Low-cost retrofit packages for residential buildings in hot-humid Lagos, Nigeria

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Abstract

Purpose – The purpose of this paper is to develop a set of affordable retrofit packages that can be applied to existing residential buildings in hot-humid regions to improve occupants' thermal comfort and reduce energy consumption.

Design/methodology/approach – A critical review of relevant literature to identify passive design strategies for improving thermal comfort and reducing energy consumption in hot-humid climates with focus on the building envelope was conducted in addition to a simulation study of an existing building typology in study area.

Findings – There is enormous potential to reduce energy costs and improve thermal comfort through building retrofit packages which is a recent concept in developing countries, such as Nigeria. Analysing the results of the retrofit interventions using building energy simulation helped in developing affordable retrofit packages which had optimum effect in improving indoor comfort temperature to the neutral temperature specified for hot humid Nigeria and further down to 3°C less than that of the reference building used. The use of passive design strategies to retrofit the building might help homeowners reduce their annual energy consumption by up to 46.3 per cent just by improving the indoor thermal comfort.

Originality/value – In addition to improving thermal comfort and reducing energy consumption, this research identified affordable retrofit packages and considered its cost implications especially to low-income earners who form a larger population of Lagos, Nigeria, as this was not considered by many previous researchers.

Keywords Nigeria, Retrofit, Thermal comfort, Low-cost, Energy performance

Paper type Research paper

1. Introduction

1.1 Background

The building sector consumes more energy compared to other sectors in many countries. Buildings are responsible to nearly 40 per cent of global energy use leading to a corresponding emission of greenhouse gases in the world (Nduka and Sotunbo, 2014; Yang et al., 2014; Ma et al., 2012). Energy consumption in developing countries is expected to increase by 2020 compared to developed countries. The increasing population size and economic advancement in many of these countries could significantly increase energy usage, causing the depletion of natural resources (Kwong et al., 2014).

This concern has led to numerous studies being conducted around the world to devise ways of improving energy efficiency in buildings. A significant proportion of most of the energy usage is because of the increasing demand for HVAC installations to satisfy the increased demand for improved thermal comfort in many buildings. Nigeria is among the countries that have the lowest net electricity generation in the world with a major portion of the nation experiencing poor power supply and blackout. The highest figures of fossil fuel consumption are from the use of domestic power generating sets to achieve indoor comfort in many homes causing a growing concern about fossil energy use and its implications for...
the environment (Amadi and Higham, 2017). Figure 1 shows the total energy consumption by economic sectors in Nigeria and peer countries.

Ma et al. (2012) and Porritt et al. (2012) agree that most of the energy consumption is from existing buildings and it is necessary to adapt these existing buildings, since population size is constantly increasing and the rate of building new houses is quite low. This is important to reduce global energy usage, promote sustainability and conserve natural resources.

Building retrofit is as one of the many ways of adapting existing buildings to the changing climate. It is one of the approaches for encouraging sustainable development at relatively low-cost, offering significant opportunities for improving building performance while reducing usage of fossil fuel energy and global carbon footprint (Ma et al., 2012).

1.2 Statement of problem
Residential building design and construction in Nigeria and in various other countries are without much consideration for the microclimate or building occupants’ thermal comfort. This is because most designers and even the homeowners give more importance to aesthetics and maximisation of available space on a site.

Seeing as the use of passive design strategies are not optimised at the design stage of many buildings in the country, this study, therefore, focusses on retrofit actions to include these strategies that are aimed at improving the building’s performance with very little cost to the homeowners.

1.3 Significance of study
There are predicted increases in the impact and frequency of weather extremities, which include flooding, hurricanes and heat waves due to the changing climate (Porritt et al., 2012). Nigeria is one of the developing countries projected to experience great risk because of climate change, and within this region, dwellings in major cities like Lagos would experience most of these extremities because of the effects of urban heat island. The city of Lagos has

![Figure 1. Total energy consumption by economic sectors for Nigeria and peer countries](image)
been selected for this research as it has been identified as the economic capital of the country having the most energy usage and CO₂ emissions. The findings from this research are expected to provide homeowners and architects with affordable retrofit packages that are useful in improving the comfort within existing homes thereby reducing energy consumption, reducing maintenance costs and adapting these buildings to the changing climate. This would also help to conserve natural resources and promote sustainable development, which according to Brundtland (1987), is the ability to satisfy our needs presently, without affecting the ability for future generations to satisfy theirs.

Previous research has measured how effective a retrofit intervention can be on saving energy (Burgett et al., 2013). On the other hand, few studies are available which show the use of simulation modelling to develop retrofit packages to improve the thermal performance of buildings. The results from this study aim to make detailed quantitative data available to advise cost effective building retrofit decisions, mostly for homeowners and building practitioners.

1.4 Aim of paper
This research is aimed at developing a set of affordable retrofit packages that can be applied to existing residential buildings in Lagos, Nigeria, and places with similar climate to improve occupants’ thermal comfort and reduce energy consumption.

2. Literature review
2.1 Energy consumption for cooling in hot-humid climates
In tropical countries, 30–60 per cent of the total energy use in buildings results from mechanical systems for improving indoor comfort, among all the other building services (Kwong et al., 2014). More cooling requirement would mean more energy consumption, which in turn could worsen climate change (Yang et al., 2014).

