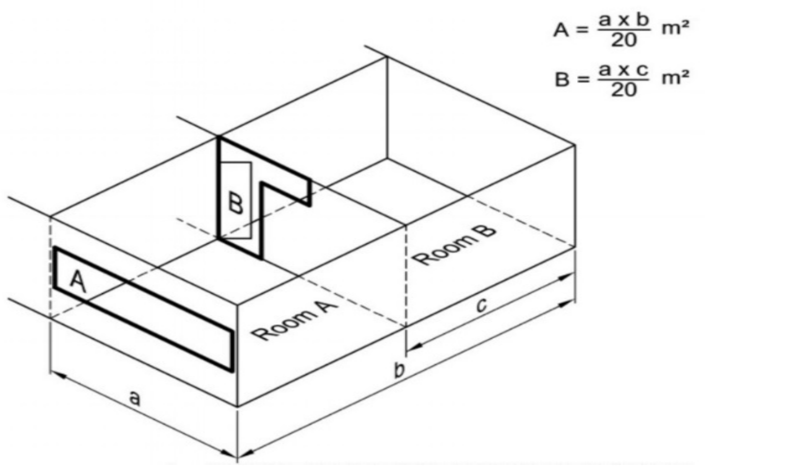


Figure 96: Natural ventilation requirement for West African buildings (ABCB 2016)

The rooms in the base case met this condition with over 10% of the opening to the floor size. Most of the rooms were angularly ventilated, thus improving ventilation. The wind-wheel from Climate Consultant shows monthly wind speeds from North, South, East and West. The building experienced high winds from all directions as seen in the wind-wheel diagram. Although, wind speeds were higher from North-East with wind speeds reaching 11m/s. This wind (North-East trade wind) during the dry season is undesirable as they are often dry and dusty, hence, the occupant would usually shut out these winds during the dry season, the South-West Monsoon wind is often cool and humid and preferred (Okorie et al. 2013).

The figure below is a windwheel or windrose simulation result of the wind speed in the base case location. The windrose monthly simulation shows the wind speeds, relative humidity, temperature, and duration in hours. it was observed that wind velocity is higher in the months of February, September, and May. The annual wind velocity is about 7.9m/s. The wind velocity range from Climate Consultant reveals that the wind velocity is greater in the months of February and September with February having the highest range of 7.9m/s. However, the annual wind velocity is 4.2m/s.

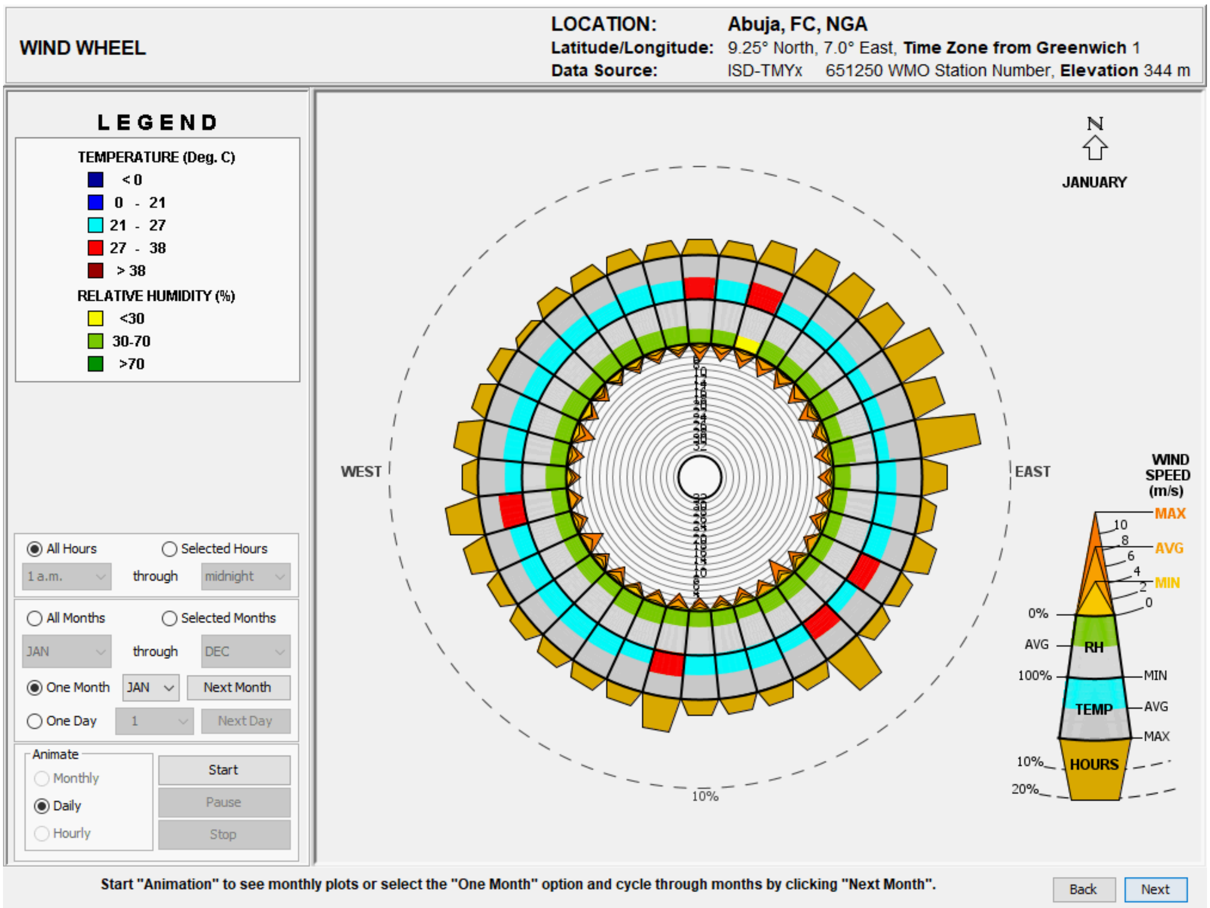
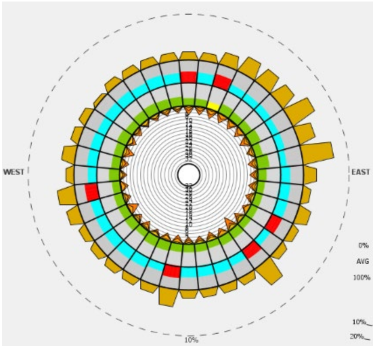


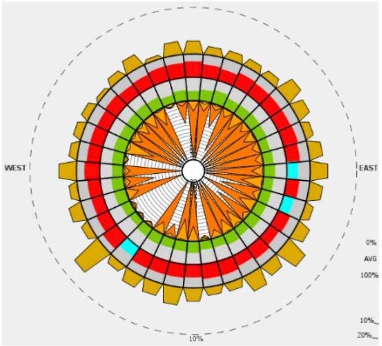
Figure 97: Wind Wheel

Table 76: Monthly Windrose Simulation (All hours)

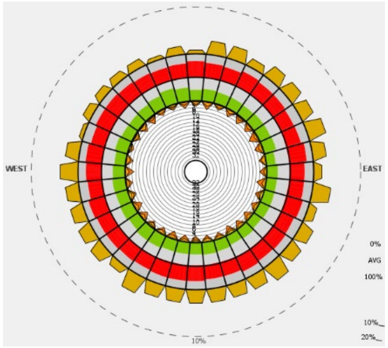
Month by month Windrose Simulations at Latitude 9.25^{0}North, Longitude: 7.0^{0}East, Time Zone from Greenwich: 1 Elevation 344m



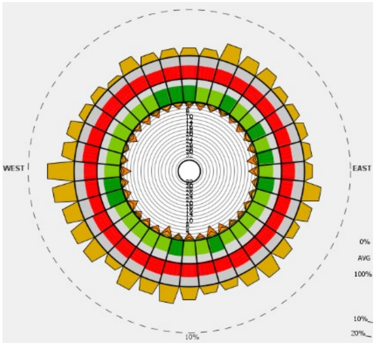
January



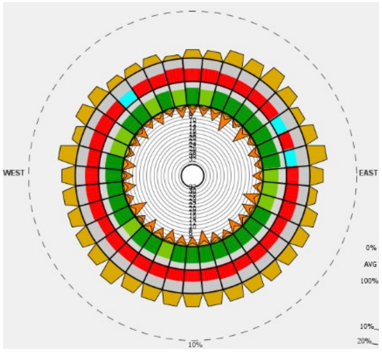
February



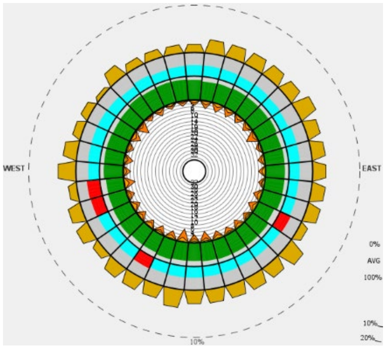
March



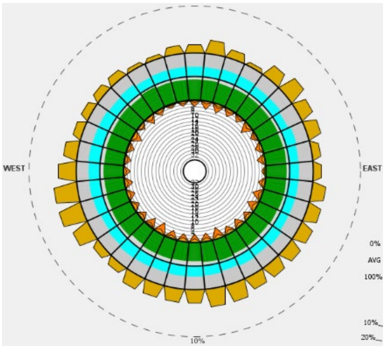
April



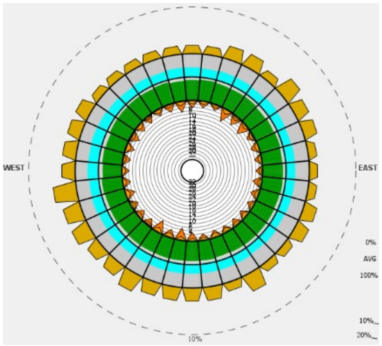
May



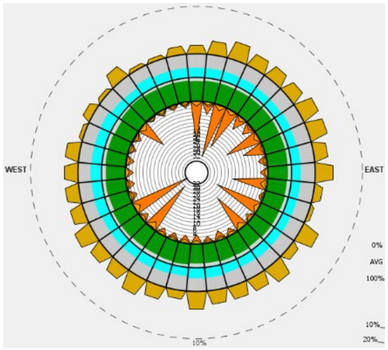
June



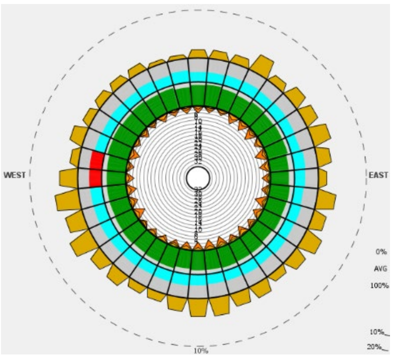
July



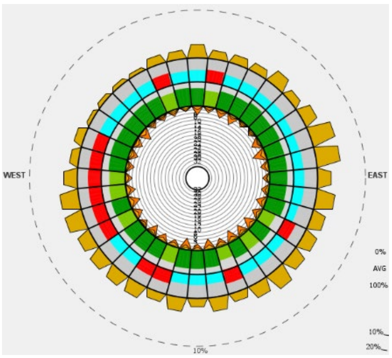
August



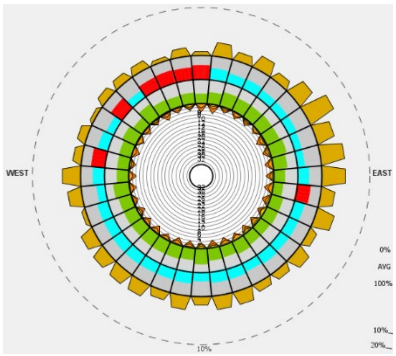
September



October



November



December

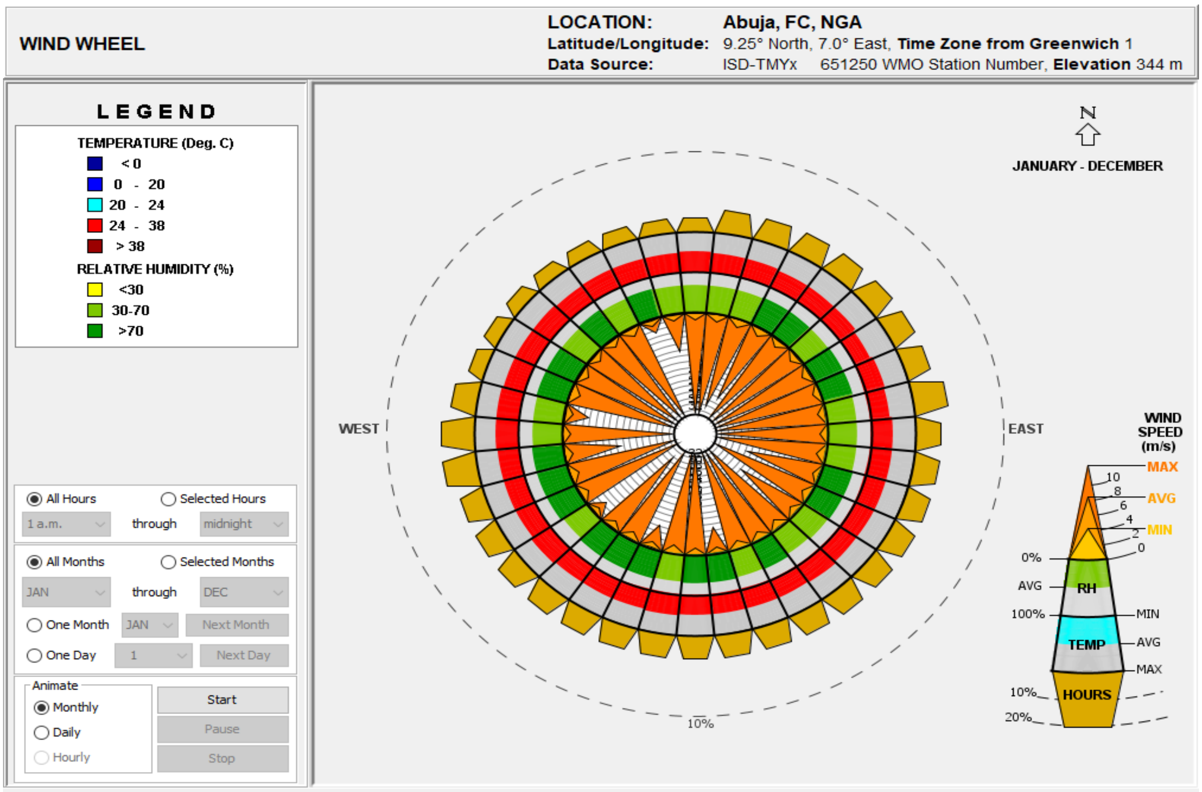


Figure 98: Wind-wheel showing annual prevailing winds.

The wind speeds are highest during the harmattan season, especially in February which is usually undesirable because it is often dry and dusty. It is recommended to orient or provide openings for buildings to benefit from desired winds (Givoni 1994; Daemei et al. 2019). It is therefore necessary to provide openings facing the direction of desired winds either opposite or angularly where the formal is not possible (ABCB 2016).

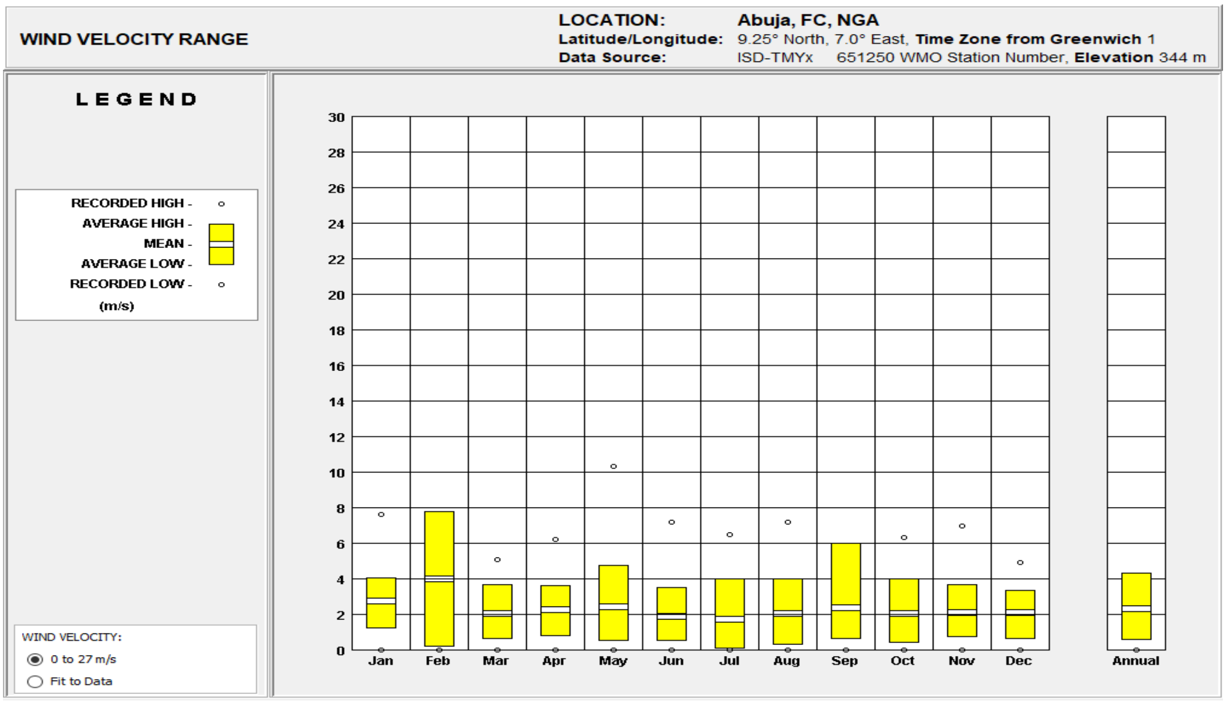


Figure 99: Wind velocity range simulation of the study area.

5.7. Building simulation results and analysis

After a careful study of the effect of passive design strategies on the base case, the investigation went ahead to analyse the heat balance and the parameters with the most impact on the building's energy demand.

5.7.1. Heat Balance

The Heat balance graph below shows the heat gains from General lighting, External infiltration, zone sensible heating, external ventilation, occupancy, solar gains (exterior windows), and zone sensible cooling. The simulation results indicated that most of the heat is gained from solar radiation through the exterior window which is not properly shaded. It also revealed that the highest cooling load was recorded in March which is the hottest month of the year in the study location. The Heat balance graph (in black line) had the following distributions: January: 353.84KWh, February : 189.51KWh, March : 68.52KWh, April : 76.07KWh, May : 158.85KWh, June : 288.64KWh, July : 357.17KWh, August : 414.28KWh, September : 392.96KWh, October : 313.12KWh, November : 262.53KWh, December : 320.03KWh.

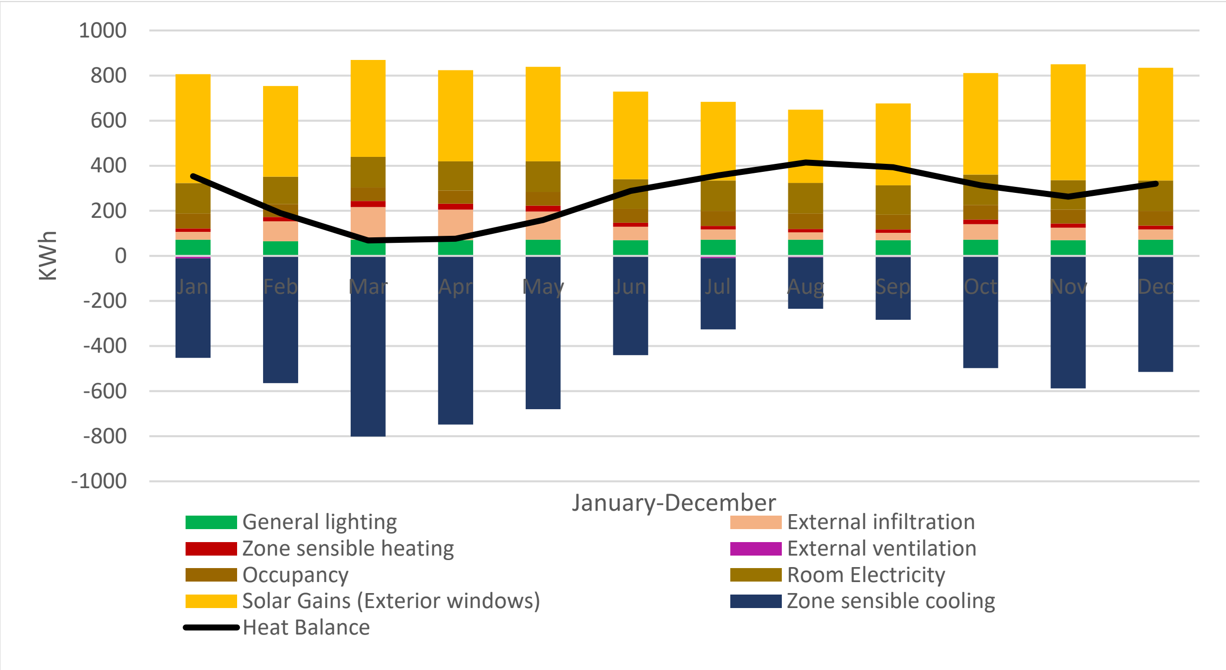


Figure 100: Heat Balance chart showing monthly heat gains.

The figure below shows a chart plot of solar heat gain through the exterior windows (orange line) and cooling electricity demand (in blue bars). There is a corresponding relationship between the two graphs as an increase in solar heat gain necessitated a higher demand for cooling. However, the four months (February, March, April, May) cooling demand went above the solar heat gain expectations as they are among the hottest time of the year.

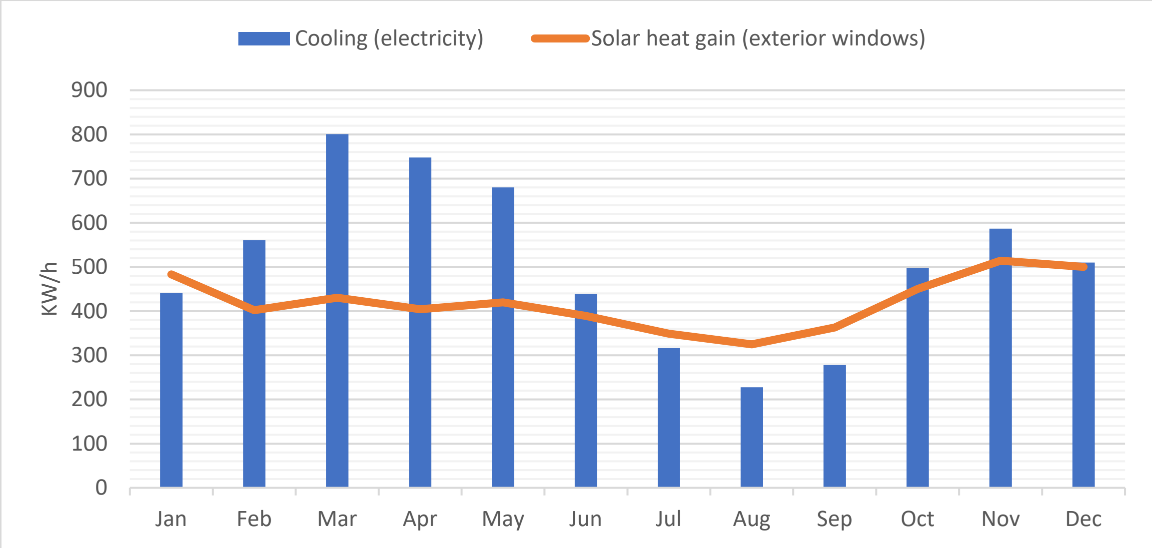


Figure 101: Graph showing monthly solar heat gain through exterior windows and cooling demand

In summary, the primary energy demand is 230.90KWh/(m²a) which is above major building energy benchmarks when compared to Passivhaus benchmark of 120kWh/(m²a) and the current United Kingdom's nearly Zero Energy Buildings (nZEBs) of 85-100KWh/(m²a).

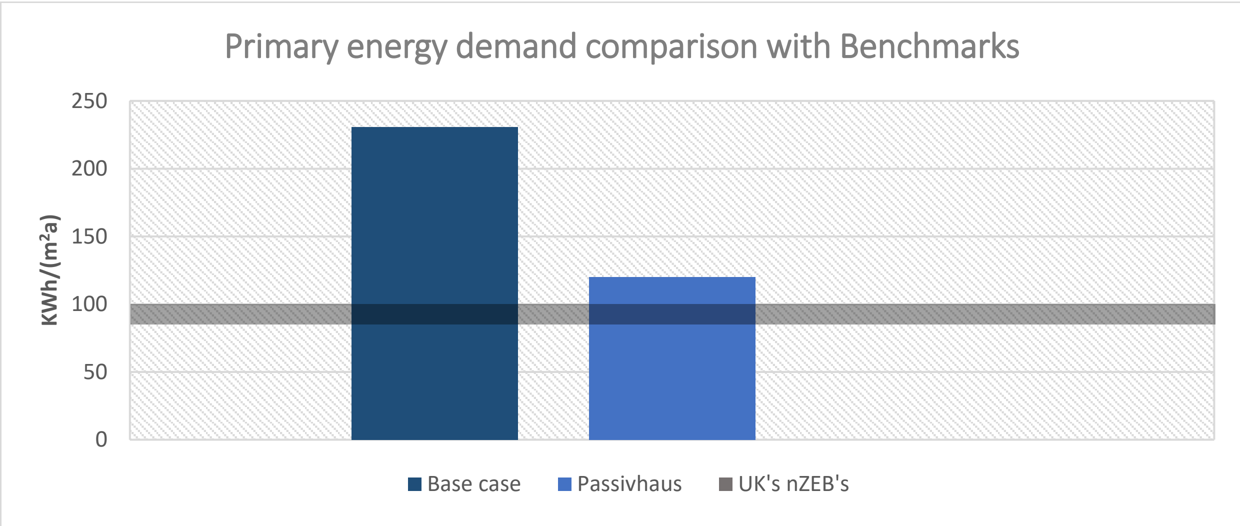


Figure 102: Chart showing primary energy demand of the base case in comparison with global standards

5.7.2. Most impacts on energy demand

After a careful analysis of the energy demand of the building. The various design parameters were identified to have the most impact on energy demand. Solar heat gains through exterior windows had the highest impact (5029.75KWh) most likely due to the unshaded windows and building orientation. Other parameters such as general lighting (845.68KWh), Zone sensible heating (232.35KWh), and occupancy (759.88KWh) were at an all-time low in comparison to solar heat gain.

5.8. Summary

The findings and analysis from the simulations established that the mean temperature of 31^0C had a significant impact on the thermal mass of the building as the building's exterior walls failed to perform effectively due to the high thermal conductivity of the sandcrete solid wall as seen in the simulation results. Thus, increasing the total energy consumption. A sensitivity simulation conducted on the glazing material indicated that the window component has a great impact on the thermal performance of the building. The study also revealed that the temperature of the building's location was at its highest in the month of March with a temperature mean of 31^0C and was at its lowest in the month of August with a temperature mean of 24^0C. The building is also not properly oriented, and the study revealed that the building's area of exposure to solar radiation could have been reduced if properly oriented and the sleeping areas would have been properly zoned.

The simulation results and analysis identified solar gains through the exterior windows as the major contributor to the energy demand of the building. The sensitivity simulation conducted revealed that local shading can greatly reduce solar heat gain. There was a corresponding relationship between an increase in solar heat gain and the cooling demand for most months. This was important to know so adequate shading is provided to prevent excessive heating and to attain optimal building orientation for best performance. Natural ventilation on the other hand met the minimum benchmark by the provision of adequate openings in various zones. The minimum daylight requirement was met since the building zones attained the minimum illumination recommendations. It was also discovered that other parameters such as general lighting, zone sensible heating, and occupancy had the least impact on the building's energy demand.

The simulation reported that the cooling load of the building was of higher demand in comparison with other parameters. This had a great impact on the Primary energy demand, bringing it to a total of 230.90KWh/(m^2a). The cooling demand was highest during the month of March to May which are usually the hottest months of the year as revealed in the monthly simulation run. It also indicated that most of the heat is gained from solar radiation through the exterior windows which were not properly shaded. Hence, a reduction in solar heat gain by providing proper shades is capable of cutting down the required cooling demand and reducing the building's energy consumption.

Chapter Six
6.0. Optimisation Simulations

The research proceeded to optimise the building (base-case) using passive design strategies. The optimisation priority is geared towards reducing the primary energy demand of the building by passive design strategies. To conduct an effective optimisation, it is important to identify the parameters that had the most impact on energy demand, then those parameters could be enhanced for best performance. The optimisation operation began by engaging one at a time optimisation to see the effect of each parameter to gradually cut down the primary energy demand.

Passive design strategies (such as building orientation, Window to Wall Ratio (WWR), Local shading, thermal mass, thermal insulation, g-value, etc.) were optimised using simulations on DesignBuilder and passive design recommendations.

The optimisation process consisted of one-at-a-time and all-at-a-time simulations of various parameters. From the above evaluation simulations conducted, it was observed that solar heat gains from the exterior windows had the highest impact on energy consumption.

The methodology of optimising the building started with determining the best building orientation, followed by the WWR of each facade, Local shading, etc. A chart of the optimisation process is presented below.

The chart below shows the optimisation process and the steps taken from the base case to the optimised case.

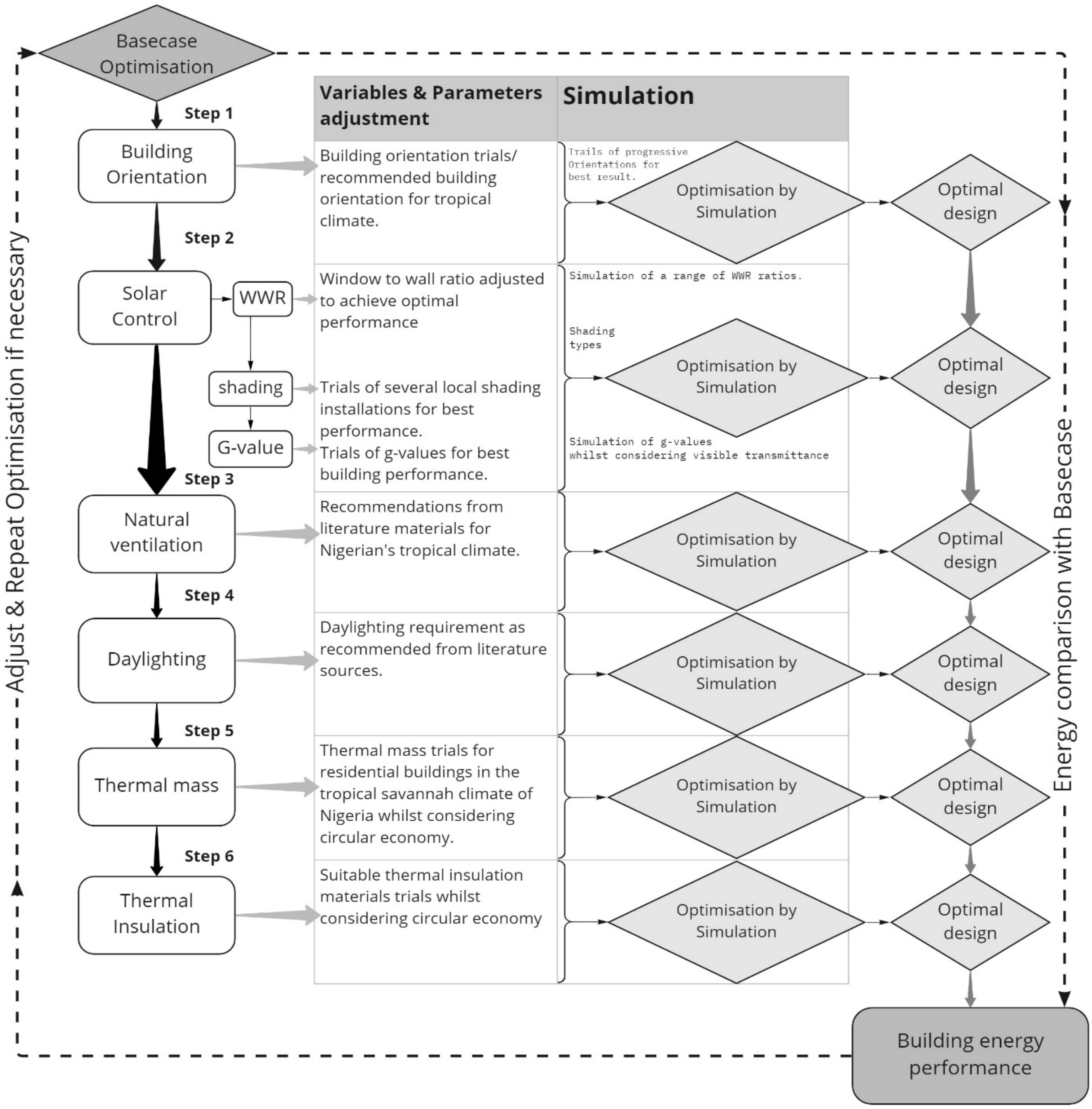


Figure 103: Building optimisation process

6.1. Building Orientation optimisation

The optimisation process started by simulating several orientations of the building to see which orientation performs best with regards to building energy efficiency. Below is a range of orientations considered.

Table 77: Building orientation optimisation trials

Simulation of different building orientations to check for the most optimised orientation with regards to energy efficiency.

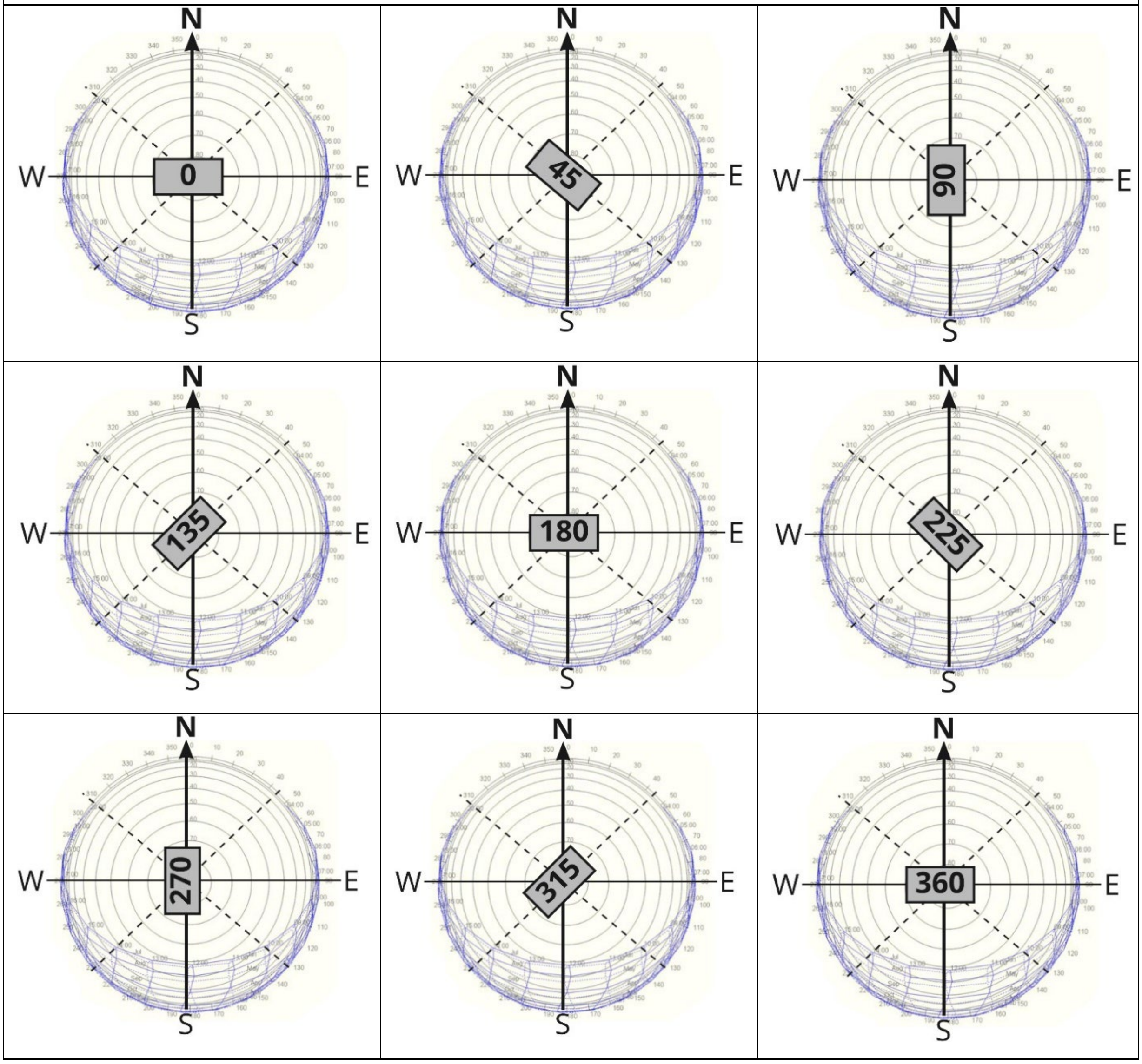


Table 78: Building orientation simulation results

Building Orientations (degrees ^{0})	Total Source Energy (KWh/m^2)
0	212.10
45	224.00
90	230.19
135	229.74
180	218.24
225	229.15
270	230.85
315	224.48

It was discovered that the 0-degree building orientation which has the longest side facing the north had the best building performance with an 8.14% energy demand reduction from 230.90 KWh/(m²a) to 212.10 KWh/(m²a). The longest side of the building is perpendicular to the North axis (thereby falling within 20°W–30°E of true North). In this new orientation the building was subjected to the following benefits:

1. The area of the building exposed to direct solar radiation from the East and West was reduced from 46.65m^2 to 32.23m^2 since in this case the longer side of the building is oriented towards the North.
2. The sleeping zones were oriented away from the East sun and moved to the North where it is shed from the southern solar radiation and buffered by adjourning zones.
3. The living zone was buffered with the kitchen zone. Hence, away from the setting sun from the West.
4. The living zone was exposed to the southwest monsoon wind which is desirable, and the kitchen zone served as a buffer against the northeast trade wind which is usually dry and dusty.

