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# The Effects of Rhythm on Building Openings and Fenestrations on Airflow Pattern in Tropical Low-Rise Residential Buildings

Peter I. Oforji [1], Emeka J. Mba [2*], Francis O. Okeke [2, 3*]

[1] *Department of Architectural Technology, Institute of Management Technology Enugu, Nigeria.*

[2] *Department of Architecture, University of Nigeria, Enugu Campus, Nigeria.*

[3] *School of Engineering, Technology and Design, Canterbury Christ Church University, Kent, UK.*

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**Abstract**

Effective passive airflow in low-rise residential buildings in hot-humid environment is crucial to maintaining good indoor thermal comfort for occupants. However, investigation of effects of the rhythm of window openings on achieving a passive airflow pattern in such buildings in the tropical climate of sub-Saharan Nigeria have been rarely studied. Therefore, this research aimed to evaluate the effects of the rhythm of window openings on passive airflow patterns for indoor thermal comfort in low-rise residential buildings in the hot-humid environment of Obosi, Nigeria. It involved experimental research using the Anemometer TA465 instrument for measuring wind velocity, relative humidity, and temperature of the purposively designated buildings in the three layouts of the study area for both wet and dry seasons. Employing the Yamane statistical formula, a sample size of 433 was obtained, and questionnaires were administered to occupants of the studied buildings and analyzed using categorical Regression Analysis (CATREG). The regression analysis showed that p=0.000, i.e. p<0.05 indicating that there was a significant relationship between the type and sizes of windows (elements used in measuring rhythm) and the intensity or force of breeze (a measure of passive airflow pattern). Further analysis of the data involved the use of Autodesk CFD 2018 (Computational Fluid Dynamics) for building wind flow simulations. The result showed variations in temperature levels (indications of differences in indoor thermal comfort) of various indoor spaces of the investigated designated floors and buildings, especially ground floors and the top-most floors of the buildings. The study underscored the need to use architectural rhythm design strategies to create a positive impact on airflow patterns in low-rise buildings, especially in densely built-up urban areas. The results of this study are instructive in noting that in order to attain passive airflow in buildings in the face of challenge of land restrictions, vertical stacking of building floors could be used once an adequate rhythm of window openings is adopted.

*Keywords:* Window Openings; Rhythm; Passive Airflow; Residential Buildings; Obosi.

## 1. Introduction

Rhythm in architecture is a design process that involves the regular and harmonious recurrence or repetition of a specific element derived from the categories of line, shape, form, color, light, shadow, and sound [1]. Basic to this definition of rhythm is the emphasis on repetition as a persuasive strategy to co-ordinate attitudes and as an instrument of repetitive purpose [2]. From the perspective of design cognition, the peculiarity of the principle of rhythm as a unique design attribute of the majority of low-rise residential buildings It is an aspect of the human cognitive process that involves collecting, gathering, recognizing, recollecting, memorizing, recalling, and processing design information [3, 4]. Rhythm is seen in such a direction as a concept that is generated by designers through some process of cognitive

* Corresponding author: emeka.mba@unn.edu.ng; f.okeke142@canterbury.ac.uk

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thought; however, it is recognized visually as appealing to the human consciousness, making it universally appealing to architects as a key component of design [1]. Because of this, Spence [5] concluded that the eye and sight have dominated architectural practice.

Rhythm as an architectural design principle has a significant influence on a building's aesthetic value, structural design, and functional performance. Since rhythm can influence a building's functional performance, its studies are necessary in mitigating the current harsh climatic conditions and escalating negative global environmental statistics with visible repercussions, as opined [6]. That is why thermal comfort studies and assessments of the built environment (housing satisfaction) are increasingly gaining prominence among scholars and practitioners [7, 8]. The visual effect of rhythm is dominant on building facades and fenestrations. According to Ajay [9], the design of fenestration is considered one of the challenges designers encounter in achieving natural ventilation efficiency for thermal comfort in buildings, since fenestration has evolved from being just essentially passive systems to also having some amount of control over the internal conditions of buildings [10]. This results from the rising dependency on and use of mechanical systems for lighting and ventilation of indoor spaces, which before now were the primary functions of building fenestration [11].

Hence, as noted by Okpalike et al. [10], in the conceptual design phase of any project, the selection of façade type, its arrangement, and the size of the fenestration system have a significant effect on determining how the building will function and also the airflow rate necessary to maintain indoor environmental quality for users' comfort and safety. This was emphasized by Ayoosu et al. [12] that window placement and fenestration size are pivotal to the quality and quantity of natural ventilation and daylight a building receives, particularly in the tropics, where Okeke et al. [13] stressed the importance of permitting more natural fresh air into the building for human thermal comfort. Therefore, building fenestrations should be utilized in buildings not just to provide visual interest to the façade but also as a tool for designers to create internal spaces that are conducive and more user-friendly. In a hot-humid environment, maintaining adequate indoor thermal comfort in spaces is more difficult because of the adverse climatic conditions, increased intensity of solar radiation due to global change in climate, high energy consumption, and emissions [7]. All this negatively impacts the indoor thermal comfort condition of residential buildings, thus calling for literature reviews on examinations, determinations, and interpretations of the various variables to enhance the indoor thermal comfort of residential buildings.

The growing concern for the quality of the indoor environment, combined with the need to reduce pollution emissions and energy consumption, has prompted a greater use of more efficient ventilation strategies. Research is mostly focused on natural (passive) ventilation because of its wide acceptance by occupants and property investors [14, 15]. The appropriate level of indoor thermal comfort in low-rise residential buildings depends on natural ventilation, which, according to Ramponi & Blocken [16], is a valuable factor in the development and maintenance of sustainable and healthy indoor environments. This was further emphasized by [17–20] that passive ventilation promotes the health of buildings and occupants. Natural ventilation is driven by wind or buoyancy, forming the airflow pattern, or most often a combination of both wind and buoyancy [21–23]. The natural performance of buildings (low-rise residential buildings) has attracted researchers for some decades. A comprehensive review of the methods for analyzing the wind ventilation performance and its prediction on buildings was provided by Chen [19], articulated by Ramponi & Blocken [16], with other literature reviews provided by [24–26].

The evaluative assessment of wind ventilation performance, which involves the implementation of the architectural design principle of rhythm that defines the building elements and fenestrations, involves prediction methods for natural ventilation [16]. Other researchers [17, 27–29] used rhythm in their experiments to show that ventilation performance can be improved by adequate airflow between the outdoor and indoor environments, which enhances thermal comfort in low-rise residential buildings. Besides, other studies have been done on the natural ventilation induced by airflow around buildings. a) the effects of airflow around buildings under various prevailing climatic conditions [30], b) the distribution of wind pressures and effect of wind pressure coefficients on building surfaces [21, 31], and c) the ventilation characteristics of open-window rooms and their effects on the indoor thermal comfort of the building [32].

In addition, based on the generic types of buildings in the tropics (for example, Nigeria), and especially in the study area showing some characteristics categorized by Guan et al. [32] in their studies on the natural ventilation induced by airflow around buildings, and because of their architectural design principle of rhythm influencing the airflow, this has attracted similar studies carried out in such scenarios. The clarification of the above assertions has involved some studies [33, 34] that have investigated the unsteady characteristics of wind pressure and its coefficient effects on building surfaces through experiments and dynamic numerical simulations. In addition, the contributions of Zhang et al. [35] and Martins & da Graca [36] described how arranging a group of buildings can directly influence the airflow field around an individual building and hence influence the surface wind pressure distribution. Also, studies carried out on building shapes categorized into low-rise and high-rise buildings determine the effects of the distribution of wind pressure co-efficiency of the buildings. Furthermore, the studies of Larson et al. [37] examined the effects of the cross ventilation rate of open-window rooms under various incident angles and the impact of wind velocities by adopting wind tunnel tests and numerical calculations.

