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COMPARISON OF COOLING ENERGY DEMAND FOR CYLINDRICAL AND RECTANGULAR SHAPED HIGH-RISE OFFICE BUILDING IN LAGOS, NIGERIA.

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Abstract
The focus of this study is to determine the energy-saving potentials while adopting appropriate and efficient building form during the design stage of high-rise office building. This is to enhance and strengthen the decision-making on adoption of efficient form in high-rise buildings towards policy making on mitigation and resilience to climate change action for sustainable cities in Nigeria. The study derived the effect of cylindrical and rectangular building shapes on the cooling energy demand of a modeled high-rise office building in Lagos, a coastal city in Nigeria. Comparison was performed with the simulation method using Autodesk Revit 2020, Green Building Studio and Insight 360 software. Window-wall ratios of 60% was used as a baseline comparison. Percentages of energy expended on space cooling, lighting, and other activities within the modeled building were determined. Result shows that cooling energy demand was lower in cylindrical-shaped high-rise base case building with a value of 19.79 (MJ/m²/year). A 4.57% reduction in the total amount of energy consumed annually was obtained in cylindrical-shaped building. The paper concludes that cylindrical-shaped building possesses a higher cooling energy saving potential than rectangular-shaped building. Consequently, cylindrical building form should be adopted for new designs of high-rise buildings to save cooling energy demand within the warm humid climate region of Lagos, Nigeria.

Keywords: Building shape, Cooling energy, High-rise office building, Warm-humid climate, Thermal comfort, Nigeria

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1. Introduction

Building shape, also referred to as building form or building configuration is fundamental to creating an efficient, functional and appealing structures; although, building form affect thermal comfort and thereby influences energy consumption in buildings (Zang et.al, 2017). Building shape affects the amount of heat received by building surfaces. This influences the perception of thermal comforts within indoor spaces and consequently cooling energy demand in the hot climate regions. Studies have shown that energy consumption for adequate functioning of buildings to meeting various occupants' needs exert negative impact on the environment such as climate change (Guozhu et.al, 2015; Hassan et al. 2021; IEA, 2022). Adverse effects of climate change is one of the contemporary challenges facing human (UNEP, 2021). Building and construction sector is a major contributor to climate change, being responsible for 38 percent of global energy-related CO2 emissions, (UNEP, 2021).Since buildings contribute immensely to climate change, they can also enhance climate change adaptation, improves resilience and addresses mitigation in the building sector. Therefore, ensuring that new buildings are energy-efficient and sustainable will contribute greatly to tackling climate change.

The impacts and challenges of changing climate on human and the built environment necessitate the adoption of design approaches for building resilience and mitigation in order to achieve sustainable cities. Design approach is key to reducing energy demand of various types of building structures; these design approaches are decided upon early during the conceptual development stage of building design. Among these design approaches is the use of appropriate building shape or form in the warm and hot environments. This helps to minimise heat gain and transfer within the interior spaces. Hence comfortable temperature is maintained while saving cooling energy.

The large surface area of high-rise buildings are means by which heat could be gained within the interior spaces as a result of exposure to solar radiation, thereby leading to higher cooling energy demand. In this study, the cooling energy demand of two high-rise buildings with cylindrical and rectangular shape in Lagos Nigeria is compared. Lagos is an industrialised and commercial city in Nigeria. It has witnessed rapid urbanisation and population growth over time.In a quest to be integrated into the global economic system coupled with the massive influx of people; the city experiences continuing proliferation of high-rise buildings. This has an implication on high energy consumption. According to Ali and Al-Kodmany, (2012), high-rise buildings utilise higher amounts of energy and materials resources for the construction and to operate.

Therefore there is a need to align with the design-based approach solution for high-energy performance buildings as been specified by UNEP Climate Change Action for resilient cities and communities (UNEP, 2021). While numerous similar research exist, presenting this study to depict actual cooling energy saving potential of a circular- shaped high-rise office building in Nigeria scenario cannot be over emphasised. A previous study on Lagos high-rise office buildings showed that the level of adoption of design approaches to enhance reduction in cooling energy is low, although, the use of day-lighting techniques and sustainable lighting systems was quite prominent in the office buildings studied, (Ezema and Maha, 2021).