The results from the optimisation revealed a significant improvement in the total building performance. The energy demand dropped from 230.90KWh/(m²a) to **212.10**KWh/(m²a), an 8.14% improvement. The cooling (electricity) load was also reduced from 2131.75KWh to 1826.08KWh.

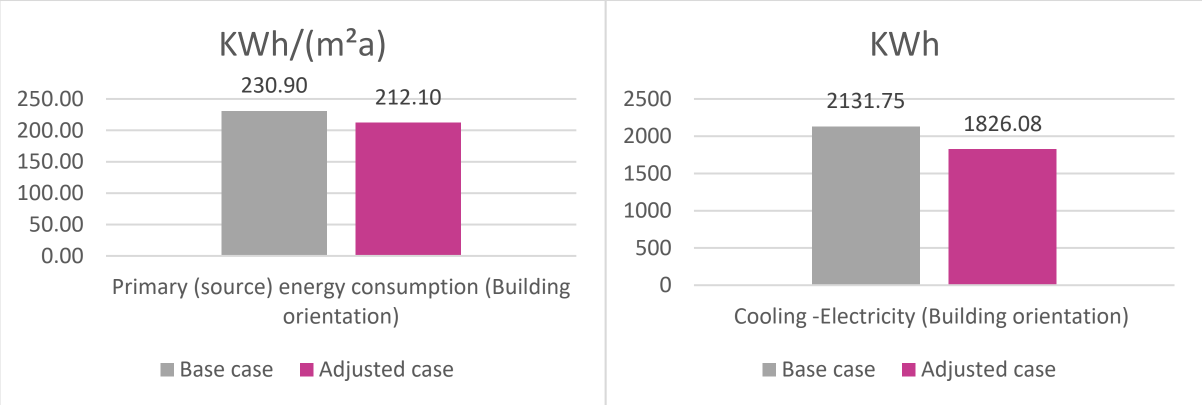


Figure 104: Building orientation simulation comparison between base case and optimal case

Therefore, optimising the building orientation to meet passive design recommendations yielded an 8.14% energy improvement.

6.2. Solar Control optimisation

The optimisation for solar control was carried out in three categories:

1. Window to wall ratio
2. Local shading
3. g-value

6.2.1. Window to Wall Ratio (WWR)

To determine the effect of changes in the window to wall ratio of the building on energy demand, the window to wall ratio was adjusted progressively from 6% to 95% for each façade independently to see the effect it had on energy demand.

The window to wall ratio of the base case building is 12.49% while the window to wall ratio of each façade is as shown in the table below. At this stage, the total primary (source) energy consumption of the building was 212.10KWh/(m²a)

Table 79: Window to wall ratio of each façade for Base case

Facades	South Façade	East Façade	West Façade	North Façade
WWR (Base case)	15.49%	6.92%	13.85%	13.71%

A total of 104 simulations were run to optimise the window to wall ratio of the building.

The table below shows the simulation results for optimisation. A total of 104 simulations were done in this phase of optimisation.

Table 80: Simulation results for WWR optimisation

WWR (%)	Primary (source) energy demand - KWh/(m²a)			
	South Façade	**East Façade**	**West Façade**	**North Façade**
6.00	216.13	212.79	216.74	216.81
6.92 (Base case)	215.73	212.10	216.18	216.69
10.00	212.81	211.68	214.13	214.46
12.00	212.66	211.52	213.66	213.17
13.71 (Base case)	211.98	210.40	212.73	212.10
13.85 (Base case)	211.82	210.13	212.10	212.64
14.00	211.78	209.73	211.39	212.42
15.00	**211.72**	208.48	210.87	211.97
15.49 (Base case)	212.10	208.05	210.43	211.63
16.00	212.19	207.36	209.52	211.13
20.00	216.26	206.63	**208.75**	210.48
25.00	219.24	**205.96**	209.13	219.71
30.00	222.33	206.83	209.90	**209.30**
35.00	224.85	207.52	210.56	209.93
40.00	226.58	209.11	212.23	130.36
45.00	227.62	210.94	213.70	131.17
50.00	228.43	211.70	216.54	132.33
55.00	229.19	213.06	217.98	133.16
60.00	231.73	214.11	219.23	135.48
65.00	233.11	216.22	221.31	137.55
70.00	234.68	217.33	223.27	138.64
75.00	236.12	218.45	225.32	140.21
80.00	236.83	220.15	226.84	141.80
85.00	237.45	221.27	228.46	143.52
90.00	240.14	221.59	229.20	145.65
95.00	240.73	221.92	229.88	146.07

After the optimisation simulations, it was discovered that the building performed better with 15% WWR for the South façade, 25% for the East façade, 20% for the West façade, and 30% for the North façade, as presented below.

Table 81: Energy consumption for each facade based on window to wall ratio

	South Façade	**East Façade**	**West Façade**	**North Façade**
Best optimisation result in comparison with 212.10	**211.72** KWh/(m²a)	**205.96** KWh/(m²a)	**208.75** KWh/(m²a)	**209.30** KWh/(m²a)
New WWR	15%	25%	20	30%

The overall optimisation of the four facades brought the energy demand of the building from 212.10KWh/(m²a) to 199.19KWh/(m²a) - an energy reduction of 12.91KWh/(m²a), thereby yielding a 6.10% energy reduction.

Table 82: Simulation result of 12.49% WWR of the base case and 22.50% of the optimised case

Total WWR	12.49% (Before WWR optimisation)	22.50% (After WWR optimisation)
Primary (source) energy - KWh/(m²a)	**212.10**	**199.19**

The chart below shows the stages of optimisation of the building from 230.90KWh/(m²a) energy demand of the base case with a 12.49% WWR to 212.10KWh/(m²a) after building orientation optimisation and to 199.19KWh/(m²a) total primary (source) energy demand of the base case.

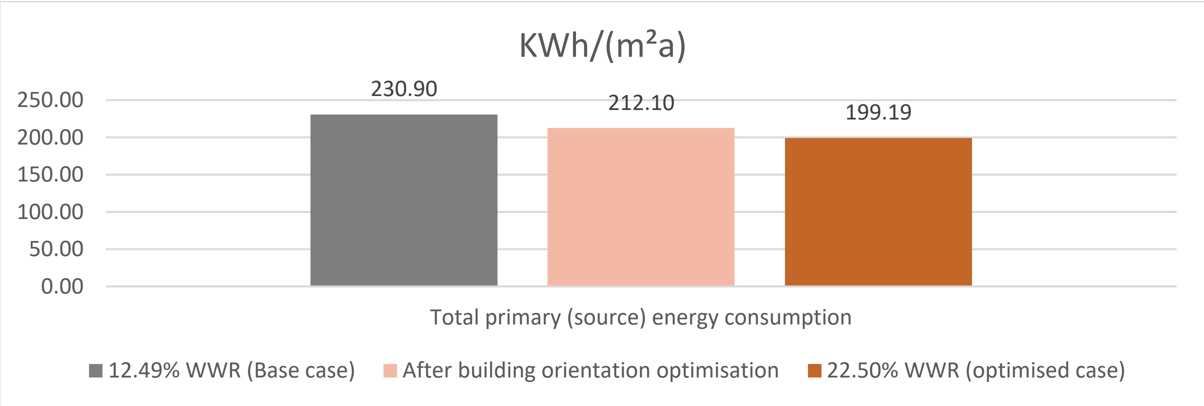


Figure 105: Total energy consumption of optimal building orientation, WWR in comparison with base case

6.2.2. Local Shading

The local shading optimisation was carried out for the four elevations (North, East, West, South) of the building one at a time. Each unique elevation was simulated with different types of shading devices to see the efficiency of each strategy as each elevation may have its own shading design. The design varied from louvres, overhang, and side fins.

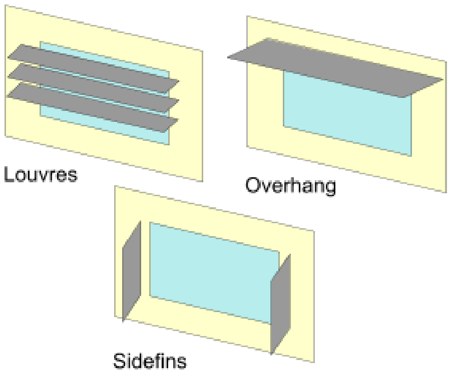


Figure 106: Shading design variations (DesignBuilder)

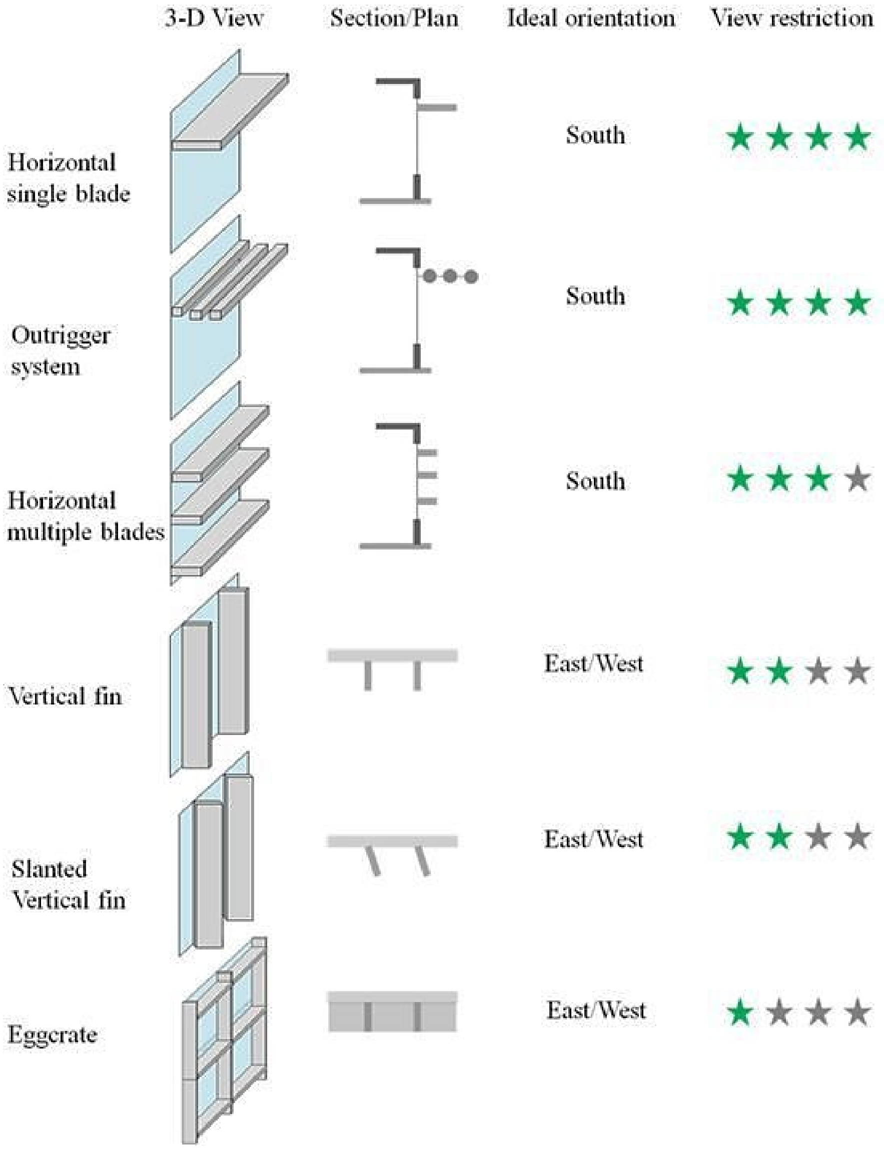


Figure 107: Local shading variations with regards to elevations and view restrictions

- North façade: According to literature studies, due to the geographical location of the building (in the Northern hemisphere) the North façade experiences little or no sunshine. Therefore, little or no shading is required (Bhatt 2014; Anumah and Anumah 2017).

- South façade experiences the most sunlight. It is suggested generally that horizontal shading devices are best suited for the South facades since the building is in the Northern hemisphere (Zain-Ahmed et al. 2002; Anumah and Anumah 2017).
- West/East facades receive direct sunlight for half a day therefore vertical shadings are best suited for East and West facades (Anumah and Anumah 2017; Gyoh 2020).

6.2.2.1. South Elevation

To achieve the best orientation for the south elevation of the building, the optimisation trials explored different strategies with variations to help decide the best solution, also considering the building is located in the southern hemisphere. A total of 110 simulations were carried out to determine the best strategy for the south elevation.

These strategies include:

A. Single horizontal overhang
B. Horizontal multiple blades
C. Box shading or egg-crate

A. Single horizontal overhang

The simulation started by using a horizontal shading device to optimise the south elevation. The Standard horizontal shading in Nigeria is 365mm wide and 75mm thick (Adunola and Ajibola 2016; Abdulkareem et al. 2018). Therefore, the study proceeded by increasing and decreasing 365mm to check for the best-optimised case.

For this experiment, the overhang projection was in the following variations of 200, 365, 400, 600, 800mm. The vertical offset from the overhang to the top of the window was kept at 200mm in all the cases. The height of the window was kept at 1.5m which is the standard window in Nigeria (Abatan et al. 2018; Awosusi 2018; Bankole 2019). The horizontal window overlap of the overhang was kept at 200mm for consistency.

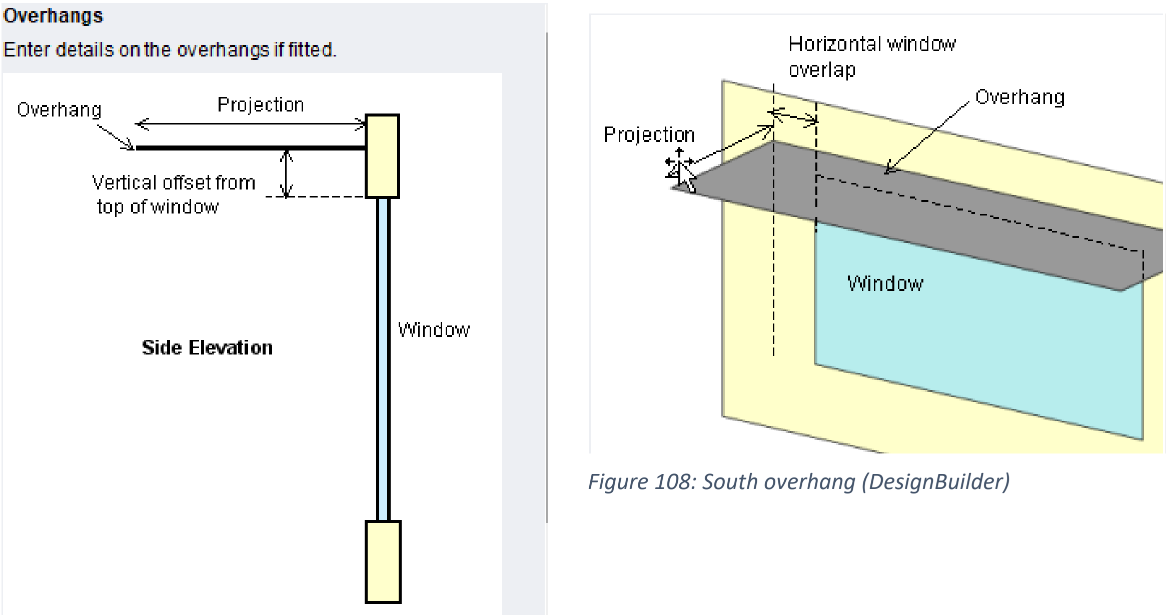
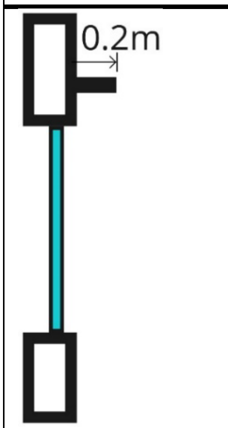
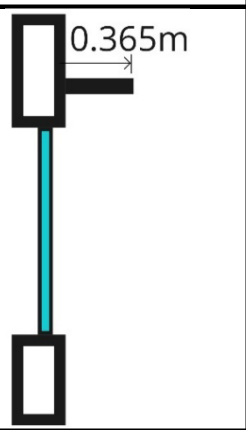
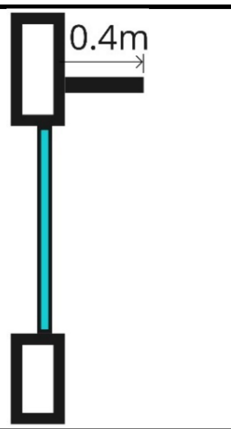
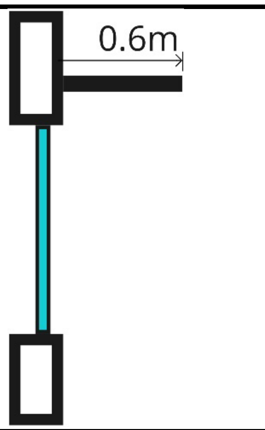
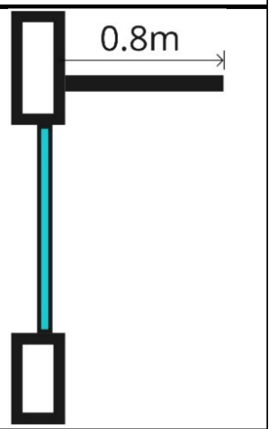


Figure 108: South overhang (DesignBuilder)

Table 83: Overhang simulation

Energy Simulation of horizontal overhang shading variations (section view) 200, 365, 400, 600, 800 (mm) - Primary source energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.10	198.43	195.24	195.03	194.12

The best-case simulation for the horizontal overhang shading for the south elevation was case 4 considering its effectiveness. There was an energy reduction from 199.19KWh/(m²a) to 195.24KWh/(m²a).

B. Horizontal multiple blades

The next strategy to experiment with was the horizontal multiple blades.

To determine the arrangement that works better, the horizontal multiple blade simulation was done in three categories, the variations are as follows.

1. Different depths of blades and Number of blades.
2. The number of blades and angle of blades.
3. Different angles of blades and variations in blade depths

Throughout the simulation, the variations shown in the figure below constantly changed for each simulation. However, the distance of the louvres from the window was kept at 50mm for consistency. The vertical offset from the top of the widow was kept the same with the spacing between louvres for each case. The horizontal window overlap was kept at 200mm all through the simulations.

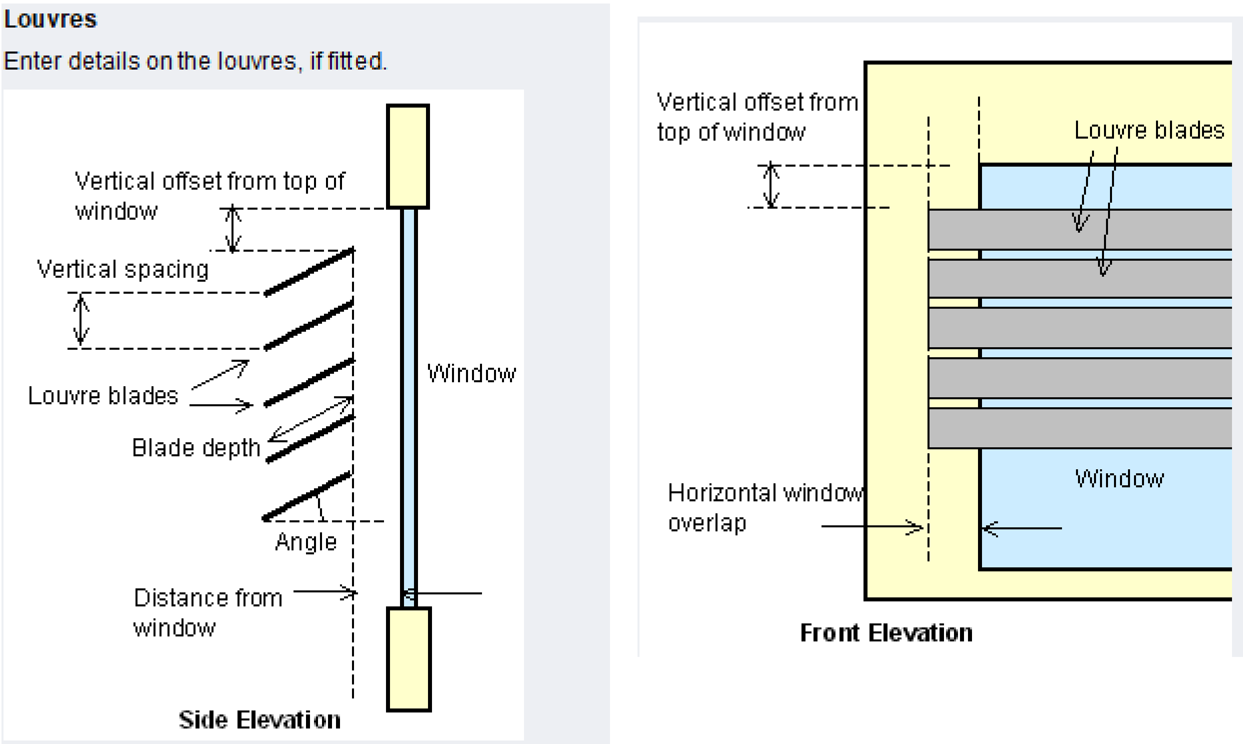


Figure 109: South elevation louvres

1. <u>Category one simulations: Different Depths of blades and Number of blades</u>

The first phase of simulations was between variable blade/louvre sizes and the number of blades. A total number of 25 simulations were run in this category. The best size was selected for simulation two.

Table 84: Different sizes of blades and Number of blades

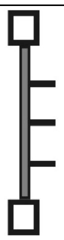
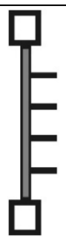
Simulations		Number of blades				
		1	2	3	4	5
Blade Depths	100	 Case 1	 Case 2	 Case 3	 Case 4	 Case 5
	200	 Case 6	 Case 7	 Case 8	 Case 9	 Case 10
	300	 Case 11	 Case 12	 Case 13	 Case 14	 Case 15
	400	 Case 16	 Case 17	 Case 18	 Case 19	 Case 20
	500	 Case 21	 Case 22	 Case 23	 Case 24	 Case 25

Table 85: Simulation results for category 1 simulations

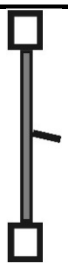
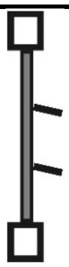
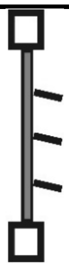
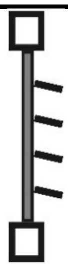
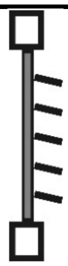
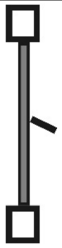
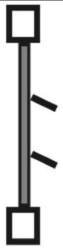
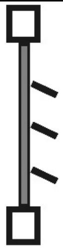
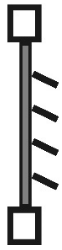
Results		Number of blades				
		1	2	3	4	5
Blade Depths	100	199.15	198.54	196.89	196.04	195.54
		Case 1	Case 2	Case 3	Case 4	Case 5
	200	198.94	198.88	198.80	197.99	197.81
		Case 6	Case 7	Case 8	Case 9	Case 10
	300	197.37	198.71	198.15	198.02	197.87
		Case 11	Case 12	Case 13	Case 14	Case 15
	400	197.23	197.20	197.19	197.05	196.74
		Case 16	Case 17	Case 18	Case 19	Case 20
	500	197.18	197.13	197.10	197.07	196.95
		Case 21	Case 22	Case 23	Case 24	Case 25

From the experiment, it was confirmed that case 5 (5 blades and 100mm blade depth) is most efficient by reducing the energy reduction from 199.19 KWh/(m²a) to 195.54KWh/(m²a).

2. Category two simulations: Number of blades and angle of blades

The second simulation was between the angles of blades and the number of blades. This is to determine the best combination of blade angles and the number of blades for optimisation. The best case (depth of blades – 100mm) in category one was selected for simulation two and kept constant.

Table 86: Category two simulations

Simulations		Number of Blades				
		1	2	3	4	5
Angles of Blades (degrees)^0	10^0					
		Case 1	Case 2	Case 3	Case 4	Case 5
	20^0					
		Case 6	Case 7	Case 8	Case 9	Case 10

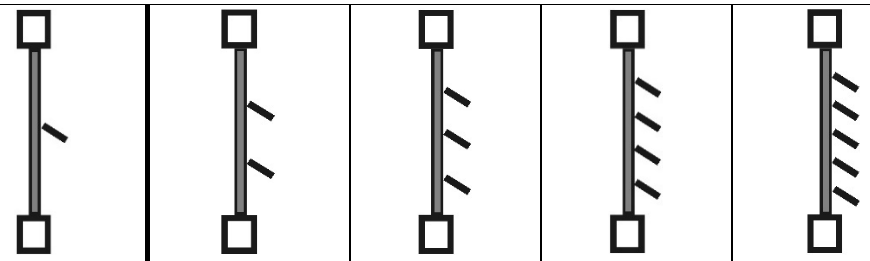
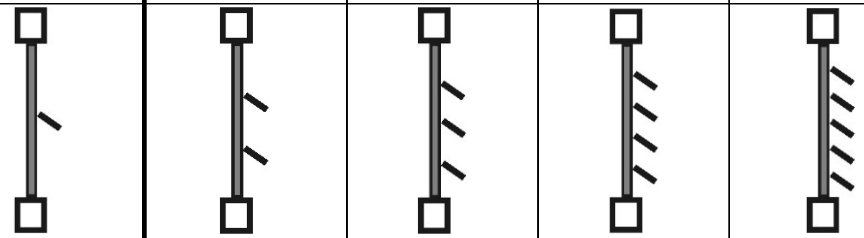
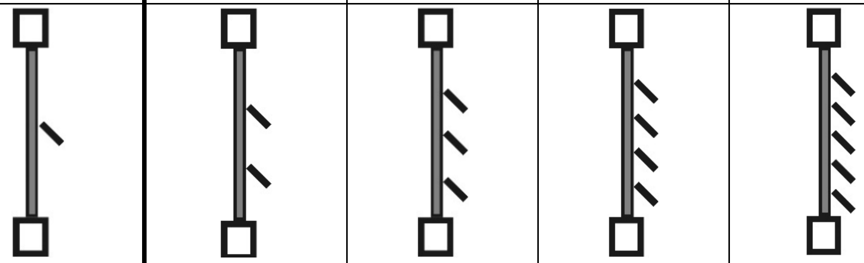
	30^0					
		Case 11	Case 12	Case 13	Case 14	Case 15
	40^0					
		Case 16	Case 17	Case 18	Case 19	Case 20
	50^0					
		Case 21	Case 22	Case 23	Case 24	Case 25

Table 87: Simulation results for category 2 simulations

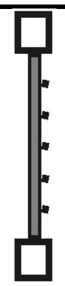
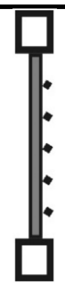
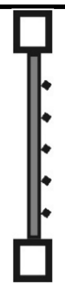
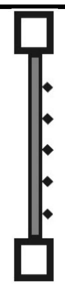
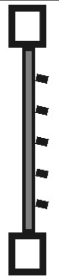
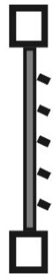
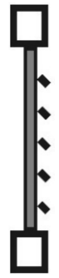
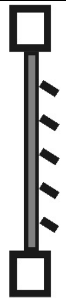
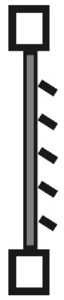
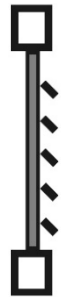
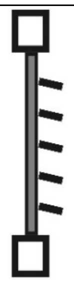
Results		**Number of blades**				
		1	2	3	4	5
Angles of Blades (degrees)^0	10^0	198.05	197.36	197.34	197.27	196.85
		Case 1	Case 2	Case 3	Case 4	Case 5
	20^0	199.26	198.82	197.52	196.66	196.51
		Case 6	Case 7	Case 8	Case 9	Case 10
	30^0	199.61	197.05	196.74	196.46	195.89
		Case 11	Case 12	Case 13	Case 14	Case 15
	40^0	199.65	198.76	197.47	196.32	195.11
		Case 16	Case 17	Case 18	Case 19	Case 20
	50^0	198.78	197.37	196.36	195.45	194.95
		Case 21	Case 22	Case 23	Case 24	Case 25

After the simulations, it was discovered that case 25 was more effective on energy demand with a blade angle of 50 degrees. Thereby reducing the energy demand from 199.19KWh/(m²a) to **194.95**KWh/(m²a).

3. <u>Category three simulations: Different angles of blades and variation in blade depths</u>

The third simulation was between the angles of blades and Variation in blade depths. This is to determine the best combination of blade angles and blade depths for optimisation. The best case (number of blades) in category two was selected for simulation three and kept constant. Therefore, this is to validate/determine a suitable angle or depth of the blade with five-blade louvres.

Table 88: Category three simulations

Simulations		**Angles of Blades (degrees)^0**				
		10^0	20^0	30^0	40^0	50^0
Depth of Blades (mm)	100	 Case 1	 Case 2	 Case 3	 Case 4	 Case 5
	200	 Case 6	 Case 7	 Case 8	 Case 9	 Case 10
	300	 Case 11	 Case 12	 Case 13	 Case 14	 Case 15
	400	 Case 16	 Case 17	 Case 18	 Case 19	 Case 20

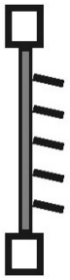
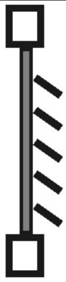
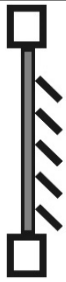
	500					
		Case 21	Case 22	Case 23	Case 24	Case 25

Table 89: Simulation results for category 3 simulations

Results		**Number of blades**				
		1	2	3	4	5
Blade Depths (mm)	100	198.85	197.51	196.89	195.11	194.95
		Case 1	Case 2	Case 3	Case 4	Case 5
	200	198.56	198.36	197.53	197.12	196.85
		Case 6	Case 7	Case 8	Case 9	Case 10
	300	198.55	197.82	197.35	196.67	195.95
		Case 11	Case 12	Case 13	Case 14	Case 15
	400	198.52	197.52	196.85	196.23	195.47
		Case 16	Case 17	Case 18	Case 19	Case 20
	500	197.86	197.33	197.23	196.85	195.24
		Case 21	Case 22	Case 23	Case 24	Case 25

In case 5, there was a reduction in the energy consumption from 199.19KWh/(m²a) to 194.95KWh/(m²a). However, in cases 9, and 13, it was noticed that the energy demand reduced to 195.11KWh/(m²a) and 195.24KWh/(m²a) respectively were relatively close to case 5 simulation. Also, cases 4 and 25 may serve as an alternative shading strategy with regards to adjusting between blade depths and the number of blades.

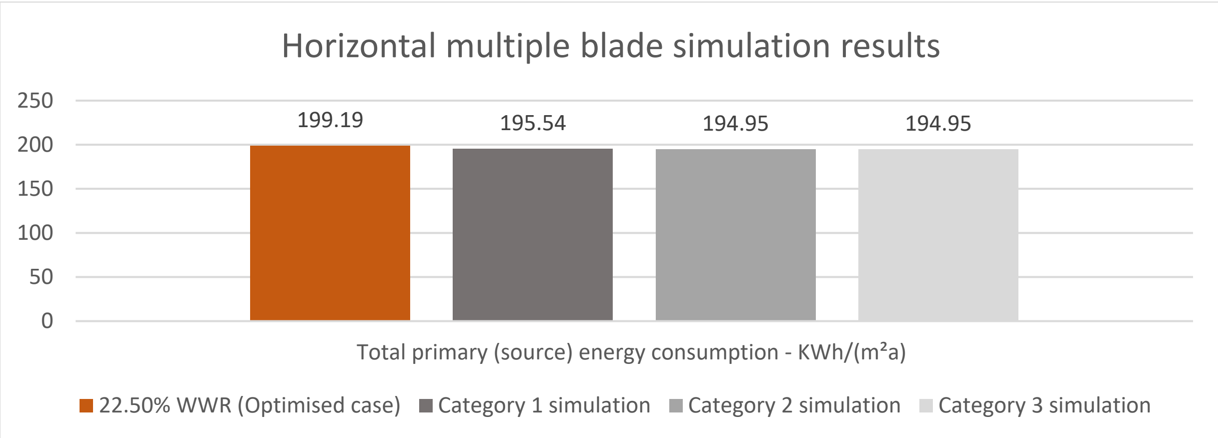


Figure 110: Horizontal multiple blade simulation results comparison

C. Box shading or egg-crate

After optimising the south elevation using the multiple horizontal blades, the research progressed to incorporate the egg crate shading by adding vertical fins to category 3 simulation (100mm blade depth, 50 degrees blade angle, 5 blades). To do this effectively, the box shading considered both the number of installed fins and the depth of fins.

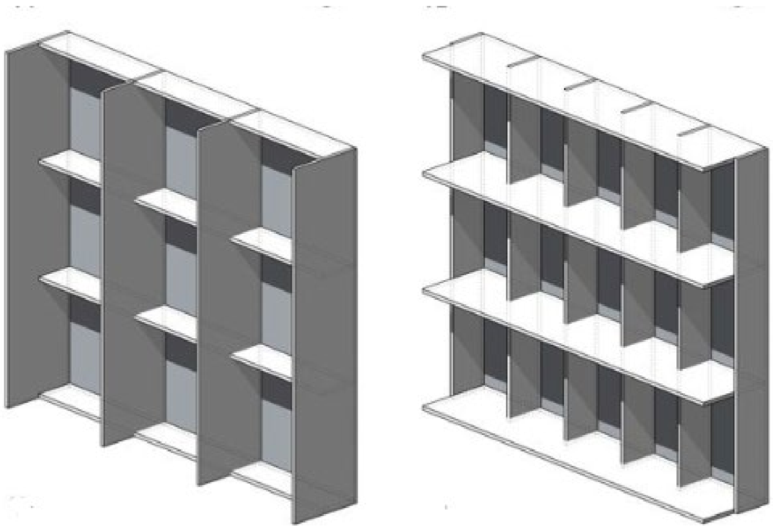


Figure 111: Egg crate or box shading

Simulation Results		Number of vertical fins (+ 5 horizontal blades @ 50^0, 100mm depth)				
		1	2	3	4	5
Fin Depths (mm)	100	197.95	197.54	197.17	196.51	195.36
		Case 1	Case 2	Case 3	Case 4	Case 5
	200	197.56	196.36	196.13	195.42	195.82
		Case 6	Case 7	Case 8	Case 9	Case 10
	300	197.25	196.82	196.75	196.33	196.14
		Case 11	Case 12	Case 13	Case 14	Case 15
	400	197.16	197.12	196.88	196.72	196.60
		Case 16	Case 17	Case 18	Case 19	Case 20
	500	196.87	196.34	196.13	196.16	195.55
		Case 21	Case 22	Case 23	Case 24	Case 25
	600	198.97	197.82	197.75	197.55	196.51
		Case 26	Case 27	Case 28	Case 29	Case 30

At the end of the experiment, it was discovered that the lowest value with regards to energy consumption was 195.36KWh/(m²a) which is higher than 194.95KWh/(m²a) from category 2 simulations.

Therefore, category 2 simulation (horizontal multiple blades - 100mm blade depth, 50 degrees blade angle, 5 blades) is adopted as the best optimisation for the south elevation.

