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RESEARCH ARTICLE OPEN ACCESS

Effect of Roof Configurations on Temperature and Thermal Comforton Residential Homes in Hot Dry Climate of Bauchi, Nigeria

Usman, Abdullahi Muhammad
Department of Architecture; Ahmadu Bello University, Zaria

ABTSRACT
Thermal comfort is one of the major problems of residential homes in Nigeria. This is why architects and engineers should find a sustainable approach to the design of comfortable buildings. The study aimed at evaluating the effect of roof configurations strategies for indoor thermal comfort in the hot-dry climate of Bauchi. A baseline model was designed and variables which are roofs and roof colours were varied with various material configuration in order to have material that will have best thermal performance for thermal comfort. In the course of the research, the baseline model was designed to maximize the use of energy efficient strategies such as daylight, air flow and evaporative cooling. The study follows a methodology of using simulation to optimise the design of passive energy efficiency strategies in buildings through adaptive thermal comfort approach using Autodesk Ecotect Analysis and EnergyPlussoftware. Findings from this study indicate that applying insulation and ventilation for roofs and use of brightest roof colour for all four orientations can improve comfort percentage of the proposed building by up to 45%. Building energy calculation is especially beneficial at the early stage of design to enable architects to make informed decisions on energy during the operational stage of the buildings. This will prevent poor building performance due to electricity failure in Nigeria.

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I. BACKGROUND OF STUDY

One of the main objectives of designing a building is to provide a comfortable condition for the building's occupants, while at the same time minimizing the building's energy consumption. Wong and Li, (2007) states that, with the global emergence of energy shortages, climatic changes and sick building syndromes associated with the common usage of air-conditioning, authorities worldwide have recognized the necessity in finding strategies that can cultivate a more sustainable design with satisfactory indoor thermal comfort. This has led to the growing interest in low energy cooling strategies that take advantage of natural ventilation which has the potential to reduce first costs and operating costs for commercial buildings while maintaining ventilation rates consistent with acceptable indoor air quality.

Globally agreed, Fanger (1970) defines thermal comfort as the condition of the mindwhich expresses satisfaction with the thermal environment. Thermal comfort is said to beachieved in a building when the highest possible percentage of all occupants are thermally comfortable.

Building form, materials, orientation and urban patterns are the most important design parameters affecting indoor thermal comfort and energy conservation in building scale (Leylian, Amirkhani, Bemanian, & Abedi, 2010). Intelligent configuration and moulding of the built form and its surroundings can considerably minimize the level of discomfort inside a building, and reduce the consumption of energy required to maintain comfortable conditions (Nayak & Prajapati, 2006).

The increased demand for buildings has to match the goal of energy efficient buildings with productive, healthy indoor environments as occupant productivity is significantly improved when thermal comfort and indoor air quality are optimized. The occupants comfort and productivity is very essential especially in learning environment and thus the need for re-strategizing the design processes for educational buildings.

In Nigeria, most buildings rarely take passive architecture and energy efficiency into consideration due to ignorance, poverty, lack of awareness and/or improper policy on building regulations by Government. Use of mechanical devices to achieve thermal comfort in buildings is not only capital intensive but also generate greenhouse gases, air and noise pollution amongst others (Nwofe, 2014). Building design in the Nigeria doesn't take sufficient account of the pre-design stage strategies that would increase the rates of thermal comfort in buildings and reduce the heating and cooling loads as a consequence.

Hence, the climate responsive sustainable building design appears as an essential factor in the first stage of the design process in order to achieve more comfortable indoor environment. It will be a logical approach for architects to pay attention to local climatic conditions during the design process (Çakir, 2006).

Problem Statement

Buildings in Nigeria are designed such that thermal cooling is provided through active means using air conditioners. This technique has left many buildings to be very hot because of the poor power supply in Nigeria. Architects have failed to explore alternative strategies that can help minimise this problem in many residential home designs and this has made most of the users to be so uncomfortable.This research therefore seeks to study how different roof configurations on some building components can improve thermal comfort in a residential homes located in a hot dry climate of Bauchi.

II. AIM AND OBJECTIVES

The aim of the research is to evaluate the effect of roof configuration for the improvement of indoor thermal comfort in the hot-dry climate of Bauchi.

The aim of this work would be achieved through the following objectives:

I. To investigate the effect of thermal performance of various building materials on different building components.
II. To investigate the effect of roof colour on thermal comfort and temperature.
III. To find out the percentage improvement of interior temperature and thermal comfort.

III. INDOOR THERMAL COMFORT

To have "thermal comfort" means that a person wearing a normal amount of clothing feels neither too cold nor too warm. Thermal comfort is important both for one's well-being and for productivity. It can be achieved only when the air temperature, humidity and air movement are within the specified range often referred to as the "comfort zone". Where air movement is virtually absent and when relative humidity can be kept at about 50%, the ambient temperature becomes the most critical factor for maintaining thermal comfort indoors. However, temperature preferences vary greatly among individuals and there is no one temperature that can satisfy everyone. Nevertheless, a zone which is too warm makes its occupants feel tired; on the other hand, one that is too cold causes the occupants' attention to drift, making them restless and easily distracted.

Thermal comfort is also considered as an important feature in the evaluation of the building performance and energy savings. Therefore, exploring buildings' thermal behaviour is necessary; to predict occupants' comfort, to identify energy consumption, and to examine alternate enhancements for achieving better indoor thermal environments and energy efficient buildings. Parameters that could affect thermal comfort are explicated in this paper to help identifying the methods of prediction of thermal comfort.

3.1 Simulation of indoor thermal comfort

Since the old age, builders used many strategies in order to achieve the desirable level of indoor thermal comfort whether they are private houses or public places. Çakir (2006) described the assessment of thermal environment as one of the oldest judgements made by man commenting on the prevailing weather by comparatively evaluating in everyday conversation. By the end of the nineteenth century, scientists become more interested in comfort studies, and all four environmental parameters (temperature, humidity, air movement and solar radiation) were able to be measured and controlled in a quantitative way. Other factors like the rate of working and clothing worn orindividual parameters have been recognised to be part of the assessment recently (Çakir, 2006). The knowledge of both environmental and individual parameters has made it possible to establish the standard of thermal comfort by many researchers such as Fanger (1970)and ASHRAE (2004). There are five advantages of knowledge of thermal comfort research which are;

i. Guiding the design of buildings and enclosed environments,
ii. Controlling over environments which are too extreme for people,
iii. Improving internal air quality, reducing the risk of sick building syndrome and promoting good health,
iv. Reducing the production of CO^2,
v. Effect of the work efficiency of the building occupants.