Koo et al. (2014) argue that the reduction of HVAC energy consumption within residential buildings will significantly contribute to achieving GHG emission reduction target. Increasing the set point temperature of cooling systems by 2°C can significantly reduce the annual energy consumption (Kwong et al., 2014; Taleb, 2014). In domestic buildings, occupant's behaviour alone has effects on energy usage with little or no cost. Through changes in behaviour of occupants such as turning lights off when not in use, energy usage in homes can reduce by 10–20 per cent (Ma et al., 2012).

According to Olofsson and Mahlia (2012), ventilation and indoor temperature are two major influencers of energy usage within buildings. Similarly, Akande's (2010) study in Nigeria showed that most of the energy being consumed by most residential buildings is because of air conditioners and light bulbs.

A survey and statistical analysis of building design features in three different climates by Amadi and Higham (2017) revealed similarity in the design of buildings, which confirms that building design in Nigeria has little or no consideration for microclimates. This is the major cause of high cooling demand and "wasteful reliance on the use of fossil fuelled generators" to achieve comfort. It is, therefore, necessary to adapt a building to its microclimate to ensure less energy consumption and mitigate the environmental impact of the building over its life cycle. Due to the outrageous energy prices in many developing countries, efficient use of energy is important for reducing cost spent by people to achieve comfort (Yang et al., 2014). It is important, therefore, to focus on passive ways of achieving thermal comfort to reduce overdependence on energy.

2.2 Achieving thermal comfort in hot-humid climates through passive design strategies
Over the years, the need to achieve thermal comfort in buildings has widely become an important issue (Kwong et al., 2014; Loonen et al., 2013; Akande, 2010; Kruzner et al., 2013;
According to Kwong et al. (2014), analysing thermal comfort helps to show how occupants perceive their indoor environment. Nagaraju (2012) describes thermal comfort in buildings in terms of the heat flux into the building from surfaces exposed to the outdoor climate. Yang et al.’s (2014) survey of indoor environmental conditions found thermal comfort is ranked highest compared to the other parameters. According to the ASHRAE (2010), “comfort can be defined as the condition of the mind that expresses satisfaction with the environment”. Hence, comfort calculation lends itself to subjective evaluation. Some parameters to consider when assessing thermal comfort include air temperature, air velocity, relative humidity, activity level or metabolic rate and thermal resistance of clothing; and these can fluctuate with time (CIBSE, 2016; Nagaraju, 2012). The thermal environment that people find comfortable is usually influenced by multiple factors. Studies have identified some of these factors which are: climate, culture, the design and operation of the building, solar space conditioning, orientation, fenestrations, building fabric, embodied energy through building materials, ventilation, daylighting, landscaping, lighting individual habit of occupants, family tradition, cost, individual aesthetic sensibilities, personal characteristics and temporal factors (Nagaraju, 2012; CIBSE, 2016; Jaffari and Matthews, 2009).

Studies have demonstrated that strategies that are passive are considered as an affordable method for reducing building energy usage. Akande (2010), Taleb (2014) and Macias et al. (2006) agree that passive cooling strategies are technologies or design features that ensure thermal comfort in buildings through low conventional energy usage. Passive cooling makes use of renewable energy like solar or wind energy to reduce reliance on mechanical forms of cooling and reduce the environmental impacts of the building (Taleb, 2014; Kruzner et al., 2013).

Kwong et al.’s research, on tropical buildings (2014), suggests that the effective temperature for thermal comfort is around 26.1°C and comfort perception is not affected by the differences in race, age and gender of the building occupants. Similarly, some residential buildings were studied in Nigeria by Akande (2010), which showed that most buildings occupants experienced thermal discomfort in indoor spaces because of high temperatures.

Kruzner et al. (2013) conducted a research, evaluating 1,000 existing homes across the USA based on orientation, roof colour and level of vegetation cover. From their study, it was discovered that most of the homes in the Northwest and Southern regions were oriented towards east-west which proved an efficient direction for proper orientation. The buildings in the warmer climate regions also had lighter roof colours which were good for reflecting ultraviolet rays from the sun. From Porritt et al.’s (2012) work also, by adding shading devices or paint coats that can reflect excess UV rays solar heat gains from the window and envelope of the building could reduce. Akande’s (2010) study explains that avoiding heat gains, employing daylighting and passive cooling methods in design of buildings in hot climates help to minimise use of energy and make thermal comfort improve. Similarly, in Peterkin’s (2009) study in Australia, he identified that the key to improving energy performance is in using passive strategies like choice of building materials, zoning of rooms, control of sun penetration and control of ventilation. Agreeing with Akande and Peterkin, Taleb’s (2014) study in Dubai showed that total annual energy consumption in residential buildings could reduce by about 23.6 per cent by using passive design measures such as green roof, double glazing, insulation, shading, use of wind catcher, solar reflective coating on interior, etc., to improve thermal comfort within the building.