All these studies have shown the existence of elaborate scientific research on the effects of airflow and the ventilation of buildings. Although there are still some questions regarding the effects of airflow on open-window buildings. In addition, the influence of airflow patterns and other climatic factors on improving indoor thermal comfort conditions as it relates to the generic-rhythm design form of low-rise residential buildings, especially in the tropics. van Ellen et al. [38] put forth a comprehensive framework focusing on adaptability and advocated for the adoption of rhythmic buildings as a strategy for future adaptable design. While their work explores the realm of adaptable architecture and its response to global sustainability challenges, it does not specifically address the role of the rhythm of architectural design elements in air flow conditions. The study of Okafor et al. [39] provided insight on indoor thermal comfort values in warm, humid tropics; however, it is a comparative evaluation of the internal thermal comfort characteristics of traditional and modern buildings in Nigeria. Thus, there is a dearth of literature on the evaluative analysis of the effects of rhythm on building openings and fenestrations on airflow patterns in tropical low-rise residential buildings, especially in the sub-Saharan environment, creating a research gap. Okpalike et al. [10] and Mba et al. [40] are recent studies on natural ventilation in the tropics using architectural design strategies of building orientation and fenestration types, respectively, with a focus on residential and educational facilities.

From the foregoing and in consonance with Gossauer et al. [41], the current study contends that the search for passive solutions to achieving a thermally conducive indoor environment must start with the building design features that admit air. Based on these, the target is to evaluate the effect of passive airflow patterns on indoor thermal comfort in low-rise tropical residential buildings and suggest solutions for enhancing it. The emphasis in this study is aimed at rhythm as an architectural design principle assumed to affect building elements and fenestrations at various levels; it determines the extent to which the outdoor airflow pattern affects the indoor thermal comfort in buildings. Therefore, the study involves the integration of rhythm as an architectural design principle taken from the peculiar characteristics of the low-rise residential buildings in the study area. It aims to investigate the effects of rhythm as an architectural design principle on building openings and fenestrations and airflow patterns in the tropics. This current study is to address the research question of to what extent rhythm as an architectural design principle on building openings and fenestrations affects airflow patterns and indoor thermal comfort conditions in low-rise residential buildings in tropical climates. Furthermore, the hypothesis tested in this study is:

***$H_0$:*** There is no significant relationship between Rhythm as architectural design principle and passive airflow pattern in low-rise building in the study area.

The significance of the information gathered from the study will be relevant in advocating the implementation of the architectural design principle of rhythm for large open windows and fenestrations in low-rise residential buildings in order to enhance airflow patterns and indoor air circulations in buildings. Furthermore, the study would assist architects and designers in working towards providing proper building opening sizes and positions for effective passive airflow to maintain adequate indoor thermal comfort. This may be achieved by using the architectural design principle of rhythm for wall openings and indirectly advocating building elements that will enhance passive indoor thermal comfort in low-rise residential buildings under the prevailing climatic challenges of the tropics.

### 1.1. Limitation of the Study

The study faced several challenges due to factors such as private ownership of the buildings under investigation, limited accessibility to designated room spaces, and low levels of literacy among respondents, leading to inadequate questionnaire responses and communication issues during the investigation. Additionally, there was a lack of timely access to documentary resources from the appropriate authority, further limiting the research process. However, the authors took proactive measures to address these challenges. With ethics approval, they conducted intimate sensitization sessions with the respondents and occupants, effectively conveying the purpose of the study. Researchers had extensive oral meetings and consultations with residents and stakeholders in their local dialect. This resulted in increased acceptance and cooperation, allowing the investigation team to access private designated building spaces for data collection through experiments, physical measurement, and questionnaire administration.

## 2. Research Methodology

In this current study, rhythm is assumed to be the design concept that involves repetitious shapes and sizes of building openings and fenestration elements that influence the extent of airflow patterns in the interior of buildings. The study therefore adopted a combination of experimental and survey research designs. Groat & Wang [42] rightly noted that besides maintaining credibility and efficiency of research procedures, this research design is effective in determining causality. The study employed a comparative experimental design that involved the comparison of two prevailing seasons (events) in the areas of study with the probability of obtaining the same results. It also involved the use of building physics equipment—Autodesk CFD 2018 (Computational Fluid Dynamics)—for data analysis. The research population consisted basically of low-rise residential buildings within the designated three layouts of Obosi, Idemili North Local Government Area of Anambra State, South-East Nigeria, which included the Awada, Ugwuagba, and Ozalla layouts. Figure 1 shows the study area in detail.

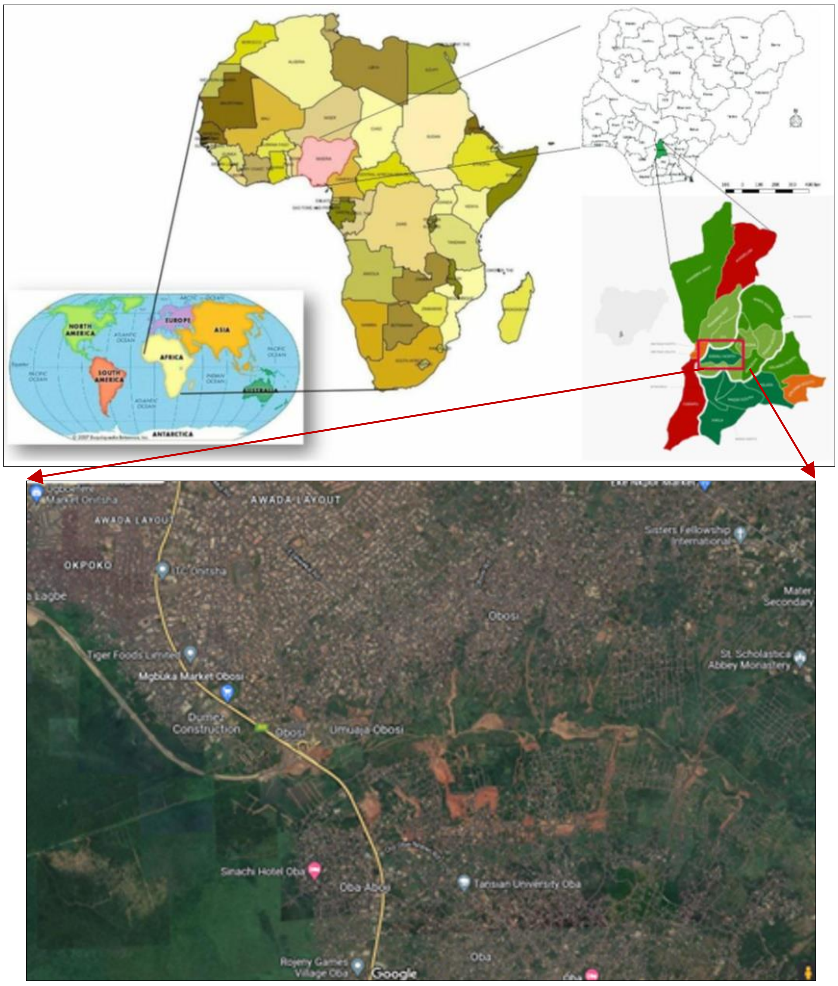



**Figure 1. A map of the Obosi Nigeria (study area)**

## 2.1. The Survey

A survey of the buildings in the study area revealed the following:

- The buildings in the study area were mostly four-story blocks of flats.
- All the buildings in the layout were 3-bedroom blocks of flats with four different architectural designs, providing the four prototype building types (A, B, C, and D) used for the simulation investigations.
- The architectural design features of the building required vertical stacking of building floors to provide enough accommodation for the high population demand.
- Typical architectural design features of the buildings in the study area included the provision of balconies where necessary, typical prototype floors, inconsistent headroom heights, and less than 3 meters. This resulted in differences in the sizes of the doors and window openings in the buildings.
- Inconsistency in the offset of building perimeters from property lines as a result of non-adherence to building codes and bye-laws of the area.

The sampling frame of the study comprised three layouts namely: Awada, Ugwuagba and Ozalla layouts based on the estimated number of low-rise residential buildings from the recorded information of Idemili North Town Planning Authority of the Local Government Area (INTPA) (Table 1).

**Table 1. Estimated number of low-rise residential buildings at Obosi, Idemili North Local Government Area, Anambra State**

| Scheme | Names of Layouts | Estimated number of low-rise residential buildings |
|---|---|---|
| 1 | Awada layout | 10,518 |
| 2 | Ugwuagba layout | 9,529 |
| 3 | Ozalla layout | 7,036 |
| | **Total** | **27,083** |

Source: Idemili north local government area, town planning authority [43].

The estimated total number of low-rise residential buildings in the study area was 27083, and this was the sampling frame for the distribution of the questionnaire because each building occupant was actively involved in the study. The Taro Yamane formula was employed to generate the sample size because the population size is finite (known).