Considering the five advantages that mentioned above, indoor environment should be designed and controlled so that occupants' comfort and health are assured. Recently, maintaining thermal comfort for occupants of buildings or other enclosures becomes one of the important goals of HVAC (Heating Ventilation and Air Conditioning) design engineers, that is because many studies and researches showed that people work better in a comfortable environmental than other states. Some of these researches which aimed to establish the right comfort zone for human beings are discussed in this paper with their effects.

3.2 Thermal comfort requirements

The human body is influenced by the surrounding surfaces through radiation in addition to absorb and emits heat through the air by convection. Therefore heat transfer by both convection and radiation needs to be considered when trying to achieve thermal comfort. The body heat transfer mechanisms cause the temperature to be specified as "felt temperature" or "operational temperature" and its measurement known as room temperature corresponds approximately with the mean value of the air temperature in the room and the mean radiation temperature from the enclosing surface areas of the room(Elaiab, 2014). The specifications of mandatory temperatures or temperature ranges for rooms and buildings are regulated by many legislative directives of the individual countries. Generally, temperatures should always be evaluated in relation to the outside temperature. A difference of 5-6 K (temperature differences are specified in Kelvin, with 1K equalling 1°C) compared to the outside temperature has proven to be a viable definition whereby room temperatures of more than 26 °C should be avoided. Research has shown that users show higher acceptance of the room temperature if the temperature can be regulated by operable windows. Users are typically less satisfied if the temperature is controlled by a central air conditioning unit that they cannot regulate individually. Figure 1shows how much impact the surface areas of a space can have on thermal comfort.

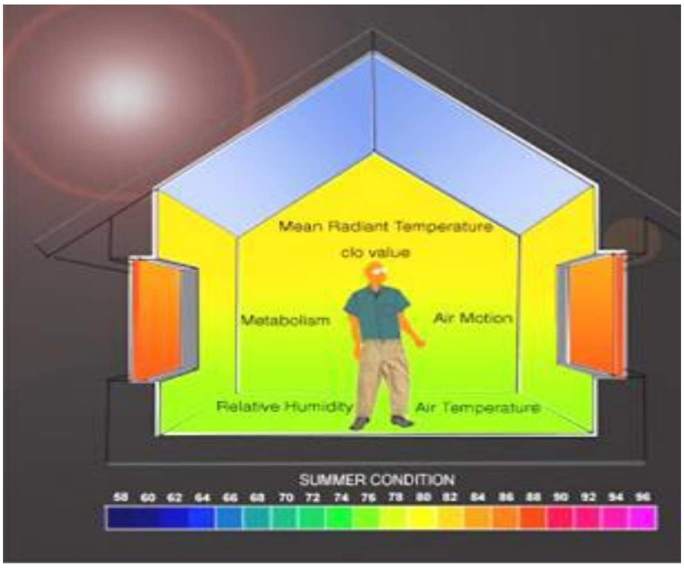


Figure 1;Parameters influencing thermal comfort. Many factors are responsible for the thermal comfort level. The human body emits heat through radiation and convection, but also perceives the heat/cold from the surrounding walls and the airflow in the room(Ulrich Knaack, 2007).

3.3 Thermal comfort principles

Fanger (1970) assured that the most important variables which influence the condition of thermal comfort are these six factors:

I. Activity level (heat production in the body),
II. Thermal resistance of clothing (Clo value),
III. Air temperature,
IV. Mean radiant temperature,
V. Relative air velocity,
VI. Water vapour pressure in ambient air.

Other researchers such as Evans (1988), ASHRAE (2004)and Szokolay (2008)have grouped these variables that influence thermal comfort into three sets as presented in Table 1; An agreement has been established about these variables in the above researches and the overall conclusion was that "these factors must be considered at an early design stage in the context of the local external climate, the function of the space and its location within the building that is because each building demands its own degree of comfort"(ASHRAE, 2004).

Table 1; Categories and factors of thermal comfort Szokolay, 2008 and **(ASHRAE, 2009)**

Environmental	Personal	Contributing factors
Air temperature	Metabolic rate (activity)	Food and drink
Air movement	Clothing	Body shape
Humidity	**State of health**	**Subcutaneous fat**
Radiation	Acclimatization	Age and gender

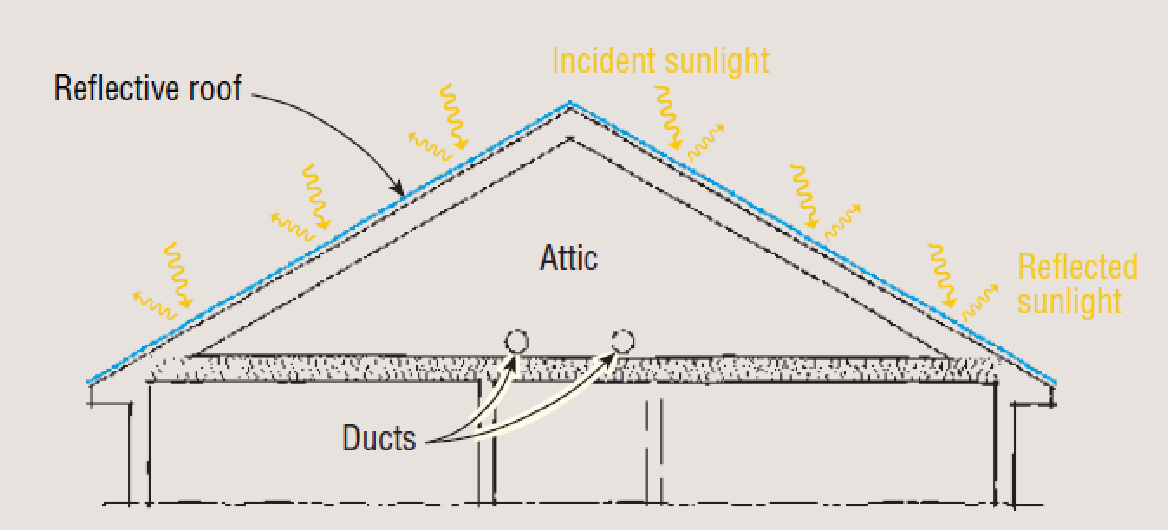
Fanger (1970) in his work has come out with a comfort equation conditional on an idea which is that "it is impossible to consider the effect of any of the physical factors influencing thermal comfort independently, as the effect of each of them and necessary requirements depend on the level and conditions of the other factors". This idea supports the "hierarchy of human needs" which was proposed by Markus, (1994)when he suggested that starting with the dominant item 1, any further needs can (and will) only be satisfied if all lower levels had been satisfied:

i. Physical/biological
ii. Safety/survival
iii. Affection/belonging
iv. Esteem (self-and by others)
v. Self-actualization