Passive cooling measures include maximising natural ventilation within the building, sizing of windows, where it is placed and its design, selecting appropriate glazing types to be used for windows, adequate shade to reduce solar heat gain, using building fabric materials that reflect UV rays, proper site selection, analysis and planning, building orientation, appropriate landscaping design, proper zoning of floor plan and using roof insulation and ventilation (Kruzner et al., 2013; Akande, 2010; Santamouris and Asimakopoulos, 1996; Taleb, 2014). For this research, the focus is on the reduction of heat gain.

Low-cost retrofit packages
2.2.1 Control of heat gains. Heat gains within a building can be internally generated or through radiation from the sun (Ochedi et al., 2016). It is assumed that the temperature within a building reflects that of the exterior environment (Yin et al., 2010). Total internal heat gains, according to Olofsson and Mahlia (2012) can be calculated as the total of all energy use from home appliances and artificial lightings, and metabolic gains from general activities of building occupants (Figure 2).

The design of building envelopes has a huge impact on energy savings. Appropriate design of the building envelope will aid thermal comfort in buildings (Koo et al., 2014; Taleb, 2014). According to Koo et al. (2014), effective passive design strategies for the building envelope include insulation of roof, glazing, use of light or reflective coloured materials, shading and use of appropriate landscaping design:

1. Shading: a key aspect of reducing heat gains directly transmitted from the sun in tropical climates involves employing the use of shading and openings (Taleb, 2014; Akande, 2010). Porritt et al.’s (2012) research evaluated a range of passive window shading interventions to reduce the need for mechanical cooling. The research concluded that using external shutters on windows will reduce heat gains by about 39 per cent and had better effect than internal shading devices.

2. Use of vegetation and greenery: according to Kruzner et al. (2013), employing the use of trees and greenery for solar shading has significant reductions in cooling energy load for dwellings.

3. Glazing type: windows occupy substantial portion of the total surface of the building envelope. The effects of a window on reducing heat getting into a building depend upon its physical features, its orientation and the climate (Olofsson and Mahlia, 2012). A good window provides adequate lighting while resisting UV radiation from the sun. Chan et al. (2009) study on double glazed facades showed that glazing has huge savings in terms of reducing cooling load of buildings. The use of single absorptive glass, showed a reduction of cooling load by 5.3 per cent yearly, which is below that with the use of the single glazing. Also, yearly savings in the cooling load of 17.7 and 7.5 per cent is as a result of using the double reflective glazing and double absorptive glazing.

4. Paints and coatings: using UV resistant paint coats has significant reductions for indoor temperature and reduces cooling loads. Using paint coats with up to
61 per cent reflection from the colour spectrum has beneficial effect on energy saving (Taleb, 2014). According to Kruzen et al. (2013), light shade of roof colours absorbs less heat and, therefore, can reduce the energy required for cooling for hotter seasons while dark roof shades absorbs more solar heat gains and would lead to increased cooling energy requirements for the building.

(5) Insulation: insufficient insulation accounts for heat gains in buildings. Insulation can be used in walls, ceiling and floors. According to Pongsuwan (2009), the use of insulation reduces heat transfer from the outside and improves thermal comfort within the building thereby reducing the need for energy consumption using mechanical cooling systems. From Porritt et al’s (2012) work on retrofits, design measures involving the protection of the external wall using UV resistant paint coats or insulating the exterior fabric proved more effective, especially for the houses having more area of external wall surface. Although interior insulation of a wall prevents heat transfer it does not provide thermal bridging, reduce condensation and can allow fungi growth inside the wall which can cause sickness to building occupants Pongsuwan (2009). It is, therefore, not encouraged in hot-humid climates as the high rate of humidity would encourage fungi growth (ASHRAE, 2010) and also prevent hot air from escaping from the inside of the building to the outside.

2.3 Retrofitting of existing buildings in hot-humid climate
There are energy efficiency codes and guides suited more to new buildings than existing buildings. Existing buildings have limited measures for improving thermal comfort and energy consumption of building occupants within. Building retrofit has been identified as one of the effective ways of improving comfort in existing buildings and reducing the energy usage, thereby adapting to the changing climate (CIBSE, 2016; Porritt et al., 2012). Retrofits, according to Freiss et al. (2012), usually require little effort to achieve significant efficiency and improvement to a building’s performance. In a movement towards a sustainable future, retrofitting of existing buildings aids in conserving already existing resources rather than producing more and depleting the natural reserves (Oginni et al., 2012). Building retrofits has huge prospects in improving energy performance, improved occupant output, lessened running cost plus improved thermal comfort (Ma et al., 2012). It also creates job opportunities which is a key aspect of social sustainability and has the advantage of being performed while the building is still functioning, without affecting the building’s daily activities.

Although the trend is new in developing countries, retrofits have been conducted to incorporate the use of efficient lighting and HVAC systems. Research works, by various authors, have shown that usage of energy in homes could be lessened by building retrofit interventions. Mahlia et al. (2005) conducted a lighting retrofit in the residential sector of Malaysia based on a survey of 427 buildings. Their study showed a significant reduction in building electricity consumption as well as CO₂ emissions with the use of efficient lamps with a lower wattage than the incandescent lamps. Similarly, Lun and Yik’s study in 2009, involved the CFD simulation study of an existing public housing block in Hong Kong, to simulate the effects of optimising natural ventilation in the building. They discovered that using strategies that optimised the use of natural ventilation within the building helped to reduce 24 per cent of occupants air-conditioning energy use. An investigation was carried out using an existing single-family villa in Dubai by Freiss et al. (2012) to simulate the impacts of thermal bridging and external wall insulation on the reduction of solar heat gains through the building envelope for both new and existing houses. After comparing different variations of wall insulations in their study, they realised 30 per cent energy savings and a
reduction in the walls’ U-values to meet with local building standards. This helped to reduce the solar heat gains through the fabric and improve the buildings overall performance.