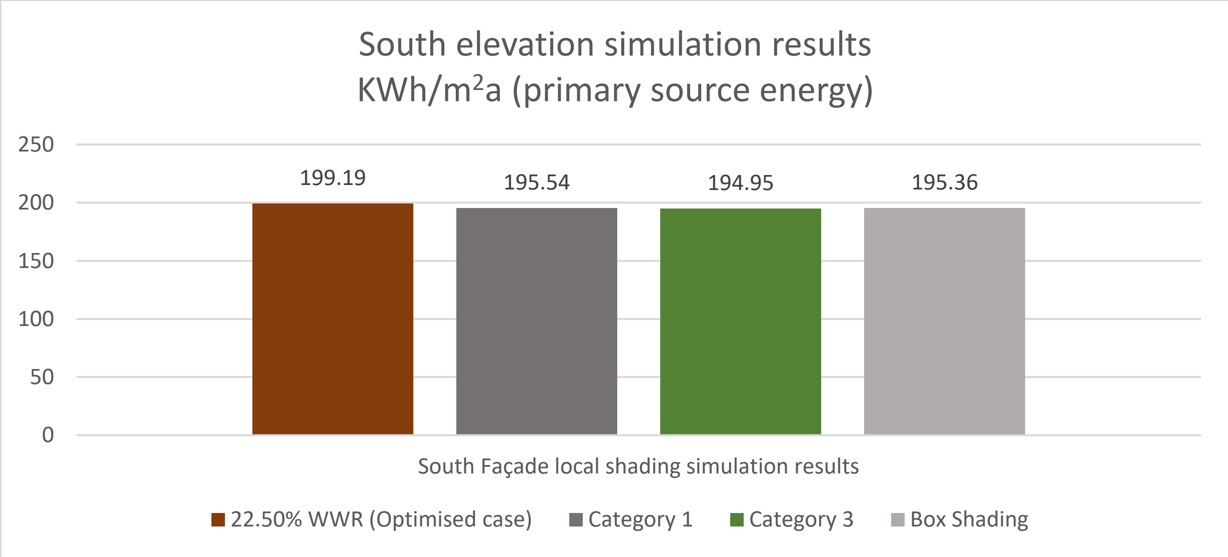


Figure 112: South elevation simulation results

6.2.2.2. West Elevation

To optimise the west elevation window shading, the optimisation was done in five categories:

A. Side fins
   1. Left side fin with variable projections.
   2. Right side fin with variable projections.
   3. Left and right sidefins with variable projections.
B. Selected Left and right sidefins with variable overhang.
C. Number of vertical fins and depth of fins
D. Number of vertical fins and angles of fins
E. The selected number of vertical fins and selected angles of fins with variable overhang

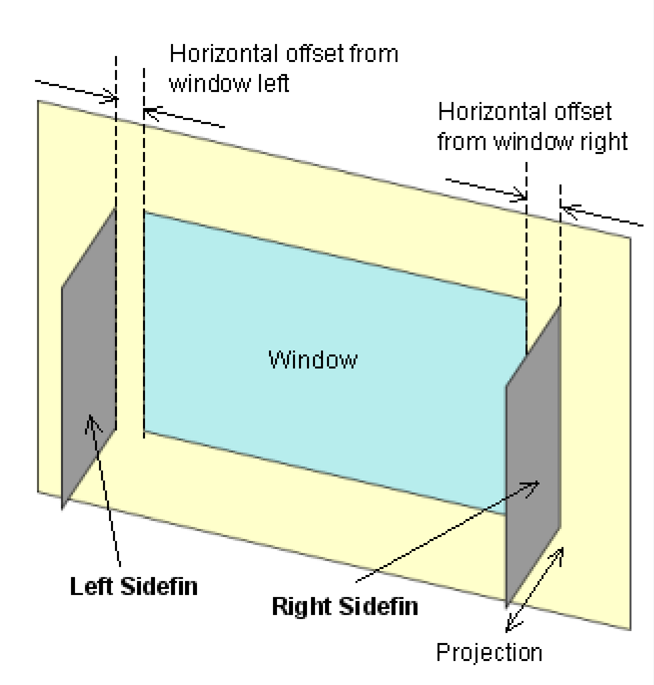


Figure 113: West elevation sidefin (DesignBuilder)

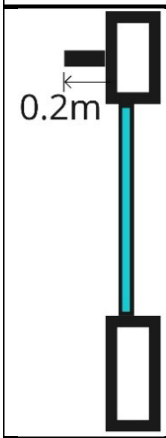
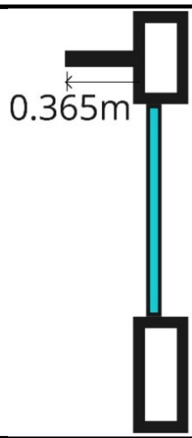
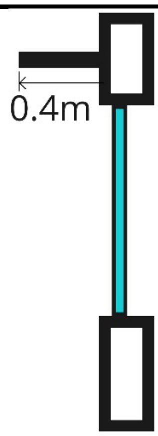
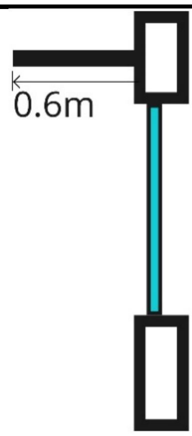
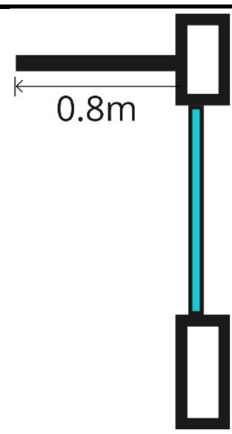
For consistency, the gap between the side fin from the window was maintained at 200mm, the bottom overlap kept at 0mm, top overlap kept at 200mm.

It is important to note that the standard projection length of side fins in Nigeria is 365mm, hence variations were made below and above this standard to determine the most optimised projection in the Nigerian context (Adunola and Ajibola 2016; Abdulkareem et al. 2018).

A. Side fins

1. Simulation - Left sidefin with variable projections

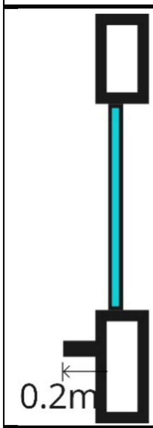
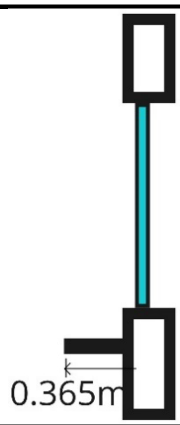
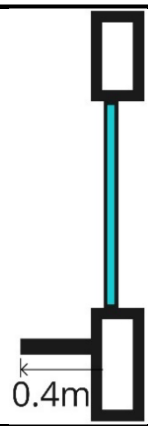
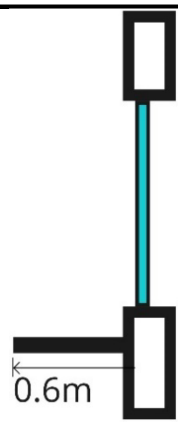
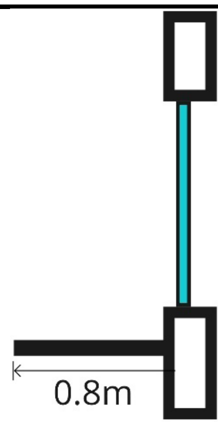
Table 90: Left sidefin with variable projection simulations

Energy Simulation of left sidefin variations (plan view) 200, 365, 400, 600, 800 (mm)				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Primary (source) energy - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.10	199.01	198.99	198.95	198.86

The simulation results revealed a little decrease in energy demand with the left side fin. Hence, there may not be much need for left side fins since there is no significant drop in the total energy demand. Therefore, case 3 sets a good balance between optimisation and material economy.

2. Simulation - Right sidefin with variable projections

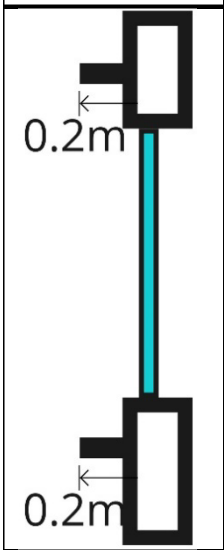
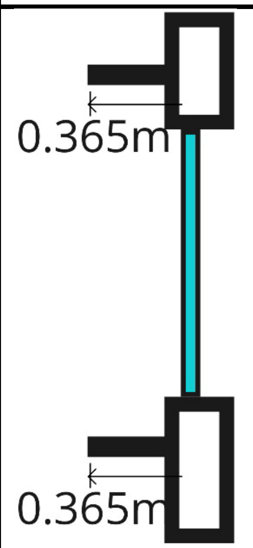
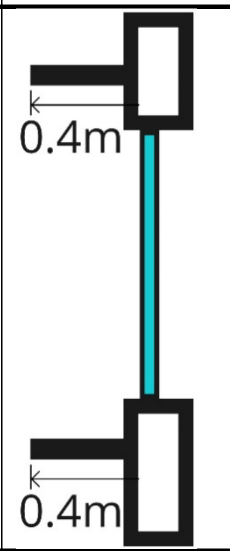
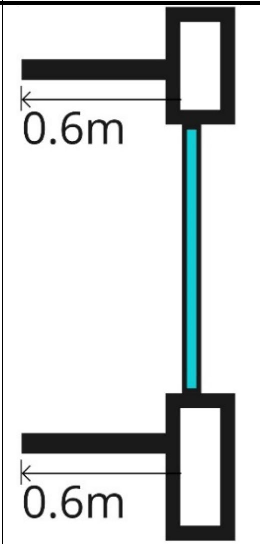
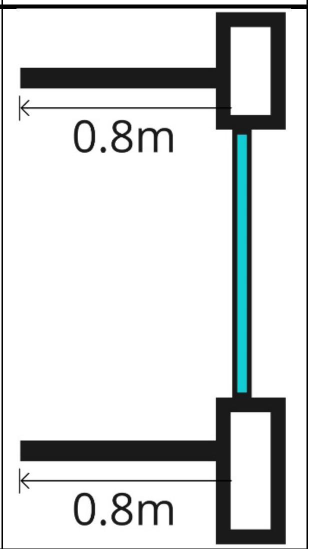
Table 91: Right sidefin with variable projection simulations

Energy Simulation of right sidefin variations (Plan view) 200, 365, 400, 600, 800 (mm)				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Primary (source) energy - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.17	199.14	199.09	199.07	199.05

Similarly, to simulation 1 above, there was no significant drop in energy demand. Therefore, case 3 sets a good balance between optimisation and material economy as well as having a significant change in energy consumption. This selection is to save ineffective/inefficient use of material (shading devices).

3. Simulation - Left and right sidefins with variable projections

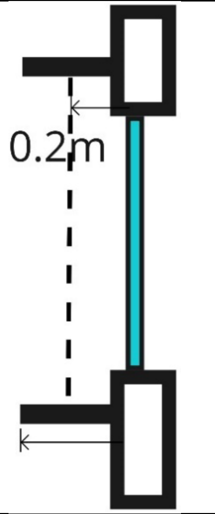
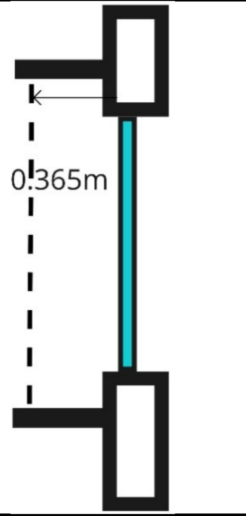
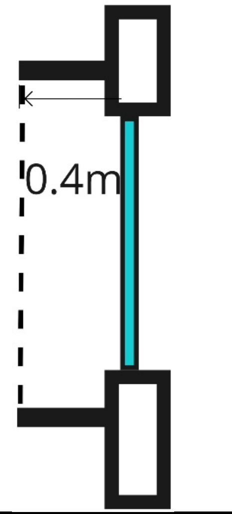
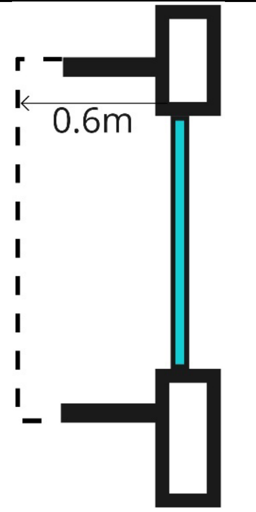
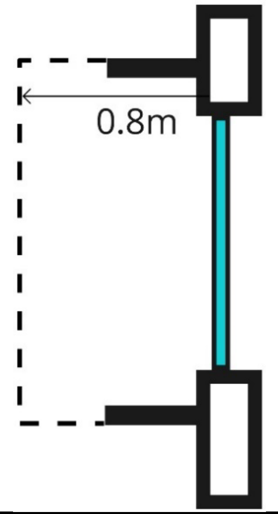
Table 92: Energy Simulation of left and right-side fin variations

Energy Simulation of left and right-side fin variations (Plan view) 200, 365, 400, 600, 800 (mm)				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Primary (source) energy - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.06	199.01	198.90	198.88	198.87

The combination of both left and right sidefins did not yield much result. Thus, no significant drop in energy demand. Case 3 sets a good balance between optimisation and material economy as well as having a significant change in energy consumption. This selection is to save ineffective/inefficient use of material (shading devices).

B. Selected Left and right sidefins with variable overhang

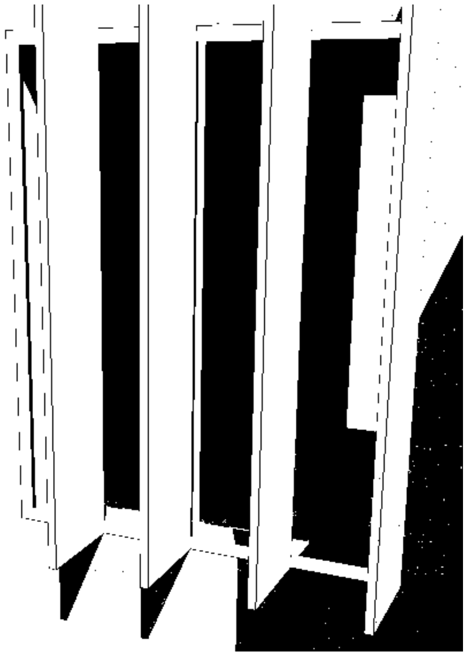
Table 93: Energy Simulation of selected Left and right sidefins with variable overhang

Energy Simulation of selected Left and right sidefins with variable overhang 200, 365, 400, 600, 800 (mm)				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Primary (source) energy - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
198.72	198.68	198.30	198.17	198.04

The experiment revealed that the overhang had very little effect on the energy demand of the building as the combined shading (Left and right sidefins with overhang) had only brought down the energy demand from 199.19KWh/(m²a) to an average of 198.38KWh/(m²a). The optimisation experiment proceeded to the next shading strategy with the use of multiple vertical fins.

C. Number of vertical fins and depth of fins

This optimisation process started by installing variable vertical shading fins. This was done while changing and depth of fins.



For consistency, the bottom overlap was kept at 0mm, while the top overlap was kept at 200mm. The thickness of fins was maintained at 20mm.

A total number of 30 simulations were done under this category to determine the best optimisation strategy for the West elevation.

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Figure 114: Window vertical fins

Table 94: Number of vertical fins and depth of fins simulation results

Simulation Results		**Number of vertical fins**				
		1	2	3	4	5
Depth of Fins (mm)	100	199.18	199.03	198.89	198.69	198.22
		Case 1	Case 2	Case 3	Case 4	Case 5
	200	200.11	200.17	199.18	198.55	198.20
		Case 6	Case 7	Case 8	Case 9	Case 10
	300	199.02	198.94	198.86	197.97	197.09
		Case 11	Case 12	Case 13	Case 14	Case 15
	400	199.14	198.25	198.03	197.31	197.25
		Case 16	Case 17	Case 18	Case 19	Case 20
	500	199.16	199.13	198.90	198.56	198.23
		Case 21	Case 22	Case 23	Case 24	Case 25
	600	199.20	199.11	198.95	198.78	198.66
		Case 26	Case 27	Case 28	Case 29	Case 30

The results from the simulations showed that case 14 delivered the lowest energy consumption at 197.97KWh/(m²a). This means that the West elevation would perform best with four vertical fins of 300mm depths.

D. Number of vertical fins and angles of fins

In this stage of the building optimisation, the building adopted the best result from category C simulation (Number of vertical fins and depth of fins). Therefore, in the simulation, the depth of the blade was 300mm.

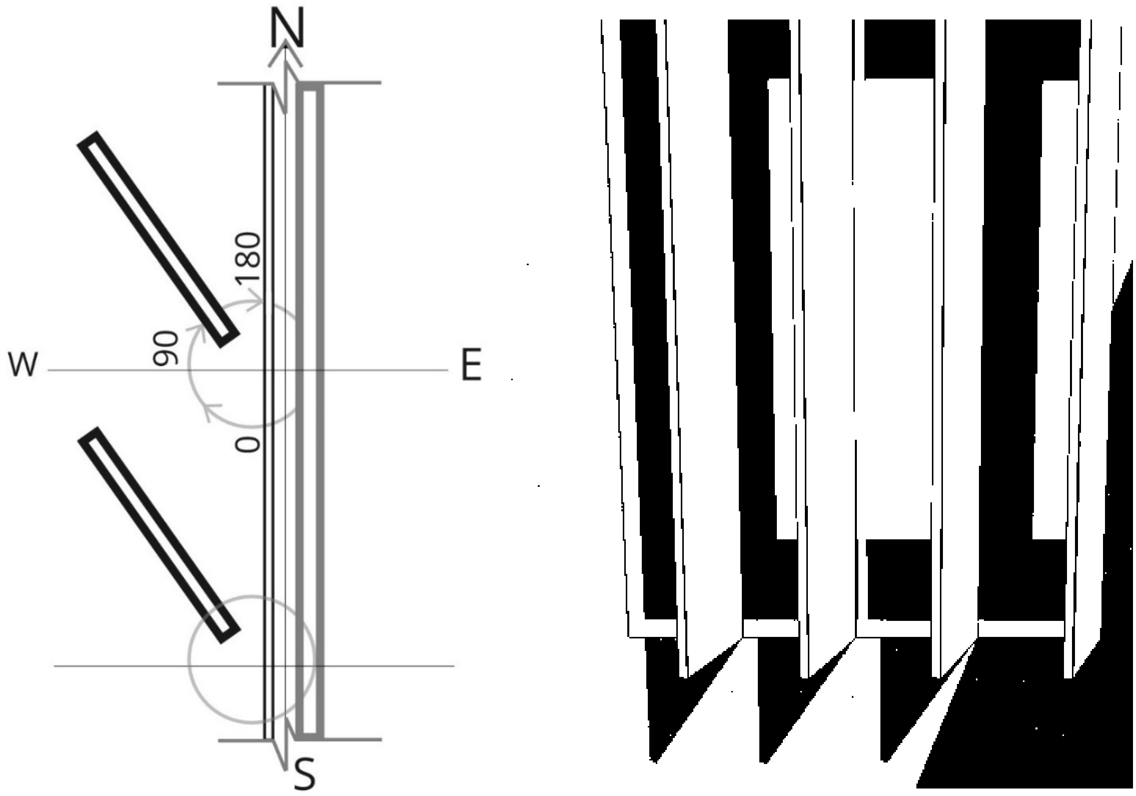


Figure 115: Angled window vertical fins

The angle of the vertical fins was progressively adjusted from 0 degrees to 180 degrees from the South to the North.

A total of 90 simulations were executed in this category.

Table 95: Angle of blades and number of vertical fins

Simulation Results		Number of vertical fins				
		1	2	3	4	5
Angle of blades (°)	10	199.23	199.21	199.18	199.15	199.13
		Case 1	Case 2	Case 3	Case 4	Case 5
	20	199.21	199.18	199.15	199.13	199.11
		Case 6	Case 7	Case 8	Case 9	Case 10
	30	199.20	199.16	199.14	199.12	199.08
		Case 11	Case 12	Case 13	Case 14	Case 15
	40	199.19	199.18	199.15	199.10	199.07
		Case 16	Case 17	Case 18	Case 19	Case 20

	50	199.18	199.09	198.48	198.92	198.59
		Case 21	Case 22	Case 23	Case 24	Case 25
	60	198.61	198.43	198.40	198.35	198.20
		Case 26	Case 27	Case 28	Case 29	Case 30
	70	197.62	197.85	198.01	198.12	198.03
		Case 31	Case 32	Case 33	Case 34	Case 35
	80	197.60	197.58	197.55	197.52	197.23
		Case 36	Case 37	Case 38	Case 39	Case 40
	90	197.59	197.50	197.47	197.45	197.32
		Case 41	Case 42	Case 43	Case 44	Case 45
	100	197.46	197.42	197.34	197.32	197.26
		Case 46	Case 47	Case 48	Case 49	Case 50
	110	197.22	197.06	196.98	196.93	196.95
		Case 51	Case 52	Case 53	Case 54	Case 55
	120	197.27	197.24	197.11	196.98	196.97
		Case 56	Case 57	Case 58	Case 59	Case 60
	130	198.45	198.39	198.36	198.14	197.95
		Case 61	Case 62	Case 63	Case 64	Case 65
	140	198.57	198.52	198.47	198.39	198.25
		Case 66	Case 67	Case 68	Case 69	Case 70
	150	198.63	198.59	198.44	198.36	198.32
		Case 71	Case 72	Case 73	Case 74	Case 75
	160	198.68	198.62	198.51	198.12	199.07
		Case 76	Case 77	Case 78	Case 79	Case 80
	170	199.34	199.28	199.25	199.13	199.02
		Case 81	Case 82	Case 83	Case 84	Case 85
	180	199.50	199.40	199.32	199.21	199.16
		Case 86	Case 87	Case 88	Case 89	Case 90

The simulation revealed that case 54 had the lowest energy demand and was the most efficient strategy (4 blades at angle 110 degrees, with blade depth of 300mm).

With case 54, the primary (source) energy was reduced from 199.19KWh/(m²a) to 196.93KWh/(m²a).

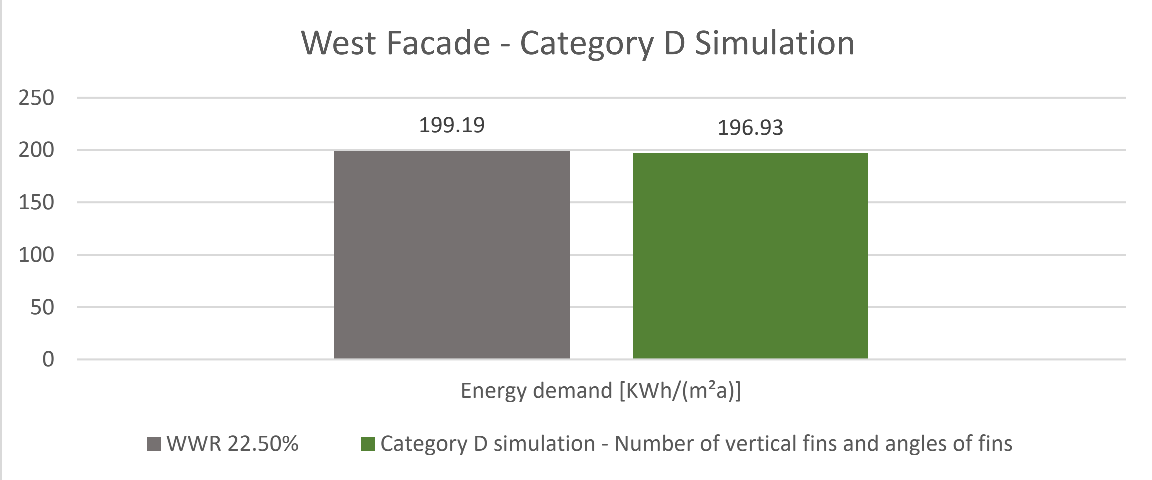
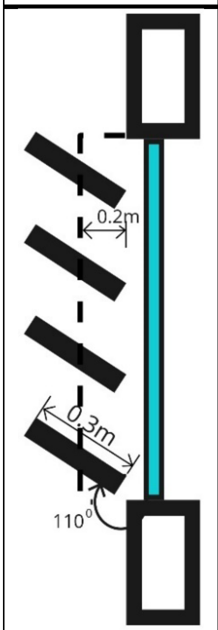
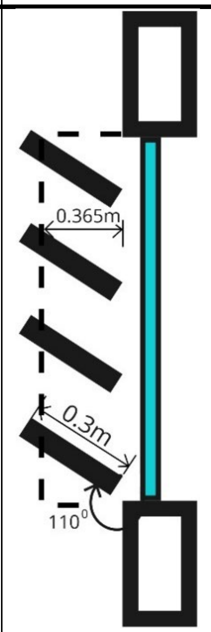
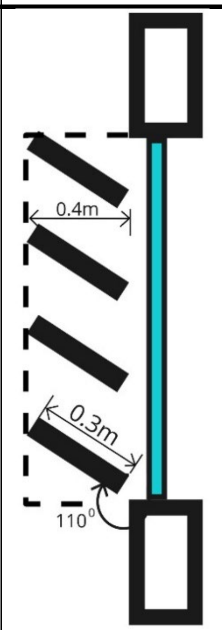
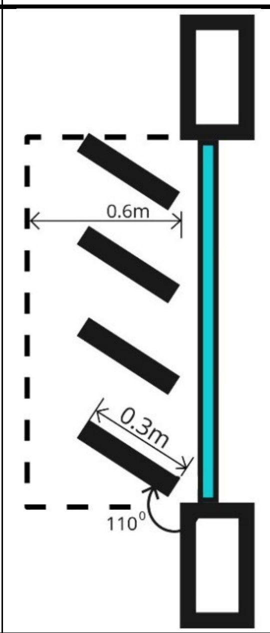
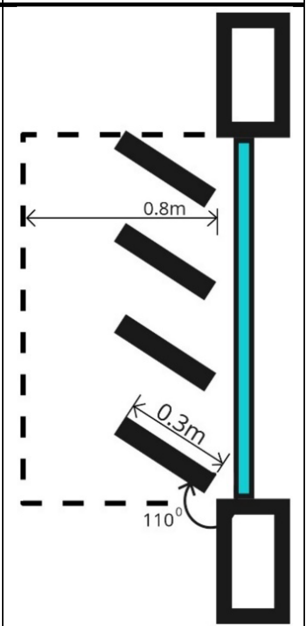


Figure 116: Category D simulation of west facade

E. The selected number of vertical fins and selected angles of fins with variable overhang

The simulation was done with the adoption of the best cases from category C and D simulations. Therefore, the parameters used were blade depth of 300mm, blade angle of 110^0, 4 number vertical fins and variable overhang.

Table 96: Simulation results for window overhangs

Energy Simulation of Category E Simulation (Plan view) 200, 365, 400, 600, 800 (mm)				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Primary (source) energy - KWh/(m²a)	Primary (source) energy - KWh/(m²a)	Primary (source) energy - KWh/(m²a)	Primary (source) energy - KWh/(m²a)	Primary (source) energy - KWh/(m²a)
196.78	196.75	196.53	196.51	196.50

The optimisation simulation revealed that the building performed best with the combination of the 0.4m overhang to the category E simulation. This brought the energy consumption from 196.93KWh/(m²a) to **196.53**KWh/(m²a). Further optimisation did not yield effective results. Hence, 0.40m overhang is ideal both in terms of energy efficiency and resource efficiency.

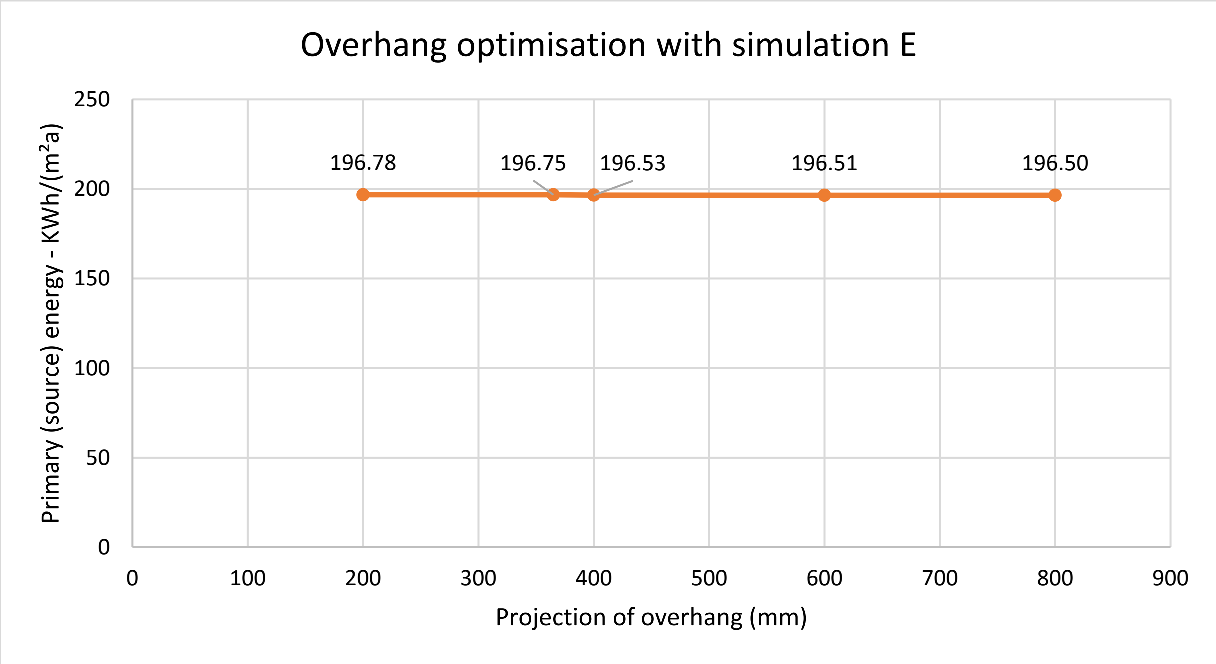


Figure 117: Energy consumption of the building based on different window overhang projections on the West Elevation

6.2.2.3. East Elevation

To optimise the East elevation, the optimisation simulation was done in five categories:

A. Side fins
   1. Left side fin with variable projections.
   2. Right side fin with variable projections.
   3. Left and right sidefins with variable projections.

B. Selected Left and right sidefins with variable overhang.

C. Number of vertical fins and depth of fins

D. Number of vertical fins and angles of fins

E. The selected number of vertical fins and selected angles of fins with variable overhang

For consistency, the gap between the side fin from the window was maintained at 200mm, the bottom overlap kept at 0mm, top overlap kept at 200mm.

The standard projection length of side fins in Nigeria is 365mm. Therefore variations were made below and above this standard to determine the most optimised projection in the Nigerian context (Adunola and Ajibola 2016; Abdulkareem et al. 2018; Bankole 2019).

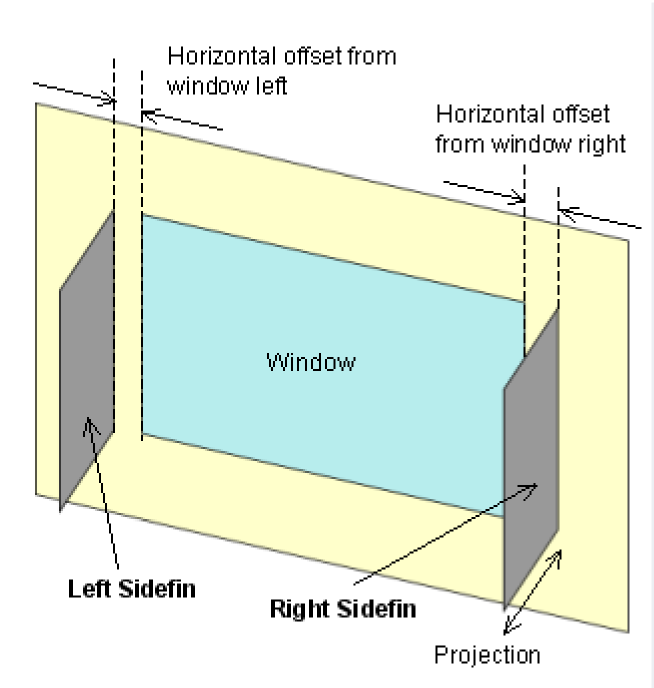
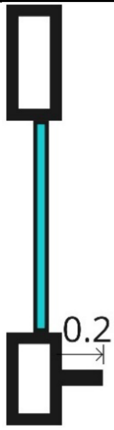
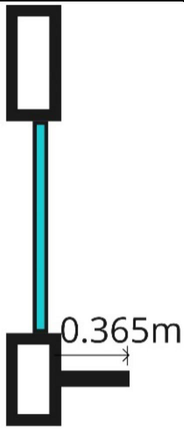
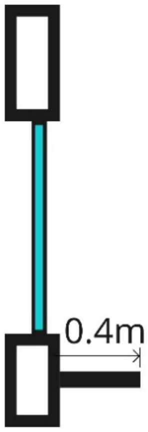
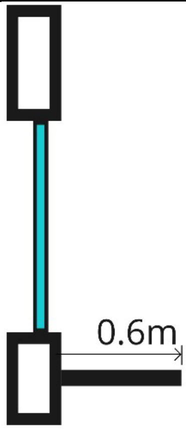
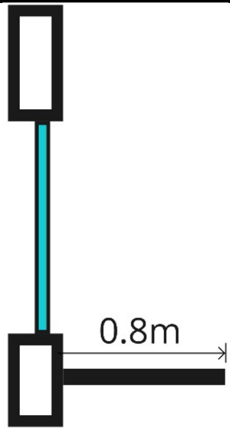


Figure 118: East Sidefin (DesignBuilder)

A. Side fins

4. Simulation - Left sidefin with variable projections

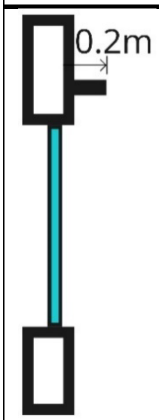
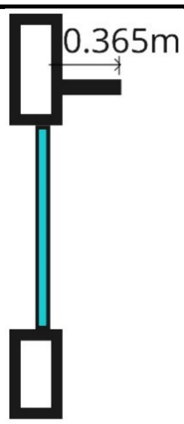
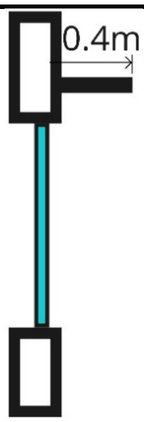
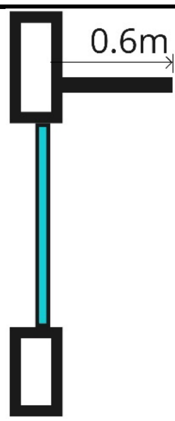
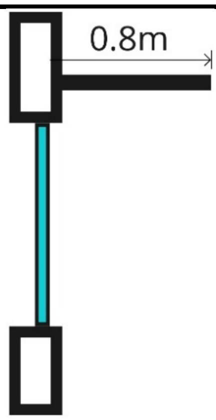
Table 97: Energy Simulation of left sidefin variations

Energy Simulation of left sidefin variations (plan view) **200, 365, 400, 600, 800 (mm) -** Primary (source) energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.14	199.10	198.95	198.92	198.89

In the stage of the optimisation, the simulation results revealed a little reduction in energy demand with the left side fin. The most effective case was case 3, which used a 400mm side fin projection. Hence, there may not be much need for longer left side fins since there is no significant drop in the total energy demand with further projections. Therefore, case 3 sets a good balance between optimisation and material economy.

5. Simulation - Right sidefin with variable projections

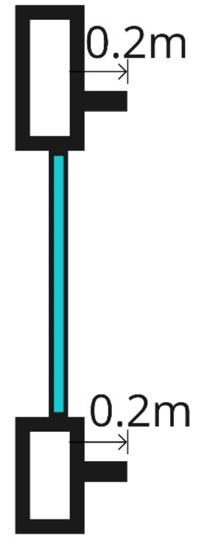
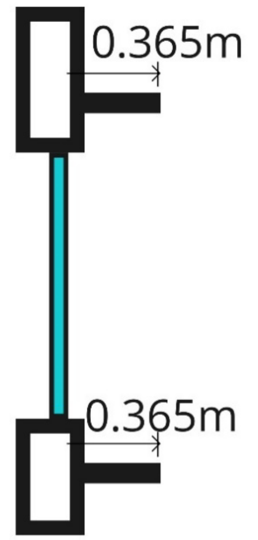
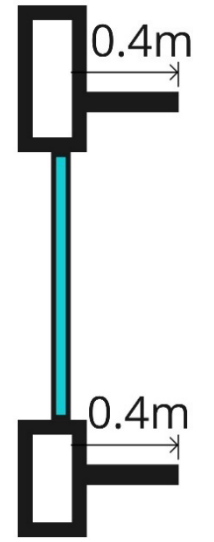
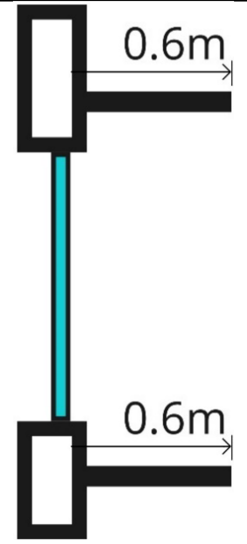
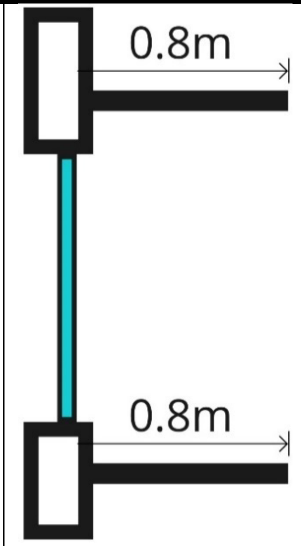
Table 98: Energy Simulation of right sidefin variations

Energy Simulation of right sidefin variations (Plan view) **200, 365, 400, 600, 800 (mm) -** Primary (source) energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.16	199.12	198.97	198.95	198.93

Similarly, to the first simulation above, there was no significant drop in energy demand after case 3, even with longer projections. Therefore, case 3 sets a good balance between optimisation and material economy as well as having a significant change in energy consumption. As stated previously, this selection is to save ineffective/inefficient use of material (shading devices).