## 2.2. Using Taro Yamane Formula to Determine Sample Size

The derived sample size of the study was 433 determined using Taro Yamane Formula:

$$n = \frac{N}{(1+Ne^2)} \tag{1}$$

where, $n$ is sample size, $N$ is population size and e is margin of error = 0.05.

Given that our population of low-rise residential buildings is 27083, then:

$$n = \frac{27083}{(1+27083(0.05)^2)} = \frac{27083}{1+67.7075} = \frac{27083}{68.7075} = 394.1782 \sim 394 \tag{2}$$

Using the names of layout as strata and applying proportional allocation, the sub-samples become:

1) Awada Layout: $\frac{10518}{27083} \times 394 = 153.0145{\sim}153$ approximately;
2) Ugwuagba Layout: $\frac{9529}{27083} \times 394 = 138.6266{\sim}139$ approximately;
3) Ozalla Layout: $\frac{7036}{27083} \times 394 = 102.3588{\sim}102$ approximately;

However, attrition of 10% gave a sample size of 433 for the non-respondents. Then using the names of layout as strata and applying proportional allocation, the sub-samples become:

4) Awada Layout: $\frac{10518}{27083} \times 433 = 168.1609{\sim}168$;
5) Ugwuagba Layout: $\frac{9529}{27083} \times 433 = 152.3485{\sim}152$;
6) Ozalla Layout: $\frac{7036}{27083} \times 433 = 112.4907{\sim}113$.

**Table 1. Estimated Sample Size of Low-rise Residential Buildings at Obosi, Idemili North Local Government Area, Anambra State, with 5% margin of Error**

| S/N | Names of Layouts | Estimated number of low-rise residential buildings | Sample size of low-rise residential buildings with 5% error margin | Sample size of low-rise residential buildings with attrition of 10% |
|---|---|---|---|---|
| 1 | Awada layout | 10,518 | 153 | 168 |
| 2 | Ugwuagba layout | 9,529 | 139 | 152 |
| 3 | Ozalla layout | 7,036 | 102 | 113 |
| | **Total** | 27,083 | 394 | 433 |

Source: Idemili north local government area, town planning authority, Anambra State, 2018.

A random sampling technique was used to select the four prototype buildings (A to D): 2 in Awada, 1 in Ugwuagba, and 1 in Ozalla based on the estimated number of buildings (see Table 2). The purposive sampling technique was then used to choose a living room, a bedroom, a kitchen, and a balcony on each ground and fourth floor of the selected prototype buildings for investigations based on the availability and willingness of occupants to participate in the study. For four days in the months of March (dry season) and October (rainy season) in 2018, multi-functional anemometers TA465 were used to collect data from the specified spaces for climatic variables of temperature, relative humidity, and wind velocity. In addition to the experimental investigations, modeling and simulation procedures were also performed on the building openings and fenestrations in the indoor spaces on the designated building floors. With the use of some scientific instruments, such as a magnetic compass to observe prevailing wind directions, a digital still camera was utilized to take photographs of the selected buildings. A 30.6-meter fiberglass and 3.6-meter metallic tape were used to measure external dimensions and openings in buildings. A scientific calculator was utilized for the mathematical complication required in data analyses. Also, data were collected from the administration of a questionnaire on the effects of poor design processes on the building openings and fenestrations of architectural design features in the study area. The results showed respondents reactions to (a) the height of individual spaces, (b) the types of window openings in the buildings, (c) doors as an alternative to airflow movement inside room spaces, and (d) window opening sizes and airflow patterns in buildings. Respondents indicated their physical observations of the effects of building openings and fenestrations on their various floors and how such differences affected their indoor thermal comfort.

Structurally, the questionnaire comprised a total of 13 questions with both nominal and ordinary structures. The questionnaire consists of two sections. The validity test of the model and simulation process was based on using simulation software in line with the strategy outlined by Fairley [44]. The reliability of the questionnaire was tested using the Cronbach method, wherein a Cronbach alpha of 0.77 was obtained, showing the high degree of reliability of the instruments used in the study and thereby authenticating the validity of the findings of the study.

The data collected for this study were analyzed based on the objective of the investigation and equally used to address the research question and hypothesis of the study. An as-built drawing of the designated building, as shown in Figure 2, was sketched and transferred to CAD to aid further analysis and building simulation.

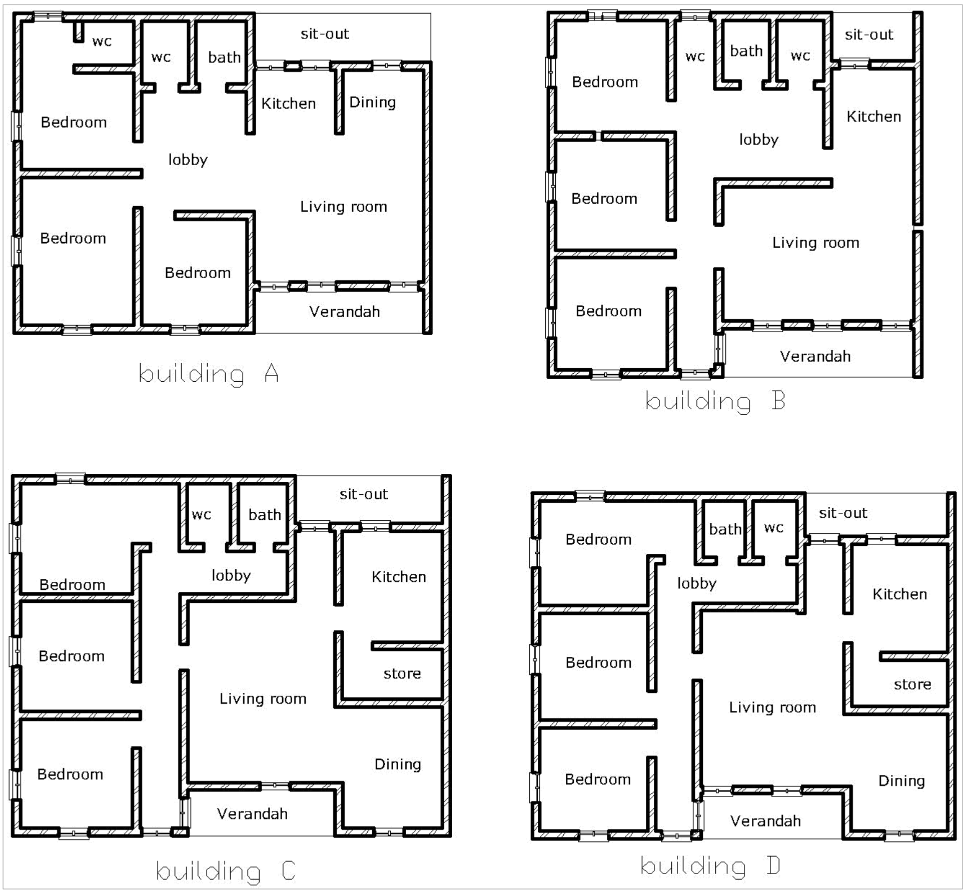



**Figure 2. Plans of the studied low rise residential building in the area**

Building plans A–D are the common plan shapes of low-rise residential buildings in the study area that were analyzed using Autodesk CFD 2018 software. Data collected from the airflow pattern and other indoor activities that affected air circulations were simulated with a model for the designated low-rise residential buildings, conditioned under their real environmental conditions. They were used to predict its effects on the designated spaces and interactions with other indoor climatic variables of the study.

## 2.3. Validating Autodesk Computational Fluid Dynamics (CFD) Data against Experimental Data

An example is given of building C on a more detailed simulation approach for validating the accuracy of Autodesk Computational Fluid Dynamics against the experimental data. The temperature calculated from the simulation is compared with the temperature measured. The input parameters are taken into consideration for model simulation, as shown in Table 3, however the balconies are not considered in the simulation.