Similar and previous studies showed that building form has significant effects on building energy demand because building form affects heat exchange in building systems. Studies such as Zang et al. (2017) presented the influence of plan shapes on the annual energy consumption of residential buildings in Tianjin, China through dynamic simulation with Design Builder software, and results indicated that plan shapes of buildings exert a significant influence on energy consumption. Catalina et al. (2011) found a 6-10 % reduction in heating energy consumption in a more compact cubical shape building over a rectangular-shaped one in France when thermal simulations were performed with consideration to the glassing area. The building form is very important to energy-efficient design as it affects heat exchange within the interior and exterior of the building.

Therefore, the focus of this study is to determine the energy-saving output while adopting appropriate and efficient building forms during the design stage of a high-rise office building in Lagos, Nigeria. Consideration is given to the window wall ratio of the base case high-rise office building for warm-humid climate characteristics of the Eko Atlantic city area of Lagos, Nigeria. This is to further enhance the decision making on adoption of efficient form in high-rise buildings and policy making on mitigation and resilience to climate change action for sustainable cities in Nigeria.

1.1 Building Form and Energy consumption in High-Rise Buildings

High-rise buildings are also known as multi-story buildings. They are often iconic, depicting the confidence and status of a nation's growing economies. They also enhance global recognition (Ali & Al-Kodmany, 2012). A higher amount of operational energy is needed in high-rise buildings. It is important to make the design of high-rise buildings energy efficient to reduce energy consumption (Suri, 2017). Building forms generally affect energy transfer from the exterior to the interior of building systems. It significantly affects cooling energy demand for the comfort of occupants. The building shape and climate of an area mostly affect thermal energy consumption (Deng et al. 2020).

Wood and Salib (2013) stated that HVAC in tall office buildings typically accounts for 30-40% of total building energy consumption. The average energy consumption of a typical high-rise office building in the US shows the percentages of energy consumed by various activities such as equipment 32%, lighting 29%, heating and cooling 33%, water system energy 6%, fans, water and control 6%. The implication is that space cooling and heating constitute highest amount of energy consumed which could be reduced through efficient building form (Yassen, 2017).

Although, adoption of an efficient building form alone could not bring the desired cooling energy savings in high-rise buildings, but it is one of the passive design strategies that can contribute to energy savings and realise energy efficient buildings. By this, there would be reduced dependence on energy sources that exert negative impact on the environment.

2.0 Methods

2.1 Study area and climatic characteristics

Lagos is a commercial city in the South-Western part of Nigeria (figure 1) and one of the fastest-growing cities in the world. It lies between latitudes 6°22′ North to 6°42′ North and longitude 2°45′ East to 4°20′ East, at an altitude of 645 m above sea level (Sojobi et al.2015). Lagos is situated along the Atlantic Coast in the Gulf of Guinea, stretching over 180 kilometers. It occupies about 3,577 square kilometers, approximately 0.4 percent of Nigeria's landmass, with about 220.6 square kilometers made up of water bodies, mangrove swamps, and wetlands (Lagos State Government 2013).

The city is of a warm-humid climate with the highest monthly average temperature of 29 Degree Celsius occurring in February and March (Adebamowo et al. 2013). It experiences two climatic seasons; the rainy season from April to October which is characterised by wet and humid conditions and the dry season from November to March being characterised by dry and cold (harmattan) conditions. The city has an annual average precipitation of 1000mm and an annual average temperature of 23-34 Degree Celsius (Lagos State Government 2013). It is of a wet equatorial climatic condition because of its proximity to the Gulf of Guinea along the Atlantic Ocean (Meteoblue, 2020). Lagos experiences high humidity throughout the year between 80-90% (Figure 2). The population of Lagos is estimated to be approximately 16 million people with a 3.54% increase from 2021 (Macrotrends, 2022). In a quest to be integrated into the global economic system coupled with the massive influx of people, the city experienced increased population growth and thus faced the problems of urban development management.