6. Simulation - Left and right sidefins with variable projections

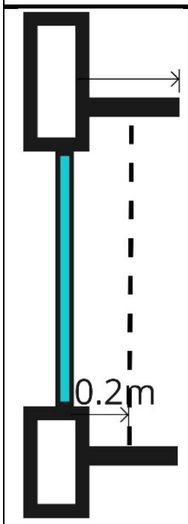
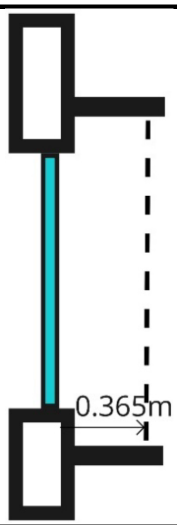
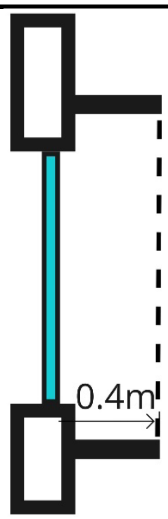
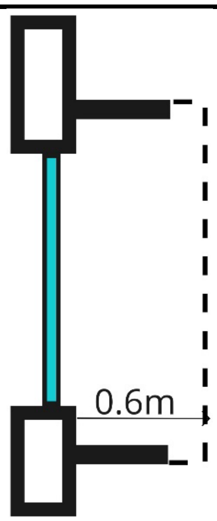
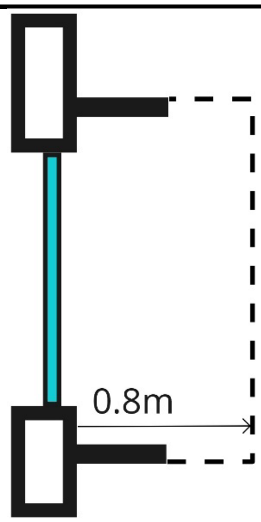
Table 99: Energy Simulation of left and right-side fins variations

Energy Simulation of left and right-side fins variations (Plan view) **200, 365, 400, 600, 800 (mm) -** Primary (source) energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
199.10	199.01	198.74	198.72	198.69

The combination of both left and right side fins yielded a little drop in the energy demand, although not very effective. However, case 3 sets a good balance between optimisation and material economy as well as having a significant change in energy consumption. Again, this selection is to save ineffective/inefficient use of material (shading devices).

B. Selected Left and right sidefins with variable overhang

Table 100: Energy Simulation of selected Left and right sidefins with variable overhang

Energy Simulation of selected Left and right sidefins with variable overhang 200, 365, 400, 600, 800 (mm) - Primary (source) energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
198.86	198.78	198.19	198.17	198.15

The overhang had very little effect on the energy demand of the building from this experiment. The best case of the experiment is case 3 with 400mm overhang projection as this variation had the most effective impact on energy demand. The combined shading (Left and right sidefins with overhang) brought down the energy demand from 199.19KWh/(m²a) to 198.19KWh/(m²a). Hence, the optimisation experiment proceeded to the next shading strategy with the use of multiple vertical fins.

C. Number of vertical fins and depth of fins

The next shading strategy was the use of vertical fins. This optimisation was done by installing variable depths of vertical shading fins.

For consistency, the bottom overlap was kept at 0mm, while the top overlap was kept at 200mm. The thickness of fins was maintained at 20mm.

A total number of 30 simulations were done under this category to determine the best optimisation strategy for the East elevation.

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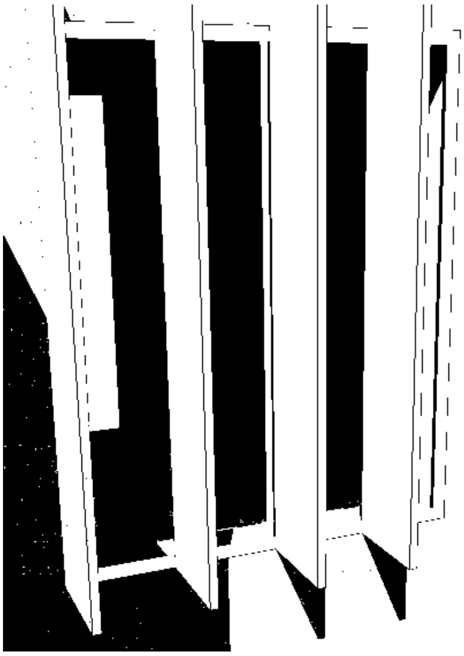


Figure 119: East vertical fins

Table 101: Number of vertical fins and depth of fins

Simulation Results		Number of vertical fins				
		1	2	3	4	5
Depth of Fins (mm)	100	199.11	199.18	198.07	197.64	197.33
		Case 1	Case 2	Case 3	Case 4	Case 5
	200	199.22	199.16	198.17	197.47	197.10
		Case 6	Case 7	Case 8	Case 9	Case 10
	300	198.13	198.14	197.89	197.08	197.12
		Case 11	Case 12	Case 13	Case 14	Case 15
	400	119.20	198.14	197.93	197.46	197.21
		Case 16	Case 17	Case 18	Case 19	Case 20
	500	199.23	199.12	198.89	197.54	197.18
		Case 21	Case 22	Case 23	Case 24	Case 25
	600	199.19	199.15	198.56	198.17	197.83
		Case 26	Case 27	Case 28	Case 29	Case 30

The results from the simulations showed that case 14 delivered the lowest energy consumption at 197.08KWh/(m²a). This implies that the West elevation would perform best with four vertical fins of 300mm depths.

D. Number of vertical fins and angles of fins

At this stage of the experiment, the building adopted the best result from category C simulation (Number of vertical fins and depth of fins). Therefore, in the simulation, the depth of the blade was 300mm.

The angle of the vertical fins were progressively adjusted from 0 degrees to 180 degrees from the South to the North.

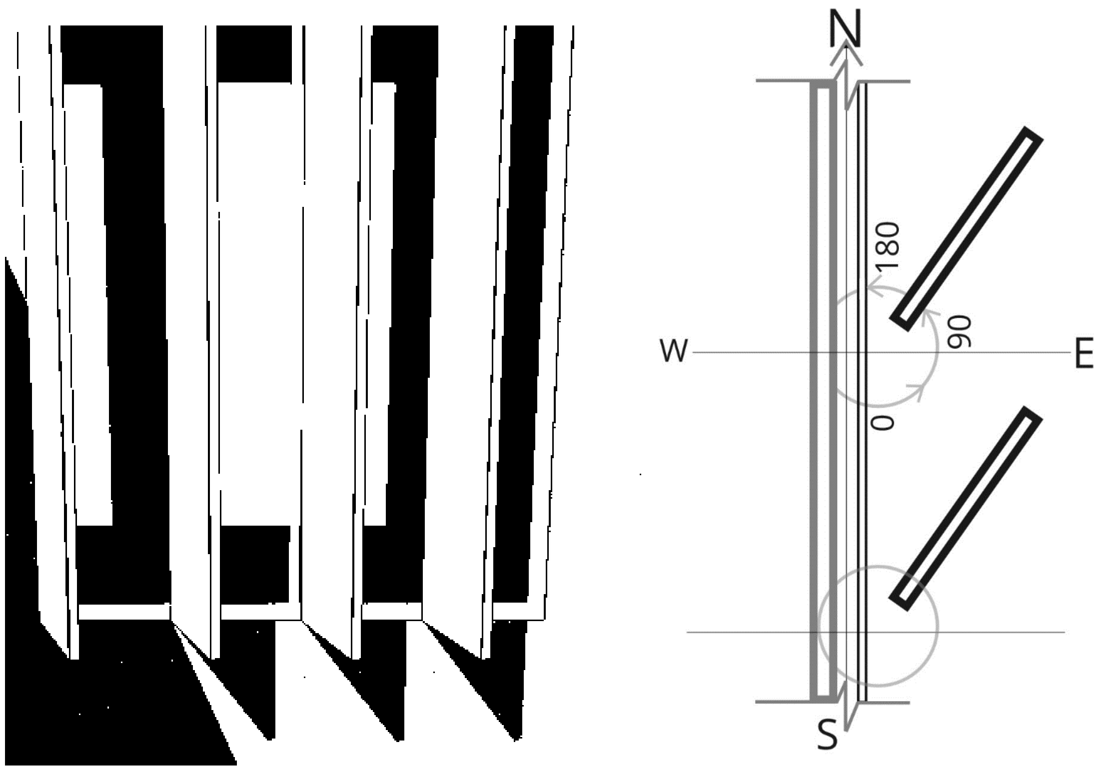


Figure 120: Angular vertical fins

A total of 90 simulations was executed in this category.

Table 102: Category D simulations

Simulation Results		Number of vertical fins				
		1	2	3	4	5
Angle of blades (°)	10	199.24	199.18	199.17	199.14	199.11
		Case 1	Case 2	Case 3	Case 4	Case 5
	20	199.21	199.18	199.16	199.15	199.14
		Case 6	Case 7	Case 8	Case 9	Case 10
	30	199.21	199.18	199.15	199.10	198.03
		Case 11	Case 12	Case 13	Case 14	Case 15
	40	199.24	199.20	199.19	199.13	198.47
		Case 16	Case 17	Case 18	Case 19	Case 20
	50	199.21	199.15	199.03	198.57	198.35

		Case 21	Case 22	Case 23	Case 24	Case 25
	60	198.61	198.47	198.31	198.27	198.14
		Case 26	Case 27	Case 28	Case 29	Case 30
	70	197.71	197.53	198.41	198.23	197.92
		Case 31	Case 32	Case 33	Case 34	Case 35
	80	197.67	197.63	197.53	197.44	197.13
		Case 36	Case 37	Case 38	Case 39	Case 40
	90	197.61	197.53	197.48	197.42	197.34
		Case 41	Case 42	Case 43	Case 44	Case 45
	100	197.57	197.51	197.48	197.40	197.35
		Case 46	Case 47	Case 48	Case 49	Case 50
	110	197.14	197.66	197.56	197.11	196.92
		Case 51	Case 52	Case 53	Case 54	Case 55
	120	197.87	197.13	196.90	196.50	116.51
		Case 56	Case 57	Case 58	Case 59	Case 60
	130	198.77	198.58	198.46	198.39	198.33
		Case 61	Case 62	Case 63	Case 64	Case 65
	140	198.61	198.58	198.44	198.37	198.23
		Case 66	Case 67	Case 68	Case 69	Case 70
	150	198.64	198.52	198.42	198.36	198.30
		Case 71	Case 72	Case 73	Case 74	Case 75
	160	198.67	198.63	198.49	198.32	198.18
		Case 76	Case 77	Case 78	Case 79	Case 80
	170	199.34	199.30	199.26	199.24	199.14
		Case 81	Case 82	Case 83	Case 84	Case 85
	180	199.52	199.48	199.41	199.33	199.23
		Case 86	Case 87	Case 88	Case 89	Case 90

The simulation revealed that case 59 had the lowest energy demand and was the most efficient strategy (4 blades at an angle of 120 degrees, with a blade depth of 300mm).

With case 59, the energy demand was reduced from 199.19KWh/(m²a) to 196.50KWh/(m²a).

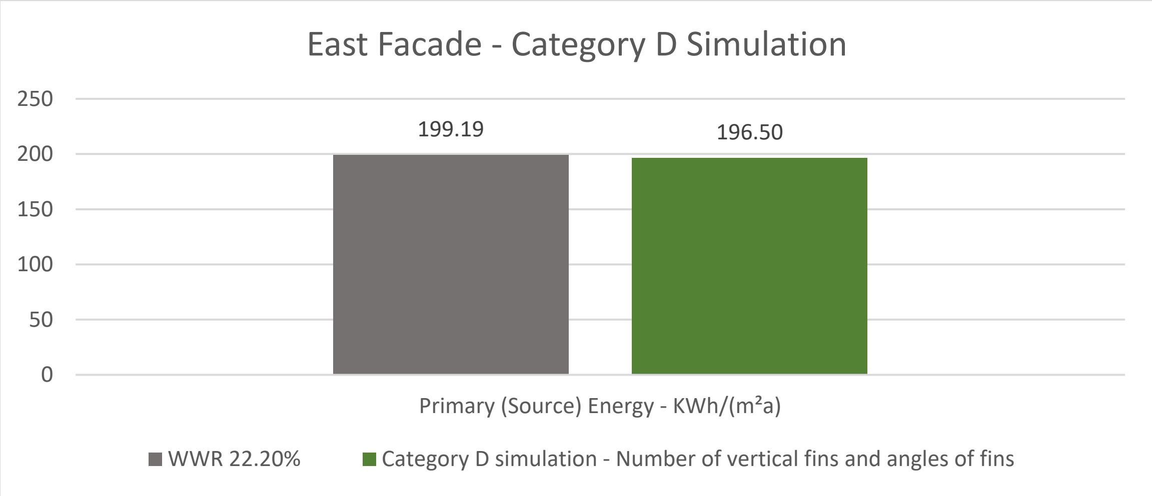
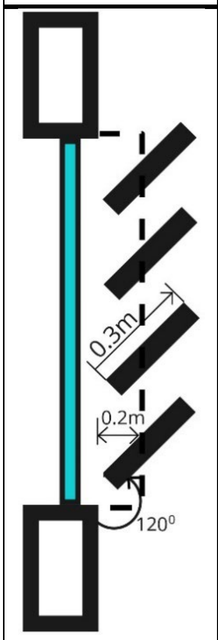
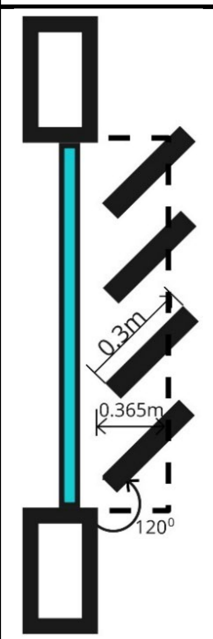
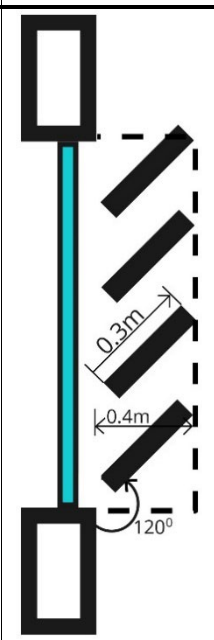
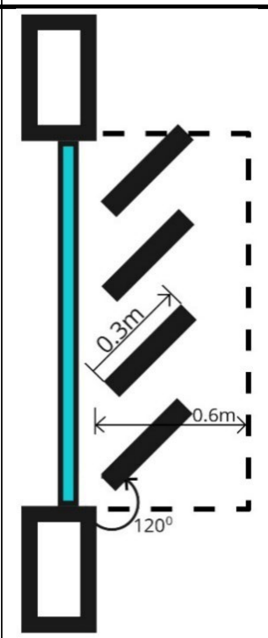
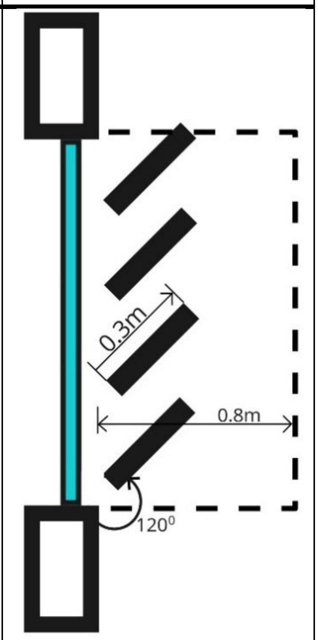


Figure 121: Category D simulation of East facade

E. The selected number of vertical fins and selected angles of fins with variable overhang

The simulation was carried out by selecting the best cases from category C and D simulations. Therefore, the parameters used were blade depth of 300mm, blade angle of 120^0, 4 number vertical fins and variable overhang.

Energy Simulation of Category E Simulation (Plan view) **200, 365, 400, 600, 800 (mm) -** Primary (Source) Energy				
Case 1	Case 2	Case 3	Case 4	Case 5
				
Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)	Total energy demand - KWh/(m²a)
196.37	196.29	196.11	196.08	196.06

After the optimisation, the simulation revealed that the building performed best with the use of the 0.4m overhang in addition to category E variables. This brought the energy consumption effectively from 196.50KWh/(m²a) to **196.11**KWh/(m²a). Other further optimisation did not yield effective results. Hence, 0.40m overhang was ideal both in terms of energy efficiency and resource efficiency.

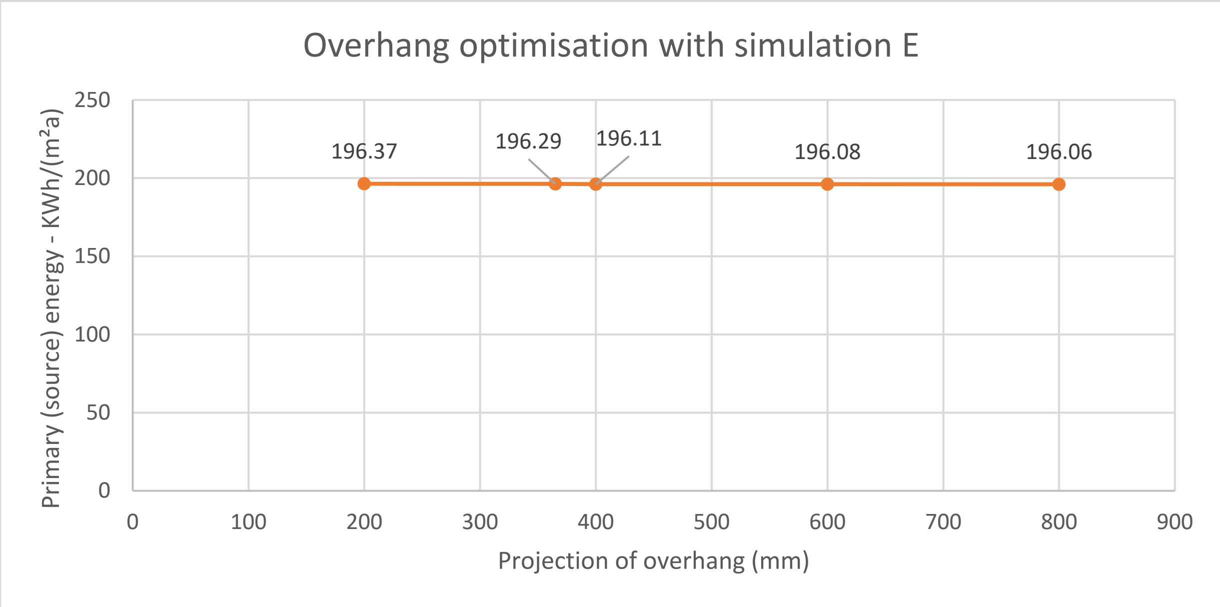


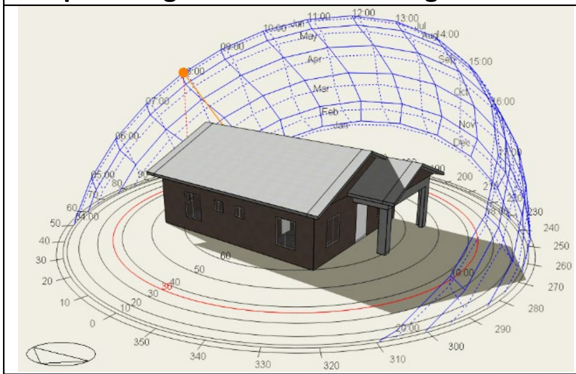
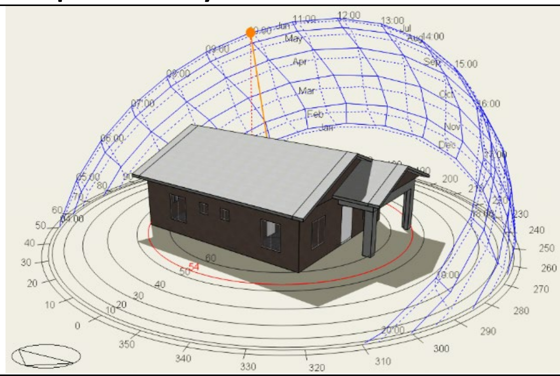
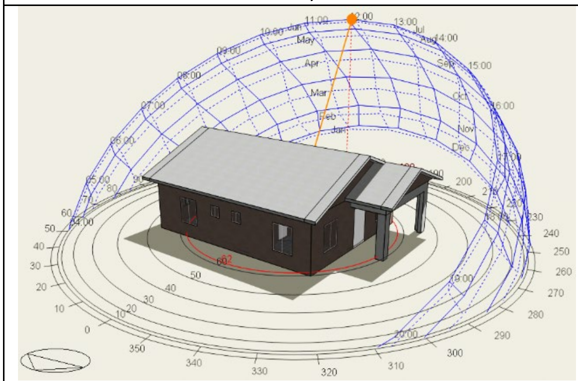
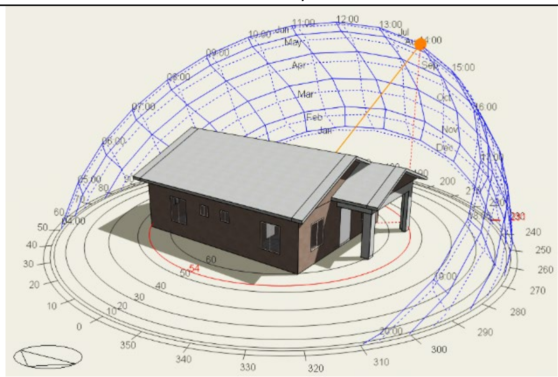
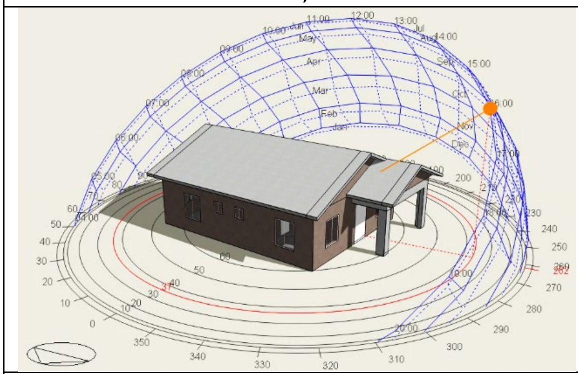
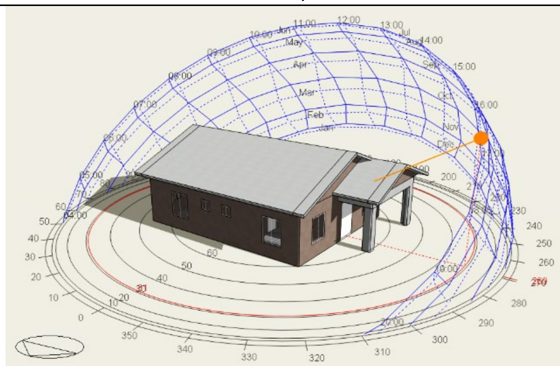
Figure 122: Energy consumption of the building based on different window overhang projections on the East Elevation

6.2.2.4. North Elevation

The North façade does not require shading due to the geographical location of the site. According to literature studies, since the geographical location of the building (is in the Northern hemisphere), the North façade experiences little or no sunshine, therefore, shading devices are not necessarily required in this elevation (Bhatt 2014; Anumah and Anumah 2017).

This is true as seen from the building simulations of the sun path diagram. The North façade of the building was observed in the month of June when the sun is at its highest peak. These observations were recorded at the times when the sun gradually rises through its hottest levels and when it begins to set and cool off in the West. The times of the day are as follows: 8:00, 10:00, 12:00, 14:00, 16:00, and 17:00.

Table 103: Building Sunpath study for 8:00, 10:00, 12:00, 14:00, 16:00 and 17:00

Sunpath diagram simulated during the sun's highest peak of the year	
	
June 15, 8:00	June 15, 10:00
	
June 15, 12:00	June 15, 14:00
	
June 15, 16:00	June 15, 17:00

At the end of the observations, it was affirmed that the North facade did not require shading devices installed as seen from the simulations at various times of the day in the highest sun-month of June. This consideration is also supported and recommended by literature studies (Bhatt 2014; Anumah and Anumah 2017).

6.2.2.5. Summary

At the end of the solar control optimisation simulations, a 6.09% energy reduction was recorded. The solar control optimisation started by discovering the best Window Wall Ratio (WWR) of buildings. It was discovered that the best WWR for the building facades are 15% WWR for the South façade, 25% for the East façade, 20% for the west façade, and 30% for the North façade, as presented in the table below.

Table 104: WWR optimisation results

Primary (source) energy	**South Façade**	**East Façade**	**West Façade**	**North Façade**
Best optimisation result in comparison with 212.10 – (After building orientation optimisation)	**211.72** KWh/(m²a)	**205.96** KWh/(m²a)	**208.75** KWh/(m²a)	**209.30** KWh/(m²a)
New WWR	15%	25%	20%	30%

The overall optimisation of the four facades brought the energy demand of the building from 212.10KWh/(m²a) to **199.19**KWh/(m²a) - an energy reduction of 12.91KWh/(m²a), thereby yielding a 6.09% energy reduction.

The next stage of optimisation is the local shading for the four facades. The optimisation process used a series of shading strategies and designs to obtain the best optimisation for each façade (North, East, West, South).

A total of 110 simulations were carried out to determine the best strategy for the **South** elevation. The simulations for the south elevation were done in 3 broad categories. These strategies fall under these broad categories: Single horizontal overhang, Horizontal multiple blades, Box shading or egg-crate. Five simulations were done for the South horizontal overhang, 75 simulations were done for the horizontal multiple blades, 30 simulations were carried out for the box shading or egg-crate strategy. At the end of the rounds of simulations in this category, there was a reduction in the energy consumption from 199.19KWh/(m²a) to **194.95**KWh/(m²a).

The **West** elevation optimisation was done also in five categories to determine the best strategy for optimisation. A total of 145 simulations were done to attain the best optimisation for the West façade. At the end of the simulations, the energy demand reduced from 199.19KWh/(m²a) to **196.53**KWh/(m²a).

Five categories of optimisation were done for the **East** elevation to determine the best strategy for the façade. 145 optimisation simulations were done to attain the best optimisation strategy. At the end of the optimisations, the energy consumption of the building was reduced from 199.19KWh/(m²a) to **196.11**KWh/(m²a).

There was no need to shade the north elevation due to the fact that the building is located in the northern hemisphere. Hence, there is no direct sun contact on the façade. This phenomenon was also demonstrated and confirmed by simulating using the sun path diagram.

All the optimisation strategies were combined (all-at-a-time) and the simulation was done. This reduced the energy consumption from 199.19KWh/(m²a) to **149.85**KWh/(m²a), yielding a 24.77% total energy reduction.

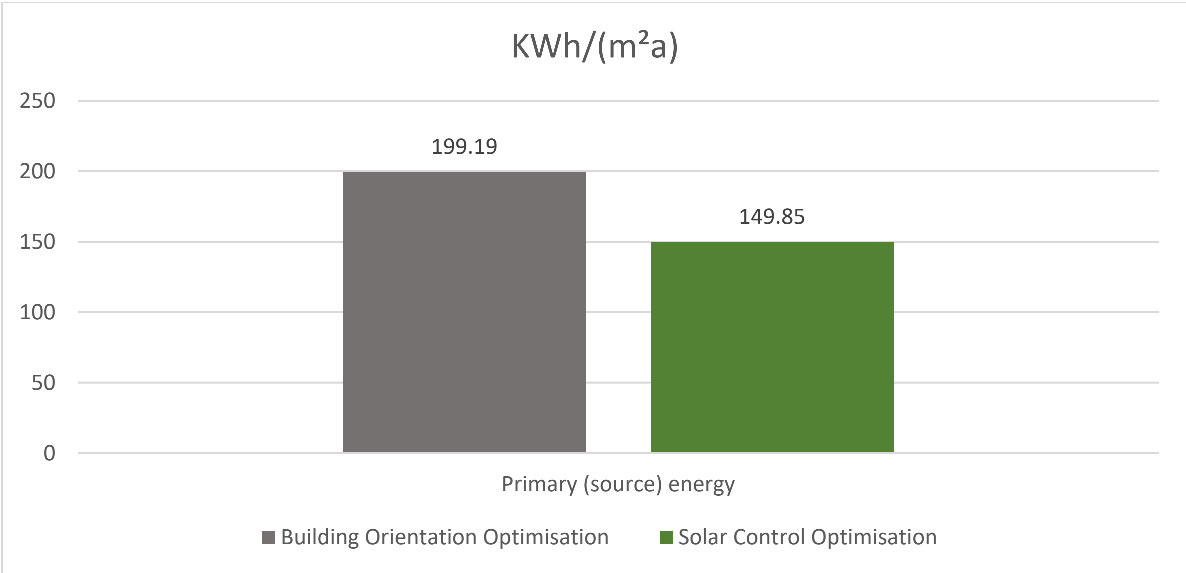


Figure 123: Solar control optimisation energy consumption comparison

6.2.3. g-value

As already identified, it was discovered that solar heat gains through the external windows had the most impact on energy demand with a value of 5029.75KWh which was the original value before the local shading optimisation, which then brought it down to 3205.16KWh. The reasons for the high gains as identified from the simulation are as follows, it was reported that the gains were through the windows which were unshaded and glazed with a g-value of 0.69 or 69.10%. In the optimisation of the window glazing, the following parameters were kept constant throughout the optimisations: An air gap of 13mm between two glazing (of the same glass type, thickness, and the same thermal conductivity for the specific cases).

6.2.3.1. First optimisation strategy

The simulation results indicated that most of the heat gain came through the windows, and this had a negative effect on the building with regards to higher cooling demand. The base case windows had a g-value of 0.69 and a light transmission of 0.74 or 74%. The window to wall ratio of the base case was 12.49% and the aluminium sliding windows had a vertical divider.

To conduct this experiment, glazing types with low g-values were selected to check their sensitivity and their effect on the building's solar heat gains through the windows and the total energy consumption of the building.

The selected glazing types with low g-value are:

Table 105: Glazing type and properties

Glass Type (Product)	Glass Thickness (mm)	Visible Transmittance (% Daylight)	U-value	Solar Heat Gain Coefficient (SHGC)
PGT Industries PGT Green Clear <gncl716.pgt>	5.72	76	2.47	0.42
PPG Industries Solarban 67 on Optiblue	5.72	43	1.22	0.22

The geometric progression of the glass g-value was a decremental factor of -0.20 or -20%. Therefore, from the original 0.69 to 0.42 to 0.22.

<u>First trial optimisation (g-value: 0.42)</u>

The results of the simulation to check the effect of the reduced g-value of the glazing to 0.42 on solar heat gain and total energy consumption of the base case is as presented below. In the first stage of the experiment, the g-value of the glazing was reduced from 0.62 of the base case to 0.42.

<u>Original properties of glazing</u>

Total solar transmittance: 69.10%

Glaze type: Bronze glazing

Thickness: 5.72mm

<u>Properties of selected glazing</u>

Total solar transmittance: 42.00%

Glaze type: PGT Industries PGT Green Clear <gncl716.pgt>

Thickness: 5.72mm

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption. The investigation revealed that the solar gains through the exterior windows had decreased from 3205.16KWh of the base case to 2201.35KWh. The results of the simulation were further compared with that of the base case to check for changes in temperatures, heat gain, and energy consumption.

Table 106: Results showing the effect of g-value variation (0.42W/m-K) in the base case glazing (run period – 1 Jan - 31 Dec)

	Building performance after Local shading optimisation	First trial glazing optimisation results
Solar gains exterior windows (KWh)	3205.16	2201.35
Total Energy Consumption KWh/(m²a).	149.85	143.35

The results show that there was a significant decrease in the solar gains through the exterior windows from 3205.16KWh to 2201.35KWh, also the cooling load reduced from 3187.40KWh to 3145.26KWh, an indication that the reduced g-value of the glazing had caused a decrease in energy consumption required in cooling down the building. The total primary energy demand also decreased from 149.85KWh/(m²a) to **143.35**KWh/(m²a).

The adjustment in the g-value of the exterior glazing had a 4.34% impact on the primary energy demand of the building.

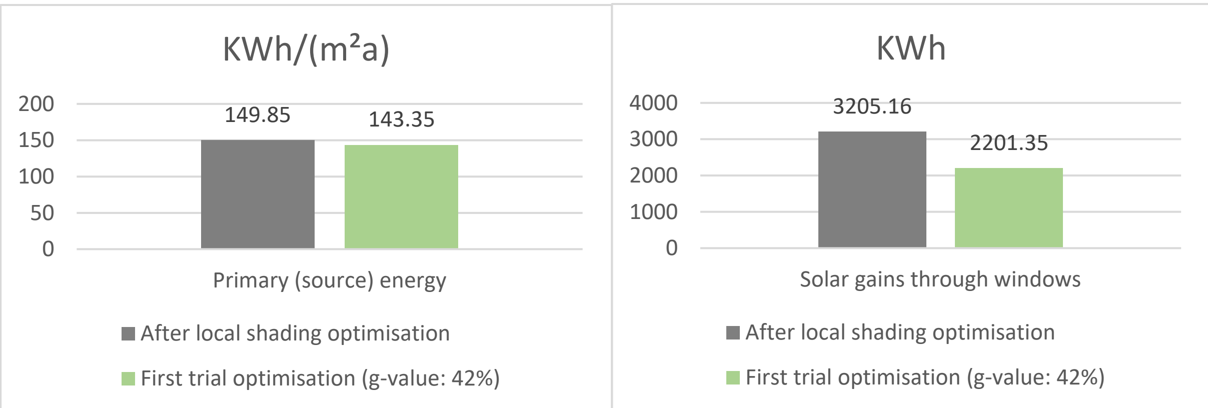


Figure 124: Glazing simulation comparison

Second trial optimisation (g-value: 0.22)

The optimisation went further to use a different glazing material with a lower g-value of 0.22. The results of the simulation to check the effect of the reduced g-value of the glazing to 0.22 on solar heat gain and total energy consumption of the base case is as presented below. In the second trial of the optimisation, a glazing material with a lower g-value (0.22) was selected.

Original properties of glazing

Total solar transmittance: 69.10%

Glaze type: Bronze glazing

Thickness: 5.72mm

Properties of selected glazing

Total solar transmittance: 22.00%

Glaze type: PPG Industries Solarban 67 on Optiblue

Thickness: 5.72mm

The results of the simulation were compared against the base case to check the effect of the change in g-value on temperatures, heat gain, and energy consumption. The investigation revealed that the solar gains through the exterior windows had drastically decreased from 3205.16KWh of the base case to 1186.68KWh. The results of the simulation were further compared with that of the base case to check for changes in temperatures, heat gain, and energy consumption.

Table 107: Results showing the effect of g-value variation (0.22) in the base case glazing (run period – 1 Jan - 31 Dec)

	Building performance after Local shading optimisation	Second trail glazing optimisation results
Solar gains exterior windows (KWh)	3205.16	1186.68
Primary (source) energy KWh/(m²a).	149.85	134.87

The results show that there was a significant decrease in the solar gains through the exterior windows from 3205.16KWh to 1186.68KWh, also the cooling load reduced from 3187.40KWh to 2819.23KWh, an indication that the reduced g-value of the glazing had caused a decrease in energy consumption in cooling down the building. The total primary energy demand also decreased from 149.85KWh/(m²a) to **134.87**KWh/(m²a) as seen in the chart below.

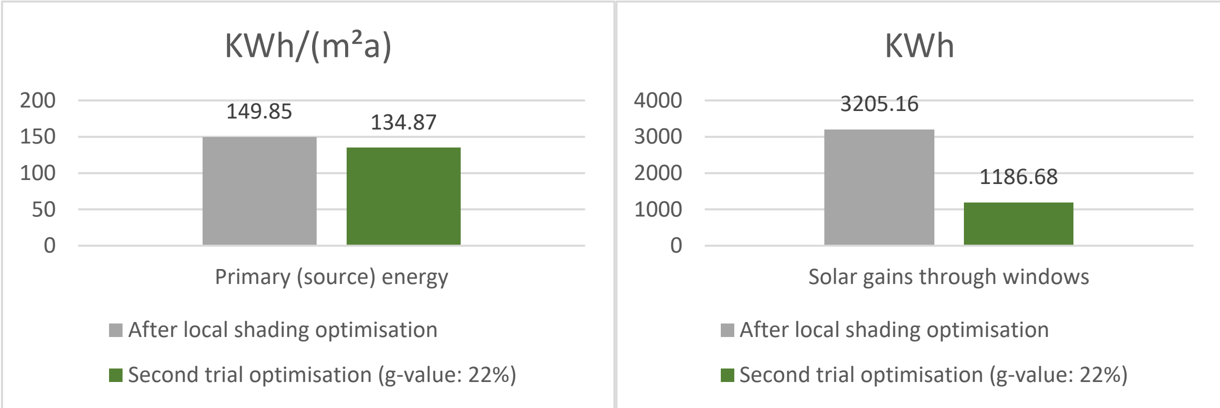


Figure 125: Energy consumption and solar gains comparison between the base case and change in g-value

The adjustment in the g-value of the exterior glazing had a 10.00% impact on the primary energy demand of the building.

In summary, the optimisation process started by reducing the g-value of the glass from 69.10% to 42% which also decreased the total primary energy demand from 149.85KWh/(m²a) to 143.35KWh/(m²a). The g-value of the glazing was further reduced to 0.22 by another material selection, summing to a total reduction of 64.5%. This reduced the energy demand of the building, further bringing it down to 134.87KWh/(m²a), amounting to a 10.00% reduction in energy demand.

Table 108: Trial g-value optimisation results

Trial Optimisation Simulations	g-value	Primary (source) energy
Base case	69.10%	149.85KWh/(m²a)
First trial	42.00%	143.35KWh/(m²a)
Second trial	22.00%	134.87KWh/(m²a)

Although there have been energy improvements from the above trial optimisations, the reduction in g-value for the selected glazing type reduced the light transmittance into the building. Thus, reducing daylighting. Consequently, it was necessary to install a material that has both a higher visible transmittance of daylight and a low g-value (see second optimisation strategy).