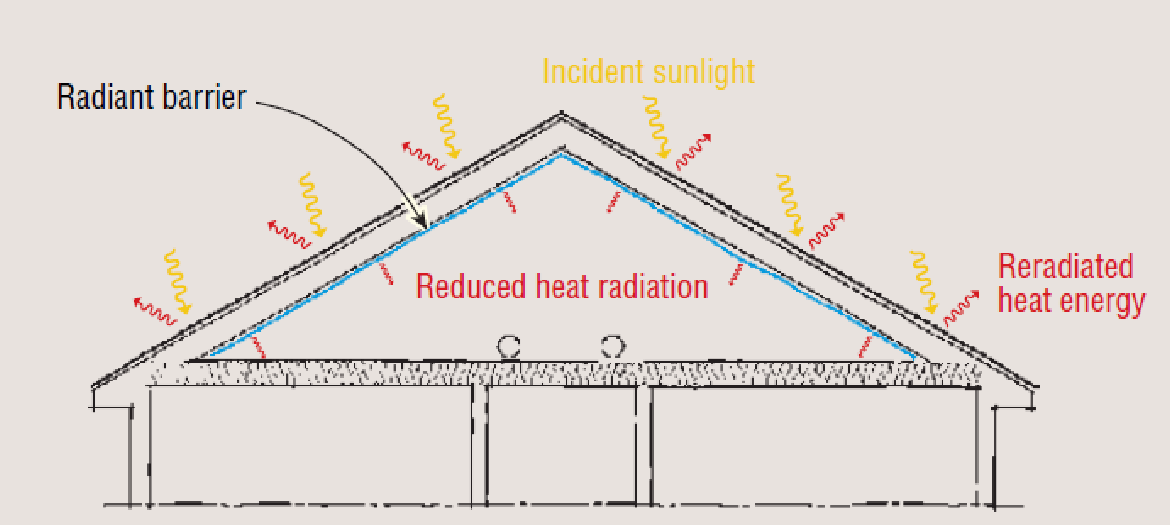
Thermal comfort is one of the basic physical/biological needs. For survival our deep-body temperature must stay around 37°C. It is therefore imperative to keep thermal conditions in buildings within acceptable limits, before any of the higher level needs could even be considered. And since it has been already looked at the environmental factors in the previous section, the other factors will be considered in this paper aiming to cover all the factors that are influencing the thermal comfort.

IV. REDUCING HEAT INGRESS THROUGH ROOF

Field research at the Florida SolarEnergy Centre (FSEC) has foundseveral effective ways to limitrooftop heat gain in sunny conditions.Using a highly reflective roofingmaterial (top) is the simplestand most effective: It stops the sun'senergy before any heat is absorbed,so that even the roof sheathing andframing stay cool. If the existingroof is dark colour or the customerprefers a darker roof, heat can stillbe blocked by adding a radiant barrierfoil just below the roof deck(middle). Savings from this methodare roughly comparable to the savingachieved with reflective roofing;however, some conductive heatingof the attic space will still takeplace, and the roof deck and shingleswill experience some increasedheat stress. A third option is toincrease the insulation between theattic and the living space below, andto run the hvac ductwork withinthe conditioned space rather thanin the unconditioned attic. Thismethod has a smaller effect oncooling loads than the reflective orradiant barrier roof systems but iseffective at reducing heating loadsas well as cooling loads, making itthe most cost-effective option inmixed heating and cooling climates.



Reflective Roof



Radiant Barrier

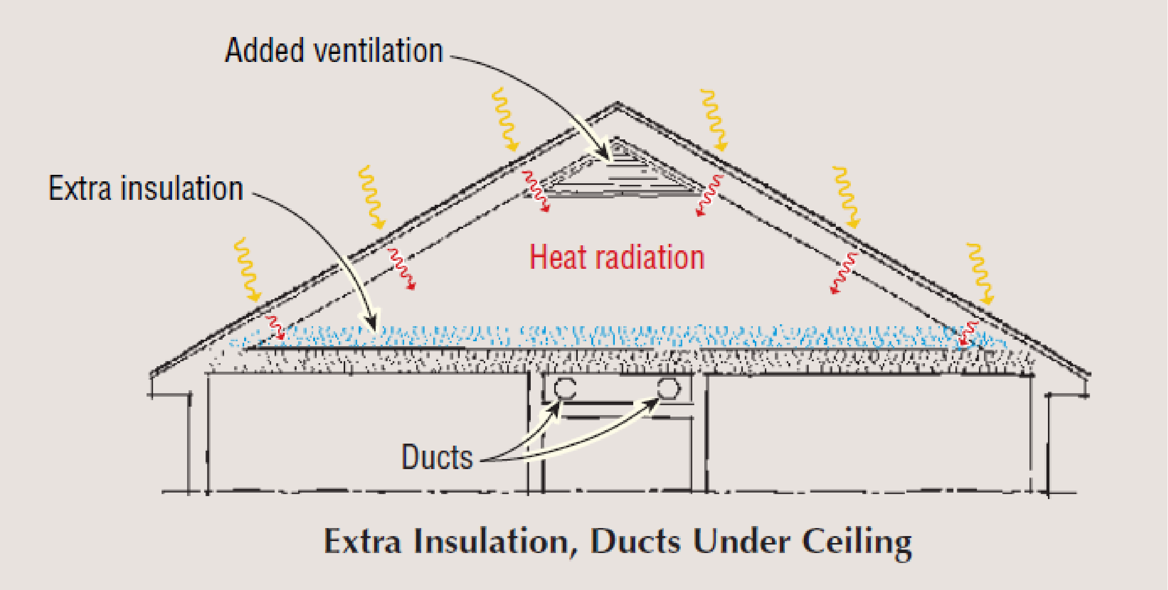


Figure 2; Different types roof configurations.