Figure1: Map of Nigeria showing Lagos (Adapted from Magellan Geographic. Santa Barbara, 1992)

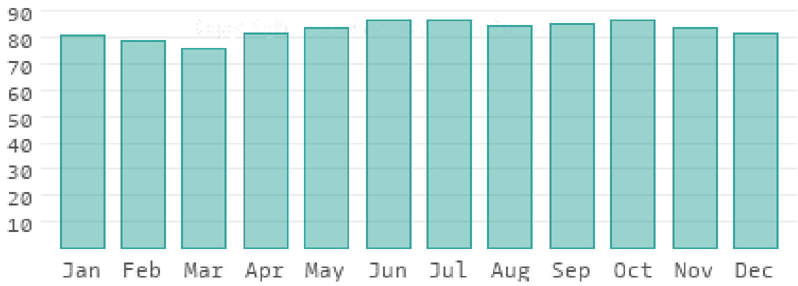

Figure 2: Average Monthly Humidity for Lagos
Source: https://www.worlddata.info/africa/nigeria/climate-lagos.php

2.2 Soft wares

The use of both Building information modeling (BIM) and Building energy modelling (BEM) tools is very crucial to achieving energy-efficient buildings from the conceptual stage. These tools are relied upon to carry out modelling and simulation in this study. Autodesk energy simulation package was employed which makes the transfer of files from one software to the other easy. This process helps to prevent interpolation issues from the modelling software to the energy analysis software. The Building energy model was created with the use of Building information modelling software, Autodesk Revit; the energy analysis software, Green Building Studio and Insight 360 to create the analysis and impact of some variables on the building performance.

Autodesk Revit 2020 is a BIM software for modelling in 2D and 3D with parametric accuracy, precision, and ease. It is used to generate the model for the case building in this study. On the other hand, Green Building Studio is cloud-based and flexible, allowing building performance simulation to be run to optimize energy efficiency earlier in the design process (Autodesk Green Building Studio 2022). Detailed energy analysis to compare different scenarios is performed in this study with Autodesk Green Building Studio.

Insight 360 is an Autodesk cloud-based software plugin for the Revit model with the possibility to adjust zones and schedule the loads. It can be used to simulate heating, cooling, and lighting energy. Inputs are taken directly from Revit. It also allows users to adjust critical parameters early in the conceptual phase (Autodesk 2022). It is adopted for the energy analytical modelling of the base case high-rise buildings.

2.3 Building Modelling and Energy Simulation

The methodology involves three distinct phases. Phase 1 is the determination of the building form and selection of the geographical location since this study seeks to compare two predominant building forms in Nigeria; the rectangular shape form (which is the most common form for high-rise buildings in Lagos) and the cylindrical shape form. The geographical location for the research is Eko Atlantic city which is a newly developed area from reclaimed land along the Lagos coastline.

Phase 2 consists of building energy model development. The modelling was done using Autodesk Revit 2020 software and the location was selected in the energy setting. The analysis of the model was carried out by specifying the geographical location and weather station in Revit's projects browser. Specifying the location is important as the distant location within the city may have varying weather characteristic which may cause an error and leads to inaccuracy in the result of the simulation. The model is an office building with a floor area of 88,200 squared meter and a human capacity of 32,000 people. The height of the model building is 210 m.

Phase 3 is the detailed building energy performance with the percentages and comparative analysis of various energy reduction options carried out with Green Building Studio. The building energy simulation for the base case high-rise building model was performed by creating the analytical energy model from the analytical energy parameters and then exported to Autodesk Insight 360 and Green Building Studio. The energy and environmental performance data were accessed in Insight 360. Design options and potential performance outcomes were generated.

The base run construction parameters for the simulation are shown in table 1. Values and specifications for the two case models; rectangular and cylindrical shape buildings' roofs, exterior walls, interior floors, windows and slabs were indicated (Table 1).