Freiss et al. (2012) maintains that although it is difficult to achieve a high level of efficiency when retrofitting existing buildings, retrofit actions that are targeted towards solving the main issues within a building can produce significant improvements both in performance and energy savings. The major limitation come across in building retrofits is the numerous uncertainties, like changing climate or changes in human behaviour, most of these have a direct effect on the selection of retrofit measures (Ma et al., 2012). Other challenges may include cost, supposed payback period, interruption to its operation and lack of government incentives (Porritt et al., 2012).

There seems to be little information regarding occupant’s comfort in major retrofit interventions. There was no indication as to whether their comfort was being compromised to reduce energy usage. This, therefore, brings up the need for retrofit interventions focussed more on the improvement of thermal comfort within the home first, with cost, energy use and CO₂ reductions as added benefits.

3. Context
3.1 Geography, climate and demography of study area
Lagos, Nigeria is situated in western Africa and in the southwestern region of Nigeria, as seen in Figure 3. It is the sixth largest city in the world and the largest city in sub-Saharan Africa. Lagos lies between latitudes 6°26′ and 6°50′N and stretches between longitudes 3°09′ and 3°46′E. The state is bound from the north by Ogun state, in the west by the Republic of Benin and the south by the Atlantic Ocean/Gulf of Guinea (Ojeh et al., 2016; Agunbiade et al., 2013). The total landmass of the state is about 3,345 km²–3,577.28 km², which is just about 0.4 per cent of the total land area of Nigeria. Water body accounts for 29.8 per cent of this while 60 per cent of the remaining areas are wetlands and remotely detached by creeks and lagoons. Lagos is along the tropical rain forest belt with wetlands and rain forest being the predominant eco-zones (Ojeh et al., 2016).
The warm, humid maritime tropical air mass interacting with the hot and dry continental air mass from the interior creates the seasons in the country; a rainy season from April to October and a Harmattan season from November to March (Braimoh and Onishi, 2007; Ojeh et al., 2016). The rain falls every month of the year with the highest amount in June because of rain-bearing southwest trade winds prevailing from the Atlantic Ocean and mean annual rainfall of 1,657 mm. The air is quite humid throughout the year, with monthly average maximum temperatures (Figure 4) ranging from 27°C in July/August to 34°C in January/February (Ojeh et al., 2016).

There are 1,885 h of sunshine per year with the sun mostly overhead. The average annual relative humidity in Lagos state is 84.7 per cent and average monthly relative humidity ranges from 80 per cent in March to 88 per cent in June. Solar radiations are quite high and readily available for most hours during the day and for Lagos, it is about 1,750 kWh/m² annually. Figures 5 and 6 show the average wind speed and direction in Lagos.

About 50 per cent of Nigeria’s population lives in the urban areas such as Lagos, compared to only 20 per cent in 1980, 16 per cent in 1970 and 13 per cent in 1960 (Olukiyesi, 2011). Lagos has a population of over 21m people currently (Ojeh et al., 2016). More than fifty per cent of Nigeria’s electrical power generation is used up by metropolitan Lagos; also, more than half of the number of vehicles in Nigeria are focussed on its road networks (Ojeh et al., 2016).

According to the LASG (2014), there are three main income groups in Lagos state. These include the lower class, middle class and the high or upper class. Figure 7 shows the average income in Naira (where Naira, n = $0.0028).

The predominant income level from the Figure 9, making up almost 80 per cent of Lagos is the low-income class.

3.2 Analysis of thermal environment
In the case of Lagos State, the influx of population has increased urbanisation (Olukiyesi, 2011). In 2006, Lagos state had about 2,195,840 households, and this has increased over
the recent years (Braimoh and Onishi, 2007; Nigeria data Portal, 2016). More attention is usually given to space allocation in providing for the teeming population (Oginni et al., 2012). In the building industry, there is little regard given to the microclimate and thermal comfort when designing. This causes most occupants to rely on mechanical cooling to
achieve thermal comfort (Adaji et al., 2016). A survey carried out by the Lagos state government (2013) revealed that 99 per cent of residents in Lagos make use of electric fans and air conditioners to achieve comfort in their homes.

From the results of several thermal comfort studies conducted it was agreed that acceptable effective temperature was higher for people living in the tropical countries as they showed a higher tolerance for warmer conditions (Kwong et al., 2014; De Dear and Brager, 2002). Some researchers have conducted some study on thermal comfort in buildings in the hot-dry and hot-humid climate regions of Nigeria. A summary of these researchers is shown in the Table I.