6.2.3.2. Second Optimisation Strategy

The second optimisation strategy involved the search for a new glazing material with a low g-value and high visible light transmittance. This was necessary because it was discovered that by lowering the g-value of the glass, the visible daylight transmittance was reduced. Hence, it was necessary to install a glazing type that is transparent and has a low g-value.

The discovered new glazing material is as presented below.

Table 109: New Glazing with low g-value and high light transmittance

Glass Type (Product)	**Glass Thickness (mm)**	**Visible Transmittance (% Daylight)**	**U-value (W/m^2- K)**	**Solar Heat Gain Coefficient (SHGC)**
AGC Glass Co. N.A. Comfort TiAC28 on Clear <TiAC28_6.AFG	5.72	70	1.19	0.27

The simulation results of the effect of the new glazing are as shown in the table below.

Table 110: Results showing the effect of g-value variation (0.22W/m-K) in the base case glazing (run period – 1 Jan - 31 Dec)

	Building performance after solar control optimisation	Selected glazing optimisation results
Solar gains exterior windows (KWh)	3205.16	1594.46
Primary (source) energy KWh/(m²a).	149.85	135.10

The results show that there was a decrease in the solar gains through the exterior windows from 3205.16KWh to 1594.46KWh. The total primary energy demand also decreased from 149.85KWh/(m²a) to **135.10**KWh/(m²a), yielding a 9.84% reduction.

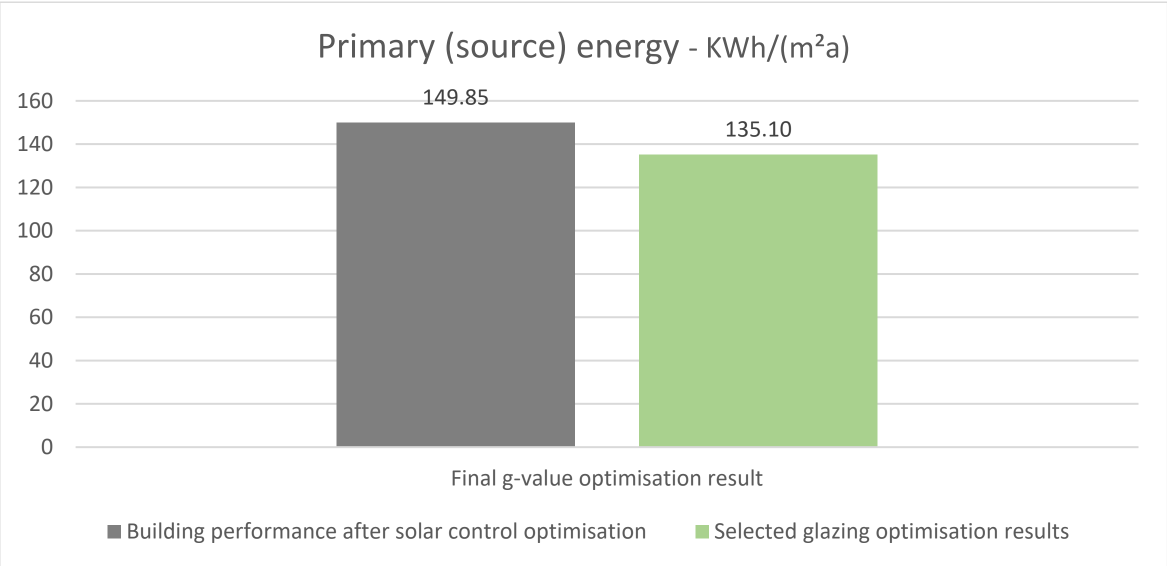


Figure 126: Building energy consumption comparison based on glazing optimisation

6.3. Thermal insulation

The base case model did not have thermal insulators on the exterior walls. Hence, it was imperative to incorporate thermal insulation material into the construction in an attempt to optimise the building and improve energy consumption.

To do this, it was necessary to select a good thermal insulating material for the exterior walls. To assess the best thickness of the thermal insulator, several applicable thermal insulation thicknesses were used and simulated to see the most effective with regard to energy efficiency in buildings.

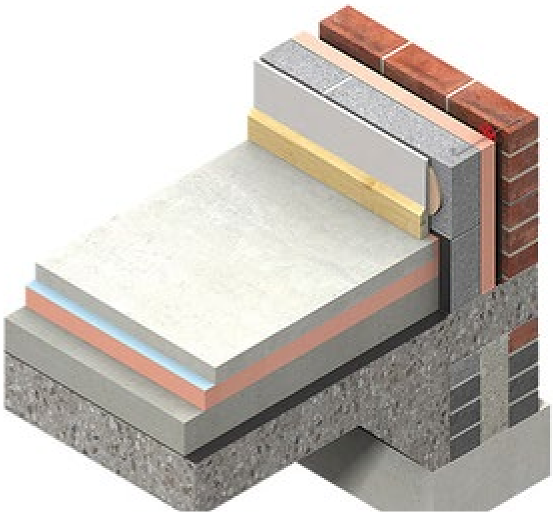


Figure 127: Exterior wall and floor assembly

The experiment used several insulation thicknesses, 50, 75, 100, 125, 150. The following was kept constant throughout the trial optimisation simulations - the composition of the exterior wall consists of 150mm brick wall of the base case, 50mm spacing between insulation and brick wall, 100mm autoclaved aerated concrete (AAC) block, and 25mm sandcrete wall plaster.

Table 111: Thermal Insulation results from varied thickness

Selected thermal Insulation	Benefits	Material thickness (mm)	Primary (source) energy
Hemp fibre	Hemp is completely recyclable and has no irritation to skin or lungs, it is protected against moulds and bacteria, it is sustainable with no harmful substance.	50	105.14KWh/(m^2a)
		75	101.92KWh/(m^2a)
		100	96.48KWh/(m^2a)
Material properties		125	95.83KWh/(m^2a)
Thermal Conductivity: 0.04W/m-K Specific Heat: 2150J/Kg-K Density: 35Kg/m^3		150	95.18KWh/(m^2a)

The simulation results revealed that the various thicknesses of the thermal insulation reduced the total energy consumption of the building gradually but significantly with 100mm hemp fibre thermal insulation.

The results of the simulation were further compared with that of the base case to check for changes in temperatures, heat gain, and energy consumption. The energy demand of the building reduced from 135.10KWh/(m²a) down to 96.48KWh/(m²a).

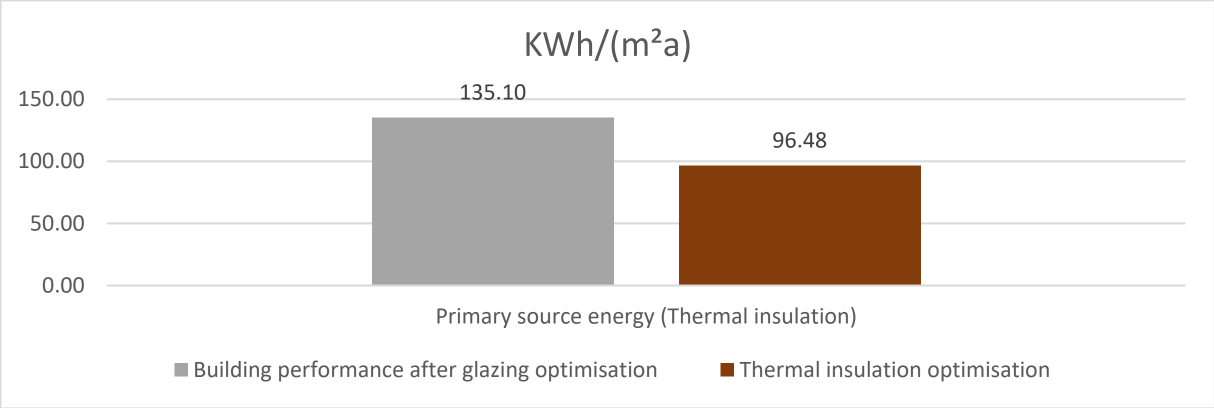


Figure 128: Building energy consumption comparison based on thermal insulation optimisation

Therefore, optimising the exterior walls using thermal insulating materials while also taking into consideration the reusability/recyclability of the material yielded a 71.19% energy improvement.

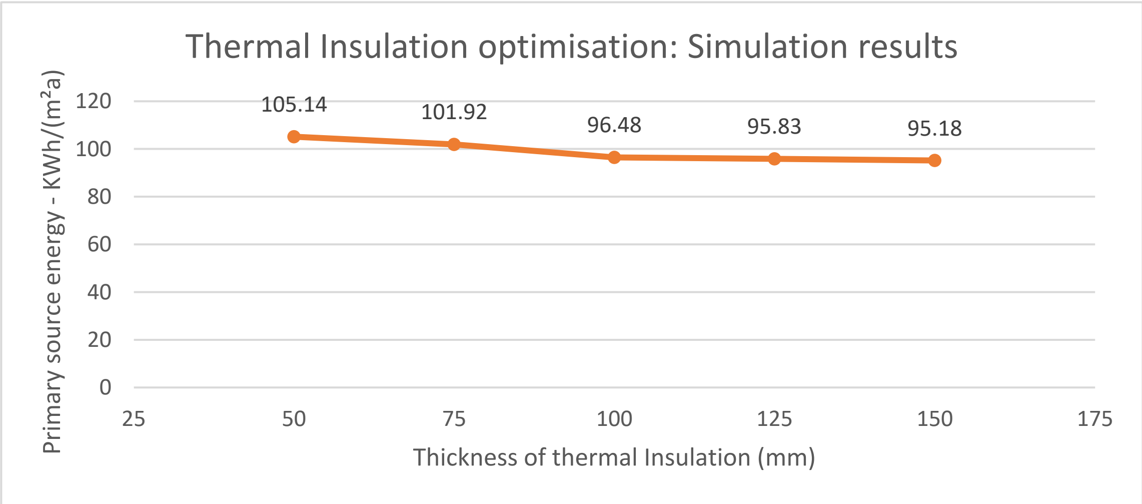


Figure 129: Energy consumption of the building based on different thickness of thermal insulation

Since 100mm thick thermal insulation was most effective with regard to energy reduction, it was selected as the best thickness for the optimisation.

6.4. Thermal mass optimisation

In order to improve the thermal mass of the building, a thermal mass material was selected, and the thickness of the material was gradually adjusted to determine the most effective with regard to the energy consumption of the building. The u-value of the material was kept constant at 2.20W/m^2-K. The volumetric heat capacity of the thermal mass material was taken into consideration, hence, the material density and specific heat capacity were considered. Therefore, it was important to consider the material of high density and specific heat capacity. According to the sensitivity experiment conducted on the thermal mass material, the variable that had the highest impact on energy demand was thermal conductivity. Hence, the construction material of the external walls which was a composition of 150mm sandcrete solid block wall and 25mm sand-cement plaster on both sides was replaced with hydra form bricks. Considerations were also made for an appropriate thermal conductivity for the thermal mass material to ensure that heat can be absorbed and released in sync with the natural heat flow of the building as well as selecting an exterior wall material with a high volumetric heat capacity - high density and specific heat capacity (LHedlund 2016). Thus, improving the thermal mass performance. Outer leaf bricks were used instead which had a lower thermal conductivity of 0.79W/m-K, a specific capacity of 840J/Kg-K and a density of 1950Kg/m^3.

As seen from the DesignBuilder settings extract below, the U-value of the brick was kept constant at 2.20W/m^2-K (or R-value of 0.46m^2-K/W) in all instances of the brick thickness change to see the effect of thermal mass.

Figure 130: Extract from DesignBuilder

Table 112: Properties of thermal mass material for exterior wall Outer leaf

Wall Material (Exterior)	Thermal conductivity	Specific Capacity	Density
Masonry - heavyweight Dry	0.79W/m-K	840J/Kg-K	1950Kg/m^3

To determine the most appropriate thickness of the thermal mass for optimisation, several wall thicknesses were simulated with the selected material. The following was also kept constant throughout the trial optimisation simulations - the composition of the selected exterior wall was maintained, 50mm spacing between the exterior wall and 100mm autoclaved aerated concrete (AAC) block, and 25mm sandcrete wall plaster as shown in the table below.

Table 113: Optimisation of thermal mass (thickness of material)

Selected thermal mass material	Material thickness (mm)	Total energy consumption
Masonry - heavyweight Dry	75	113.44KWh/(m²a)
	100	112.98KWh/(m²a)
	125	112.36KWh/(m²a)
	150	111.51KWh/(m²a)
	175	111.72KWh/(m²a)
	200	111.87KWh/(m²a)
	225	111.89KWh/(m²a)

At the end of the simulations, it was established that the appropriate thickness of the material is 150mm. This optimisation recorded an improvement in the primary (source) energy demand of the building from 135.10KWh/(m²a) to **111.51**KWh/(m²a).

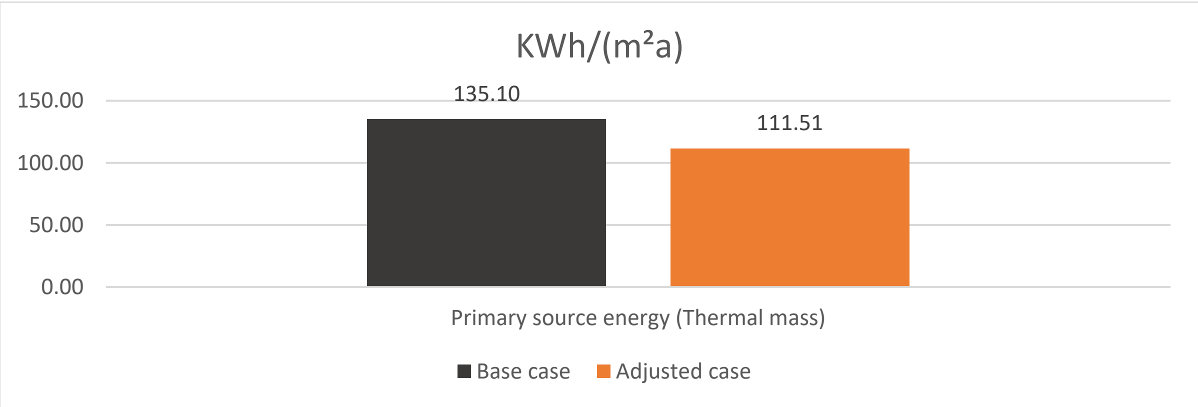


Figure 131: Energy consumption comparison based on thermal mass optimisation

This optimisation helped improve the thermal performance of the building by reducing heat transmittance through the walls into the building. It was recorded that the thermal mass of the building had improved by 17.47% and the walls could retain heat for longer periods and slowly dissipate it at night when the temperature is relatively cool. After establishing the best case for the thermal mass and thermal insulation optimisation with respect to thickness and material selection, the optimisation operation went on to combine both the best results of the thermal mass and thermal insulation optimisations. To do this, the best optimisation for the thermal mass with regards to material type and thickness was used as constants and the thickness of the best thermal insulation was adjusted to determine the best case for the combined optimisation of the thermal mass and insulation.

Table 114: Best optimisation cases based on simulations.

Selected thermal mass material	Material thickness (mm)	Primary source energy
Masonry - heavyweight Dry	150	84.61KWh/(m²a)
Hemp fibre	50	86.97
	75	85.92
	100	85.87
	125	84.19
	150	84.30
	175	84.44
	200	84.72
	225	84.89

The results from the optimisation simulations revealed that the combination of the thermal mass and insulation work better with a thermal insulation thickness of 125mm. This was combined with the best result from the thermal mass optimisation which delivered the best performance with a 150mm thickness. The combined optimisation reduced the energy consumption of the building from 135.10KWh/(m²a) to **84.19**KWh/(m²a).

Finally, the exterior wall composition was made up of a brick wall (150mm outer leaf) to slow heat gain, an insulator to absorb emitted heat (125mm) and another internal brick (100mm) to further deter heat penetration into the building. This combination gave a U-value of 0.34W/m²-K.

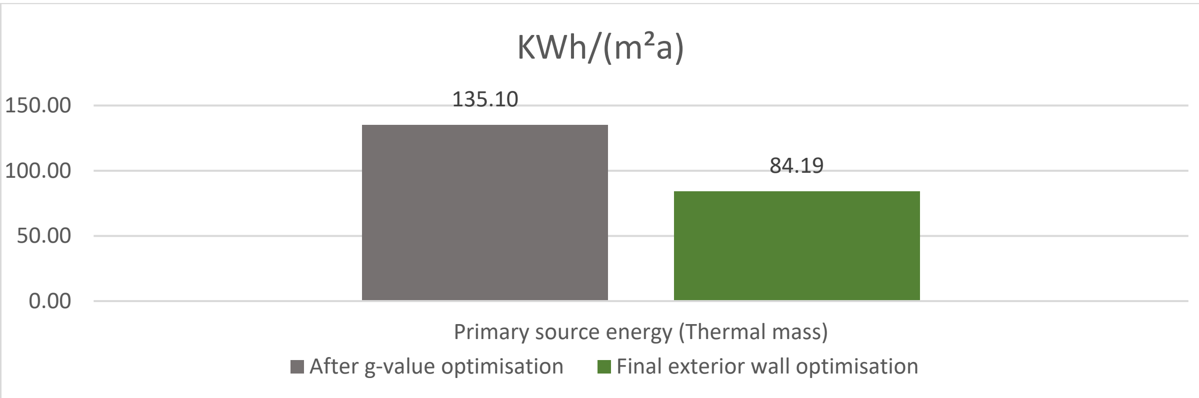


Figure 132: Thermal mass optimisation simulation result

6.5. Natural ventilation optimisation

The optimisation for the natural ventilation of the building was done using passive design recommendations. The base case did not have ventilated roof. Hence, roof vents were provided to allow for roof ventilation to reduce the heat in the roof and allow for air circulation within the roof space.

The building orientation also allowed for proper positioning of the building to benefit from the South-west monsoon wind. The optimisation process also ensured that each room met the minimum window opening recommendations as demonstrated by the Nigerian energy efficiency building design guide and the Australian Building Codes Board. The guides say the minimum size of the opening must be at least 5% of the floor area of the room in warm climates (ABCB 2016; Federal Ministry of Power 2017). Concession applies for rooms adjoining another room with access to the natural ventilation of 5%. It is important to note that Australia and Nigeria shares relatively similar climatic conditions as they both come under the hot, tropical savannah climate regions (Arnfield 2020). The above ABCB recommendations are specific to West African tropical climate of which Nigeria comes under (ABCB 2016; Federal Ministry of Power 2017).

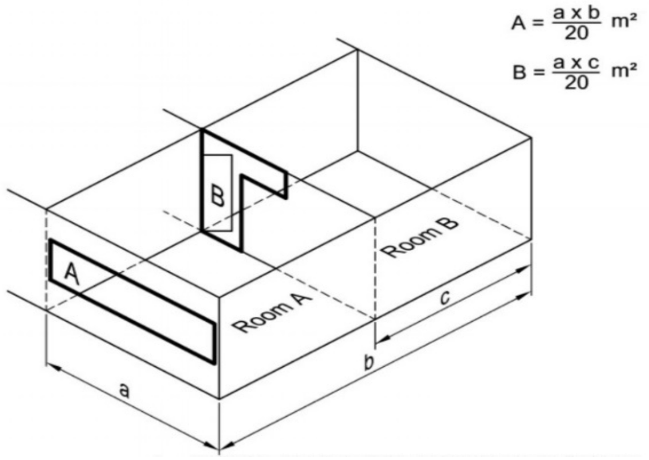


Figure 133: Natural ventilation requirement for West African buildings (Source: ABCB, 2016)

CIBSE AM10 and CIBSE Guide F recommend the following for habitable spaces, it specifies that room depths should be 2 times the ceiling height for single-sided ventilation (W ≤ 2H) and 5 times the ceiling height for cross ventilation (W ≤ 5H) (CIBSE Guild F & AM10 2012).

The base case had a sliding window of 50% opening area, the windows open area was increased to 100% window opening area by using projected windows and simulated for best performance because, in hot climates, occupants would naturally stay outside or open windows and doors during hot periods to cool down the interior spaces (Ochedi 2018).

Another major deficiency of the base case was that the roof was not ventilated. Hence, it was easy for the roof zone to build up heat overhead and transfer it into the interior space. Therefore, the roof was naturally ventilated by the installation of roof vents. The base case model infiltration rate at 50 Pa (ac/h) was 11.62ac/h. This was adjusted to 0.6ac/h for an improved construction.

The results from these optimisations had an improvement on the building. With the above passive strategies incorporated, the energy consumption of the building further dropped from 84.19KWh/(m²a) to **82.76**KWh/(m²a), thus, attaining a 1.70% improvement.

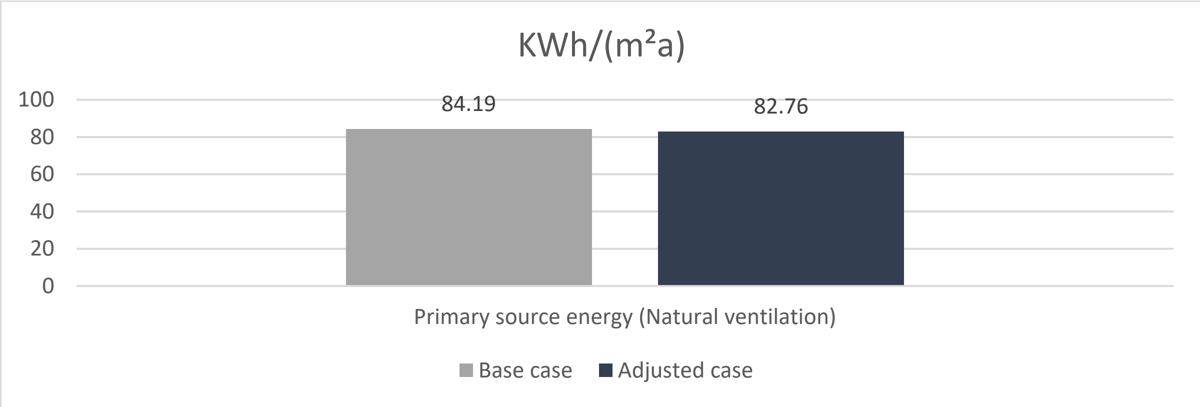


Figure 134: Optimisation result (Natural ventilation)

6.6. Daylighting optimisation

The new orientation of the building helped maximise the influx of the North-East diffuse light into the building. The building zones already met the passive design recommendations of the Nigerian energy efficiency building design guide and the ABCB recommendations for tropical climates by having a minimum opening area of 10% of the floor area of the room (Federal Ministry of Power 2017; ABCB 2018). It is important to note that Australia and Nigeria shares relatively similar climatic conditions as they both come under the hot, tropical savannah climate regions (Arnfield 2020). The above ABCB recommendations are specific to West African tropical climate of which Nigeria comes under (Federal Ministry of Power 2017; ABCB 2018).

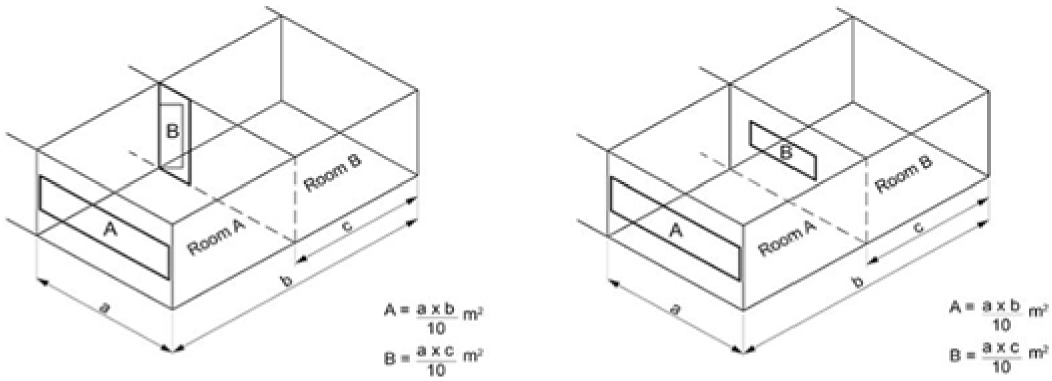


Figure 135: Daylighting requirement for West African buildings (Source: Australian Building Codes Board - ABCB, 2018)

The table below shows the zones that met the minimum daylight recommendations.

Table 115: Daylighting assessment according to BREEAM and CIBSE

Zone	Room area	Zones with a minimum of 10% threshold
Sitting room/ circulation area	39.07	✓
Master Bedroom	11.88	✓
Bedroom	10.93	✓
Kitchen	10.30	✓
Store	2.33	✓
Toilet/Bathroom	2.54	✓
Toilet/Bathroom 2	2.54	✓
Lobby	3.22	✓

The g-value optimisation of the window, which included the replacement of glazing with a glass of low g-value and high visibility helped improved the daylighting of the zones. Therefore, further allowing 70% daylight visibility transmittance for enough illumination. Also, the replacement of the sliding windows with projected windows did not only improved natural ventilation but also improved daylighting since window opening increased from 50% to 100% (Abbakyari and Taki 2017; Ochedi 2018). In addition, the upper portion of the exterior doors was made translucent to allow for more light.

A simulation with these new optimisations implemented presented a better illumination of the zones in the building space. The total energy consumption reduced from 82.76KWh/(m²a) to 81.15KWh/(m²a).

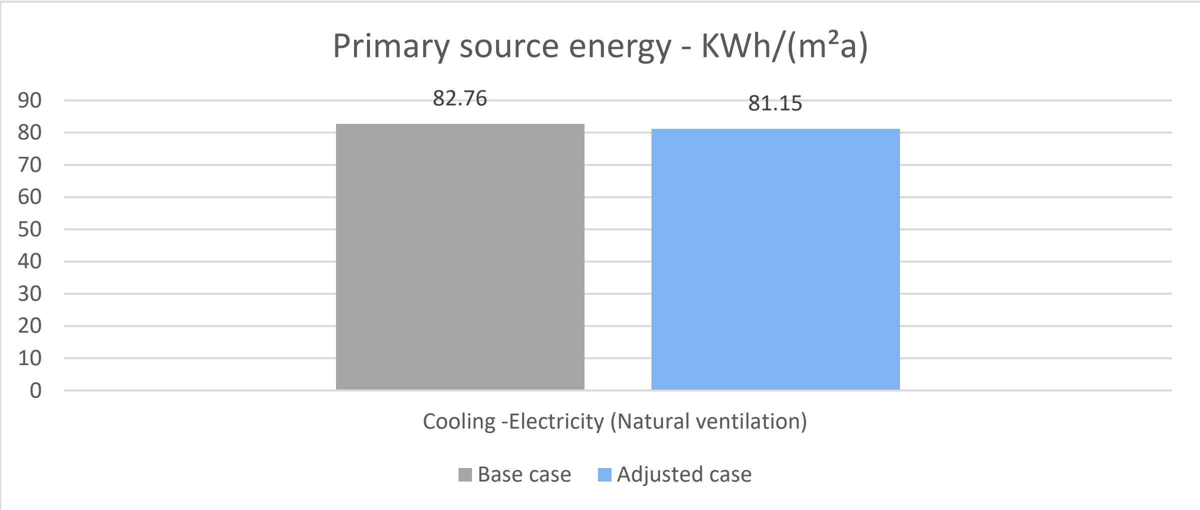


Figure 136: Optimisation simulation results (Daylighting)

6.7. Roof material optimisation

The roofing sheets (previously an aluminium of 0.45 gauge) had a high thermal conductivity of 160W/m-K which was replaced with a less heat conductive material (roof tiles of 0.84W/m-K) to reduce heat transmission. Several gauges or thicknesses were tried to identify the best roof gauge or thickness for the roof tiles. The results of the simulation trials are as presented below:

Table 116: Best optimisation cases based on simulations.

Selected roof material	Material thickness (mm)	Primary source energy - KWh/(m²a)
Roof tile Thermal Conductivity: 0.84W/m-K Specific Heat: 800J/Kg-K Density: 1900Kg/m³	4.00	81.42
	5.00	80.89
	6.00	80.67
	9.00	80.45
	10.00	80.66

The results from the simulation trials showed that 9mm roof tile thickness delivered the best optimisation result with total energy consumption from 81.15KWh/(m²a) to **80.45**KWh/(m²a) of the building. Hence, 9mm thick roof tile was chosen for the optimisation.

Also, the roof was previously not insulated leading to the ease of heat transfer into the building. During optimisation, the roof was insulated with hemp fibre and several thicknesses were tried to obtain the optimal thickness for the insulation.

Table 117: Roof material properties

Selected material	**Material thickness (mm)**	**Primary (source) energy consumption KWh/(m²a)**
Roof tile Thermal Conductivity: 0.84W/m-K Specific Heat: 800J/Kg-K Density: 1900Kg/m³	9.00	80.45
Hemp fibre Thermal Conductivity: 0.038W/m-K Specific Heat: 2150J/Kg-K Density: 35Kg/m³	50	79.31
	75	78.92
	100	78.79
	125	78.71
	150	78.53
	175	78.52
	200	78.53
	225	78.54

After the roof insulation optimisation, it was discovered that 150mm of hemp fibre delivered a better optimisation result. The optimisation simulation yielded a positive result. The total energy consumption reduced from 80.45KWh/(m²a) to **78.53**KWh/(m²a).

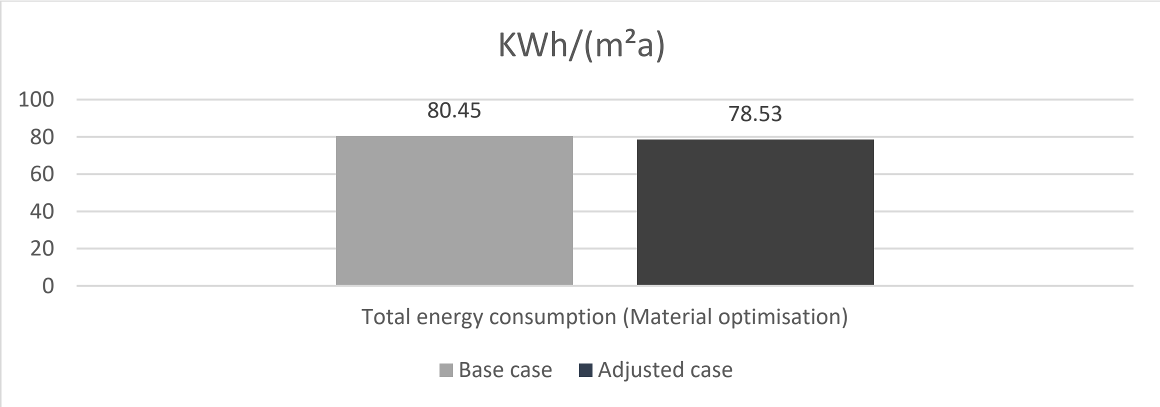


Figure 137: Roof optimisation simulation result

Therefore, optimising the roof material to meet the passive design requirements while also taking into consideration the reusability/recyclability of the material yielded a 7.64% energy improvement.

6.8. Overall primary (source) energy improvement

After conducting one-at-a-time and selective joint all-at-a-time optimisation on the base case. The optimisation process recorded major improvements in terms of temperature, heat gains and energy consumption of the building. Also, the new building orientation put the windows in an advantageous position to capture the south-west monsoon wind as stated in building orientation optimisation.

The optimisation process progressed to selecting the best optimisation strategies which included combining the above passive design strategies to obtain an overall primary energy demand of the building. The total energy demand reduced from 230.90KWh/(m²a) to **78.53**KWh/(m²a), cutting energy consumption down by 152.37KWh/(m²a) which yielded a total of 65.99% improvement with the use of passive design strategies.

6.9. Comparison between typical Nigerian residential building (base case) and the optimised model based on passive design strategies

The total energy demand of the base case - typical Nigerian residential building was 230.90KWh/(m²a) and that of the optimised case based on passive design strategy was 78.53KWh/(m²a). The table below shows the final comparison of the base case performance and the optimised case performance.

Table 118: Final comparison of the base case performance and the optimised case performance

	Base case results	Optimised case results
Room Electricity (KWh)	1587.47	1412.00
Cooling (Electricity) (KWh)	2131.75	44.79
Solar gains exterior windows (KWh)	5029.75	1594.46
Primary (source) energy demand KWh/(m²a)	230.90	78.53

A comparison between the cases showed that there was a significant improvement just from the implementation of passive design strategies.

It is important to note that solar heat gains through exterior windows (which previously had the highest impact on energy demand) at 5029.75KWh, the cooling electricity (previously at 2131.75KWh) and overall primary energy demand (previously at 230.90KWh/[m²a]) reduced to 1594.46KWh (for solar heat gains), 44.19KWh (for cooling electricity), and **78.53**KWh/(m²a) for primary energy demand respectively. The overall optimisation caused a 65.99% energy reduction.

Below is a graphical comparison of the base case and optimised case.

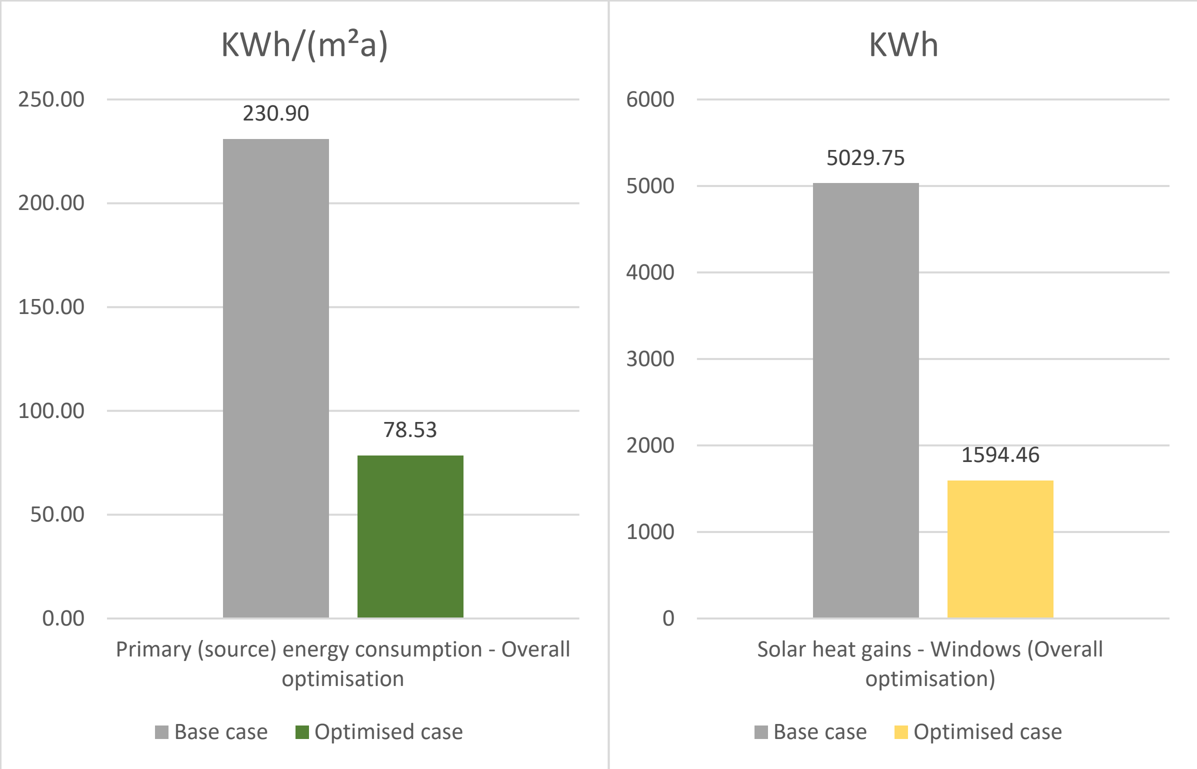


Figure 138: Graphical final comparison of the base case performance and the optimised case performance

6.10. Multivariate pareto simulation

The materiality of the building was considered based on circular economy principles to ensure the use of reusable and recyclable materials, hence, incorporating circular economy into the optimised building for a resource-efficient building. A multivariate Pareto optimisation simulation was conducted to optimise the building. The Pareto optimisation simulation was also done in DesignBuilder, therefore, the analysis type was 'optimisation', the objectives were to minimise the total site energy consumption and minimise thermal discomfort. As earlier mentioned, the design variables for the multivariate Pareto optimisation simulation include building orientation, window to wall ratio, local shading, g-value, thermal mass, thermal insulation, natural ventilation, daylighting, roof vent area and roof material.

A total of 4900 optimisation simulations were carried out during the operation in order to achieve an optimal design. The figure below is the final result of the Pareto optimisation.