**Table 2. Input parameters for building model**

| No. | Parameters for Building C | Input values meters |
|---|---|---|
| 1 | Building height | 3000 mm |
| 2 | Window width | 1200 mm |
| 3 | Window sill height | 900 mm |
| 4 | Window height | 1200 mm |

The model simulation took into account specific input parameters, as indicated in Table 3, to address the particular aspects of the study, which focused on the interaction of indoor airflow patterns and their impact on indoor thermal conditions through building openings or fenestrations. Building height was considered to determine the optimal height that would facilitate desired airflow patterns and influence the indoor environment. A value of 3000mm was chosen to provide suitable movable spaces and adequate headroom for airflow, thereby enhancing indoor thermal comfort and promoting air circulation within the space. In the case of building model C, the input parameters included window width (1200 mm), window sill height (900 mm), and window height (1200 mm). These parameters were specifically chosen to represent the window sizes and fenestration designs of the low-rise residential buildings in the study. They served as standardized building openings and fenestrations, allowing for controlled airflow within the designated building spaces. Balconies were excluded from the investigation as they did not offer precise, standardized enclosures or controllable spaces to examine the permissible airflow inside the buildings. The study focused on the sensitivity of window parameters and their impact on the standardization of building openings and fenestrations in the designated low-rise residential buildings. Although the authors did not experiment with other social parameters, Since building occupants serve as a valuable resource for gathering data about the performance of buildings, indoor environmental quality, and their impact on comfort and productivity [45], the authors relied on administering questionnaires to get respondents reactions to parameters that may differ from the designated values used in the CFD modeling. The analysis of their responses is shown in the result section.

Building C, modeled using Autodesk Revit, is shown in Figure 3. This model reveals the building walls, window openings, and interior air volume to show air flow movement in Autodesk CFD. In the process of designing a computational fluid dynamics (CFD) model, grid convergence is an essential step to achieving optimal results. However, the grid independence test process lacks standardization. To select the optimal grid, a random sampling method was employed to compare CFD results for different grid conditions of the target model. The flow rate, temperature, and other relevant indicators were analyzed across different simulation models to determine the optimal grid. Specifically, coarse, medium, and fine grids were selected and tested. After comparing the results, the medium grid was determined to be the optimal grid and was subsequently utilized for the simulation.

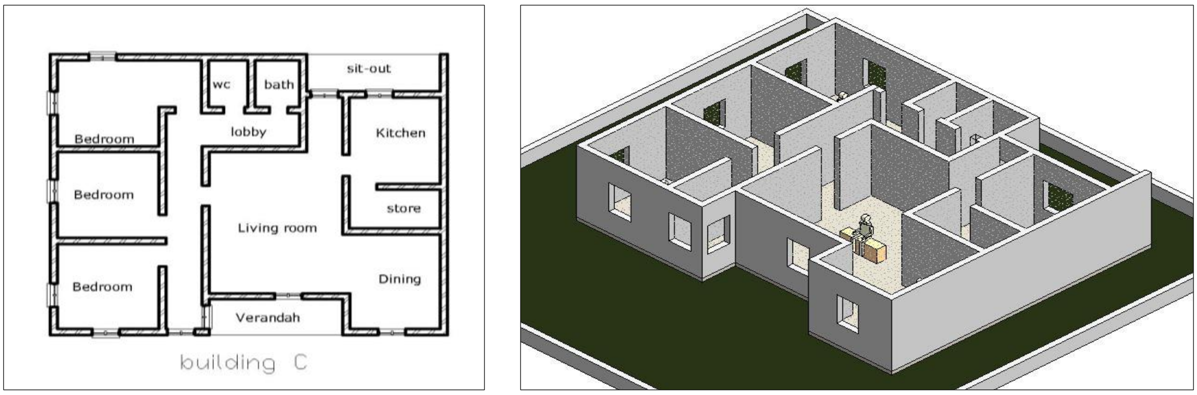



**Figure 3. Building C floor plan and 3D model in Autodesk Revit 2018**

Scenario Environment: The boundary conditions defined the environment. Autodesk CFD 2018 software for model and simulation processes for Building C and integrating all the climatic factors affecting the building model, with coefficient (u-values) of the wall at 3.11 W/m$^2$.k, under pressure of the study area as 101200 Pascal (Pa), Building C during the dry season. The Scenario Environment from Autodesk CFD is shown in Figure 4. Boundary conditions for the simulation are stated and shown in Table 4.

**Table 3. Boundary conditions for building model C**

| Parameters for Boundary conditions | Input values |
|---|---|
| 1. Film with coefficient (U-values) | 3.11 W/m$^2$.K |
| 2. Pressure (Pa) | 0 Pa |
| 3. Temperature (Celsius) | 35.2 °C |
| 4. Total heat generation (Watts) | 60 W |
| 5. Relative Humility (%) | 50% |
| 6. Velocity (m/s$^2$) | 1.6 m/s$^2$ |
| **Other simulation Parameters** | |
| Scenario Environment (Pa) | 101200 Pa |

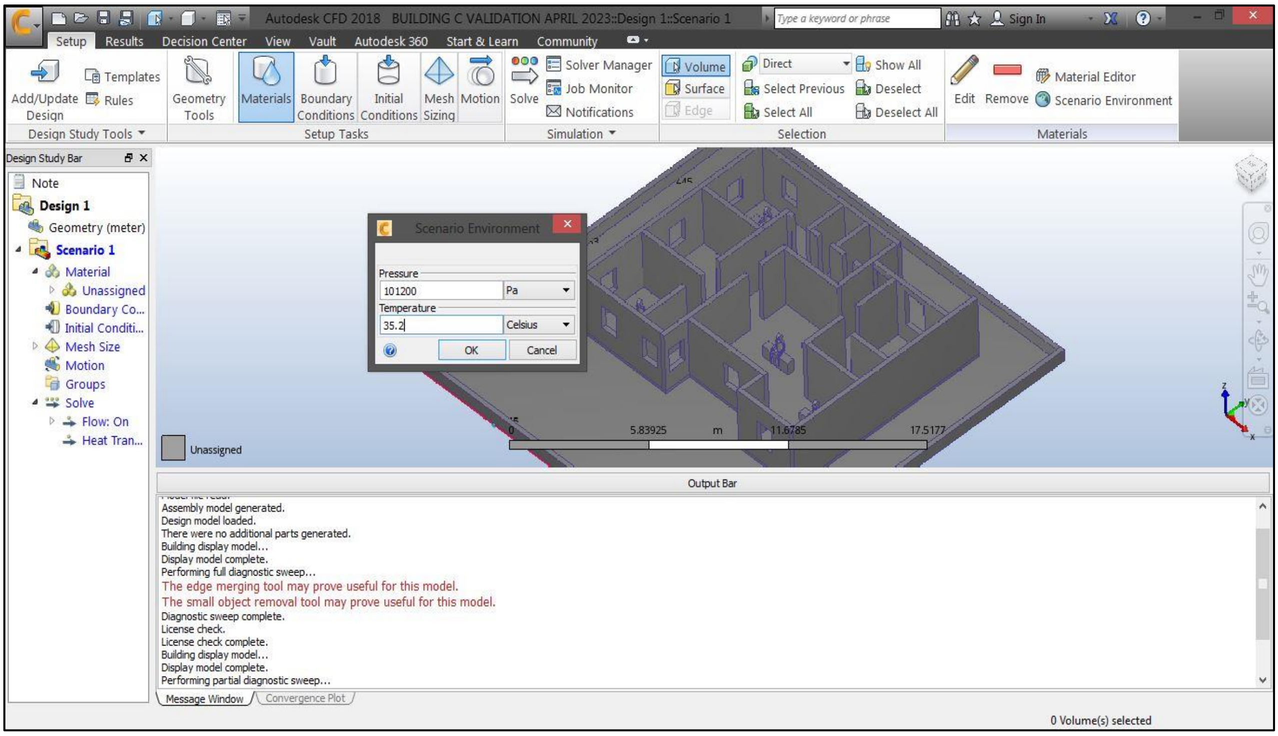



**Figure 4. Scenario Environment**

The film with the coefficient (u-values) of the wall at 3.11 W/m$^2$.k and the temperature (Celsius) set at 35.2 represents the external temperature and is the same as the scenario environment. Total heat generation (watts) set at 60 represents the metabolic rate of a human model. An average of the relative humility as shown in Figure 5 for building C in the dry season for the simulation was 50% (58.1+41.9=100/2), figures derived from Table 4 of the data presentation.