The more recent researches of Adebamowo (2007), Adunola (2012 cited in Efeoma and Uduku, 2016) and Efeoma and Uduku (2016) for hot-humid climate regions of Nigeria, identify a much higher neutral temperature than the 26°C suggested in ASHRAE (2010) or CIBSE (2016). The differences in their results can only be as a result of clothing and activity levels of respondents that were surveyed by the authors. It could also be as a result of the different methods employed by the researchers in carrying out their study and the time of the year the study was done. Although there is some discrepancy among the neutral temperature for the hot-humid region of Nigeria, the acceptable comfort range specified according to Efeoma and Uduku’s research (2016) is 25.4–32.2°C. This goes to show that over the years, people in hot humid Lagos have grown to adapt to a higher range of temperatures mostly because of the unreliability of electricity power supply in the country.

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>RATE PER DAY ($)</th>
<th>RATE PER MONTH (N)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOWER CLASS</td>
<td>&lt;2</td>
<td>&lt;48,000</td>
<td>79.5</td>
</tr>
<tr>
<td>MIDDLE CLASS</td>
<td>2–10</td>
<td>48,000–240,000</td>
<td>18.7</td>
</tr>
<tr>
<td>UPPER CLASS</td>
<td>&gt;10</td>
<td>&gt;240,000</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Note: Naira, N1 = US$0.0028
Source: Lagos state government (2014)

Table I. Summary of thermal comfort research done in Nigeria

<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher</th>
<th>Location (climatic zone)</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Efeoma and Uduku</td>
<td>Port harcourt (Hot humid)</td>
<td>Neutral temperature = 23.13°C</td>
</tr>
<tr>
<td>1988</td>
<td>Ojosu et al. (cited in Efeoma and Uduku, 2016)</td>
<td>Hot dry (Hot humid)</td>
<td>Acceptable comfort zone = 18–24°C</td>
</tr>
<tr>
<td>2007</td>
<td>Adebamowo</td>
<td>Lagos (Hot humid)</td>
<td>Neutral temperature = 29.09°C</td>
</tr>
<tr>
<td>2008</td>
<td>Ogbonna and Harris</td>
<td>Jos (Hot dry)</td>
<td>Neutral temperature = 26.27°C</td>
</tr>
<tr>
<td>2007</td>
<td>Adebamowo</td>
<td>Bauchi (Hot dry)</td>
<td>Neutral temperature = 28.44°C</td>
</tr>
<tr>
<td>2012</td>
<td>Adunola</td>
<td>Ibadan (Hot humid)</td>
<td>Neutral temperature = 32.3°C</td>
</tr>
<tr>
<td>2016</td>
<td>Efeoma and Uduku</td>
<td>Enugu (Hot humid)</td>
<td>Neutral temperature = 28.8°C</td>
</tr>
</tbody>
</table>

Source: Adapted from Efeoma and Uduku (2016)
4. Methodology
The primary research method employed in this study is quantitative, using simulation study to model an existing building typology in Lagos and check if it is within the acceptable comfort range calculated for hot humid Nigeria by previous researchers. EnergyPlus simulation engine was chosen to carry out the dynamic simulation study as it has been used by many researchers of similar studies with positive outcomes (Porritt et al., 2012; Chan et al., 2009). It makes use of hourly climatic data for selected locations and has the added advantage of saving time and money when compared with a range of quantitative research methods.

The framework of the methodology has been outlined and a case study will be used to show its application. The simplified steps of the methodology (Figure 8) are as follows.

5. Research findings
5.1 Case study building
To evaluate the thermal comfort of a building in any location requires building and site-specific information. This, therefore, led to a selection of suitable case study in Lagos (Figures 9 and 10), to simulate real-life conditions of a typical building in the study area to compare the various retrofit interventions. The building is a flat having three apartments located in Ikorodu, Lagos. The dwelling has a net floor area of 79 m². Its external walls are made of the hollow sandcrete blocks. The roof is clad with aluminium sheets and asbestos ceiling. The internal floor is...
finished with ceramic tiles. It has single glazed, clear sliding windows in aluminium frames. The external doors are made of aluminium as well.

Figure 11 shows the building model and main components of the building. The various components which make up the external envelope are shown in Table II, with their

<table>
<thead>
<tr>
<th>Case study</th>
<th>Building envelope</th>
<th>Description</th>
<th>$U$-value (W/m².K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>External walls</td>
<td>Hollow sandcrete blocks (150 mm), internal and external plaster (12 mm each)</td>
<td>0.987</td>
</tr>
<tr>
<td></td>
<td>Roof</td>
<td>Aluminium roof (5 mm) on 50 mm wooden purlins</td>
<td>2.113</td>
</tr>
<tr>
<td></td>
<td>Ground floor</td>
<td>Ceramic tiles (8 mm) on 200 mm screed and concrete slab</td>
<td>1.870</td>
</tr>
<tr>
<td></td>
<td>Glazing</td>
<td>Single glazed sliding windows with aluminium frame</td>
<td>5.894</td>
</tr>
<tr>
<td></td>
<td>External doors</td>
<td>Single hinged Aluminium doors (50 mm)</td>
<td>5.872</td>
</tr>
</tbody>
</table>

**Source:** Design Builder (2017)
corresponding $U$-values. These are considered as they are in direct contact with the environment and affect the performance of the interior of the building. The sun path diagram (Figure 12) also shows that the sun is directly over the building throughout most of the day. The highest $U$-value is from the single glazed window and external aluminium door while the lowest is from the walls. The daylighting study for the building indicates less solar gains in the bedroom because it is recessed.