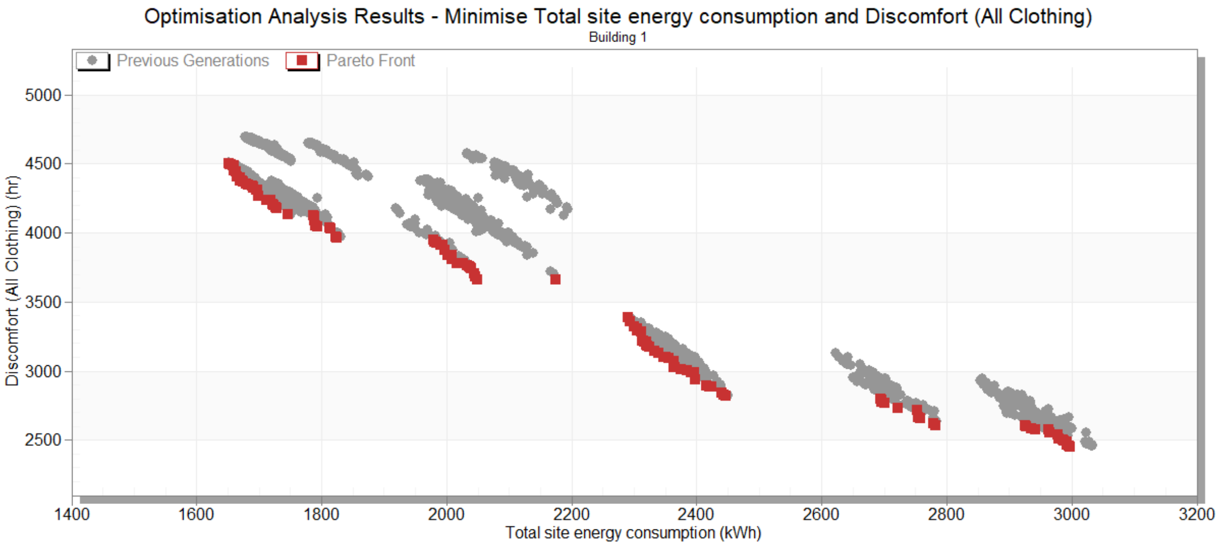


Figure 139: Multivariate Pareto optimisation simulation

The multivariate optimisation simulation revealed the best parameter for the design variables for achieving an optimal design with circular economy materials incorporated. The design variables and the optimal design parameters from the multivariate optimisation simulation are as follows. For Local shading devices - 400mm overhang. For Building orientation - 5 or 355 degrees of true North. For Thermal mass - hydra form bricks with a volumetric heat capacity of 1638KJ/m^3.K, a thickness of 150mm, a thermal conductivity of 0.79W/m-K, and a specific heat capacity of 840J/Kg-K and a density of 1950Kg/m^3. For Thermal insulation – thermal conductivity of 0.038W/m-K, a specific heat capacity of 2150J/Kg-K, a density of 35Kg/m^3, 100mm hemp fibre insulation. For Roof material - 10mm thick roof tile of thermal conductivity: 0.84W/m-K, Specific Heat: 800J/Kg-K, Density 1900Kg/m^3, 150mm hemp fibre insulation. For roof vent area – 0.5m^2, For g-value - 60% visible daylight transmittance, Solar Heat Gain

Coefficient (SHGC) of 0.40, triple glazing and u-value of 1.20KW/m². For Daylighting - external 6mm glazing with light transmittance of 0.89 or 89%. For Natural ventilation – 54% window opening area. For the window to wall ratio – 22%. The optimisation result is as presented. When compared with the base case results, it was discovered that thermal discomfort was minimised from 4718.00hr/yr. to 4487.90hr/yr. and the total site energy was reduced from 12026.02KWh to 1659.26KWh. Thus, yielding 86.20% total site energy reduction.

Below is a graphical comparison of the base case and optimised case.

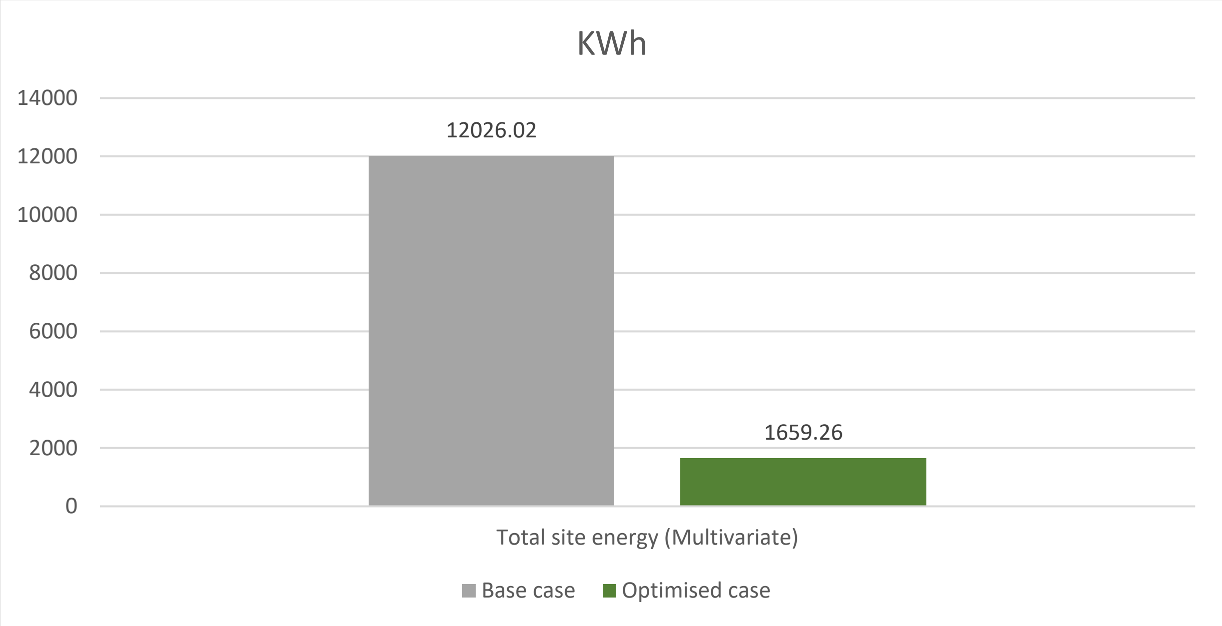


Figure 140: Graphical comparison of the base case and optimised case (Multivariate)

From the results of the optimisation simulations, it can be seen that the combined circular economy and passive design strategies produced a much more optimised building that is both energy and resource-efficient. Hence, the strategies are therefore employed in the development of the framework for the incorporation of circular economy in the design of energy-efficient buildings in the tropical savannah region of Nigeria.

6.11. Summary

After the identification of typical Nigerian building materials and their properties in terms of thermal conductivity, specific heat capacity, density, U-value, etc. The study assessed the recommended passive design strategies for Nigerian residential tropical climate buildings with the use of dynamic energy simulation in DesignBuilder. It was discovered that the typical residential building (base case) did not employ most of the recommended passive design strategies. The primary energy demand of the building (base case) was 230.90KWh/(m^2a). The simulation reports revealed that solar heat gain (which was recorded at 5029.75KWh) had the highest impact on temperatures, heat gains and energy consumption. This prompted a sensitivity assessment/analysis as to what parameter had the most impact on the building energy performance. The study identified that the thermal conductivity of materials and the g-value of the glazing had a greater influence on the simulations. Hence, providing a direction to the relevant building's components for effective optimisation. The research went further to optimise the base case based on recommended passive design strategies, one-at-a-time and selected strategic joint [all-at-a-time] dynamic energy optimisations whilst considering circular economy principles. The simulation results revealed a significant improvement of 65.99% in the overall performance of the building, thereby decreasing the total energy demand of the building to 78.53KWh/(m^2a). It is also important to note that various sensitivity simulation of optimisation outcome was carried out to confirm that the building performance is proportionate to parameters variance. This was done for variables such as Window to Wall Ratio (WWR) and Local shading. These results provided a building optimised according to dynamic energy simulations and passive design recommendations, thus, achieving a building that is energy efficient and can incorporate circular economy principles for resource efficiency since recommended materials for optimisation can be reused or recycled. After identifying the best case between the typical Nigerian residential building and the optimised building based on passive design strategies, circular economy principles were applied to the passively designed building (optimised case). This was done with special emphasis and consideration of the materiality of the passive design. Therefore, the building was designed according to passive design recommendations and took into consideration the material composition of the building for a circular economy. This cuts across the reusability and recyclability of the thermal mass material, optimised glazing materials, window shading devices, and façades/elevations' components based on the building's orientation, aperture, vent materials, etc.

Chapter Seven

7.0. Incorporation of the circular economy into the passively designed building

7.1. Introduction

After the identification of major aspects of circular economy in the building. It was expedient to incorporate these interventions into the optimised case of the passively designed building. As previously discussed, the building material components were optimised/exchanged for high-performance materials based on the simulation/experimentation analysis which assisted in identifying building materials of high-performance values. These materials in the simulation recorded better performances when used in passive design strategies such as thermal mass, glazing materials for daylighting/window shading devices, façades/elevations' components based on the building's orientation, aperture, and vent materials, etc.

It is important to note that one common phenomenon between passive design strategies and circular economy principles is their materiality. To achieve a good passively designed building, the materiality of the building components plays a significant role in terms of its performance. Likewise, in a circular economy, the materiality of the building components ensures potential reusability and recycling.

Therefore, while adopting passive design strategies in a building, the reusability and recyclability of the building components are considered alongside. Consequently, these passive design components are designed for disassembly and recycling. The incorporation of circular economy into the building was done using two major principles of circular economy. The 7S model was used as a Design for Disassembly guide and the ReSOLVE framework was used as a Design for Recycling guide (EMF 2013,2014; De and Eden 2019).

7.2. Classification of building components/materials into the 7S model and ReSOLVE framework

For the ease and potentiality of reusing and recycling building components, it is essential that the building is designed and constructed in modules. Modular construction would ensure the ease of deconstruction in a circular economy. That means the building becomes susceptible to the ReSOLVE framework of the circular economy - regenerate, share, optimise, loop, virtualise, and exchange (EMF 2013,2014). It is therefore important to classify the building of the optimised case into the 7S model – System, Site, Skin, Structure, Services, Space and Stuff (De and Eden 2019). As earlier discussed, the 7Smodel entails:

1. System: includes all services that enable the overall functionality of the building.
2. Site: the specific location of the building.
3. Skin: the envelope of the building or the building exterior cover.
4. Structure: the structural components on which the building is built upon.
5. Services: this consists of all mechanical, plumbing, and electrical installations in the building.
6. Space: the fixed internal components of the building such as the wall partitions, doors, etc.
7. Stuff: this includes elements such as furniture which are movable.

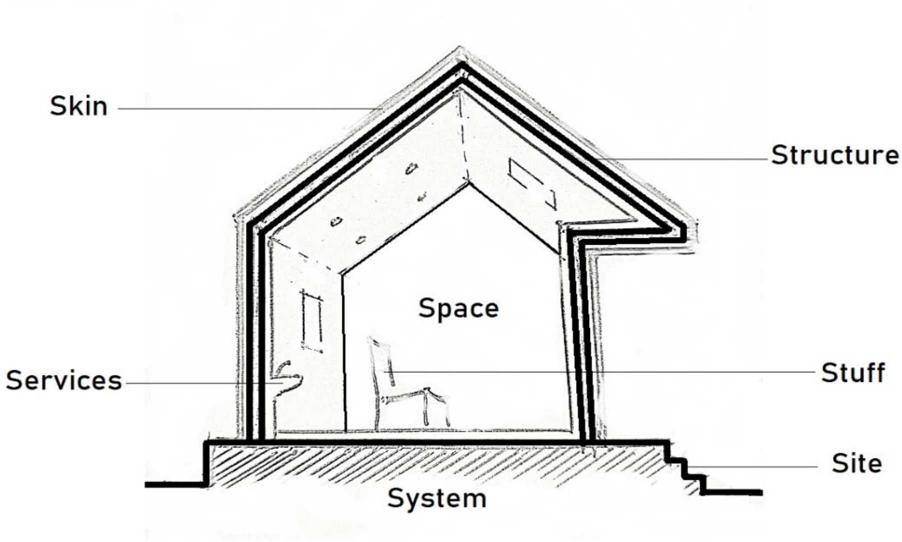


Figure 141: The 7S Model

Therefore, building components can be classified into the 7S model as seen in previous pieces of literature which are demonstrated in the table below (Atmaca and Atmaca 2016; Akanbi et al. 2018; Tazi et al. 2021).

Table 119: 7S Model and building components

7S Model	System	Site	Skin	Structure	Services	Space	Stuff
Roof	Superstructure	-	Roofing sheets	Roof trusses	Electrical, Mechanical, plumbing	Penthouse, dormers	Movable components
Walls	Superstructure	-	Paint, Plaster,	Loadbearing walls,	Electrical, Mechanical, plumbing	Walls, partitions	Movable components
Fenestrations	Superstructure	-	-	Steel frame	-	Windows, doors, vents	Movable components
Floor	Substructure	-	Tiles, carpet, floor finishes	Slab	Electrical, Mechanical, plumbing	-	Movable components
Building structure	Framework	Foundation	-	Roof, column, slab, beam, cantilever.	Electrical, Mechanical, plumbing	Service ducts	Movable components
Building exterior	Substructure		-	Foundation	Electrical, Mechanical, plumbing	compound	Movable components

Also, building materials can as well be classified into the ReSOLVE framework as seen in previous studies demonstrated in the table below (Atmaca and Atmaca 2016; Akanbi et al. 2018; O'Grady et al. 2021; Tazi et al. 2021). The table below shows building materials that can be regenerated or reused/recycled, shared, optimised, looped, virtualised and exchanged according to the ReSOLVE framework.

Table 120: Classification of Building materials into the ReSOLVE framework

ReSOLVE Framework	Regenerate/ Reuse/Recycle	Share	Optimise	Loop	Virtualise	Exchange
Roof	Roof tiles (clay, concrete), Slate	Reusable and recyclable materials such as Roof tiles (clay, concrete), Slate, etc.	Reusable and recyclable materials such as aluminium roofing sheets, clay tiles, concrete	Reusable and recyclable materials such as slate	Roofing sheets	Reusable and recyclable materials such as slate
Walls	Hydra form bricks, adobe bricks, sand cement blocks	Reusable and recyclable materials such as Hydra form bricks, adobe bricks, sand cement blocks	Reusable and recyclable materials such as plaster or paint can be repainted or washed	Reusable and recyclable materials such as hydra form bricks, clay walls	Bricks, timber, concrete, steel, tiles	Reusable and recyclable materials such as hydra form bricks, clay walls
Fenestration	Glass, Steel, aluminium	Reusable and recyclable materials such as Glass, Steel, aluminium	Reusable and recyclable materials such as glazing	Reusable and recyclable materials such as aluminium windows and glazing	Windows, doors, vents	Reusable and recyclable materials such as aluminium windows and glazing
Floor	Concrete, steel, clay tiles	Reusable and recyclable materials such as Concrete, steel, clay tiles	Reusable and recyclable materials such as Carpet/rug, clay tiles	Reusable and recyclable materials such as clay tiles	Carpet, tiles, concrete	Reusable and recyclable materials such as clay tiles
Building structure	Steel, concrete, bricks	Reusable and recyclable materials such as Steel, concrete, bricks	Reusable and recyclable materials such as steel structure	Reusable and recyclable materials such as steel frames	Steel, timber, bricks	Reusable and recyclable materials such as steel frames
Building exterior	Concrete, steel, clay tiles, concrete paving	Reusable and recyclable materials such as Concrete, steel, clay tiles, concrete paving	Reusable and recyclable materials such as concrete or paving	Reusable and recyclable materials such as concrete paving	Paving, tiles, grass	Reusable and recyclable materials such as concrete paving

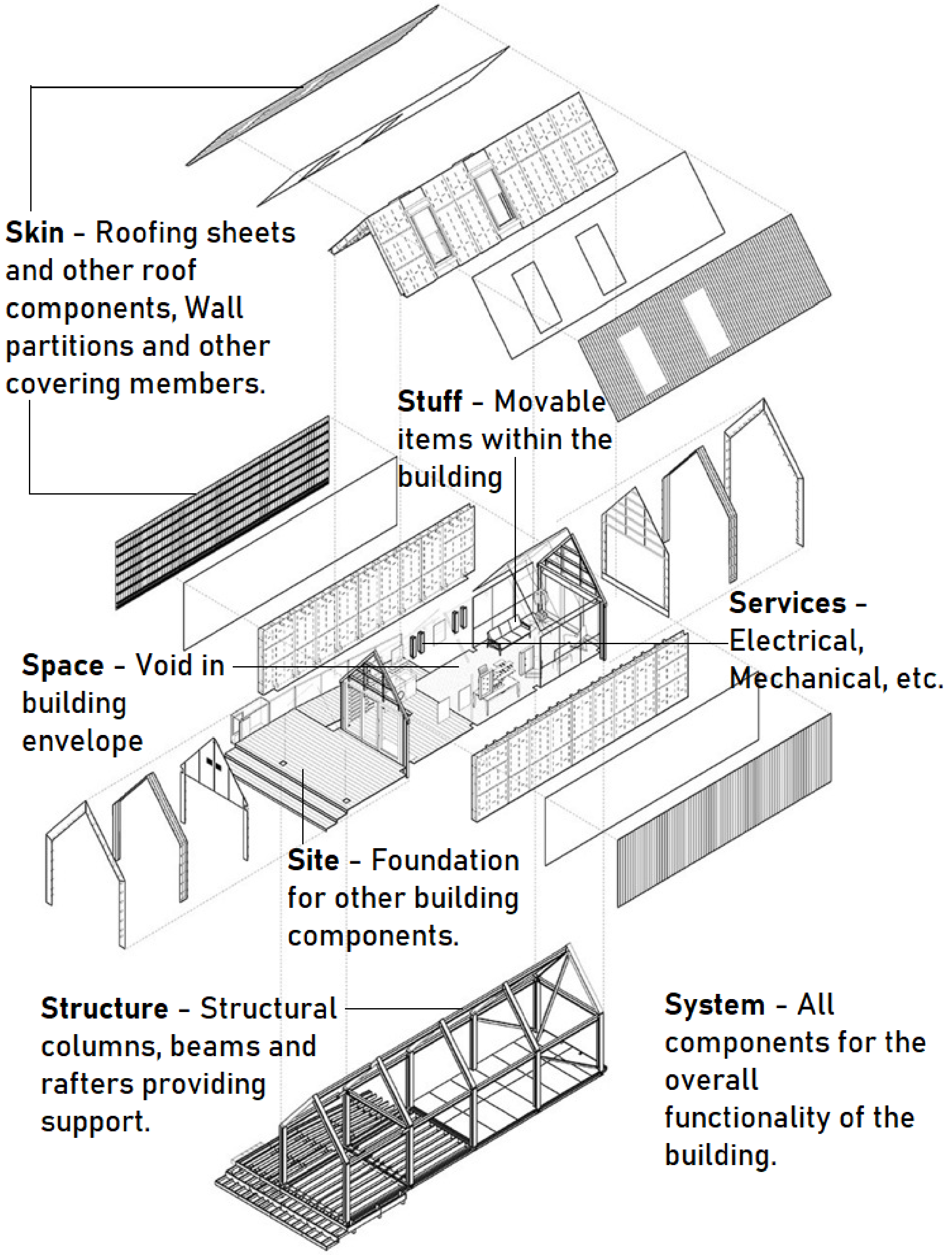


Figure 142: Separated building components into the 7S Model. Adapted from Arup, Image by Arup.

7.3. Design for disassembly, Reuse and Recycling

According to Cruz Rios et al. (2019), Design for Disassembly (DfD) also known as design for deconstruction allows for futuristic disassembly or deconstruction of buildings and the reuse, recycling, and remanufacturing of their components (Cruz Rios et al. 2019).

In the study conducted by Cruz Rios et al. (2019), they analysed the key principles for the application of the concept of Design for Disassembly which included:
(1) Proper documentation of material components and methods for disassembly.
(2) Design of accessible connections to ease building deconstruction, for example, the use of bolts, screws, etc., and minimising welded connections hence, promoting prefabricated/modular design.
(3) The separation of components that are non-reusable and non-recyclable.
(4) Standardisation of component parts to possess the same dimensions, shape, and other attributes.
(5) Design to reflect the best labour practices, productivity, and safety.
There is a range of methods to ensure the disassembly of building components when necessary.

Prefabrication of buildings is a very common approach in the design for disassembly. Minunno et al. (2018) used a qualitative approach to revisit the design, construction, and demolition stages of prefabricated buildings. Hence, the circular economy framework is applied to foster the prefabrication of circular buildings (Minunno et al. 2018). In Gibb's (1999) categorisation, prefabricated components were categorised into four levels, based on the degree of prefabrication implemented in the product:

1. Elements and components,
2. Panels (non-volumetric elements),
3. Volumetric
4. Entire modules.

Sparksman et al. (1999) defined prefabrication as a manufacturing process that usually takes place in a specialised facility where several materials and components are joined together to form a component of the final installation (Sparksman et al. 1999).

Table 121: Prefabrication Category (Gibb 1999)

	Prefabrication Category	Description
1	Component manufacturing and subassembly	This is carried out in a factory and not considered for on-site production.
2	Non-volumetric pre-assembly	Refers to pre-assembled units not enclosing usable space
3	Volumetric pre-assembly	Refers to pre-assembled units enclosing usable space
4	Whole-building prefabrication	Refers to pre-assembled volumetric units forming the actual structure and fabric of the building.

It is important to note that popular assemblage methods for the ease of disassembly include nuts and bolts, screws, quick release, clamps, etc.

Table 122: Popular assemblage methods for easy disassembly

Nut and Bolt 	Screws 
Quick-release 	Clamps 

Several researchers have used literature sources to identify the strategies and methods for the application of circular economy in buildings (Adams et al. 2017; Nussholz and Milios 2017; Minunno et al. 2018). Minunno et al. (2018) identified the following steps below in providing solutions towards circular economy of buildings.

Table 123: Steps for application of circular economy to buildings (Minunno et al. 2018)

	Strategy	Prefabricated and Traditional Buildings	Barriers of Traditional Buildings
1.	Reduction of construction waste and the lean production chain	Adopt the lean production chain to reduce construction waste	TB degree of complexity and variable measures are a barrier toward lean production
2.	Integration of scrap, waste, and by-products into new components	Use of by-products in concrete	No barriers were found in the literature
3.	Reuse of replacement parts or entire components	Use of second-life components	Technically complex, elevated time, and cost requested
4.	Design toward adaptability (reduction through life extension) during operational stages	Adaptability during the operational phase	Low adaptability of components due to monolithic nature of the TB; knowledge gap on space adaptability
5.	Design toward disassembly of goods into components to be reused	Reusability at the EoL	Monolithic structures with chemically bonded connections
6.	Design for recycling of construction materials	Recyclability at the EoL	Concrete is intensively used in TBs; however, in the recycling process, its characteristics decrease with scarce saving of CO_2 emissions
7.	Systems to track materials and components within their supply chain	Tracking the components	Practicable only when component can be disassembled and reused

7.3.1. Process of Design for Disassembly, Reusability and Recyclability

The process of design for disassembly is dynamic and requires a dynamic approach towards a reconstructable building at any given time of the building's lifespan (Ghaffar et al. 2020). The process below was considered based on studies conducted on pre-existing principles and works of literature on the subject matter. Based on the findings in this research, a practical approach to the process of design for disassembly involves the following.

Structure type, Support system, components, standardisation, assemblage methods.

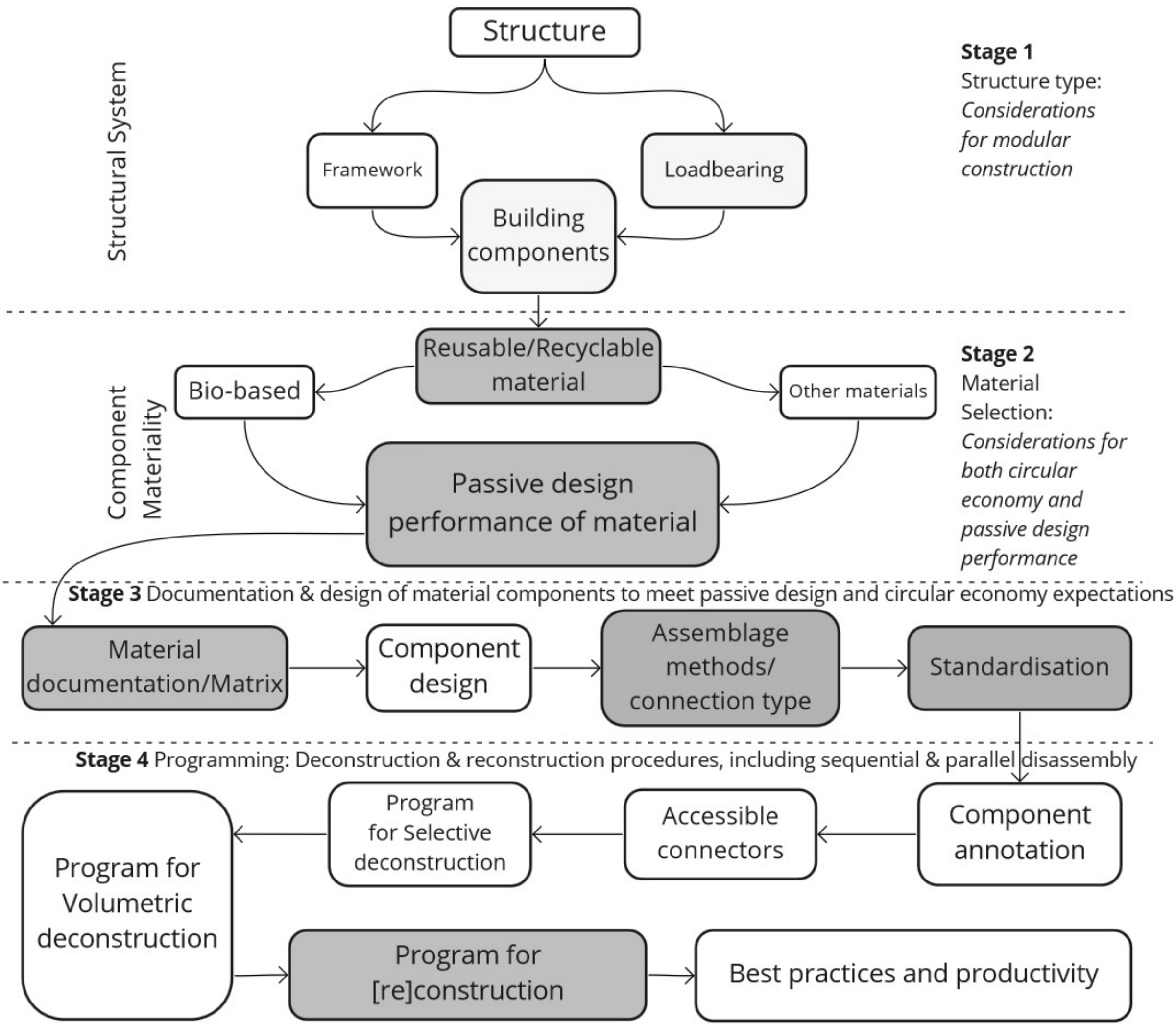


Figure 143: Process of design for disassembly

The process of design for disassembly as indicated from the chart above proceeds from determining/choosing the appropriate structural system of the building, whether a framework system which would usually consist of column, beam and slab or a loadbearing system. However, both systems can deliver a modular structure that can easily be disassembled. The type of structural system is important to define the various components of the building (Webster and Costello 2006). Hence, building components are designed in conformity to the adopted structural system.

The second stage would be to make a selection of reusable/recyclable building materials with good passive design and circular economy performance. This is essential to ensure building components/materials are positively responsive to passive design strategies and have the potentiality for a circular economy.

The material selection could either be biobased or artificial as long as the component composition is susceptible to the principles of circular economy and passive design strategies.

The third stage involves a matrix of materials with regards to their properties. At this stage, the material qualities such as density, specific heat capacity, thermal conductivity, thermal transmittance (U-value), etc. are identified and rated in terms of passive design and circular economy expectancy. This is to check that the material is feasible and viable for energy and resource-efficient building. After the material is evaluated and documented the various building components can then be designed in modules to fit into the framework or act like a loadbearing member of the building. Also at this stage, considerations are made for accessing connectors, whether for assembly or disassembly or general servicing and maintenance of the building. Therefore, special spatial considerations for operation space. The assembly methods and connection types would then be decided and marked. Another important step is the standardisation of components. This is done by maintaining the properties of material components and identifying them for common use and production. This is an important aspect of circular economy in buildings as components become universal and can easily be replicated.

The fourth stage is programming, the components are annotated to numbered/labelled for easy identification and connection in order of assembly. This is followed by annotating accessible connectors and fasteners for easy identification, sorting, and replacement including general maintenance. Thereafter, the building is programmed for selective disassembly. Hence, a detailed process of how the building can be selectively disassembled whether for selective optimisation of separate components. The building is also programmed for a volumetric disassembly, in this case, the schedule is for a total disassembly. Therefore, the building is programmed for both a sequential and parallel disassembly procedure.

After disassembly, a schedule is required for the [re]construction or [re]assembly of the components of the building. This would entail a laid-out process for assemblage with the right connectors. The step by step process of reconstruction is detailed and referenced with the appropriate components. Finally, best practices for construction and deconstruction are recommended, production and reproduction are specified.

7.3.1.1. Recommended building materials

After the identification of applicable aspects of circular economy in buildings, it is important to classify/categorise reusable, recyclable building materials into various uses because the reusability/recyclability of a component is highly dependent on its materiality (Adams et al. 2017; Pomponi and Moncaster 2017; Minunno et al. 2018). Good knowledge of building materials is required to successfully design for recycling during building use and at end of life. This is done not in isolation from passive design principles. Therefore, every building component is considered in the context of passive design strategies and circular economy. Hence, these materials need to be specified at the design stage of the building, whilst ensuring that the construction materials are also feasible with passive design strategies. Vernacular materials are important in construction as they are usually durable which is a key aspect of circular economy in buildings (O'Grady et al. 2021). Vernacular materials such as stones, clay, and timber are not only valuable in vernacular architecture but also have a potentially greater role in circular solutions as they can be reused, and recycled (Akanbi et al. 2018; Hopkinson et al. 2019). For example, stone is a firm vernacular material which provides support to a structure and can easily be reused or transformed into aggregates or recycled for other uses as in concrete (Zhao et al. 2020). Vernacular materials such as stone and clay have been in use since ancient times and offer a greater role in circular solutions (Danja et al. 2017). Clay is another vernacular material which is used for making bricks for construction such as walls. Adobe bricks can be reused and recycled which is a valuable component of circular economy, timber is another vernacular material which has recyclable potential for a circular economy, for example, timber can be recycled into particle boards, furniture, etc (Akanbi et al. 2018). This potential or role can help keep materials at their highest possible value which is a circular solution vernacular materials offers.

Major reusable and recyclable building materials as identified by previous studies (Akanbi et al. 2018; O'Grady et al. 2021; Tazi et al. 2021) have been broadly categorised under the following categories (RubberBond 2019; BuildGreenNH 2020).

Bio-based recyclable materials
Animal-based materials
Plant-based materials

Mineral / Other recyclable materials
Earth materials
Concrete materials
Glass materials
Metals

Synthetic recyclable materials
Chemical compositions

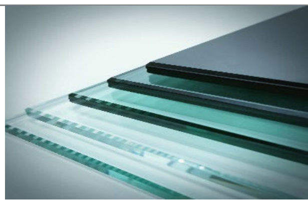
Table 124: Recyclable building materials - major categories and description

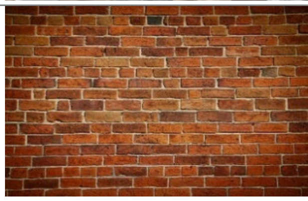
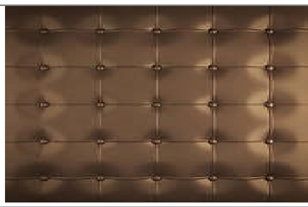
Class	Categories	Description	Representation
Minerals / Elementary / Other recyclable materials	Glass Materials	Glass, a non-crystalline material form usually from rapid cooling known as quenching, is often a transparent, amorphous solid (Cusack 1987).	
	Concrete materials	A composition of fine or/and coarse aggregate bonded together with cement that cures over time (Industrial Resources Council 2020).	
	Earth materials	These are the naturally occurring materials including minerals, rocks, soil and water on Earth (Klein and Philpotts 2019).	
	Metals	Metals are elements comprising 25% of the Earth's crust, present in many aspects of modern life, its strength and resilience have led to their frequent use (Yonezawa 2017).	
	Plaster	Usually a protective or decorative coating for moulding and casting of decorative elements (Weyer et al. 2015).	
Bio-based materials	Animal materials	These are usually by-products obtained from animals that can be utilised as construction material (Ockerman and Hansen 2000).	

	Wood materials	These are construction materials obtained from wood that may be converted to timber for further use.	
	Plant-based aggregates	Plant-based aggregates form a wide variety of construction materials that can be used, reused and recycled since most of them are recyclable and biodegradable (Ansell et al. 2020).	
Synthetic materials	Chemical Compositions	These are building materials obtained from the formation of chemical compounds (Bayer 1947).	

Table 125: Recyclable building material and possible applications of products.

Class	Categories	Possible products	Representation	Possible applications
Elementary / Other materials	Glass Materials	Fibreglass		Roofing, Windows, Insulation, etc.

		Glass		Glazing, Partitions, etc.
	Concrete materials	Concrete slabs		Paving, Slabbing, etc.
		Bricks		Masonry
	Chemical compositions	Plastic		Partitions, Boards, isolators, etc.
		polyvinylchloride		Pipes, plumbing kits, etc.
		Polyurethane		Floor coating, polishing, etc.
	Metal	Steel		Beams, columns, slabs, etc.
		Metal components		Pipes, Rectangular bars, circular bars, etc.
	Plaster	Mouldings and rendered components		Wall rendering, Floor rendering, Ceiling, etc.

Earth materials	Clay		Ceramics, isolators, etc.
	Stones		Wall cladding, decorations, protection, etc.
	Hydra form Bricks		Walls, insulation, Partitions, etc.
Animal materials	Leather		Wallcovering, Furniture, etc.
	Wool		Insulation,
Wood materials	Timber		General construction
	Woodchips		Lagging, Biofuel, etc.
Plant-based materials/aggregates	Newspaper wood		Partitions, panels, furniture
	Fabrics		Curtains, backdrops, etc.

	Straws		Insulations, padding, etc.
	Hemp Fibre		Insulation
	Wood wool		Slab, partitions, etc.
	Sawdust		Particleboards, Insulators, etc.
	Bamboo		Scaffolding, General construction, etc.

The above materials are known to be either reusable or recyclable and can easily be incorporated into the materiality of a passive design (RubberBond 2019; BuildGreenNH 2020). Research on the application of circular economy principles in the built environment has been limited most especially within whole systems context (Adams et al. 2017). Adams et al. (2012) purported that most recovered waste is downcycled, in which the value, quality and overall functionality are usually lower than the original product (Adams et al. 2017). However, there are many potentials for up-cycling of building products. Adams et al. (2017) identified key aspects in applying circular economy across a building's life cycle, these aspects were derived from literature studies as shown in the table below.

Table 126: Circular economy aspects across a building's life cycle stage

Life cycle stage	Circular economy aspect
Design	DfD Design for adaptability and flexibility Design for standardisation Design out waste Design in modularity Specify reclaimed materials Specify recycled materials
Manufacture and supply	Eco-design principles Use less materials/optimise material use Use less hazardous materials Increase the lifespan Design for product disassembly Design for product standardisation Use secondary materials Take-back schemes Reverse logistics
Construction	Minimise waste Procure reused materials Procure recycled materials Off-site construction
In use and refurbishment	Minimise waste Minimal maintenance Easy repair and upgrade Adaptability Flexibility
End of life	Deconstruction Selective demolition Reuse of products and components Closed-loop recycling Open-loop recycling
All stages: management of information including metrics and datasets	

The above circular economy strategies are aimed first at prolonging the useful life of products and components which is followed by closing material flows through recycling at the end-of-life (Bocken et al. 2016; Stahel 2016). Therefore, the quality of resources is maintained over time possibly beyond a single life (Braungart et al. 2007), thereby reducing resource extraction and waste generation (Zink and Geyer 2017).

The studies revealed that the lack of end-of-life considerations during a building's commissioning, design and construction is a major challenge for circular economy in buildings (Adams et al. 2017).

The studies of Adams et al. (2017) and Kibert (2004) identified three lifecycle stages:

(1) Material and component manufacture

(2) Design and planning

(3) End-of-life

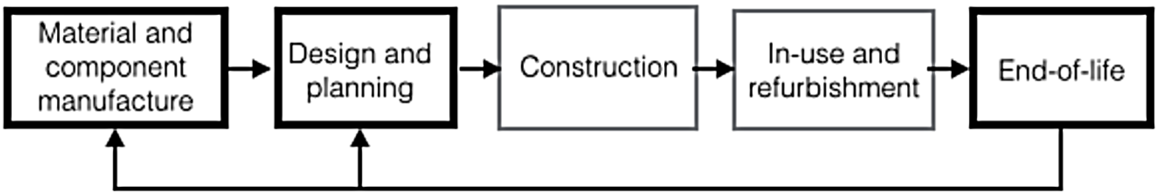


Figure 144: Illustration of the construction value chain for buildings based on Adams et al. (2017) and Kibert (2004)

Nussholz and Milios (2017) also offered an overview of the circular strategies developed from literature for three selected lifecycle phases (Nussholz and Milios 2017).

Table 127: Overview of circular strategies for increasing resource efficiency in the construction of buildings, from Nussholz and Milios, 2017).