V. METHODOLOGY

The methodology implemented in this paper is based on an analytical literature study and comparative simulation work for research variables. The literature study was carried out to investigate and analyse the two walls configuration. There follows an experimental simulation study for a typical residential 4 bedroom duplex chosen to represent the common type of housing in bauchi. The 3D view is shown in the following figures

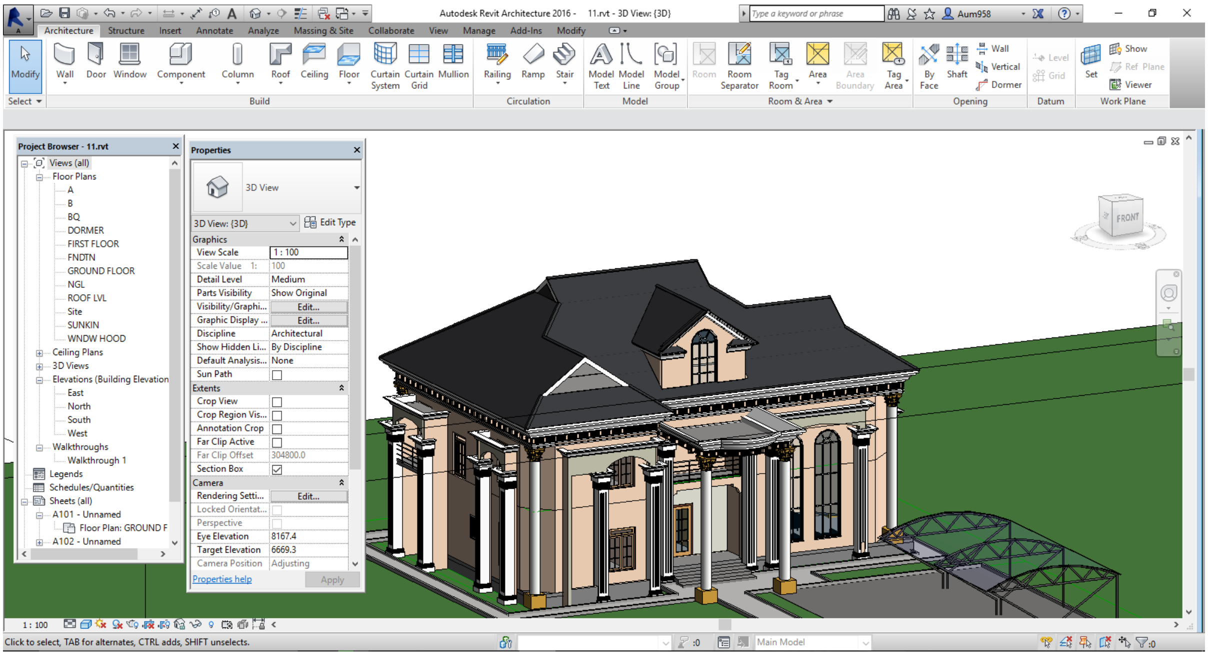


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Figure 3; 3D view of a typical residential building in Bauchi

5.1 Building energy simulation software

The main goal of this project was to determine the thermal performance of the roof configurations in building. The most popular and advanced simulation software that can be used for this type ofanalysis for office buildings are the following: BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r,IDA ICE, IES/VES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS.

5.2 Choosing an analysis method

The most important step in selecting an energy analysis methodis matching method capabilities with project requirements. Themethod must be capable of evaluating all design options with sufficientaccuracy to make correct choices. (Sonderegger, 1985).

5.3 Dependent and Independent Variables

The dependent variables predicted are interior temperature and thermal comfort. Thermal comfort is measured in terms of indoor dry bulb air temperature and operative temperature, both measured in degree Celsius. As discussed, dry bulb temperature is the most common index for the specification of comfort (Nicol, Hunphreys, & Roaf, 2012). However operative indoor air temperature combines the effect of surface temperature of the wall surface as well as air temperature and is considered more accurate.

The independent variables examined are classified into two groups. However each of these variables are categorised based on Material component and Insulation.These variables are examined as part of the process of creating a suitable base-case on which to test the performance of Dependent variables.

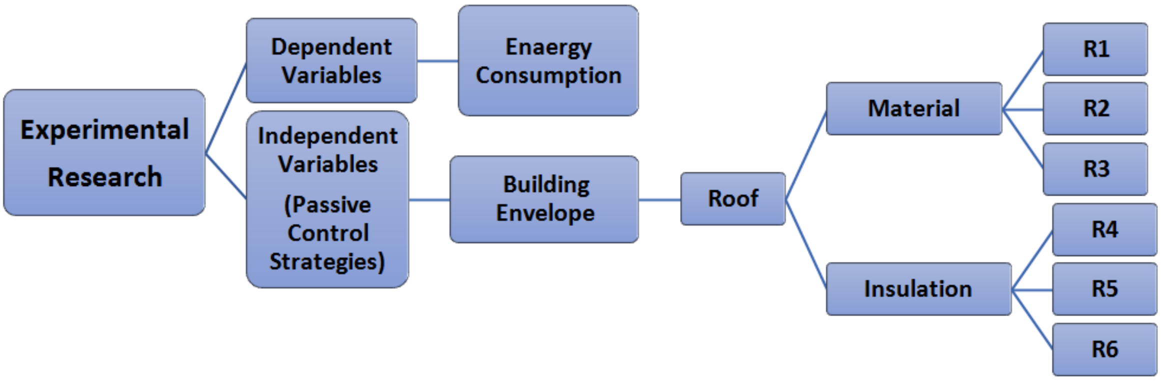
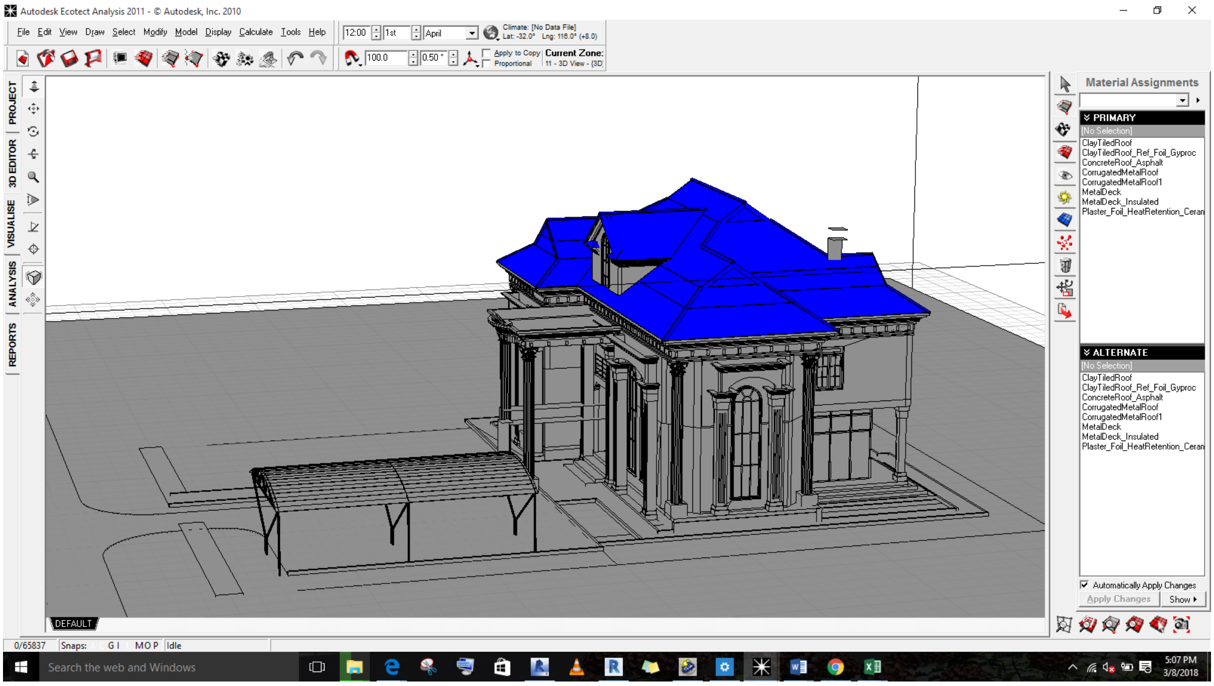