Table III shows the indoor operative temperature for the two main seasons in Nigeria, although the dry/harmattan season records the highest temperature, the annual indoor temperature for the building, 30.31°C, is within the acceptable comfort range of 25.4 – 32.2°C calculated by Efeoma and Uduku (2016) for hot humid Nigeria but above the neutral temperature of 28.8°C (Figure 13).

The HVAC template used to run the simulation is natural ventilation with an air change rate of 5AC/H. The occupancy level was calculated based on the housing density and total

![Figure 12. Building components, sun path and daylighting study](image)

**Source:** Design Builder (2017)

<table>
<thead>
<tr>
<th>Time</th>
<th>Operative temperature (°C)</th>
<th>Air speed (m/s)</th>
<th>Relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>30.31</td>
<td>2.73</td>
<td>60.36</td>
</tr>
<tr>
<td>Dry/harmattan Season</td>
<td>33.91</td>
<td>2.64</td>
<td>52.93</td>
</tr>
<tr>
<td>Wet/rainy season</td>
<td>28.09</td>
<td>2.05</td>
<td>73.66</td>
</tr>
</tbody>
</table>

**Table III.** Thermal comfort analysis

**Source:** Design Builder (2017)

![Figure 13. Comparing the annual operative temperature of the building with that calculated for the study area](image)

**Source:** Adapted from ASHRAE standard 55 (2010) and Efeoma and
floor area of the building. The activity and clothing insulation (0.5 clo) were input using
ASHRAE (2010) standards for each suitable building zone activity and climate type.
Lighting type used for the simulation is the commonly used type in Nigeria, which
is the incandescent bulbs. The highest level of heat gains is from solar radiations through
windows (Table IV). To offset the cooling demand in the building will require
23,205.37 kWh of energy annually, using mechanical cooling system. The use of equipment
and lighting resulted in 10,576.37 kWh of electricity usage annually with total CO₂
emissions of 6,409.27 kg. The simulation results show the need to reduce the operative
temperature and make the building more comfortable for the occupants thereby reducing
their reliance on mechanical cooling systems.

Retrofit interventions are therefore necessary and will be employed using the case study
building as a reference for a range of retrofit interventions that can be carried out for buildings
found in Lagos, Nigeria and in most hot humid regions in the world. These interventions will
be done to reduce the indoor operative temperature for the building to the neutral temperature
of 28.8°C according to Efeoma and Uduku (2016). This would help to improve the thermal
comfort of the occupants, reduce cooling cost and enhance energy security.

5.2 Simulation results for retrofit interventions
Noting that not all the elements and features of an existing house can be modified, such as
the building form or orientation, it is therefore important to identify the ones with the most
negative effect on the reference building’s performance (Figure 14). The various retrofit
interventions applied to the building using EnergyPlus simulation tool were selected based
on the main passive design issues that needed to be addressed in the building.

The addition of window shading in the form of overhangs, side fins and a combination of
both were simulated, with the corresponding results shown in the table below. Each had
varying results in terms of indoor operative temperature, total energy usage, CO₂ emission
and total cooling load. The percentage reduction for each was calculated, including the
amount of solar heat gains (SHGs). The combination of fins and overhang had the highest
reduction in annual SHGs (30.5 per cent), followed by overhangs (17.1 per cent) and side fins
(16.1 per cent). Double glazed low emissivity windows had the most reduction in SHGs
through the window from 4,998.13 kWh to 2,569.85 kWh (49 per cent).

Additional windows were added to the bedroom to improve cross ventilation but had no
effect on the operative temperature. Also, high-level vents and roof ventilation had no effects
on simulation result.

A range of retrofit interventions to reduce the U-values of the various components of the
building envelope were also simulated. Each has been ranked according to how efficient
they were in improving the indoor comfort temperature and bring it close to the neutral
temperature. The use of roof insulation which has been advised, in the Federal Republic of
Nigeria (2017) proved the most effective by 3.3 per cent in reducing solar heat gains

<table>
<thead>
<tr>
<th>HVAC template</th>
<th>Natural ventilation – no heating, no cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial lighting</td>
<td>Incandescent bulbs</td>
</tr>
<tr>
<td>Annual internal heat gains (kWh)</td>
<td>Lighting – 3,048.69</td>
</tr>
<tr>
<td></td>
<td>Equipment – 792.29</td>
</tr>
<tr>
<td></td>
<td>Occupancy – 3,681.84</td>
</tr>
<tr>
<td>Annual solar heat gains from windows (kWh)</td>
<td>4,998.13</td>
</tr>
<tr>
<td>Annual total electricity usage(kWh)</td>
<td>10,576.37</td>
</tr>
<tr>
<td>Total CO₂ emissions (kg/year)</td>
<td>6,409.27</td>
</tr>
<tr>
<td>Annual cooling load (kWh)</td>
<td>23,205.37</td>
</tr>
<tr>
<td><strong>Source:</strong> Design Builder (2017)</td>
<td></td>
</tr>
</tbody>
</table>

**Table IV.** Cooling load, energy consumption and resulting CO₂ emissions
through the roof resulting from the overhead sun in Lagos. Cladding both for interior and exterior west facing wall was also simulated using various materials from wood to the common stone tiles used in Lagos. Each of these generated a different result which is also ranked in the table below. The use of paint coating with thermal emissivity of 0.5 was also simulated with improvement to the buildings indoor comfort temperature.