Table 1: Base run construction for building models

base run construction	building parameter specification	rectangular building	cylindrical building
Roofs	R20 over Roof Deck - Cool Roof U-Value: 0.26	1,764 m²	1,749 m²
Exterior Walls	R13 Wood Frame Wall U-Value: 0.49	35,384 m²	27,793 m²
Interior Floors	Interior 4in Slab Floor U-Value: 4.18	88,200 m²	87,378 m²
Slabs On Grade	Slab edge uninsulated U-Value: 0.17	1,764 m²	1,748 m²
Fixed Windows	North Facing Windows: Pilkington RW33 double glazing (1/4 in + 1/4 in) (102 windows) U-Value: 2.86 W / (m²-K), SHGC: 0.76 , Vlt: 0.81	7,931 m²	5,123 m²
	Non-North Facing Windows: Pilkington RW33 double glazing (1/4 in + 1/4 in) (306 windows) U-Value: 2.86 W / (m²-K), SHGC: 0.76 , Vlt: 0.81	23,792 m²	20,929 m²

Source: Author's Computation (2022)

3.0 Simulation Result and Analysis:

The climatic data obtained from Apese, Lagos State Meteorological Station was used to perform the simulation of the building. The simulation results showed the energy use intensity for the rectangular-shaped building having a total of 811.2 MJ/m²/year (Table 2). Space cooling consumes 36.6 % of the total energy use, while figure 3 shows other aspects of energy consumption by the building. Furthermore, the energy use intensity for the cylindrical-shaped building gives a total of 774.1 MJ/m²/year (Table 3). Space cooling consumes 35.8 % of the total energy use, while figure 4 shows other aspects of energy consumption by the building.

Table 2: Total energy use intensity for rectangular shaped building model

WWR 60% Lagos Rectangular building form	Location: Apese, Lagos State Building Type: Office Floor Area: 88,200 m² Electric Cost:$0.09/kW Fuel Cost: $0.01 / MJ	Energy Use Intensity (MJ/m²/year) 811.2

Source: Author's Computation (2022)

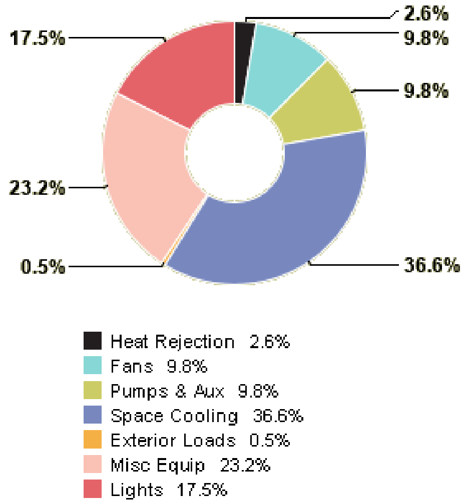

Figure 3: Simulated Energy consumption for Rectangular Shaped Building
Source: Author's Computation (2022)

Table 3: Total energy use intensity for cylindrical shaped building model

WWR 60% Lagos Cylindrical Building Form	Location: Apese, Lagos State Building Type: Office Floor Area: 87,384 m² Electric Cost: $0.09/kWh Fuel Cost: $0.01 / MJ	Energy Use Intensity (MJ/m²/year) 774.1

Source: Author's Computation (2022)

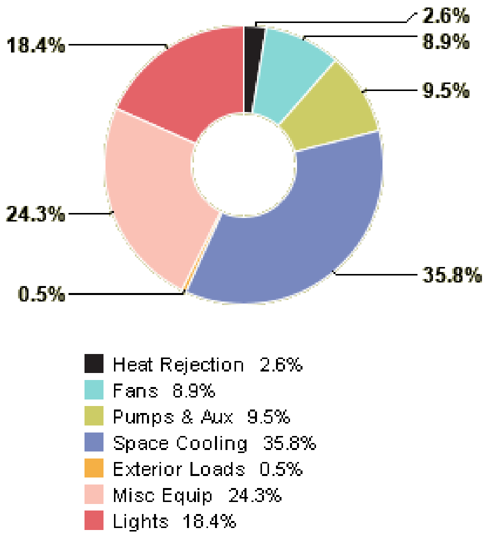

Figure 4: Simulated Energy Consumption for Cylindrical Shaped Building
Source: Author's Computation (2022)

3.1 Building form and total energy consumption

Simulation for the two building models was performed with the same climactic data from Lagos. 60% window wall ratio was used as the baseline for the opening in the building to compare the relationship between the performance of two high-rise buildings' shape and the energy consumption. Based on the simulation result, the cylindrical-shaped building has a 4.57% reduction in the total annual value of energy consumption. The rectangular building consumes 811.2 MJ/m²/year, while the cylindrical building consumes 774.1MJ/m²/year (Figure 5). This energy analysis gives an annual energy reduction value of 37.1MJ/m²/year.