Figure 4; Dependent and Independent Variables

In roof simulation different types of insulations were inserted than simulation runs many times to calculate the possibility reduction that can be achieved by adding these materials, example of these materials are polystyrene, bitumen, asphalt and air gap in different thickness. Table 2 provides the proposed roofs explaining their layers, thicknesses, and thermal conductance.

Table 2; Composition of simulated roof types; (CIBSE, 2007).

Roof code	Description	Thickness (mm)	U-Value W/m² °C	Time Lag (Hours)
R1	Outside: cement rendering Concrete reinforced Inside: sand cement plaster	150	0.89	7
R2 (business as usual)	Corrugated roofing sheet No Roof Ventilation	0.75	7.14	-
R3	Corrugated roofing sheet Polystyrene No Roof Ventilation	50	0.55	4.5
R4	Corrugated roofing sheet Roof Ventilation	0.75	7.14	-
R5 (most preferred)	Corrugated roofing sheet Polystyrene Roof Ventilation	50	0.55	4.5
R6	5 colours of roofing sheet	-	-	-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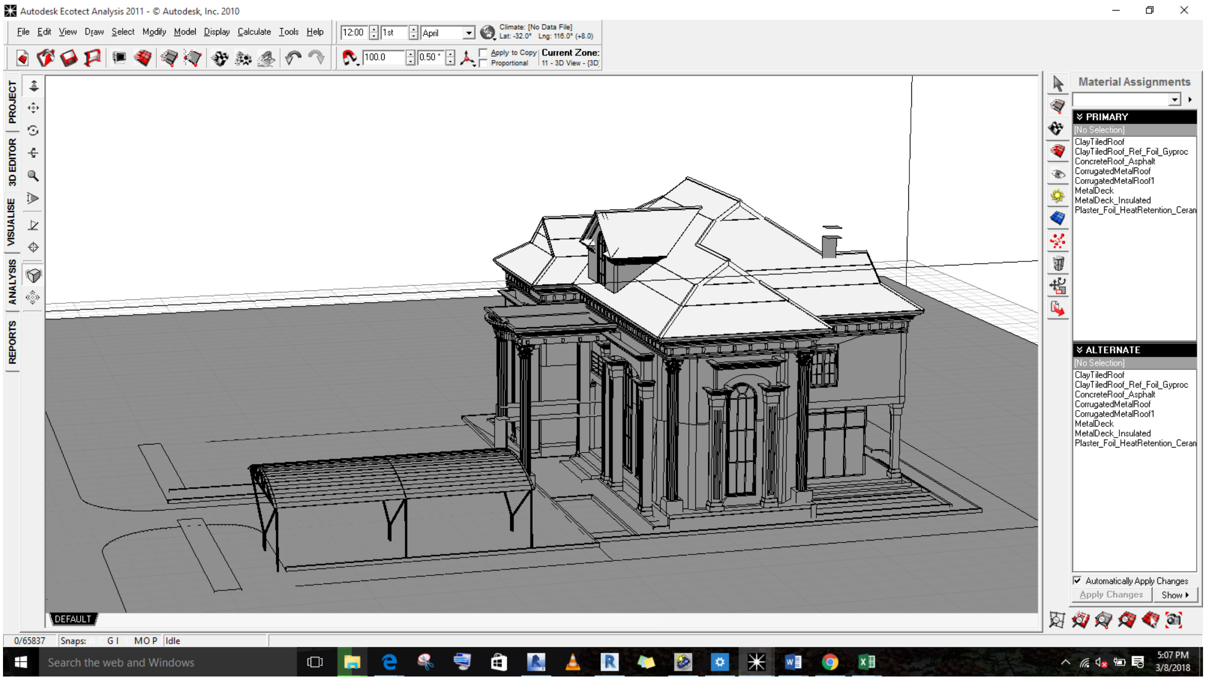
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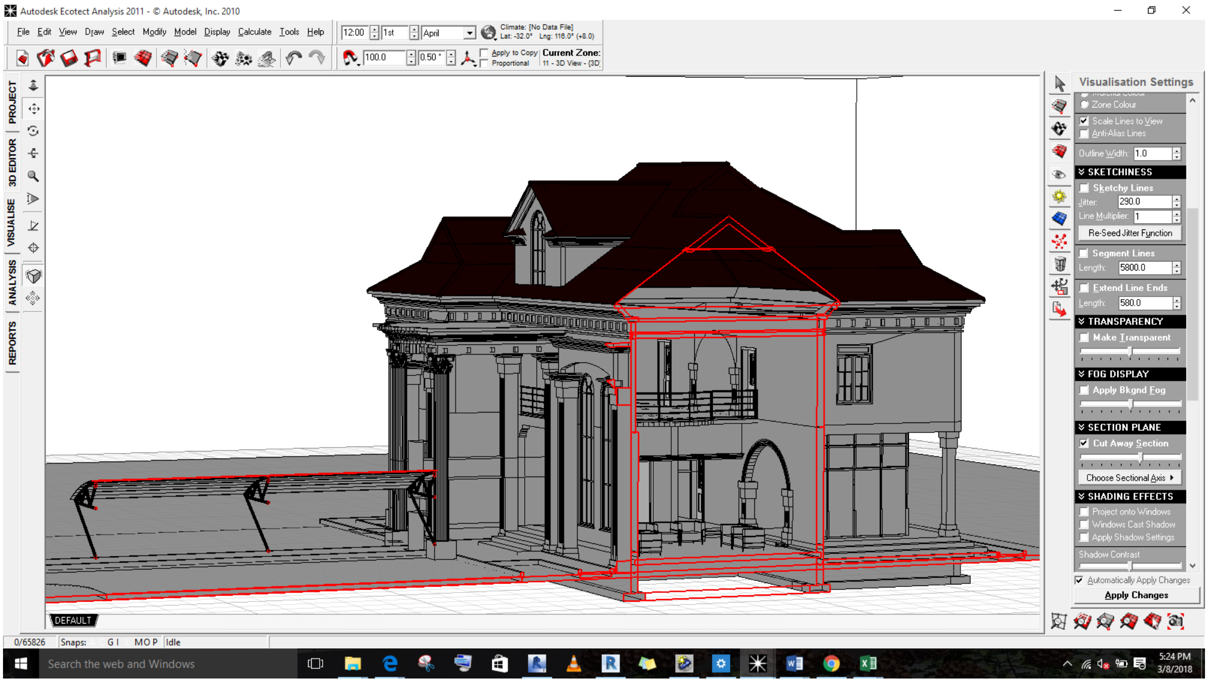