Lifecycle phases	***(1) Material and component production***	***2) Design***	***(3) End-of-life***
Circular strategies	- Use fewer hazardous materials - Design for recycling - Prolonged lifespan - Design for product disassembly - Design for product standardisation - Use of secondary materials - Take-back schemes	- Design for disassembly - Design for adaptability and flexibility - Design for standardisation - Design out waste - Design for modularity - Specify recyclable materials - Design to reintegrate secondary production	- Disassembly - Selective demolition - Enable reuse of products and components - Closed-loop recycling - Open-loop recycling

7.3.1.2. Material selection matrix for passive design and circular economy

To achieve a building that is resource and energy-efficient, the building must include material components of adequate performance, with regards to passive design and circular economy. Therefore, the components of passive design and circular economy need to be considered critically to make the best decision on the material selection. To do this, a performance matrix with ratings of individual components was developed based on this research.

From the simulation results, it was established that the thermal conductivity, density, specific heat capacity, volumetric heat capacity, etc. had a significant impact on temperatures, heat gain and energy demand. Therefore, they are important considerations in the matrix. It was also observed that the u-value and material thickness plays a key role in passive design. Based on this research, thermal insulation, and thermal mass are necessary aspects of passive design in the Nigerian context to consider in the matrix when selecting building materials for circular economy and passive design. The RESOLVE framework and the 7S Model of the Circular Economy were also employed in the matrix evaluation while also considering the reuse, upcycling and downcycling potentials of material components.

The table below shows the various abbreviations in the matrix.

Table 128: Abbreviations in the Matrix table

S/N	Word	Abbreviation
1	Thermal conductivity	TC (W/m-K)
2	Thermal transmittance	U-value (W/m^2-K)
3	Material thickness	T (m)
4	Site	-
5	Structure	-
6	Skin	-
7	Space	-
8	Services	-
9	Stuff	-
10	System	-
11	Passive Design Performance	PDP
12	Circular Economy Performance	CEP
13	Thermal Mass	TM
14	Reuse	R
15	Regenerate	Re
16	Share	S
17	Optimise	O

18	Loop	L
19	Virtualise	V
20	Exchange	E
21	Upcycling	UC
22	Downcycling	DC
23	Volumetric Heat Capacity	VHC
24	Thermal Insulation	TI
25	Thermal Resistivity	R-value (m^2-K/W)

In the performance matrix table, each material component is ranked based on its potential performance. Therefore, each material potentiality in a circular economy and passive design is ranked on a set scale. Consequently, the potentiality of a material to be viable (or efficient) as a thermal mass (TM) material, and effective as a thermal insulation material (TI) is ranked 1 (if it is suitable) or 0 (if it is not). It is important to note that the U-value of materials are also dependent on their thickness (T) which was taken into consideration in the matrix. The thermal conductivity and U-value of materials are also considered. Based on this research (after conducting several simulations and studies) it was established that the ideal u-value and thermal conductivity of insulation materials should be a maximum of 0.10W/m-K for thermal conductivity and a maximum of 1.00W/m^2-K for thermal transmittance. The volumetric heat capacity of the thermal mass material should be a minimum of 1500KJ/m^3.K. The thermal conductivity of thermal mass materials should be in the range of 0.50-2.00W/m^2-K. These ranges are also supported by various works of literature (House-Energy 2013; TheGreenAge 2013; Bhatt 2014; LHedlund 2016; Gyoh 2017; DesignBuilder 2019; Gyoh 2020). The considerations have been based on this research as earlier mentioned. In the same vein, the components of circular economy such as reuse, regeneration, share, optimisation, loop, virtualise, and exchange are scored accordingly in the table below. For example, a reusable material is scored 3 and scored 0 if it is not reusable. A material that is regeneratable/recycled is scored 2 and scored 0 if it is not regeneratable. A material gets 1 for the other components of the ReSOLVE framework - (Share, Optimise, Loop, Virtualise and Exchange) if the material is susceptible to the respective circularity components and scores 0 if it is not. Also, a material that can be downcycled scores 1 and a material that can be upcycled scores 2 as upcycling is more desirable (Eberhardt et al. 2019b; Giama et al. 2019). The materials can also be evaluated on aspects of passive design strategies such as their efficacy and their material potentiality in a circular economy when used as a thermal mass (TM), and thermal insulation (TI). Therefore, thermal insulation (TI) and thermal mass (TM) is scored 1 point each if the material possesses potential (by falling within the required range) for each of the passive design strategies as seen in the table below.

Table 129: Weighting factor and ranges for passive design and circular economy parameters

S/N	Variables	Abbreviations	Weighting factor/Range
1	Daylighting	DL	1
2	Thermal Mass	TM	1
3	Thermal Insulation	TL	1
4	Reuse	R	3
5	Regenerate	Re	
		Upcycling (UC)	2
		Downcycling (DC)	1
6	Share	S	1
7	Optimise	O	1
8	Loop	L	1
9	Virtualise	V	1
10	Exchange	E	1
11	Thermal transmittance *(Insulation materials)*	U-value (W/m^2-K)	Maximum of 1.00W/m^2-K
12	Volumetric heat capacity *(Thermal mass)*	VHC (KJ/m^3.K)	Minimum of 1500KJ/m^3.K
13	Thermal conductivity *(Insulation materials)*	TC (W/m-K)	Maximum of 0.10W/m^2-K
14	Thermal conductivity *(Thermal mass)*	TC (W/m-K)	0.50-2.00W/m^2-K

A weighting factor is also assigned to the components of the 7S model (Structure, Skin, Stuff, Services, System, Space, Site) based on the building material quantity in weight. Therefore the components with the highest quantity of material get a higher weighting factor due to their high potentiality for reuse and recycling as a result of the quantity of material of various categories and for the need to prioritise the reuse or recycling of such material components as observed from previous studies (Atmaca and Atmaca 2016; O'Grady et al. 2021). Therefore, Space (including walls and floors) – 7 points, Structure (foundation, frame system) – 6 points, Skin (including roof, external cladding and finishes) – 5 points, Stuff (such as lighting, fixtures, furniture, doors and windows) – 4 points, Services (pipes, wires, building services) – 3 points, Site (building's location) – 2 points, System (support infrastructure for the building) – 1 point (Atmaca and Atmaca 2016; O'Grady et al. 2021). The weighting factor of a specific category is used to multiply the total score obtained from the summation of the passive design performance (PDP) and the circular economy performance (CEP). This helps to determine the potentiality of the material based on its quantity, thereby assisting to consider and prioritise material components for reuse, recycling and potentially designing out waste.

7.3.1.3. Material selection matrix

Developed material selection matrix based on this research.

Material Selection Matrix		Passive Design Performance (PDP)							Circular Economy Performance (CEP)							Score
Category	Material/Component	Properties	(TC)W/m-K	Thickness (m)	R-Value	U-value	TM	TI	R	Re	S	O	L	V	E	
7 Space	Hydra form Brick Steel Concrete Slab Roof timber Aluminium Roofing sheets Asbestos ceiling boards Wooden Door Wall Cladding	C 0.84 KJ/Kg-K nsity 1920.00 Kg/m3 C 1612.80 KJ/m3.K	0.720	0.200	0.28	3.60	1	0	3	2	1	1	1	1	1	**77**
7 Space		C 0.84 KJ/Kg-K nsity 2100.00 Kg/m3 C 1764.00 KJ/m3.K	1.400	0.150	0.11	9.33	1	0	0	2	0	0	1	1	0	**35**
7 Space	Hemp fibre	C 2.15 KJ/Kg-K Density 35.00 Kg/m3 VHC 75.25 KJ/m3.K	0.038	0.100	2.63	0.38	0	1	3	2	1	1	1	0	1	**70**
2 Site	Paving stones	SHC 0.84 KJ/Kg-K Density 2000.00 Kg/m3 VHC 1680.00 KJ/m3.K	0.960	0.100	0.10	9.60	1	0	3	2	1	1	1	1	1	**22**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**
Category	Select Material	SHC 0.00 KJ/Kg-K Density 0.00 Kg/m3 VHC 0.00 KJ/m3.K	0.000	0.000	#DIV/0!	#DIV/0!	0	#DIV/0!	0	0	0	0	0	0	0	**#DIV/0!**

Matrix Materials Parameters Notes

Figure 145: Material selection matrix

Material Selection Matrix

7.3.2. Material Documentation

The good thing about the matrix is that it also serves as a material passport platform, in addition to the evaluation of passive design performance of materials. Therefore, the constituents of the building can be documented for present and future considerations and references (Munaro et al. 2019). Material passport platforms could also be used for documentation after evaluating material components using the matrix table.

The material passport is a concept that is already being adopted in Europe. The passport is an effective digital document that contains information on all the composition of a particular component/product or building (BAMB 2016; Kaminski 2019). Duncan Baker-Brown of BBM Sustainable Design, a champion in circular economy explains that a material passport lists all the ingredients of a structure, which has useful potentials to manage a facility – this includes but is not limited to making changes redevelopment or extensions (Kaminski 2019). Dutch Architect Thomas Rau of the RAU Architects headed the pioneering of the concept of material passports several years ago (Kaminski 2019).

There are front runner platforms for material passports such as the BAMB material passport platform and the Madaster platform (Kaminski 2019). These platforms are also able to estimates the future worth of the materials by drawing information from sources like the London Metal Exchange (Kaminski 2019). The platform can automatically generate a material passport that describes the materials (including quantity) in each building layer and the ease of retrieving them (Matthias Heinrich and Lang 2019). It as well calculates the circularity index, which determines the building use of virgin or recycled materials and other relevant information, it also tells whether they can be reused and their assemblage method (BAMB 2016). This makes it easier to change or deconstruct a building, thereby increasing its value by quoting figures of materials' worth (BAMB 2017; Kaminski 2019; Matthias Heinrich and Lang 2019).

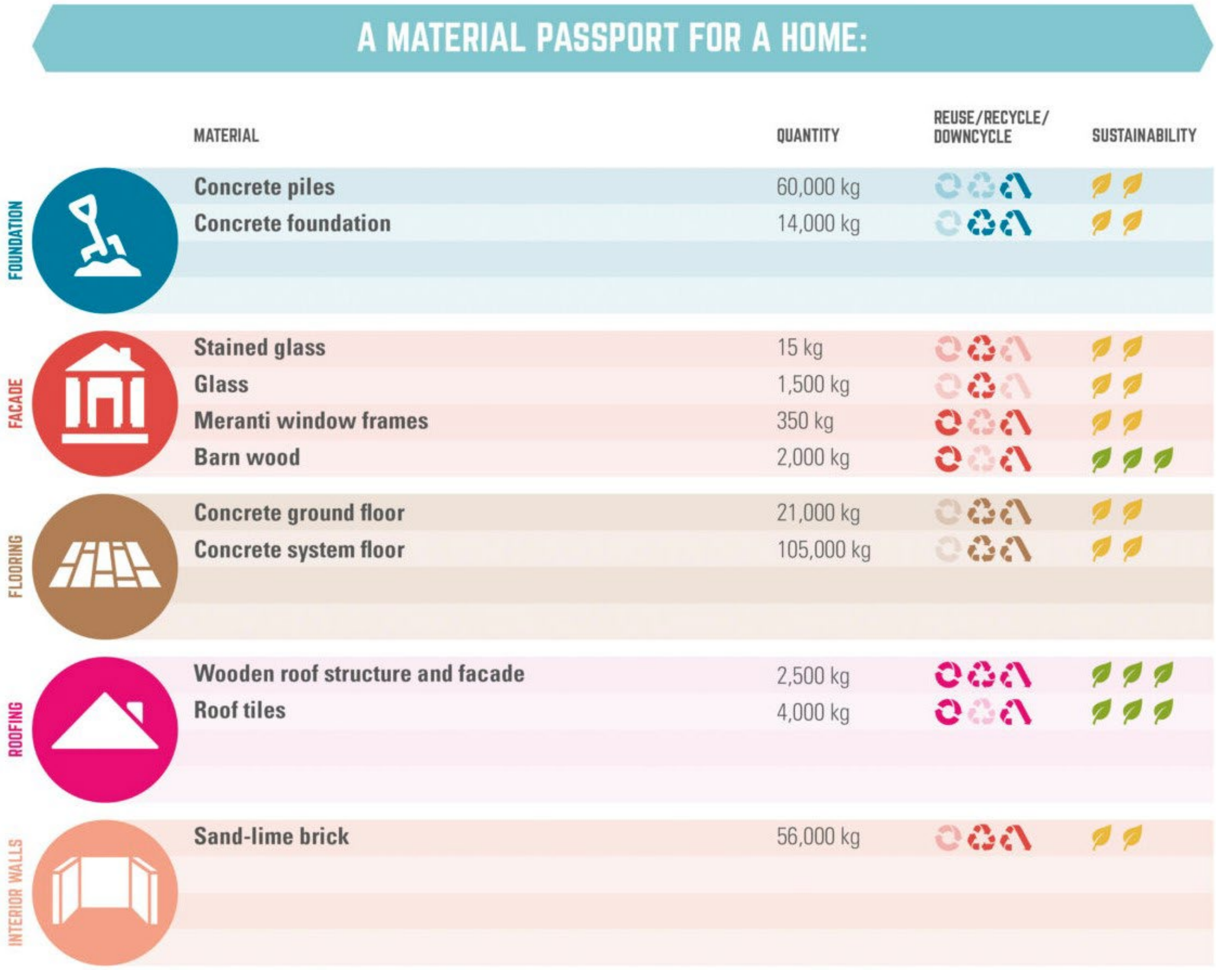


Figure 146: A material passport derived from sustainability consultant Metabolic (Kaminski 2019)

7.3.3. Component Design

The ease of assembly and disassembly is largely dependent on the design of the building components (Kanters 2018). From previous studies, it can be seen that components are expected to be easy to fix, adaptable, and durable (Esa et al. 2017; Ranta et al. 2018; De and Eden 2019; Rasmussen et al. 2019). The durability of material components is essential as it allows for futuristic repurposing. It is also important that the materiality of components is reusable and recyclable for an easy transition into a circular economy. As recommended by previous studies (EMF 2014; BAMB 2017; Kanters 2018; Ajayabi et al. 2019; Altamura and Baiani 2019; De and Eden 2019; DesigningBuildings 2021), it is important to consider the following whilst designing building components:

1. How are components connected?
2. What are the connectors?
3. What is the material composition of each component?
4. How durable are the component materials?

5. How are they disassembled?
6. What is the ease of disassembly?
7. What are the standardisation parameters of the component?
8. How can the components be optimised?
9. How can the components be reassembled?
10. Are components designed in a unit, are they assembled/disassemble as a unit (monolithic) or as a composite?
11. What are the possible/potential uses for the components?
12. How can the material component be recycled?

These questions are very important whilst designing for disassembly as they set the basis for standardisation of universal building components that can easily be assembled, or dismantled for optimisation, reuse, or recycling.

7.3.4. Assemblage method and connection type

The ease of deconstruction is feasible or determined by the connection type of components or the assemblage method of building components (Kanters 2018). Popular connection types for easy disassembly include nuts and bolts, screws, clamps, and quick release methods. Therefore, building components such as steel beams and columns could easily be connected by nuts and bolts instead of welds or rivets. Similarly, timber members can easily be bolted together.

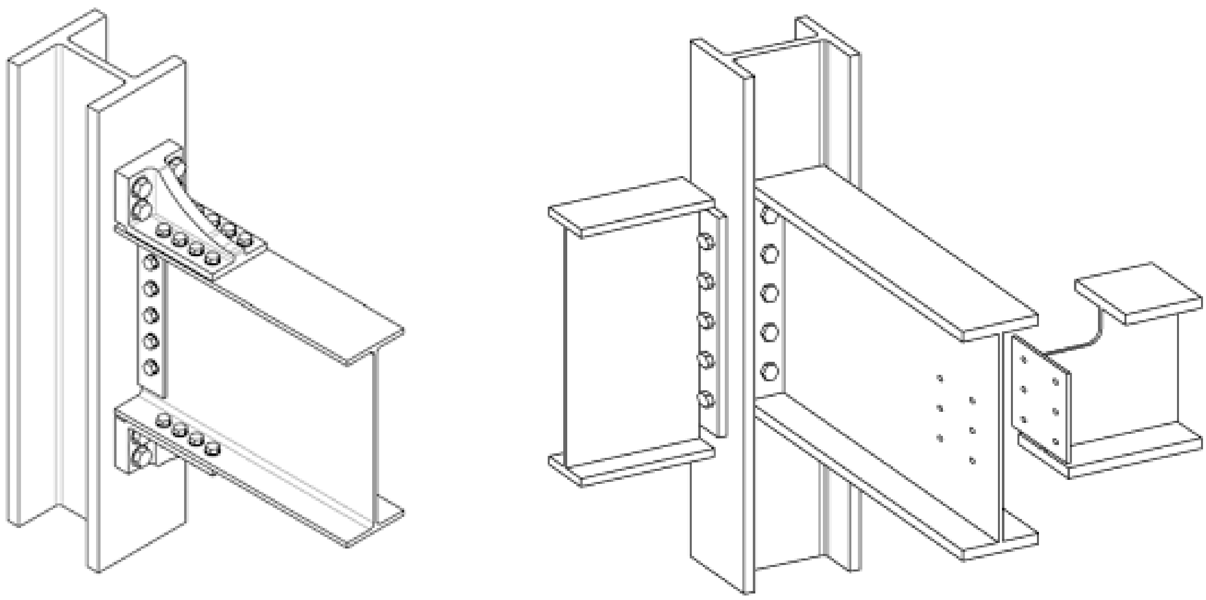


Figure 147: Beam and Column nut and bolt connection (Hamburger et al. 2009)

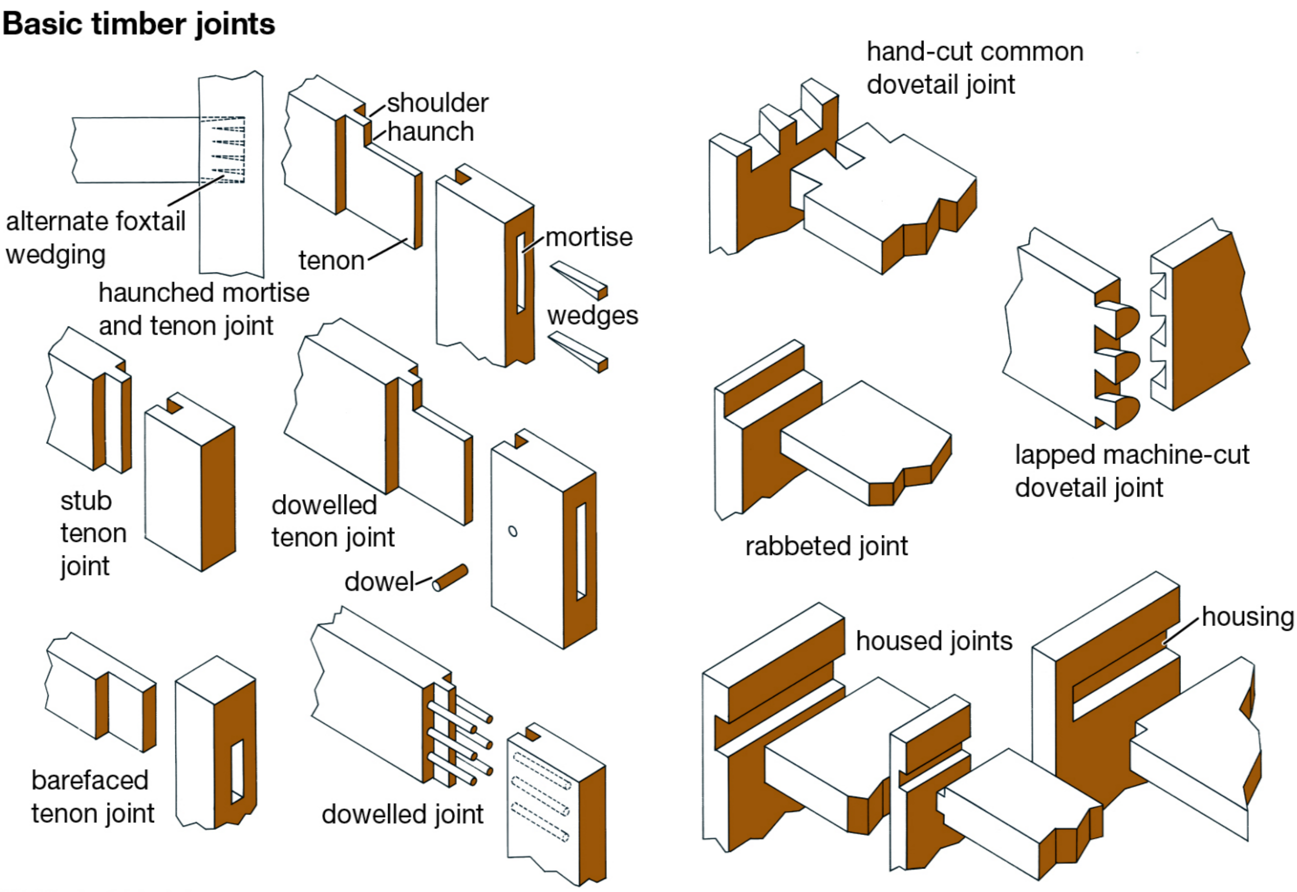


Figure 148: Basic timber Joints

Other components may include lock keys for easy separation or steel plates and connectors for easy anchorages. These do not only ease the process of construction or deconstruction but also help preserve component members from destruction during assembling and disassembling (Kanters 2018).

Figure 149: Steel Connectors

7.3.5. Standardisation

Prefabrication of building components is one of the sure ways for the standardisation of building components (Gibb 1999; Klinge et al. 2019). In this case, components are designed and manufactured to very strict standards in terms of dimensions, weight, size, quality, quantity, performance, and specifications. DesigningBuildings described standardisation as the use of modules, components, interfaces or processes that are repeatable in projects (DesigningBuildings 2021).

Standardisation can simply be defined as the process of agreeing on a standard specification for specific products. This is usually intended to foster compatibility with other products, economies of scale, and facilitation of maintenance, repair and operation (Yasin and Rjoub 2017; DesigningBuildings 2021).

Therefore, standardisation as a working process helps to define common specifications, procedures, and methods of a product. This is intended to ensure greater reliability, consistency, compatibility, quality, and compliance for a particular product (Sparksman et al. 1999; DesigningBuildings 2021).

7.3.6. Component Annotation

For building components to easily be identifiable, documented and specified, they must possess a nomenclature (Sanchez and Haas 2018). This is a naming and/or numbering system that enables component members for easy identification, matching, and assemblage. The annotation usually bears guides for installation, safety and other relevant information (Matthias Heinrich and Lang 2019).

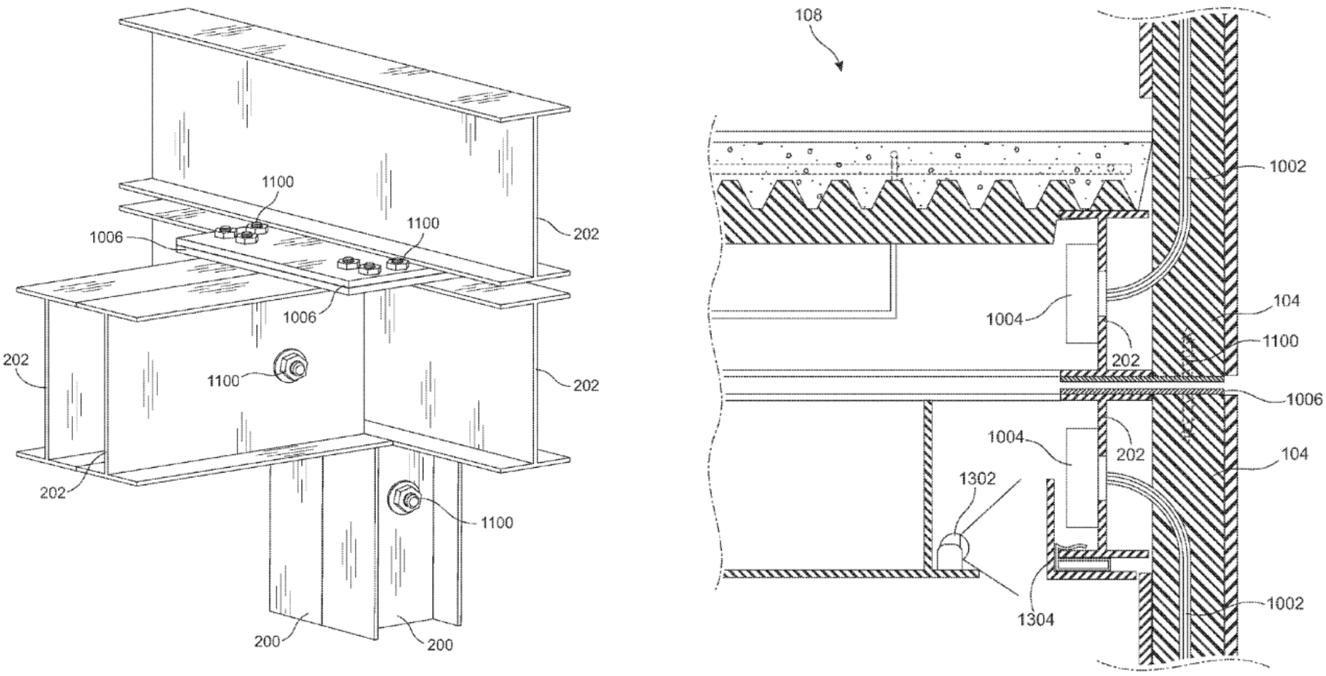


Figure 150: Annotation of components with numbers (Ingjaldsodottir and Thorsteinsson 2011)

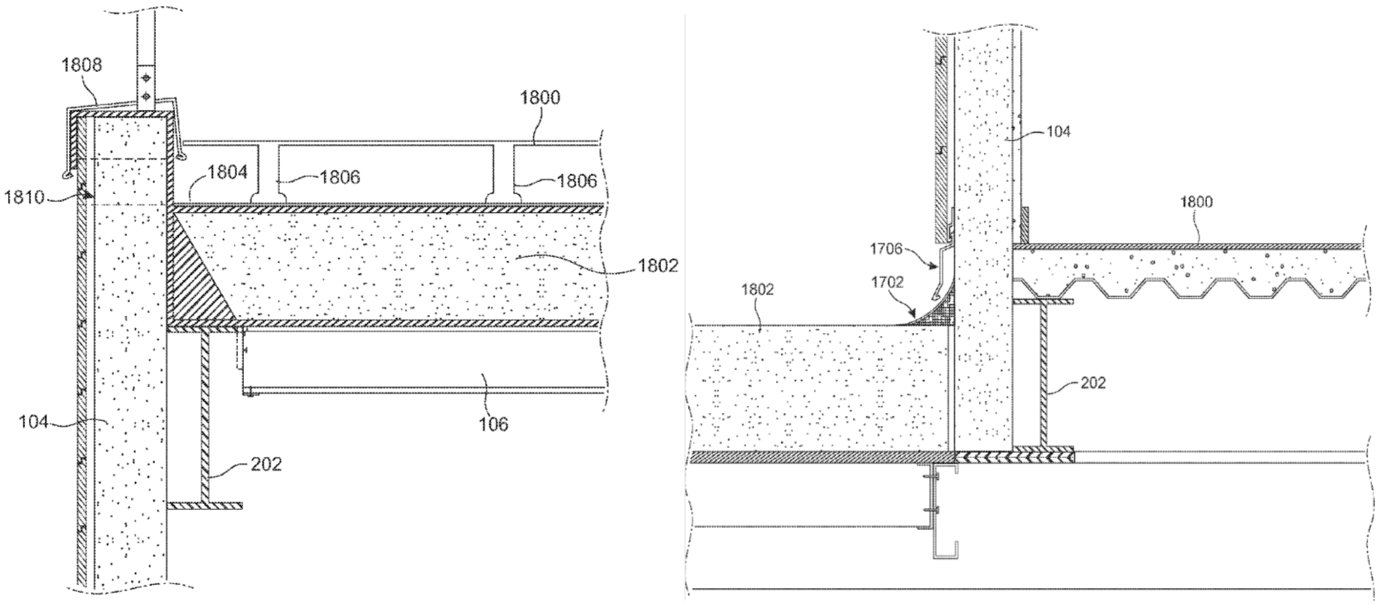


Figure 151: Annotation of components with numbers for each component type (Ingjaldsodottir and Thorsteinsson 2011)

Designers could make use of a specific number to label a standard component. Therefore, the number may be used as a marker to represent the component size, shape, quality, texture, chemical and physical properties, weight, specifications, etc. as seen in the figures above. It could also be used to describe the installation procedure or method (Ingjaldsodottir and Thorsteinsson 2011).

7.3.7. Accessible Connectors

Another important aspect of designing for disassembly is the provision of component connectors that are accessible. This is vital because connectors are required to be accessible for assembly and disassembly as well as during repairs, maintenance, optimisation, serving, etc. Inaccessible connectors would make deconstruction difficult if not impossible (Güngör 2006).

7.3.8. Program for Selective and Volumetric Deconstruction

As it is for buildings before construction to have a plan or program of works, so it is necessary to have a deconstruction program for a safe, and efficient deconstruction (Chini 2001; Esa et al. 2017). Therefore, a building could be programmed for selective or volumetric deconstruction. In selective deconstruction, components are dismantled from the main building selectively or one at a time depending on the operation (Sanchez and Haas 2018). A component may be selectively removed for repair, maintenance or optimisation.

On the other hand, volumetric deconstruction consists of an overall disassembly of the entire building. In any case, it is necessary to have a schedule of deconstruction to prevent an instant collapse of the structure that may lead to destruction (Sanchez and Haas 2018; De and Eden

2019). Therefore, for a safe and efficient deconstruction, it is imperative to have a program for components disassembly.

7.3.9. Program for [Re]construction

Similar to the deconstruction program, the program for reconstruction is geared to identify and instruct on the installation procedures for components (Sanchez and Haas 2018). This way, the construction protocol is documented and described for every stage of construction. The labelled building components are further specified to the corresponding connectors (De and Eden 2019).

7.3.10. Best practices and productivity

Recommendations of best practices for safety, productivity, effectiveness and efficiency are documented as a guide for installation and disassembly (De and Eden 2019). It is expected that each building design has its uniqueness and design, hence, the implementation strategy may vary a little, but the same principle. Safety is a crucial issue in disassembly procedures and the best safety measures must be taken to avoid or prevent accidents and failures (Bodar et al. 2018). Therefore, it is highly recommended that safe schedules for assembly, disassembly and maintenance are prepared and followed strictly.

Proper construction and deconstruction management can help ensure high productivity at various stages of the project, such as resources, machinery and time management can greatly improve the productivity of a project (Crowther 2005). Also, the project can effectively and efficiently be programmed by considering the effectiveness of strategies for the project, methods, materials and design (Basti 2018; Benachio et al. 2020).

Chapter Eight

8.0. An approach for the application of circular economy and passive design strategies in the design of Nigerian residential buildings

Based on this research and analysis, circular economy can be incorporated into energy-efficient building design in the tropical savannah climate of Nigeria by adopting the following procedures and recommendations.

8.1 Design the building using passive design strategies

After conducting several optimisation simulations, the specific design parameters for each design variable towards achieving energy efficiency in Nigerian residential buildings was established which primarily informed the development of the framework. It is important to consider the reusability and recyclability of building materials for a circular economy while designing the buildings using passive design strategies.

8.1.1. Building Orientation

In this research, it was discovered that the 0-degree building orientation which has the longest side facing the north had the best building performance. Thus, confirming that the best orientation for the region was within 20°W–30°E of true North. Hence, buildings in the tropical savannah region of Nigeria should be orientated within this range or with the longer side perpendicular to the North.

8.1.2. Window to Wall Ratio

From the simulations, it was observed that the building performed better with 15% WWR for the South façade, 25% for the East façade, 20% for the West façade, and 30% for the North façade which is in line with the general recommendation for south, west and east orientations around 20%, but for north orientation is 20%–40%.

8.1.3. Local Shading

The horizontal multiple blades (with 100mm blade depth, 50 degrees blade angle, 5 blades) can be adopted as the best shading strategy for south elevations in the tropical savannah climate of Nigeria. For the West elevation, a blade depth of 300mm, blade angle of 110^0, 4 number vertical fins and 400mm overhang is appropriate for a standard window size of 1.2m by 1.5m and for East elevation, blade depth of 300mm, blade angle of 120^0, 4 number vertical fins and 400mm overhang is best for optimal performance for a standard window size of 1.2m by 1.5m for optimal performance. The simulation revealed that local shading is not required for the North elevation of the building in this region.

8.1.4. g-value

Based on this research, it is best to install a glazing type that is transparent with a low g-value. An ideal glazing type should have a visible transmittance of at least 60%, a U-value of not more than 1.60W/m^{2}K, a Solar Heat Gain Coefficient of not more than 40%, an example of such Glass product is AGC Glass Co. N.A. Comfort TiAC28 on Clear <TiAC28_6.AFG.

8.1.5. Thermal Insulation

The use of Hemp fibre is most ideal for thermal insulation considering its recyclability and biobased potential. It was discovered that hemp fibre of 100mm thickness, Thermal Conductivity of 0.04W/m-K, Specific Heat of 2150J/Kg-K and Density of 35Kg/m^3 was most effective for tropical savannah climate buildings in Nigeria. Hence, it is recommended that buildings in this region adopt these parameters for thermal insulation and the U-value of thermally insulating material does not exceed a maximum of 1.00W/m^2-K while a maximum of 0.10W/m-K for the thermal conductivity of the material should not be exceeded based on this research.

8.1.6. Thermal Mass

Based on this research, the most effective and appropriate thermal mass is the hydra form bricks with a thickness of 150mm, the thermal conductivity of 0.79W/m-K, a specific heat capacity of 840J/Kg-K and a density of 1950Kg/m^3. Based on this research, it is important that a minimum volumetric heat capacity of 1500KJ/m^3.K is used. The thermal conductivity of thermal mass materials should be in the range of 0.50-2.00W/m^2-K Therefore, these thermal mass properties are recommended in the design of tropical savannah climate buildings in Nigeria.

8.1.7. Natural Ventilation

The recommendation for the minimum size of the opening should be at least 5% of the floor area of the room in warm climates as seen in this research and as also recommended by the Nigerian Building Energy Efficiency Code (ABCB 2016; Federal Ministry of Power 2017). Window opening area should be between 50 - 100% such as the use of projected windows to maximise opening area. The roof should be ventilated where possible.

8.1.8. Daylighting

A window opening providing daylight as observed from this study should have a minimum area of 10% of the floor area of the room, this is also the recommendation of Arup and the Federal Ministry of Power, Nigeria (Arup (Madrid & Lagos offices) and Design Genre 2016; Federal

Ministry of Power 2017; ABCB 2018). It is also important to install glazing with high visibility and low g-value.

8.1.9. Roof Material

A less heat conductive material such as roof tiles of 0.84W/m-K is ideal to reduce heat transmission and insulation with hemp fibre of 150mm thickness, Thermal Conductivity of 0.038W/m-K, Specific Heat of 2150J/Kg-K and Density of 35Kg/m^3 as seen in this research is recommended. Hence, these roof materials are recommended for tropical savannah climate buildings in Nigeria.

8.2. Design for disassembly by splitting building components into the 7S model

Based on the studies on design for disassembly as seen from this research and from the literature review, the steps are recommended when designing the building for disassembly.

a. Determine the best structural system for the building, such as frame structure or load-bearing structure.
b. Design building components into detachable segments, modules, for the ease of deconstruction.
c. Establish assemblage methods and connection types for the various building components.
d. Standardise building components to ensure greater consistency, reliability, compatibility, quality, and compliance.
e. Annotate components for easy identification, matching, and assemblage.
f. Ensure component connectors are accessible for the ease of assembly, deconstruction and maintenance.
g. Prepare a programme for selective or volumetric deconstruction to ensure a safe, and efficient deconstruction.
h. Prepare a programme for reconstruction.
i. Prepare manual or guidelines for best practices, safety, and efficiency.

8.3. Design for recycling

The material selection matrix can be used to sort reusable and recyclable materials into the various building components in conjunction with the 7S Model and ReSOLVE framework.

a) Select materials using the material selection matrix based on the ReSOLVE framework to established the reusability and recyclability of building materials or do a study to determine the reusability and recyclability potential of the building material.
b) Use the matrix to determine the energy efficiency potential of each selected material or do a study of each material to establish their potential energy efficiency before final selection and use.
c) Sort building materials based on the 7S Model into various building segments.

This ensures that the materials have been considered for reuse and recycling in a circular economy as well as its energy efficiency.

8.4. Design for end of life

Determine the end-of-life products after the deconstruction of the building with regards to material reuse and recycling.

Use materials with the potentiality of reuse and recycling.

Determine how the building will be deconstructed.

Design the building for the ease of disassembling, such as the use of detachable connectors to hold components in place, e.g. nuts and bolts.

Determine other uses/transformation of the building's remains after the end of life.

Prepare a guide towards the harnessing of the building's remains and the recovery of the building's material components.

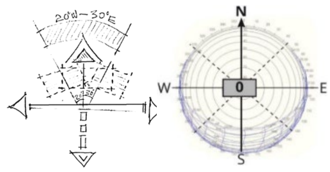
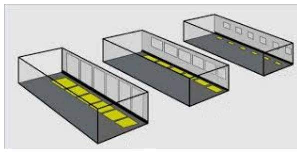
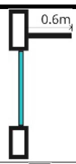
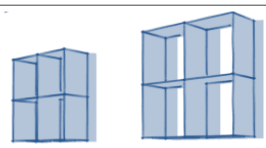
8.5. A framework for incorporating passive design strategies into circular economy

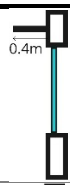
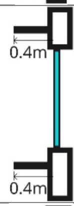
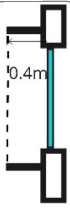
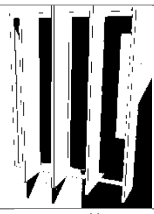
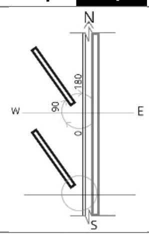
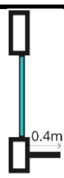
In the end, a framework for the design of energy and resource efficient buildings in the tropical climate of Nigeria was developed based on the evaluated strategies from this research.