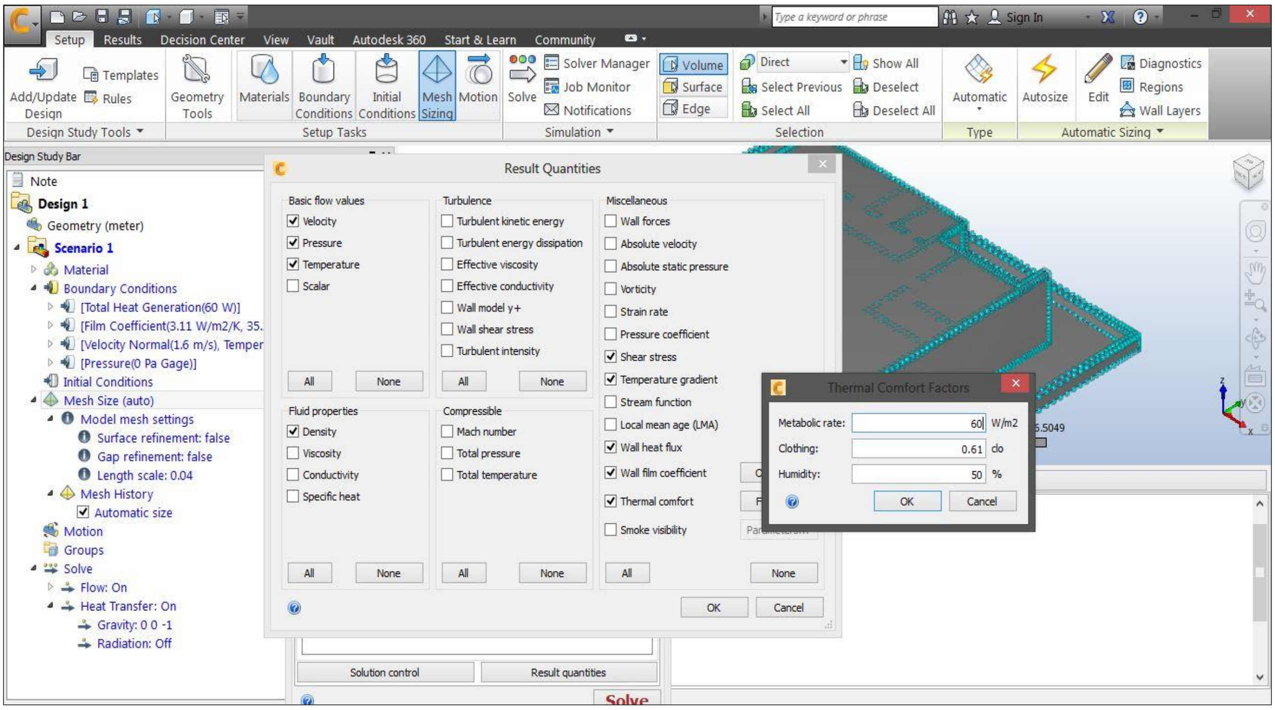



**Figure 5. Metabolic rate and Relative Humility**

Simulation results as shown below in Figure 6 show how airflow moves and initially the heat from outside is hot but gradually becomes cool as it circulates within the interior building space as shown in Figure 7 to Figure 9.