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Figure 5; Various colour simulated roof types

Figures 5 showed the details of roof configuration that were simulated. The roof simulation was carried out in two stages; the first simulation was for material configuration after that material with the best result was simulated with various colours available in the market. This will give out a roof type that has the best thermal performance in material and in colour.

Parametric analysis with computer simulations

The aim of the parametric analysis is to observe the response following a modification in a variable. Parametric analyses are conducted for reasons including the need to determine(Hamby, 1994);

I. Which parameters require additional research for strengthening the knowledge base, thereby reducing output uncertainty?

II. Which parameters are insignificant and can be eliminated from the final model

III. Which inputs contribute most to output variability?

IV. Which parameters are most highly correlated with the output?

V. The consequence of changing a given input parameter

The parametric analysis is used to examine the consequence of changing a given independent variable on electricity consumption and thermal comfort using computer simulations. Figure 6 describes the process of parametric analysis conducted. The steps are:

I. Define the model, its independent and dependent variables. This includes defining the climatic profile as discussed in Section.

II. Vary the values of each independent variable one at a time, in a rational and incremental manner using the whole building energy calculation software EnergyPlus

III. Record the corresponding value of the dependent variable

IV. Assess and compare the influences of each input/output relationship through statistical methods

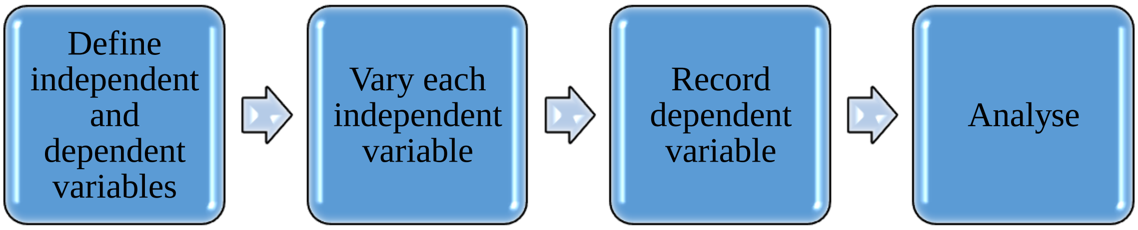

Figure 6;Parametric Analysis Procedure

VI. RESULTS AND DATA PRESENTATION

This sections presents in detail how the collected data were analysed. The analysis was done in line with the research questions and it was conducted in a three-stage process. First a baseline model was designed with common construction materials in Nigeria (business as usual). The second stage involve applying different independent variables and the results were observed and recorded. The third stage involves interpretation and presentation of results in various tables and charts.

The results of energy consumption presented here are with the mechanical cooling set to adequate. The indoor temperature is therefore maintained about an average of 25˚C. The dependent variable used to examine the thermal performance of the variables is annual andmonthly energy consumption.

6.1 Environment for the Experiment

Autodesk's ECOTECT is building analysis software that allows user to easily design andwork in 3D. ECOTECT offers a wide range of analysis options from acoustics to energyefficiency tools. ECOTECT's tool related to energy efficiency can be found under thermalanalysis in interface of the ECOTECT as shown in Figure 6.For this tool to be used properly it requires the adherence to some specific principleswhen constructing the model that will be analysed. Since this research deals with ways to improve thermal comfort and passive control strategies in buildings, results from this tool will be described in this section.

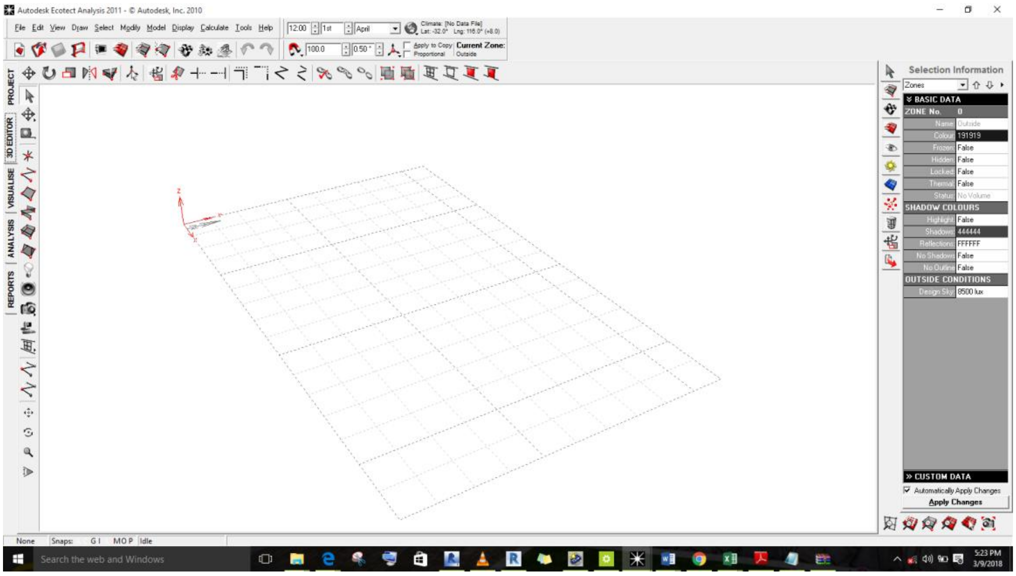

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Figure 7;Interface of Autodesk ECOTECT

ECOTECT was used to compare five different strategies that can improve energy efficiency inbuildings, these focuses on window, roof, walls, thermostat temperature control, and shadingdevice. For each of the five strategies several different materials were taken into consideration.Several materials were appointed to the corresponding building components afterwards an ECOTECT simulation was ran to observe how these behaved all together in regards energy consumption.

6.2 Temperature with Proposed Roofs

The hourly Resultant Temperature (RT) in both a hot season and a cold season days was estimated with the implementation of the various proposed roofs and then been tested on top floors. The following is the result of RT as can be seen in Table 3 below.