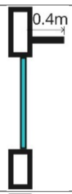
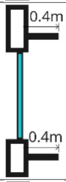
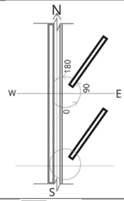
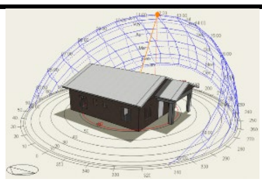
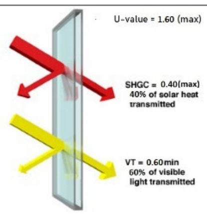
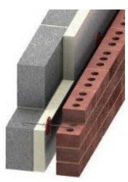
Table 130: A framework for the design of energy and resource efficient buildings in the tropical climate of Nigeria

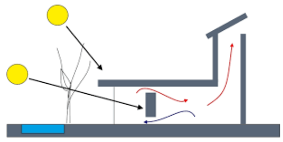
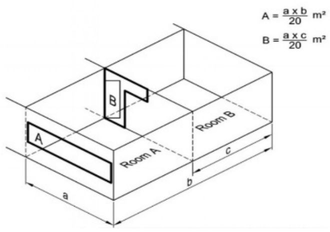
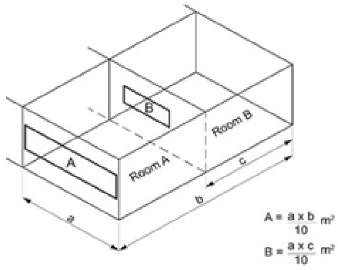
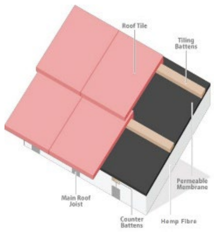
A FRAMEWORK FOR THE DESIGN OF ENERGY AND RESOURCE EFFICIENT BUILDINGS IN THE TROPICAL SAVANNAH CLIMATE OF NIGERIA

This framework has been established based on this research conducted in the tropical savannah climate of Nigeria. The parameters for each passive design strategy/design variable recommended in this framework are informed by this research and the specific design parameters can be appropriated for the design of residential buildings in the tropical savannah region of Nigeria.

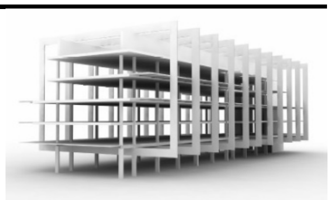
Strategy	Parameters/Recommendation	Description	Illustration
Building Orientation	0 degree of true North Or within 20°W–30°E of true North	The longer side of the building should be perpendicular to the North	
Window to Wall Ratio	15% for South façade, 25% for the East façade, 20% for the West façade and 30% for the North Facade	Each façade WWR should have a unique ratio. However, a WWR of between 20%-30% is ideal.	
Local shading	*Note: The Parameters below are for a standard Nigerian residential window size of 1.2m by 1.5m and parameters based on these guidelines should be adjusted proportionately to chosen window sizes.*		
South Elevations	Single horizontal overhang	Horizontal overhang shading of 0.6m	
	Horizontal multiple blades • Different depths of blades and Number of blades.	5 blades with 100mm blade depth	
	• The number of blades and angle of blades.	5 blades at 50 degrees and 100mm blade depth	
	• Different angles of blades and variations in blade depths	5 blades and 100mm blade depth at 50 degrees	
	Box shading or egg-crate	(100mm blade depth, 50 degrees blade angle, 5 blades) + 100mm vertical fin	
Overall Recommendation	The horizontal multiple blades with 100mm blade depth, 50 degrees blade angle, 5 blades) can be adopted as the best shading strategy for south elevations		

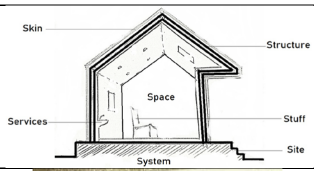
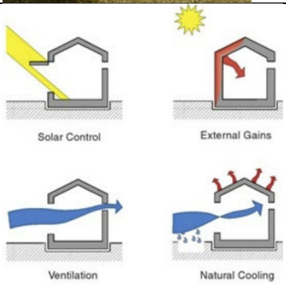
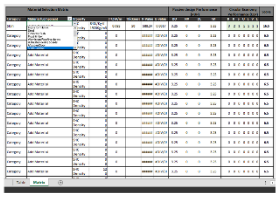
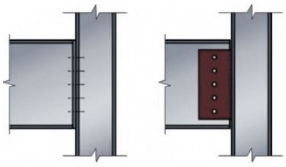
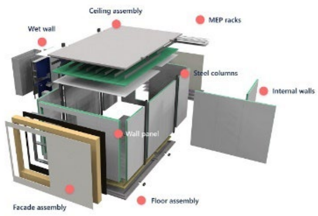
West Elevation	Side fins • Left side fin with variable projections.	A vertical fin of 400mm depth	
	• Right side fin with variable projections.	A vertical fin of 400mm depth	
	• Left and right side fins with variable projections.	Vertical fins of 400mm depth	
	• Left and right side fins with variable overhang	Vertical fins of 400mm depth with 400mm wide overhang	
	• Number of vertical fins and depth of fins	Four vertical fins of 300mm depths.	
	• Number of vertical fins and angles of fins	Four blades at angle 110 degrees, with a blade depth of 300mm	
	• Number of vertical fins and angle of fins with variable overhang	0.4m overhang + 4 blades at angle 110 degrees, with a blade depth of 300mm	
Overall Recommendation	For the West elevation, a blade depth of 300mm, blade angle of 110^0, 4 number vertical fins and 400mm overhang is appropriate		
East elevation	Side fins • Left side fin with variable projections.	A vertical fin of 400mm depth	

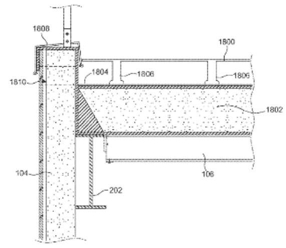
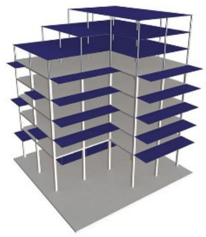
	• Right side fin with variable projections.	A vertical fin of 400mm depth	
	• Left and right sidefins with variable projections.	Vertical fins of 400mm depth	
	• Left and right sidefins with variable overhang.	Vertical fins of 400mm depth with 400mm wide overhang	
	• Number of vertical fins and depth of fins	Four vertical fins of 300mm depths.	
	• Number of vertical fins and angles of fins	Four blades at angle 120 degrees, with a blade depth of 300mm	
	• Number of vertical fins and selected angles of fins with variable overhang	0.40m overhang + 4 blades at angle 120 degrees, with a blade depth of 300mm	
Overall Recommendation	for East elevation, blade depth of 300mm, blade angle of 120^0, 4 number vertical fins and 400mm overhang is best for optimal performance		
North Elevation	The North façade does not necessarily require shading due to the geographical location of the climatic region	Therefore, shading devices are not necessarily required as affirmed from the simulations	
g-value	A material with a low g-value and high visible light transmittance is recommended	60% minimum Visible Daylight transmittance, Maximum Solar Heat Gain Coefficient (SHGC) of 0.40 and a maximum U-value of 1.60 W/m^2-K.	
Thermal Insulation	Hemp fibre is very ideal for thermal insulation considering its recyclability and biobased potential. A thermal conductivity range between 0 - 0.10W/m-K, A u-value range of 0 - 1.00W/m^2-K is recommended	Hemp fibre of 100mm thickness, Thermal Conductivity of 0.038W/m-K, Specific Heat of 2150J/Kg-K and Density of 35Kg/m^3 are recommended	

Thermal Mass	Hydra form bricks with a thickness of 150mm, Thermal conductivity of 0.79W/m-K, a specific heat capacity of 840J/Kg-K and a density of 1950Kg/m^3 are recommended. The volumetric heat capacity should be a minimum of 1500KJ/m^3.K	Effective and appropriate thermal mass includes hydra form bricks, concrete, etc. The thermal conductivity of thermal mass materials should be in the range of 0.50-2.00W/m^2-K	
Natural Ventilation	The minimum size of the opening should be at least 5% of the floor area of the room	Window opening area should be 50-100% such as the use of projected windows to maximise opening area. The roof should be ventilated where possible	
Daylighting	A minimum opening area of 10% of the floor area of the room	Glazing - 60% minimum Visible daylight transmittance	
Roof	Roof tile - Thermal Conductivity:0.84W/m-K Specific Heat: 800J/Kg-K Density: 1900Kg/m^3	Roof tiles of maximum U-value: 130.00W/m^2-K are ideal to reduce heat transmission	
	Thermal insulation - Thermal Conductivity range between: 0 - 0.040W/m-K	150mm Hemp fibre recommended: Maximum U-value of 0.30 W/m^2- K	

Based on this research, incorporating circular economy principles into an energy-efficient building would require that the building is designed for disassembly, reuse and recycling. Hence, the following steps are recommended and should be considered.

Structure	Determine the structural system suitable for the building	Framework or Loadbearing. This would aid the ease of deconstruction.	

Building components	Building components should ideally be designed in modules (modular construction)	Building members such as slabs, columns, beams, walls, etc.	
Reusable/ Recyclable material	Identify and select reusable and recyclable building materials	These materials may also be biobased materials	
Passive design performance of buildings	Whilst selecting reusable and recyclable materials, it is highly recommended to consider the energy efficiency potential of the material	This may include the thermal performance of the material, considering parameters such as density, specific heat capacity, volumetric heat capacity, thermal conductivity, U-values, g-values, etc.	
Material documentation	Document the materials considered towards achieving an energy and resource efficient building.	Make a document of the properties of the construction materials and note any other relevant information as well as the quantity.	
Matrix	Determine material fit for use with respect to energy efficiency and circular economy. Input the materials into the material selection matrix for evaluation, selection and documentation	Use the material selection matrix to evaluate each building material for selection with regards to energy efficiency and circular economy potential	
Component Design	Design building components for easy assembly and disassembly as well as considerations for maintenance, reuse and recycling.	Ensure the materiality of components is reusable and recyclable.	
Assemblage method/connection type	Use appropriate assemblage method and connection type to aid disassembly.	Use assemblage methods such as nuts and bolts instead of welds or rivets.	
Standardisation	Use strict standards in terms of dimensions, weight, size, quality, quantity, performance, and specifications.	Design to standards to ensure greater reliability, consistency, compatibility, quality, compliance, economies of scale, facilitation of maintenance, repair and operation.	

Component Annotation	Annotate components for the ease of identification, installation, description, matching, or as a marker to represent the component size, shape, quality, texture, chemical and physical properties, weight, specifications, etc.	Use a naming and/or numbering system that enable component members for easy identification, matching, and assemblage.	
Accessible Connectors	Ensure component connectors are accessible for the ease of assembly and disassembly.	Connectors should be accessible for assembly and disassembly as well as during repairs, maintenance, optimisation, serving, etc.	
Program for selective and volumetric deconstruction	Prepare a schedule or programme for selective or/and volumetric deconstruction. This is to ensure a safe, and efficient deconstruction.	A component may be selectively or volumetrically removed for repair, maintenance or optimisation	
Program for [Re]construction	Prepare a program to instruct on the installation procedures for components. the construction protocol is documented and described for every stage of construction.	The labelled building components may be further specified to the corresponding connectors.	
Design for end of life	Determine the end-of-life of products after the deconstruction of the building with regards to material reuse and recycling by using materials with the potentiality of reuse and recycling.	Determine other uses/transformation of the building's remains after the end of life. Prepare a guide towards the harnessing of the building's remains and the recovery of the building's material components.	
Best practices and productivity	Make recommendations of best practices for safety, productivity, effectiveness and efficiency. These can be documented as a guide for installation and disassembly.	it is highly recommended that a guide for best practices during construction, deconstruction, and maintenance are prepared and followed strictly.	

The above recommendations should be followed as a guide towards achieving energy and resource efficient buildings in the tropical region of Nigeria.

8.6. Current and potential difficulties of obtaining proposed solutions in Nigeria

Although the proposed solutions for Nigerian residential buildings are feasible, there may be some current and potential difficulties in obtaining the proposed solutions in Nigeria. The following current and potential difficulties have been identified.

- Generally, the use of insulation in Nigerian residential buildings is not a common practice, consequently, locally based industries or the market for insulation materials such as hemp fibre and other insulation materials are currently scarce in Nigeria (Gyoh 2020). Therefore, it may be difficult to easily access building insulation due to its low demand which influences supply. Potential alternatives for obtaining insulation products may be through importation. As the awareness of building insulation and its benefits increases, the demand for building insulation materials is believed to also increase which is expected to develop the market.

- Modular construction which usually involves an industrialised process is not popular in Nigeria (Bankole 2019). Hence, obtaining and managing building components in modules may be a potential difficulty considering how building industrialisation is unpopular in Nigeria. It is believed that when modularity in buildings becomes a common practice in Nigeria, the Nigerian building industry will also become more industrialised to accommodate modular building construction.

- The proposed solutions may be more expensive than the existing building design and construction system. Thus, this may be a potential difficulty for the adoption of the proposed solutions due to the increased build cost. To alleviate any extra cost implications, the Nigerian Government can introduce a programme or scheme that covers the additional cost or a form of incentive as a way of encouragement.

Chapter Nine

9.0 Conclusion

9.1. Introduction

This chapter provides an overview of this research work and its contributions toward achieving the outlined research aim and objectives. It also provides an overview of how the research has informed the various strategies, recommendations and conclusions. It summarises the research work undertaken, its various contributions to knowledge and how the research has bridged identified research gaps. The chapter presents the research limitations and areas for further study.

9.2. Research Summary

This research is geared towards developing a framework or guide for the design of residential buildings in the tropical savannah climate region of Nigeria using passive design strategies, the components of which can be reused/recycled after the first life by potentially designing buildings for disassembly in tropical Nigeria.

The study discussed and addressed key aspects of passive design strategies and their relationship with circular economy and how both interventions can be combined with regard to energy and resource efficiency. To this end, the study systematically followed the outlined research objectives and methods for developing a framework/guide for incorporating circular economy in the design of energy-efficient residential buildings in Nigeria.

To understand the works and contributions done in building circularity, the study conducted a systematic review on the application of circular economy principles in buildings. Also, the study reviewed works of literature that provided relevant information and data for analysing and discussing major concepts of passive design and circular economy interventions. Excerpts from these studies were published in peer-review Journals and at international conferences.
Further on, literature reviews of past work on the Nigerian tropical climate, its residential buildings, and recommended passive design strategies for the weather condition in the study area were considered under the components of passive design strategies for the tropical savannah climate of Nigeria. In addition, the study collected building data and information on Nigerian residential buildings leading to the research adopting a typical Nigerian residential building in the study area for the base case - a base case determined by the Nigerian Federal Ministry of Power, Edge, and GIZ, in a research project carried out towards the development of the Nigerian Building Energy Efficiency Code (BEEC). Hence, this was adopted as the base case for this research.

Based on studies on circular economy and passive design strategies, the research optimised the base case by simulating the model on DesignBuilder using various passive design strategies whilst considering the reusability and recyclability of materials in a circular economy.

The research went further to conduct a series of building simulations on the base case with the obtained weather data files and building information data of the study area. This was followed by a series of optimisation simulations to determine the best strategies for the building's energy performance within the Nigerian context. Hence, the research gained several passive design strategies from the many trial simulations which helped to establish specific parameters and design setups for the tropical savannah climate of Nigeria.
The research progressed to evaluate the principles of circular economy using the 7S Model and ReSOLVE framework. The 7S model was used in developing the principles for design for disassembly while the ReSOLVE framework was used in proposing the various principles to design for recycling. These circular economy interventions were incorporated into the optimised case for a resource and energy-efficient residential building. Furthermore, under the circular economy aspect, the study developed a material selection matrix based on this research and literature review to assist in selecting materials for a circular economy in buildings. Using the material selection matrix, reusable and recyclable materials were incorporated into the optimised building, with the various materials incorporated, the building was further optimised using multivariate Pareto simulation. This further improved the energy performance of the building.

The framework is unique to the tropical savannah climate of Nigeria which guides designers and developers towards achieving energy and resource efficiency in Nigerian residential buildings. The guide lays out the various steps to design new residential buildings using passive design strategies. It goes on to include the steps for incorporating circular economy in the design for recycling and design for disassembly as well as the end of life considerations.

The framework is particularly important as it combines major interventions for energy and resource efficiency most especially for a developing country like Nigeria where energy efficiency in building and circular economy are still at their infancy and there is little or no awareness on passive measures towards improving the performance of buildings with regards to energy and resource efficiency.

The various literature and systematic reviews conducted in this research reveal that these principles (circular economy and passive design strategies) have not been combined as guidance for achieving energy and resource efficiency in buildings. The principles of circular economy as seen in this research are still gradually building momentum towards its application in buildings. Hence, this research in its novelty based on research findings, simulations and optimisations has crafted an approach for the application of these principles or strategies in achieving residential buildings that are not only energy efficient but resource-efficient for the tropical savannah climate of Nigeria. It is important to note that these strategies are the building blocks to cutting down emissions and improving energy and resource efficiency in buildings.

In order to reminisce on this research journey, it is imperative to re-state the central aim of the research with the intent to account for how the research objectives were realised towards achieving the overall aim of the research.

The aim of this research is to develop a framework that will serve as a guide for incorporating circular economy in the design of energy-efficient residential buildings in the tropical savannah climate of Nigeria.

The research objectives are as follows.

1. To conduct a review of literature to identify the components for passive design and circular economy in Nigeria.

The study conducted a literature review of the Nigerian tropical climate by gathering relevant information and data on the climate zone and its characteristics, it went further to analyse the Nigerian weather based on previous studies in the study area. The Nigerian residential building stock was also studied to identify major building typologies in the region. This was followed by an overview of energy efficiency interventions on Nigerian residential buildings. This was necessary to understand previous interventions, the status quo, and considerations. This exercise helped in the identification of the major and applicable passive design strategies for the Nigerian tropical savannah climate. Hence, the components of passive design in the region were identified and their various potentials in achieving an energy-efficient building. The components of circular economy in Nigerian buildings were also identified with regard to its applications and benefit in Nigeria.

2. To assess these passive design components (i.e., thermal mass, daylighting, natural ventilation, building orientation, local shading, thermal insulation, WWR, g-value) for achieving optimal energy performance in Nigerian residential buildings.

To be able to assess the components of passive design in the tropical savannah climate of Nigeria, it was necessary to identify the typical base case of Nigerian residential building typology for simulation. The base case building was identified as a representation of the majority of residential buildings in Nigeria, this identification helped in establishing the typical energy consumption of Nigerian residential buildings which formed the basis for comparison with the optimised case. The identified case was further modelled, calibrated and validated with respect to the Nigerian Federal Ministry of Power report and the obtained weather data. This was followed by simulation preparations which involved putting the relevant weather data file, setting model parameters and assigning construction information. The parameters and variables for comparison between the optimised case and base case were set up as this was primarily to establish the total energy consumption of the models. The building simulation to determine the energy consumption of the base case was conducted which was followed by the analysis of simulation results to assess the effectiveness and to identify the relevant passive design strategies for Nigerian residential buildings. This also helped identified what parameters and variables with the highest impact on the energy consumption of the building. The information gained from this operation informed the optimisation simulations which were done one-at-a-time, all-at-a-time and multivariate (Pareto) simulations targeted at reducing the energy consumption of the building.

3. To compare, and select the best passive design case based on simulations.

After the completion of the optimisation process of the building, a comparison of the results between the base case and optimised case was done quantitatively, this is to check the most optimised building case. The best case was selected based on energy performance and the various passive design parameters engaged in achieving energy efficiency in buildings were adopted for the development of the framework.

4. To adopt circular economy interventions.

The research progressed to explore, analyse and develop the approach for the application of circular economy in Nigerian residential buildings. Building on the findings from the literature review, it was important to articulate the principles and process for design for disassembly (DFD) and design for recycling (DFR). This was done using the 7S model for design for disassembly and the ReSOLVE framework for design for recycling. The building components were classified into major building categories (Site, Skin, Structure, Stuff, Space, System, and Services) of the 7S model. The research further identified recommended reusable and recyclable building materials, likewise, the building materials were also categorised into various classes of materials. The next step was to classify building components into the 7S model for ease of assembly and disassembly as well as to identify assembly methods. Also, major building components were ranked with respect to the 7S model based on the quantity of materials. Based on the findings of this research, reusable and recyclable building materials were rated with regard to the ReSOLVE framework. This paved way for the development of the material selection matrix, in order to assist in the sorting and selection of building materials for a circular economy. Aspects of design for disassembly (DFD), reuse and recycling were analysed and discussed. These aspects include, material documentation, component design, assemblage method/connection type, standardisation, component annotation, accessible connectors, program for selective and volumetric deconstruction, program for [re]construction and best practices for productivity. The selected materials based on the matrix were incorporated into the optimised case and a multivariate Pareto simulation was run to evaluate the building energy performance. The process of design for disassembly was established and adopted based on this research findings.

5. To develop an approach for the application of circular economy principles in Nigerian residential buildings.

After obtaining first-hand information and simulation results of the optimised building, the research progressed to develop the approach for the application of circular economy principles in Nigerian residential buildings. It was imperative to consider the reusability and recyclability of building materials for a circular economy whilst designing the buildings using passive design strategies. The findings of this research informed the development of the approach for the application of circular economy principles in the design of residential buildings in Nigeria.

The research adopted the best optimisation strategies for the building based on the optimisation simulations conducted. Hence, it recommended the specific parameter for each design variable. These design variables or passive design strategies include building orientation, window to wall ratio, local shading, g-value, thermal mass, thermal insulation, natural ventilation, daylighting, and roof material. The approach for the application of circular economy in Nigerian residential buildings was established and the process for its application was discussed. The process included how to design for disassembly using the 7S model, how to design for recycling using the ReSOLVE framework in addition to the material selection Matrix. It finally addressed the process of design for end of life.

6. To establish a framework for the incorporation of circular economy in the design of energy and resource-efficient residential buildings in Nigeria.

Finally, from the findings and results gathered from this research, a framework is developed for the incorporation of circular economy in the design of energy and resource-efficient residential buildings in Nigeria. The establishment of the framework is based on the works of this research, which is specific to aid the design of new residential buildings in the tropical savannah climate of Nigeria. The framework presents a holistic approach to energy and resource efficiency as it combines both principles in its intervention. This is done through a step by step guidance, coupled with the specifications of the design variables and parameters for the region. The framework recommends a range of passive design strategies and specifies the requirement of the relevant design parameters within the Nigerian context as well as circular economy principles.

9.3. Research contributions to the body of knowledge

Firstly, this research combined two sustainability design interventions (passive design strategies and circular economy) to achieve energy and resource efficiency in Nigerian residential buildings. As seen during the systematic literature review, these two principles have not been combined in the building sector before which is one of the novelties of this research. Secondly, this research provides a holistic approach to attaining energy and resource efficiency in buildings for the Nigerian tropical savannah climate which is also the first of its kind. It is important to note that the research is rooted in the Nigerian context and it provides a framework for the incorporation of circular economy in the design of energy-efficient residential buildings in Nigeria. It describes the challenges of the Nigerian building industry with regard to energy and resource efficiency. The research assessed and identified the circumstances of the country, and explored and developed possible interventions through research on how to attain energy and resource efficient residential buildings in Nigeria.

Although the study area of this research is in the tropical savannah climate of Nigeria, there are aspects that may be appropriated within the global context. The contributions of this research to the body of knowledge are categorised under the following subheadings below.

9.3.1. Theoretical Contributions

The theoretical contributions of this research and the systematic literature review go beyond the Nigerian context as it presents an understanding of the nature of work done in this field of research globally through the exploration of design variables and interventions on passive design and circular economy. These contributions include:

1. Articulation of proposed interventions for the application of circular economy and passive design in buildings – This research provides an understanding of the existing interventions for circular economy and passive design in buildings as recommended interventions have been reviewed and analysed in relation to similar prepositions by other researchers. Therefore, researchers can easily explore the identified studies and build upon the existing knowledge.
2. Identification of research gaps in this field of research – The research reveals areas that have not been researched since this research conducted a systematic literature review on a wide range of works of literature in this field and has identified research gaps or aspects not yet dealt with. This exposed areas for further research.
3. Recognition of recent advancements in the application of circular economy in buildings – The research presents the trend of circular economy interventions and recent strategies that could be applied in buildings for resource efficiency and waste reduction. It is important to note that the interventions explored and analysed in the systematic

review are found to be global and applicable in the Nigerian context as they are strategic in repurposing building waste and improving the availability of building materials which is a much-needed intervention in Nigeria. Hence, researchers can easily acknowledge the recent advancements in circular economy with regards to buildings for further advancements.

4. Awareness and benefits of circular economy and passive design strategies in buildings – The research was able to establish the number of literature in the subject area which is also a reflection of the awareness level among scholars and interest groups in places of publication globally. It also discussed the benefits of circular economy and passive design mostly for energy and resource efficiency as well as environmental protection. Therefore researchers can have an understanding of the awareness level of the topic and the corresponding places of publications. The research also helps researchers to acknowledge and appreciate the benefits and amount of the work done in the fields of interest.
5. The data gathered and documented in this research provides relevant information and data on the Nigerian building sector, climate, materials, etc. These data and analysis as seen in this research are very limited and this research provides data that can be utilised by researchers, practitioners, policy-makers, institutions in the design, construction and formulation and execution of implemented policies on energy and resource efficiency in the Nigerian built environment.
6. The distinction of relevant studies and interventions - Through the literature extraction and analysis of strategies, this research have been able to identify and distinguish research of great interest based on their various aspects of intervention in this subject. This will help scholars to easily find and consult relevant works of literature and existing proposition.
7. The research is based within the Nigerian tropical climate as the research describes the Nigerian energy and resource situation, including the climatic and weather conditions. It also provides information about previous energy and resource interventions and the state of building sustainability in the nation. It talks about the situation and challenges in the Nigerian building industry and provides solutions based on the Nigerian climatic configuring. This information becomes very handy for researchers to conduct studies in Nigeria.
8. This research presents various research approaches and methods that can be integrated into distinctive fields. The methods and approaches demonstrated in this research as it relates to passive design and circular economy can be adopted by various experts to assess, evaluate and optimise buildings within the Nigerian savannah climate. Fields of research interests such as Architects, Builders, Engineers, Environmentalist,

Policies makers and Developers can adapt or build upon these methods of research for other future works. The research explains the step by step process in which different design variables and parameters were simulated and analysed towards achieving an optimal design. These research approaches and methods provide insights on how similar operations can be done in this field of study.

9. Combination of both circular economy and passive design strategies - Most studies as seen in this research have not combined both circular economy and passive design strategies in their approach or in the preposition of design solutions for achieving energy and resource efficient buildings. This holistic approach is absent not only in the Nigerian context but also globally. Hence, this research developed a framework that forms a basis to understand the practicality of this unique intervention. Therefore other researchers can easily identify the components for the application of both principles in buildings based on the outcomes of this research.

These contributions will assist other researchers to conduct further studies and building upon existing knowledge as well as bridging research gaps. It has been well demonstrated in the literature that the non-application of circular economy principles would lead to scarcity of resources in the future and the possible barrier to this is the unawareness of developers of circularity principles. Although, as observed from findings that there is a growing awareness amongst researchers which is expected to increase in the coming years from results indications and projections (Number of publications on circular economy per year: 4 publications in 2017, 18 publications in 2018, 25 publications in 2019, 23 publications in 2020, 26 publications in 2021). Therefore, it is imperative to sustain this positive progression from a linear economy into a circular economy by raising its awareness, intensifying more focused research on obscured areas as identified in this research and preposition of more solutions for energy and resource efficiency in buildings.

9.3.2. Practical Contributions

In the field of practice most especially in design and construction, as it relates to the state of the Nigerian residential building infrastructure, this research provides a framework for attaining energy and resource efficiency in Nigerian residential buildings. Hence, developers can follow this framework or guide by adopting the recommendations in Nigeria. This is a new development in a country where the awareness of passive design strategies are still in infancy or not known and circular economy principles are still very alien. This framework developed based on this research, results and analysis of multiple simulations in the Nigerian context, therefore, acts as a template for the design of residential buildings in the region. It is important to recall that there is an inadequate power supply in the country, therefore, buildings can easily get overheated which would prompt the use of alternative sources of power, consequently, increasing operational CO_2 emissions, building energy consumption due to irresponsive design. Hence, this research has crafted a design guide as a working document based on the experimentation of the Nigerian climate and associated weather conditions. Therefore, the research presents a holistic solution in terms of energy and resource in which developers can apply the design variables and parameters recommended in this research to achieve energy and resource efficient building in Nigeria. The identification of building materials and principles compatible with circular economy, specific design variables and parameters for the Nigerian climate will provide professionals information and knowledge for the execution of energy and resource efficient residential buildings in Nigeria. The knowledge gained from this research will also promote the practice of passive design and circular economy principles in Nigeria. Thus, contributing to the development of energy and resource efficient buildings in the Nation. In addition, this research is expected to have substantial impacts in various sectors such as Education, Economy, Society, especially in this research context.

9.3.2.1. Educational impacts

In the Nigerian built environment, energy efficiency and circular economy in buildings are still new concepts, the developed framework will improve knowledge in teaching and learning energy and resource efficiency in Nigerian residential buildings. The methodology employed in this research will be useful in carrying out similar studies in different regions. Hence, this will improve the knowledge in this field and contribute to the research development in this area.

9.3.2.2. Economic impacts

The use of this framework will ensure that energy bills are all-time low and building materials are more accessible, reusable and recyclable. This will improve energy savings in Nigerian residential buildings and make resources more available.

9.3.2.3. Societal impacts

The use of this framework will improve the quality of life of occupants generally since occupants are able to save in energy and have little or no need for alternative power supply (which also means less noise and other pollution from generators) thus, improving living conditions of occupants. The buildings would have less need for electricity and become more habitable due to improved building physics thereby improving the well-being of residents.

9.3.3. Material selection matrix – Contributions

Based on the findings of this research, a material selection matrix was developed as a tool to help determine the ideal building materials and design variable potentialities that can be employed to achieve energy and resource efficiency in Nigerian residential buildings. This implies that both researchers and developers can use this tool to pre-determine the viability of building materials. It also identified strategies that can be adopted by developers in the building sector towards achieving energy and resource efficient buildings in the Nigerian climate. Therefore, it helps the user to consider the materiality of the building, evaluate the potentialities and decide on the materials to be used. The material selection matrix also assists in material documentation, therefore building materials are considered and selected for use, as well as documented for reference purposes, analysis, general records, etc. The matrix can also be used to calculate and keep records of the material properties of the building. These properties may include the specific heat capacity, density, thermal conductivity, volumetric heat capacity, u-value, material thickness, etc.

9.3.4. The application of circular economy in buildings - Contributions

The application of circular economy in buildings is a rather new development in circular economy most especially within the Nigerian built environment. As seen in this research, reduction of building waste is least considered in Nigeria and building materials are either scarce or expensive or both. This research explored and developed possible ways of applying circular economy in the design of residential buildings in Nigeria of which the concepts may be extended to other similar regions. The research recommends a holistic approach for the application of circular economy in buildings, right from the design stage to the end of life of the building, thereby extending circular economy intervention into the building sector which is a new development in Nigeria. Thus, researchers, practitioners, policymakers, and environmentalists can use the developed concepts in this research in their various fields of endeavours with regard to energy and resource efficiency in buildings.

9.3.5. Environmental protection – Contributions

The optimisation of the building based on this research has a significant reduction of the energy consumption of the building thereby potentially reducing the operational CO_2 emissions of the building and subsequent buildings designed based on the developed framework. Thus, the adoption of the recommended passive design strategies will cut down CO_2 emissions within the Nigerian residential building stock which is expected to increase in the coming years. It is important to note that Nigeria is a population hot spot and the country is in a deficit of buildings, the design and construction of business as usual buildings would increase the energy demand of buildings as well as CO_2 concentration and embodied energy. Therefore, this research provides a framework for buildings to be designed in an energy and resource efficient manner thereby safeguarding the environment. The comparison of the optimised building energy performance using passive design strategies against global building energy benchmarks revealed that the total energy consumption of the optimised case was below the United Kingdom's nearly Zero Energy Buildings (nZEB) and the Passivhaus benchmarks. Also, the design for disassembly principles as recommended in the developed framework will reduce the embodied energy in buildings. Assembled buildings as seen in this research have less embodied energy and are easier to construct and assemble. Therefore, the development of the framework based on the research will reduce the building energy consumption, operational CO_2 emissions and embodied energy.

9.4. Research limitations

The research is unique and has used many resources to accomplish its aim. However, the research is not without a few limitations. The limitations are outlined below.

1. There is very little research on energy efficiency with regard to Nigerian tropical buildings. Therefore, it was difficult to find existing studies in the area.
2. Circular economy is a new concept in Nigeria and globally. Consequently, there are only very few publications to provide insight within the Nigerian context and the interventions/discussions in buildings are absent.
3. The Nigerian building industry falls short of prioritising energy efficiency in buildings and the awareness level is low. Thus, making it difficult to find buildings that have adopted the principles of energy and resource sustainability.
4. There are no functional or existing schemes and programmes for the reuse and recycling of building materials in Nigeria which makes it difficult to appraise the efforts and impacts of circular economy within the Nigerian building industry.
5. Participation levels of government and professionals for sustainable buildings in Nigeria are extremely low and there is little or no information regarding current and future plans for energy and resource efficiency in Nigerian buildings.

9.4.1. Methodological limitations

The research methodology adopted in this research was carefully considered as it relates to the Nigerian context. However, the following methodological limitations have been identified.

1. Although the use of literature review helped to gain an understanding of the research context and gaps. However, pieces of literature on the research topic were limited in the Nigerian context which limited the review of previous works of research in the study area.
2. It was difficult to conduct a review of previous methodologies adopted within this research topic based in Nigeria due to the lack of previous studies on the topic in the Nigerian context.

9.5. Conclusion and closing remarks

The research comes very useful at a time when the Nigerian building sector needs major interventions as it relates to energy and resource efficiency in buildings. Building occupants in Nigeria are experiencing significant distress from inadequate power supply, poor residential building infrastructure, and scarcity of building materials, just to say the least. With the growing population, there is a need for more sustainable housing infrastructure. This research has accomplished its aim by developing a framework that will serve as a guide for incorporating circular economy in the design of energy-efficient residential buildings in Nigeria. The current research work will potentially serve as a guideline to resolve the crisis of energy-inefficient buildings, non-reusable, and non-recyclable building materials that are causing environmental pollution (including carbon emissions, building waste, etc.) and recession of building materials in Nigeria. If implemented, the developed framework based on this research will reduce energy consumption in residential buildings and ameliorate the availability of building materials in the Nigerian building sector. Although, the implementation of the proposed measures in this framework may potentially increase the build cost.

While the framework is specifically developed for the tropical savannah climate of Nigeria, it may also be applicable to regions of similar climatic and geographic conditions. It is recommended that the developed framework and the knowledge gained from this research be utilised by the relevant authorities and stakeholders as a guide for the design of residential buildings in the tropical savannah climate of Nigeria. The framework will assist professionals, government authorities, policy-makers, regulatory bodies, trainers, trainees and the general public in the delivery of energy and resource efficient residential buildings in Nigeria.

9.6. Suggested areas for future research

Although the research has crafted solutions and established a strong base of knowledge, it has also opened up other areas for future research in this field. The following areas have been suggested for future research.

1. Assessing the thermal properties and performance of recycled local building materials in the Nigeria context. It will be useful to know the thermal performance and properties of recycled local building materials in Nigeria and evaluate how they compare with original building material properties and performance.
2. Evaluating the impact and strain of solar radiation on Nigerian building materials. It is important that building materials remain viable in order to be reusable and recyclable in the Nigerian context. Therefore, further research should be done to evaluate the impact of solar radiation on Nigerian building materials.
3. Exploring strategies towards the standardisation of building components in Nigerian buildings. The use of similar building components would improve the reusability of components in buildings. Therefore, further research is needed to develop strategies towards the standardisation of building materials in the Nigerian context.
4. Improving the energy efficiency and circular economy potentials of existing buildings in Nigeria. Many existing buildings in Nigeria are neither energy nor resource-efficient. Therefore, further research is needed to identify ways of improving the energy efficiency performance and circular economy potentials of existing Nigerian buildings.
5. Exploring the possibilities of establishing a programme or scheme for the reuse and recycling of building materials in the Nigerian building sector. In Nigeria, there are no government programmes or schemes in charge of building waste management. Hence, it is important to explore the possibilities of developing programmes or schemes for the reuse and recycling of building materials in Nigeria.

Publications from this Research

2022

- Akhimien, N., Tawheed A., Latif, E. and Hou, S. 2022. Circular Economy in Buildings', in A. P. T. Zhang (ed.), *The Circular Economy - Recent Advances in Sustainable Waste Management*, IntechOpen, London. 10.5772/intechopen.107098.

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