Table V shows the various interventions, ranked in descending order according to their effectiveness in reducing the annual operative temperature. The use of rockwool for roof insulation proved the most effective while the use of wooden side fins was the least effective.

5.3 Cost analysis
The simple payback is the number of years the savings from the retrofit packages will take to return to the home owner the initial capital cost (Burgett et al., 2013). The cost analysis was carried out by calculating the simple payback period to compare each retrofit package and determine how long it would take to get back the money invested. Analysing the cost helps to compare alternative measures and indicates if they are effective in cost or not (Ma et al., 2012). Cost analysis was used by Mahlia et al. (2005) to calculate the economic viability of some lighting retrofit actions.

The effectiveness of each retrofit intervention was measured by comparing the thermal comfort before and after the retrofit intervention. The capital cost to carry out each intervention is analysed in Table VI, showing the individual unit costs and the total cost per unit or m².

5.4 Retrofit packages
A combination of retrofit interventions based on their effectiveness in improving comfort temperature and cost were selected to form various packages that can be applied to bring the building down to the neutral temperature calculated by Efeoma and Uduku (2016) and further to the much cooler 26°C calculated by ASHRAE (2010) standard 55 for the hot humid climate type. From Table VII, the cheapest intervention ranked according to the cost of implementation, is the use of the 500 mm overhangs for window solar shading, while the use of rockwool for roof insulation turned out to be the most expensive of all the retrofit interventions. This was used to determine the suitable retrofit packages. Figure 15 shows the three different packages.
5.4.1 Package 1 – no cost. Behavioural adjustments. Based on Lun and Yiks (2009) reducing the input wattage of bulbs or reducing the hours of operation of the lighting to reduce emissions from building energy consumption helps in significant energy savings. This will also help in reducing the amount of internal heat gains resulting from its use. Also, Hansmann (2014) suggests that the simple act of opening windows at night makes use of the diurnal cycle to help flush out hot air from the building and introduce cool air into it. These simple steps do not cost anything from building occupants and can greatly improve the thermal comfort and energy usage. This was simulated in DesignBuilder by reducing the operational hours in the lighting schedule and using lighting control.

5.4.2 Package 2 – low cost. This package is a combination of the “No-Cost package” and the addition of shading and paint coating.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Purpose</th>
<th>Annual operative temperature (°C)</th>
<th>Annual energy usage (kWh)</th>
<th>Annual CO₂ emissions (kg)</th>
<th>Annual cooling load (kWh)</th>
<th>U-values (W/m².K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Roof insulation Rockwool 150 mm</td>
<td>Insulation at ceiling level</td>
<td>29.31</td>
<td>9,941.81</td>
<td>6,024.73</td>
<td>20,369.87</td>
<td>0.198</td>
</tr>
<tr>
<td>2. Roof insulation EPS 150 mm</td>
<td>Insulation at ceiling level</td>
<td>29.32</td>
<td>9,659.57</td>
<td>5,853.70</td>
<td>19,099.79</td>
<td>0.209</td>
</tr>
<tr>
<td>3. Wooden Side fins+ overhang, 500 mm</td>
<td>Solar shading</td>
<td>29.35</td>
<td>9,849.52</td>
<td>5,968.81</td>
<td>19,954.56</td>
<td>–</td>
</tr>
<tr>
<td>4. Double glazing 6 mm/13 mm argon filled</td>
<td>Reduce Solar heat gains</td>
<td>29.42</td>
<td>9,911.45</td>
<td>6,006.33</td>
<td>20,233.21</td>
<td>1.493</td>
</tr>
<tr>
<td>5. Exterior cladding wood 15 mm</td>
<td>To insulate wall from solar radiation</td>
<td>29.46</td>
<td>9,860.15</td>
<td>5,975.24</td>
<td>20,240.21</td>
<td>0.918</td>
</tr>
<tr>
<td>6. Exterior cladding stone 9 mm</td>
<td>To insulate wall from solar radiation</td>
<td>29.52</td>
<td>9,966.99</td>
<td>6,039.99</td>
<td>20,626.05</td>
<td>0.987</td>
</tr>
<tr>
<td>7. Interior cladding stone 9 mm</td>
<td>To insulate wall from solar radiation</td>
<td>29.50</td>
<td>10,069.14</td>
<td>6,118.26</td>
<td>21,207.24</td>
<td>0.987</td>
</tr>
<tr>
<td>8. Exterior cladding PVC 10.5 mm</td>
<td>To insulate wall from solar radiation</td>
<td>29.54</td>
<td>9,971.77</td>
<td>6,042.88</td>
<td>20,671.29</td>
<td>0.929</td>
</tr>
<tr>
<td>9. Interior cladding wood 25 mm</td>
<td>To insulate wall from solar radiation</td>
<td>29.53</td>
<td>9,941.59</td>
<td>6,024.60</td>
<td>20,764.43</td>
<td>0.875</td>
</tr>
<tr>
<td>10. Paints with 0.5 thermal emissivity</td>
<td>To reflect solar radiations on walls</td>
<td>29.66</td>
<td>10,142.33</td>
<td>6,146.25</td>
<td>21,272.19</td>
<td>–</td>
</tr>
<tr>
<td>11. Wooden overhangs, 500 mm</td>
<td>Solar shading</td>
<td>29.75</td>
<td>10,207.87</td>
<td>6,185.96</td>
<td>21,567.13</td>
<td>–</td>
</tr>
<tr>
<td>12. Wooden side fins, 500 mm</td>
<td>Solar shading</td>
<td>29.82</td>
<td>10,195.90</td>
<td>6,178.71</td>
<td>21,513.26</td>
<td>–</td>
</tr>
</tbody>
</table>