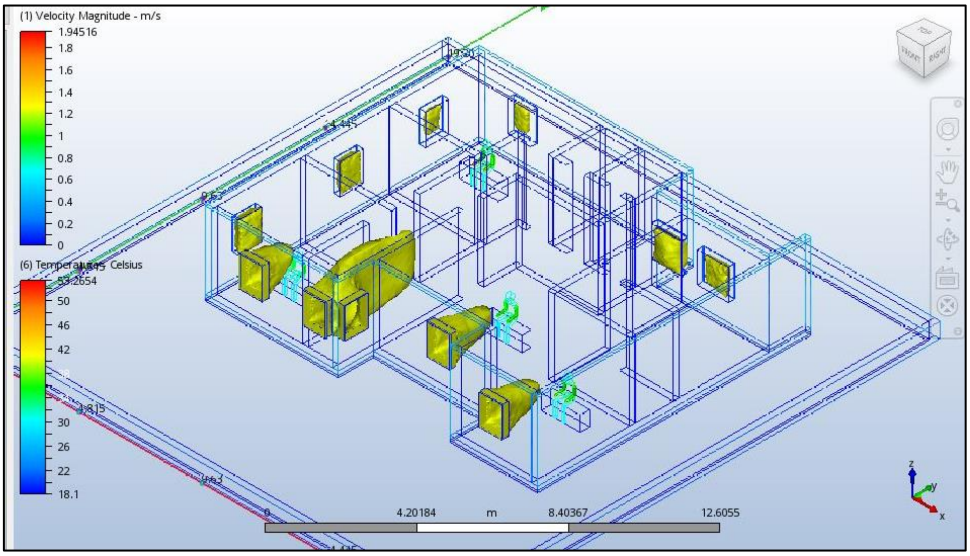



**Figure 6. Air flow Velocity and temperature**

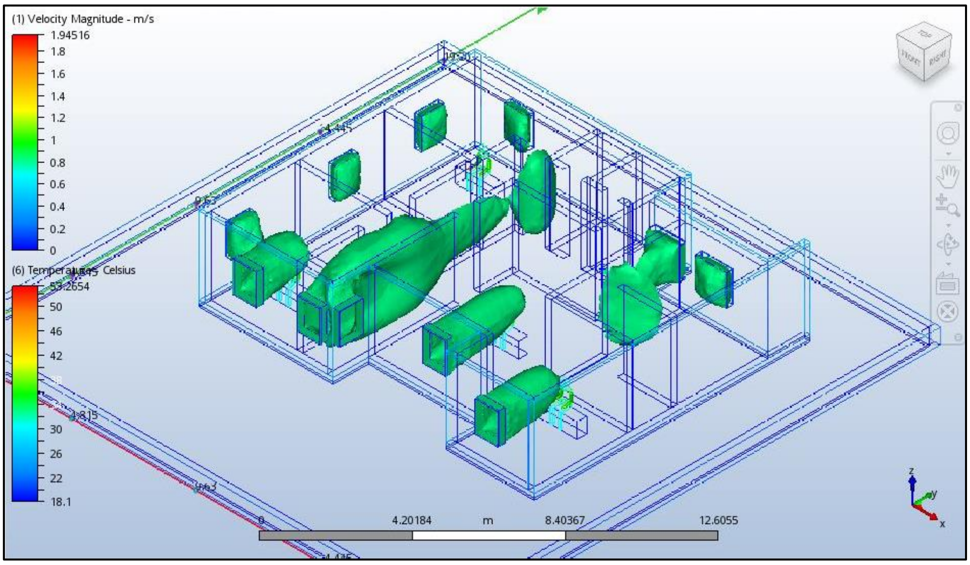



**Figure 7. Air flow Velocity and temperature**

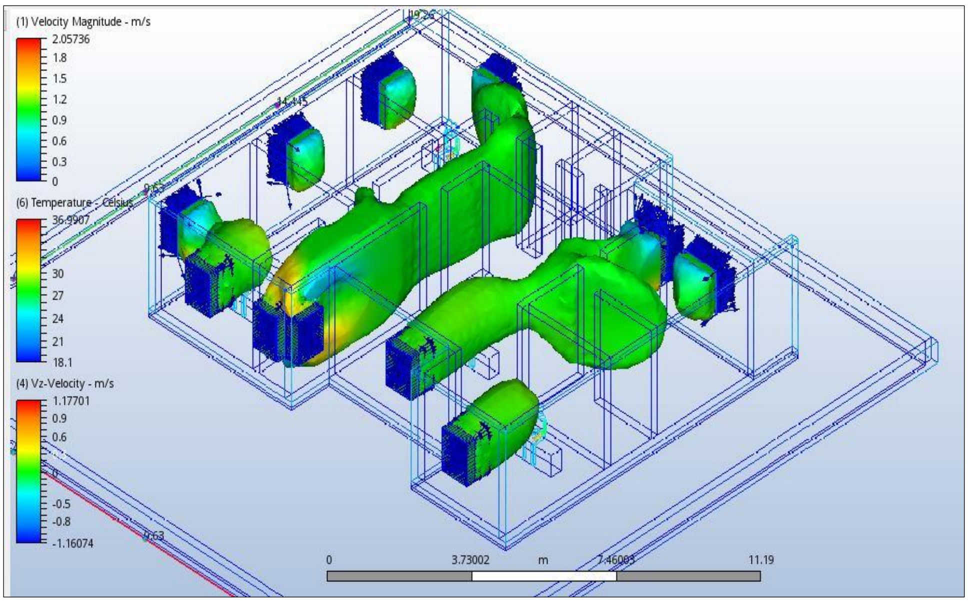



**Figure 8. Air flow Velocity and temperature**

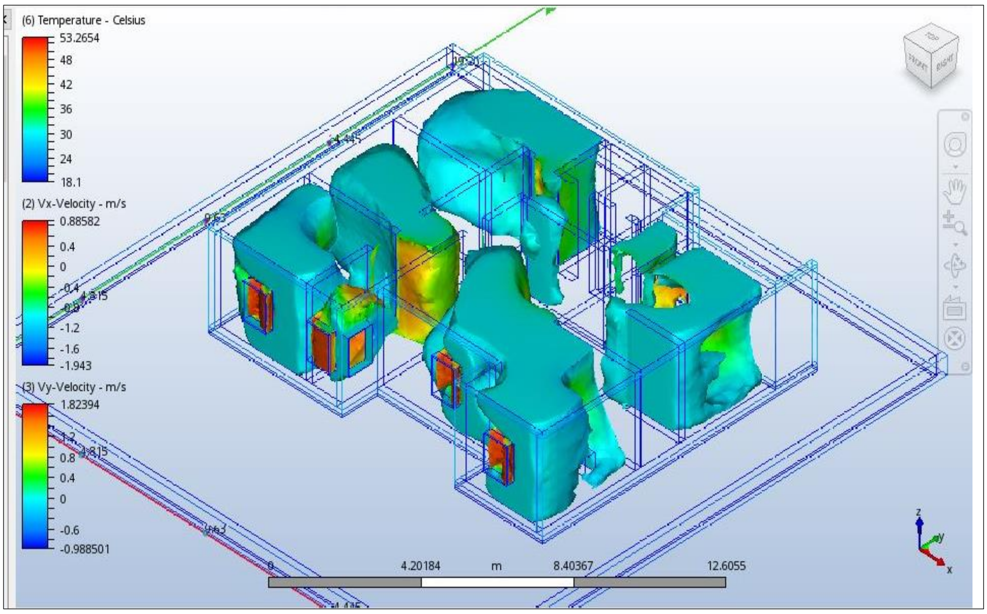



**Figure 9. Air flow Velocity and temperature**

The temperature calculated from the simulation is compared with the measured temperature. The maximum temperature measured is 35.2ºC. The temperature calculated is 34.9 ºC, and the margin of error is 0.3.

This same process was repeated for the other studied low-rise residential building plans (A, B, and D). Further classification of the objective involved the analysis of the collected data from the administered questionnaires. Since categorical regression assigns numerical values to the categories in order to quantify categorical data, Categorical Regression Analysis (CATREG) was used for hypothesis testing at the 0.05 level of significance. This was used to address the objective of revealing how the changes in temperature were affected by changes in height and the positioning of openings in the buildings. Also indirectly, the airflow velocity that could cause changes in indoor temperature was determined by variations in the sizes of the building openings. The interpretation of the objective was used to address the research question of the study. Figure 10 shows a flow chart of the research method pursued for the objectives of the study.

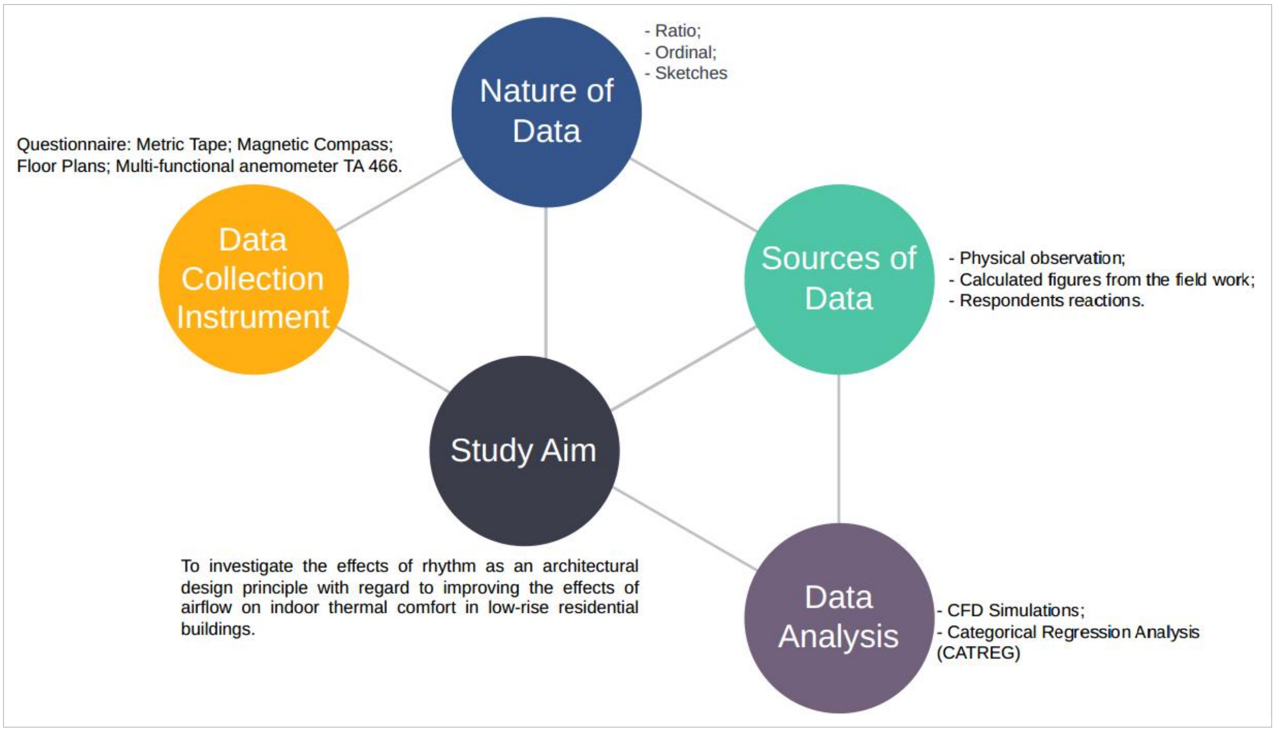



**Figure 10. Summary of Research Methods**

A total of 433 questionnaires were administered, and 394 were properly filled. This was possible because the respondents were greatly encouraged to fill out the questionnaires, stressing the importance of the information and the time limit for its return. Accordingly, efforts were made for the urgent and on-the-spot return of the questionnaires. Hence, the response rate is 90.99%, as indicated in Table 5.

**Table 4. Questionnaires distributed to occupants of the designated buildings**

| S/N | Layouts | Number Distributed | Number Returned | Percentage of Returned (%) |
|---|---|---|---|---|
| 1 | Awada Layout | 168 | 153 | 91.07 |
| 2 | Ozalla Layout | 113 | 102 | 91.07 |
| 3 | Ugwuagba Layout | 152 | 139 | 90.84 |
| | **Total** | 433 | 394 | 90.99 |

Table 5 showed that 168 of the questionnaires were distributed to Awada, 152 to Ugwuagba, and 113 to Ozalla layouts, respectively, according to the number of buildings and occupants.

## 3. Results

### 3.1. Simulation Data of Building Openings Showing the Effects of the Principle of Rhythm

The study investigated, using modeling and simulation procedures, the impacts of outdoor airflow on the building openings and fenestration in the living rooms of the four proto-type buildings in the study area for the effects of the architectural principles of Rhythm on low-rise residential buildings. Using the same simulation parameters and different window sizes and placements, each of the designated buildings (A–D) was simulated at the ground floor and fourth floor levels. There were relative temperature differences as a result of the convectional impact of wind velocity on the different floors (see Tables 6 and 7).