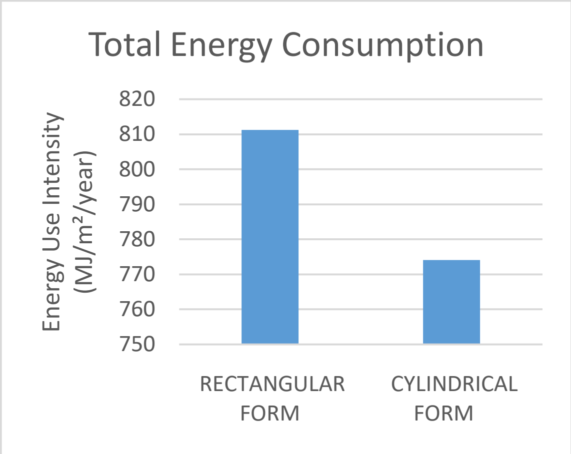

Figure 5: Total energy consumption for rectangular and cylindrical building form models
Source: Author's Computation (2022)

3.3 Building Form and Cooling Energy Consumption

The simulation result shows 36.6 % of the total energy consumption for space cooling in the rectangular-shaped high-rise building and 35.8% for space cooling in the cylindrical-shaped high-rise building (Figure 6). Rectangular building form consumes more cooling energy than cylindrical building form. An energy-saving value of 19.79 (MJ/m²/year) was obtained in the cylindrical building form compared to the rectangular form building. The total cooling energy consumption by rectangular and cylindrical shaped buildings are 296.9 MJ/m²/year and 277.1 MJ/m²/year respectively, (Figure 6). The outcome of energy saving from cylindrical shaped high-rise office building over rectangular shaped high-rise office building is corroborated by Lapisa, (2019), where an extensive numerical simulation was performed using TRNSYS (R) and CONTAM (C) softwares under mono-zone thermal design to show that a compact building shape with appropriate orientation reduce the energy consumption for cooling and heating systems up to 81%.

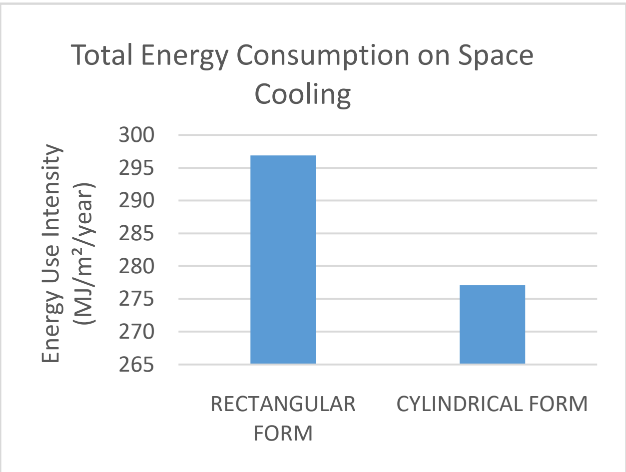

Figure 6: Space cooling energy consumption for rectangular and cylindrical building form models
Source: Author's Computation (2022)

4.0 Conclusion

This study has investigated the effects of building shape on the energy consumption of high-rise office building models. A comparison of rectangular and cylindrical building shapes was carried out. Results have indicated that the cylindrical-shape building model has a lower space cooling energy of 19.79 (MJ/m²/year) compared to a rectangular building. Moreover, the cylindrical-shaped building has a 4.57% reduction in the total amount of energy in use annually. A total value of 37.1MJ/m²/year of energy reduction was achieved annually. The cylindrical-shaped building has a better cooling energy performance than rectangular-shaped building. Consequently, cylindrical building form should be adopted for new building designs to save cooling energy demands within the warm humid climate region of Lagos, Nigeria.

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