Source: Design builder (2017)
Window solar shading. The use of the 500 mm side fins and overhang was chosen over the other retrofit interventions as it proved to be the most cost effective. Figures 16 and 17 show the daylighting map for the reference building within the building before and after the addition of the shading. Based on this, the daylighting is adequate in most rooms and the solar heat gain is also reduced as indicated by the absence of the red colour (10 per cent daylight factor) in the second image.
Low emissivity paint coats. This type of paint has been chosen in place of the usual type as it has UV resistant qualities. It can be applied for both roof and wall surfaces. For this study, it was only simulated for the external walls.

5.4.3 Package 3 – additional cost. This package is a combination of the “No-Cost package”, the “Low-Cost package”, and the addition of Polystyrene sheets for roof insulation at ceiling level.
Roof insulation. The use of the expanded polystyrene sheets has been selected instead of the commonly used Rockwool, as it is more effective and less expensive as shown in Tables V and VI.

Table VII shows the percentage reductions based on the application of the various retrofit packages to the reference building. Package 1 has minimal reductions in indoor operative temperature but shows favourable reductions in energy consumed, cooling load and resulting CO₂ emissions at no cost to the home owner. Package 2 has 6.7 per cent reductions in indoor operative temperature and costs the home owner ₦49,134 to achieve. The third package although having a capital cost of ₦422,310 to implement records the most reductions in temperature, energy consumption, cooling load and resulting CO₂ emissions.

The simple payback period of each retrofit package was determined using the income identified for the low-income class (Section 3) as the cash flow and the capital cost of implementation as the initial investment.

The formula is as follows:

\[ PP = \frac{I}{C}, \]

where PP is payback period, \( I \) is investment amount, \( C \) is the cash flow due to energy savings per year.

Figures 18 and 19 show the percentage reductions in the various parameters considered in this study for the reference building and with the use of the building retrofit packages. Figure 20 shows the combination of the packages.

Although the research focussed on only passive retrofit measures, the use of energy efficient lamps was also simulated. Reducing the power density from 28 to 5 W/m² to comply with that stipulated in the building energy efficiency code of Nigeria (2017), resulted in annual internal heat gains reduction by 82 per cent with the operative temperature reducing by 3.5 per cent and a further reduction by 33 and 18.8 per cent, respectively, in annual energy consumption and cooling load. This was achieved by changing the lighting template from incandescent lamps to compact fluorescent lamps.
6. Conclusion and recommendations

6.1 Main findings and outcomes

This study targeted improving the thermal comfort of building occupants within homes in Lagos, Nigeria and in various similar climate regions, using suitable building retrofit packages. This study assessed various energy efficiency measures. Analysing the results of the simulated retrofit interventions helped in developing affordable retrofit packages which had optimum effect in improving indoor comfort temperature to the neutral temperature specified for hot humid Nigeria and further down to 3°C less than that of the reference building. Comparing the simulation results with the reference building, it can be envisaged that these passive design strategies for retrofitting might help homeowners reduce their annual energy consumption up to 46.3 per cent by improving their indoor thermal comfort.

These results, therefore, show that building retrofits can be conducted not just for reducing energy consumption by HVAC and lighting systems but to improve thermal
comfort within homes and can be done affordably to benefit many homeowners, whether low income or not. Also, implementing the “No Cost” package in many homes would help improve behaviour of occupants and make them realise that these little actions can go a long way in improving their quality of life. The use of Design Builder software proved an effective tool in this study for carrying out in-depth building performance analysis and can therefore be used by researchers for similar study. The research findings will also provide guidance to architects on potentials of applying various building retrofit using passive design strategies in Lagos, Nigeria and places with similar climates, to improve building performance, adapt existing buildings to the changing climate and promote sustainable development. While the results presented from this study were for the reference building, a building retrofit framework drawn from the methodology used in this research can be applied to similar cases. One of the limitations of the research was that there was no way of validating the actual cost savings using the retrofit packages as the energy bills from the household was not used during this study.

6.2 Recommendations
A post occupancy survey would prove useful in understanding whether the building occupants are satisfied with the building retrofit results in terms of thermal comfort and energy usage to validate the research in a real-life situation. Architects and planners should endeavour to apply passive design strategies at the design stage, to improve building performance and promote sustainability in new construction. Independent policies should be added to the Building Code for Nigeria by the government, to include building retrofit as a sustainable option for adapting existing buildings to the changing climate.

References


Further reading


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