**Table 5. Simulation Data for building openings and fenestration showing effects of architectural principles of rhythm in Building "A" (ground floor)**

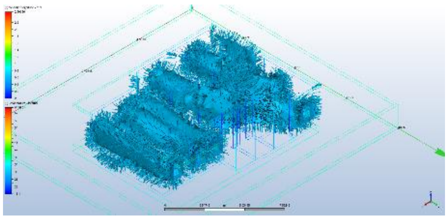
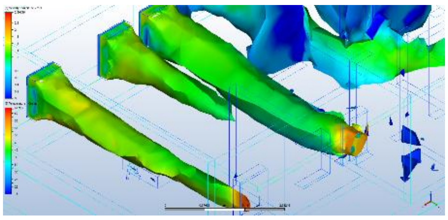
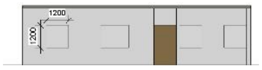
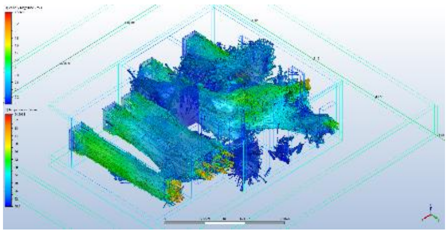
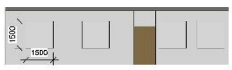
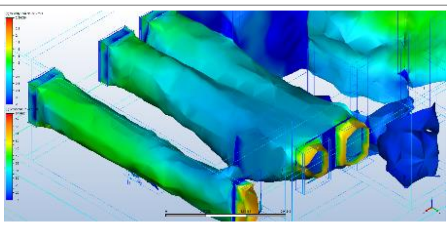
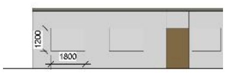
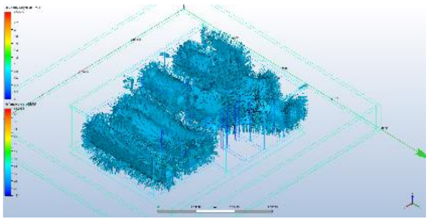
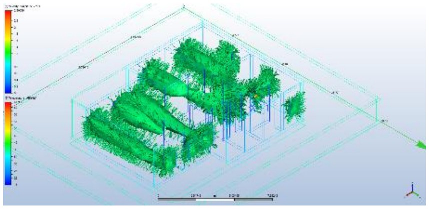
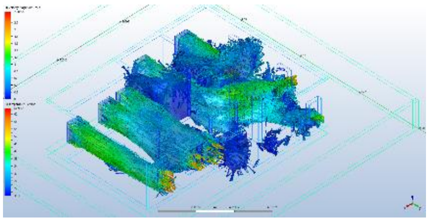
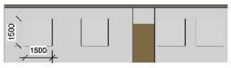
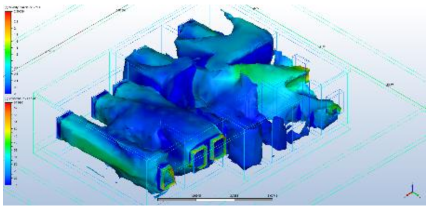
| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm (4ft × 3ft) |  |  | 29.7 ºC |
| 1200 ×1200 mm (4ft × 4ft) |  |  | 29.1 ºC |
| 1500 × 1500 mm (5ft × 5ft) |  |  | 28.5 ºC |
| 1200 × 1800 mm (4ft × 6ft) |  |  | 30 ºC |

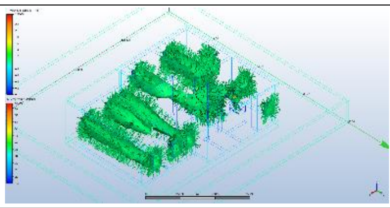
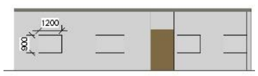
**Table 6. Simulation data for building openings and fenestration showing effects of architectural principle of rhythm in building "A" (fourth floor)**

| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm (4ft × 3ft) 1.0m $^{2}$ |  |  | 29 ºC |
| 1200 × 1200 mm (4ft × 4ft) 1.44m $^{2}$ |  |  | 28.7 ºC |
| 1500 × 1500 mm (5ft × 5ft) 2.25m $^{2}$ |  |  | 28.1 ºC |
| 1200 × 1800 mm (4ft × 6ft) 2.16m $^{2}$ |  |  | 29.3 ºC |

The window openings and fenestrations were typical and vertically aligned (showing the principle of rhythm). Simulation indicated that the indoor airflow pattern was affected by the building window opening sizes, which experienced differences in temperature values between the ground floor and the fourth floor of prototype Building "A". This may be a result of the impact of wind velocities at different levels on the building. The simulation process indicated lower indoor temperature readings on the upper floor and higher indoor temperature readings on the lower level. The ground floor level tends to experience hotness of weather and land evaporation processes, which tend to move upwards to be condensed with cooler air at the top. This might be the resultant effect of the relative difference in temperature between the ground floor plan and the last floor plan in Building "A".

Table 8 shows the simulation process results for the ground floor of Building B using the same simulation parameters. When compared to the last floor of the same Building B with the same simulation parameters, as shown in Table 9, there were relatively differences in the indoor temperature conditions of the designated spaces of the building. The lowest temperature was 27.7 ºC on a window area of 2.16m$^2$ while the smallest window area of 1.0m$^2$ had the highest temperature of 30 ºC. Table 9 showed the fourth-floor indoor spaces also had lower temperature readings in general, indicating improved airflow. The lowest temperature was 28 ºC on a window area of 2.16m$^2$ while the smallest window area of 1.0m$^2$ has the highest temperature of 29.4ºC.

**Table 7. Simulation data for building openings and fenestration showing effects of architectural principle of rhythm in building "B" (ground floor)**

| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm (4ft × 3ft) 1.0m $^{2}$ |  |  | 30 ºC |

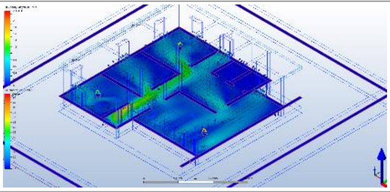
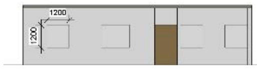
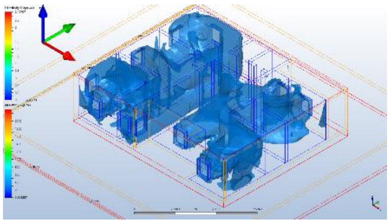
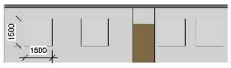
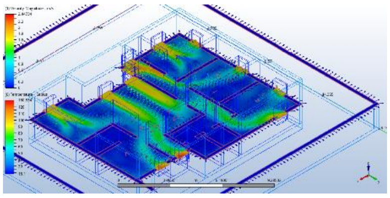
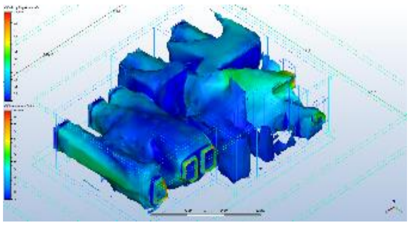
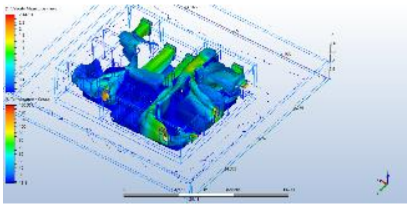
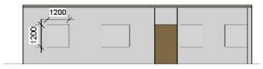
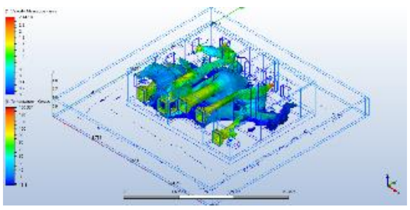
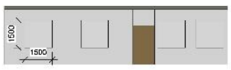
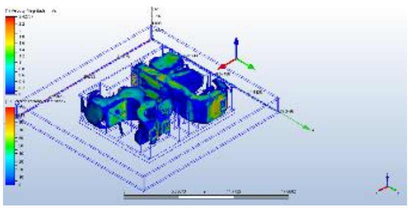
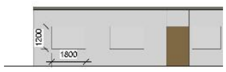
| | | | |
|---|---|---|---|
| 1200 × 1200 mm (4ft × 4ft) 1.44m $^2$ |  |  | 28.6 ºC |
| 1500 × 1500 mm (5ft × 5ft) 2.25m $^2$ |  |  | 28.2 ºC |
| 1200 × 1800mm (4ft × 6ft) 2.16m $^2$ |  |  | 27.7 ºC |

**Table 8. Simulation data for building openings and fenestration showing effects of architectural principle of rhythm using building "B" (fourth floor)**

| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm (4ft × 3ft) 1.0m $^2$ |  |  | 29.4 ºC |
| 1200 × 1200 mm (4ft × 4ft) 1.44m $^2$ |  |  | 29 ºC |
| 1500 × 1500 mm (5ft × 5ft) 2.25m $^2$ |  |  | 28.3 ºC |
| 1200 × 1800 mm (4ft × 6ft) 2.16 m $^2$ |  |  | 28 ºC |

The indoor spaces on the ground and fourth floor levels of Building "C" were also investigated under the same simulation parameters. They also indicated the same relative effects of airflow patterns on even larger window openings and fenestrations on the respective floors. The simulation also revealed that there were relative higher temperatures at the ground floor spaces and lower temperature readings at the last floor indoor spaces of the building "C" (see Tables 10 and 11). The lowest temperature is maintained on a window area of 2.16m$^2$, while the smallest window area of 1.0m$^2$ has the highest temperature.