Table 3Resultant Temperature on top floor with various proposed roofs on January 1st

HOUR	OUTSIDE	R1	R2	R3	R4	R5
	(C)	(C)	(C)	(C)	(C)	(C)
0	21	22.5	21.5	22.3	22.2	21.9
1	20.3	22.3	21.3	22.1	22	21.7
2	19.7	22.1	21.2	21.9	21.8	21.6
3	19.3	22	21	21.8	21.7	21.4
4	19	21.8	20.9	21.7	21.5	21.3
5	18.9	22.1	21.1	21.9	21.8	21.5
6	18.9	22	21.1	21.9	21.7	21.5
7	20.2	22.2	21.3	22	21.9	21.7
8	22.5	22.5	21.6	22.4	22.2	22
9	25	22.8	23	22.8	22.5	22.3
10	27.4	23.1	23.8	23.2	22.8	22.7
11	29.5	23.4	24	23.6	23.1	23
12	31.1	23.7	24.5	23.9	23.4	23.2
13	32.2	23.9	24.8	24.2	23.6	23.5
14	32.8	24.1	25	24.4	23.8	23.7
15	32.9	24.2	25.1	24.5	23.9	23.8
16	32	24.2	25.2	24.4	23.9	23.7
17	30.6	24	25.3	24.2	23.7	23.6
18	29	23.9	24.9	24	23.6	23.4
19	27.4	23.7	24.5	23.7	23.4	23.2
20	25.9	23.5	24.4	23.5	23.2	23
21	24.4	23.3	24.2	23.2	23	22.7
22	22.8	23	23.9	22.9	22.7	22.5
23	21.3	22.7	22.8	22.6	22.4	22.2

The results revealed that by applying R2, a potential increase in the resultant temperature of a maximum of about 1.2° C is achieved in cold season, particularly during the daytime. In addition by using R2 a potential increase in the temperature of a maximum of about 3.4° C is achieved in hot season, particularly at early day hours and midday hours when compared with the R1. This means that R1 has the lowest performance in reducing temperature as can be seen in Figure 8 below, particularly during hot season and this will definitely reduce the number of comfort hours and also increase energy consumption when mechanical systems of heating and cooling applied.

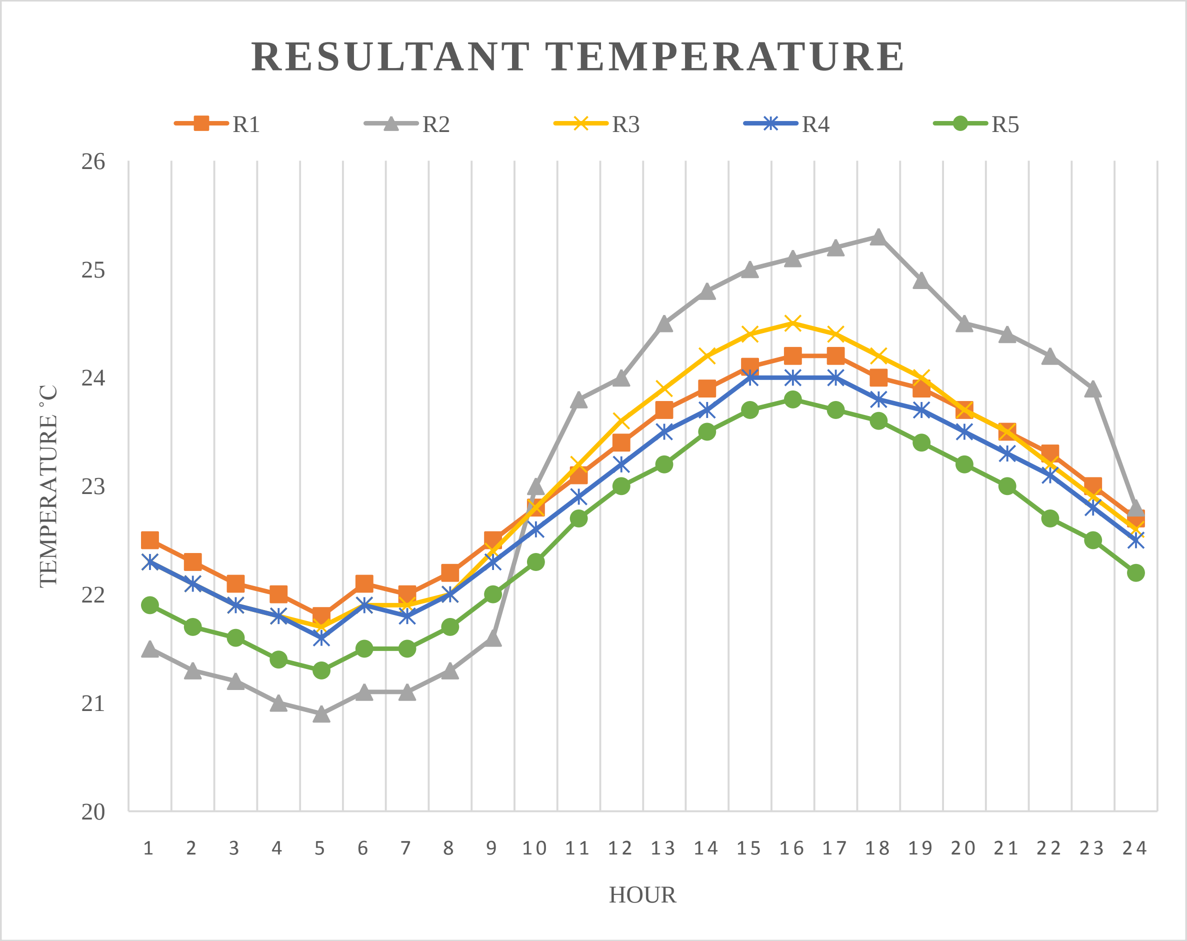

Figure 8;Resultant temperature on top floor with various proposed roofs

By applying R3 (which composed of roofing insulation without ventilation), similar results to those of R4(which composed of metal roofing with ventilation) are obtained with very slightly higher potential reduction and increase of the resultant temperature in hot season, however, during cold season a significant different between those two roof types occurs mainly at day time when the difference in temperatures is about +1.0° C at R3 type. This will however, leads to an assumption that roof with ventilation can be tantamount to roof with insulation and without ventilation. But when insulation and ventilation are applied a better roof performance can be achieved as can be seen in R5 which shows the best result from the simulation.

The results revealed also by incorporating insulation materials and providing roof ventilation, a possible increase in the temperature ranging from 0.2 to 3.1 °C could be obtained in cold season. In addition, a potential reduction in temperature of a maximum of 2.2 °C could be obtained in hot season. Overall, greater increase and reduction in temperature in cold season and hot season respectively are attained with greater thickness and lower thermal conductance of the insulation material. Besides, it is noticed that the magnitude of reduction in RT in hot season is lower than the magnitude of increase in RT in cold season. This can be clarified by the thermal analysis of the existing fabrics presented; where the analysis indicates that the total heat gain through roof in a hot season day is lower than the total heat loss through roof in a cold season day.

6.3 Thermal Comfort with Proposed Roofs

The percentages of comfort hours, where the PMV ranges from +1 to -1 (percentage of dissatisfaction is ± 25%), in hot season and cold season of the year were estimated with the implementation of the various proposed roofs (see Figure 8). The potential increase or reduction of the percentage of comfort hours comparing with the R1 is also provided in Table 4.

Table 4percentage of increase or decrease of comfort hours for the proposed roofs

	R1	**R2**	**R3**	**R4**	**R5**
MONTH	**(%)**	**(%)**	**(%)**	**(%)**	(%)
Jan	98.79	99.06	99.19	99.44	99.48
Feb	83.33	84.33	85.33	85.58	87.62
Mar	57.39	58.93	59.93	60.18	62.22
Apr	31.53	32.53	35.53	35.78	41.82
May	30.11	31.11	34.11	34.36	40.4
Jun	29.58	30.58	33.58	33.83	39.87
Jul	44.09	45.22	47.82	48.07	50.11
Aug	63.84	64.98	67.98	68.23	70.27
Sep	59.44	60.58	64	64.25	66.29
Oct	47.45	48.18	51.04	51.29	53.33
Nov	88.61	90.03	91.72	91.97	94.01
Dec	99.46	99.46	99.6	99.85	99.89
AVERAGE	61.135	62.0825	64.1525	64.4025	67.10917

The result revealed that by applying R2, a possible increase of the percentages of comfort hours of about 0.2% to 1.5% takes place in cold season, while an increase of percentages of comfort hours will happened of about 0.9% in hot season.

Furthermore, average increase in percentages of comfort hours of about 0.9% occur annually when using R2 roof type. By applying R3, difference results to those of R2 are obtained with higher potential increase of the cold season percentages of comfort hours of about 2.1%, while an increase of the percentages of comfort hours will take place of 3.1% and 2.0% in hot season and in the whole year respectively.

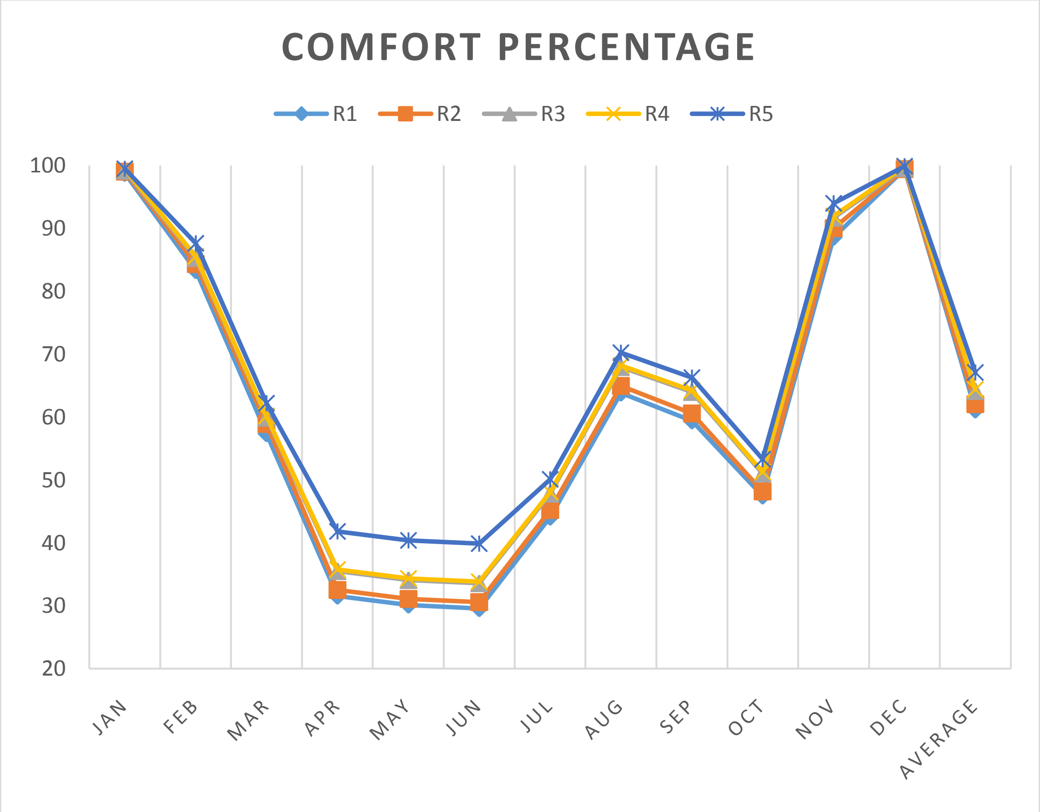

Figure 9; Percentage of comfort hours for various proposed roofs

As can be seen from the Figure 9 above, the results revealed by incorporating insulation material and providing roof ventilation increase in the percentage of comfort hours of about 1% could be obtained in cold season time. Besides, by using insulation materials providing roof ventilation a possible increase in the percentages of comfort hours ranging about from (2.0% to 8.5%) could take place in hot season times. Taken as a whole, applying insulation materials and ventilation in the proposed roofs could lead to a slight annual increase of the percentages of comfort hours about 6.0%. Overall, greater increase in comfort hours is attained with greater insulation material. In a comparison between the potential improvements in the thermal comfort in the five columns (R1 to R5) in the above table, it is observed that the magnitude of the potential improvement by applying the proposed roofs is significantly great during cold season than that in hot season and annually times. This can be somewhat explained by that the climate is already warm during cold season and the existing of thermal comfort is higher in cold season.

VII. CONCLUSION

Energy conservation and thermal comfort are affected by many factors which start right from the design stage, through the operational stage, up to the demolition stage. Climate Responsive Design principles are beneficial right from the design stage because buildings are designed based on natural ventilation, local climate and materials, and using renewable and clean technologies. Climate Responsive Design principles therefore allow buildings to maintain comfort with minimal mechanical support. Adaptive approach was used in evaluating thermal comfort for building users in this research.

Building energy calculation is especially beneficial at the early stage of design to enable designers to make informed decisions on the energy use in the operational stage of the buildings. This will not only prevent poor building performance due to electricity failure, but also adapt buildings to the endemic electricity crisis in Nigeria.

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