**Table 9. Simulation data on building openings and fenestration showing effects of architectural principle of rhythm using building "C" (ground floor)**

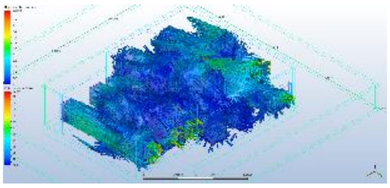
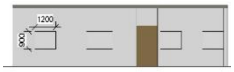
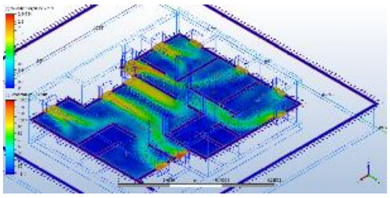
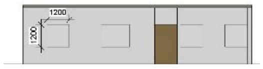
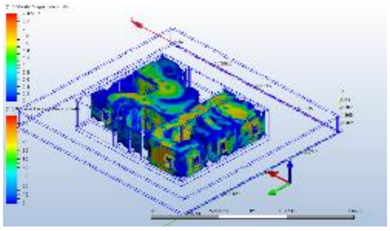
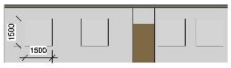
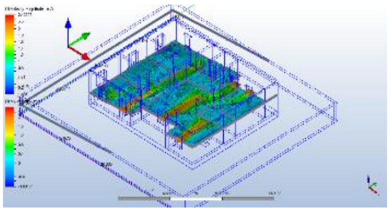
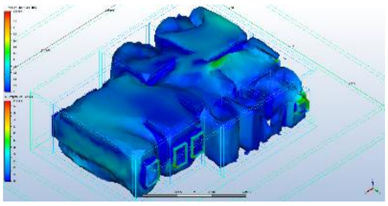
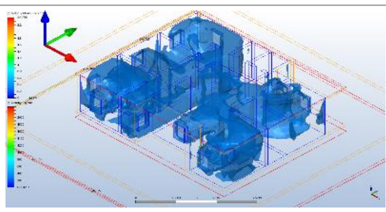
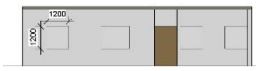
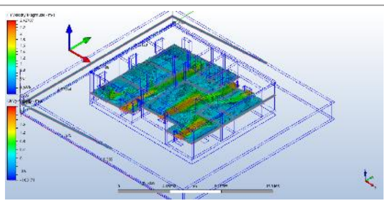
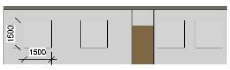
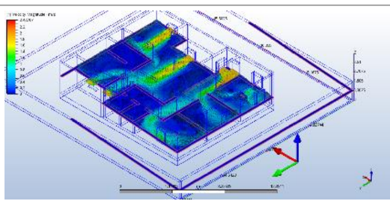
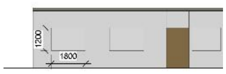
| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm<br>(4ft × 3ft)<br>1.0m $^2$ |  |  | 29.8 ºC |
| 1200 × 1200 mm<br>(4ft × 4ft)<br>1.44 m $^2$ |  |  | 29.2 ºC |
| 1500 × 1500 mm<br>(5ft × 5ft)<br>2.25 m $^2$ |  |  | 28.9 ºC |
| 1200 × 1800 mm<br>(4ft × 6ft)<br>2.16 m $^2$ |  |  | 28.61 ºC |

**Table 10. Simulation data on building openings and fenestration showing effects of architectural principle of rhythm on building "C" (top most floors)**

| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm<br>(4ft × 3ft)<br>1.0 m $^2$ |  |  | 29 ºC |
| 1200 × 1200 mm<br>(4ft × 4ft)<br>1.44 m $^2$ |  |  | 28.9 ºC |
| 1500 × 1500 mm<br>(5ft × 5ft)<br>2.25 m $^2$ |  |  | 28.7 ºC |
| 1200 × 1800 mm<br>(4ft × 6ft)<br>2.16 m $^2$ |  |  | 28.5 ºC |

Tables 12 and 13 revealed the data of the simulation effects of airflow patterns on both the ground floor and last floor indoor spaces in the designated building "D" using similar simulation parameters. There were also relative changes in temperatures due to the various sizes and positions of openings and fenestrations in the designated spaces investigated. The lowest temperature was 28.66 °C on a window area of 2.16m$^2$, while the smallest window area of 1.0m$^2$ had the highest temperature of 29.8°C on the ground floor. This shows that a horizontal increase in window size has a greater effect on the volume of admissible air than a vertical increase in window size, and the architectural effect of rhythm prompted changes in temperatures on the last (topmost) floor of the building. A comparison with the ground floor showed relative lower temperatures in the designated upper-floor indoor spaces.

**Table 11. Simulation data of building openings and fenestration showing effects of architectural principle of rhythm on building "D" (ground floor)**

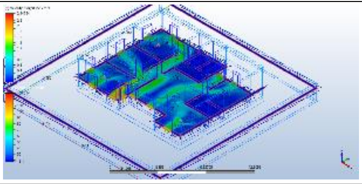
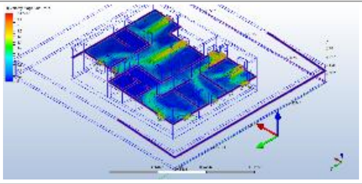
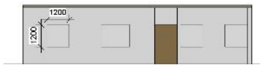
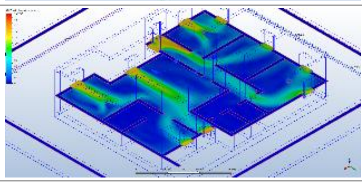
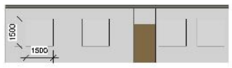
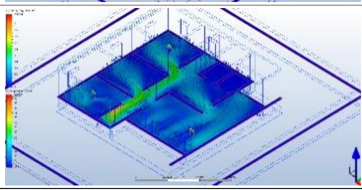
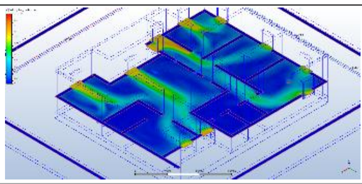
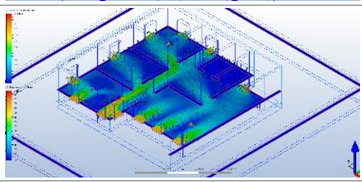
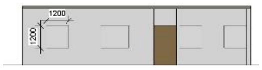
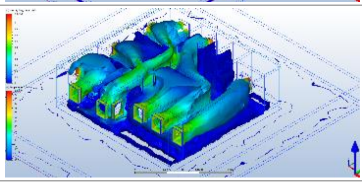
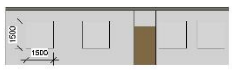
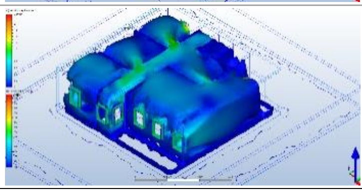
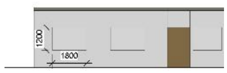
| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900mm<br>(4ft × 3ft)<br>1.0m$^2$ |  |  | 29 °C |
| 1200 × 1200mm<br>(4ft × 4ft)<br>1.44m$^2$ |  |  | 28.5 °C |
| 1500 × 1500mm<br>(5ft × 5ft)<br>2.25m$^2$ |  |  | 28.7 °C |
| 1200 × 1800mm<br>(4ft × 6ft)<br>2.16m$^2$ |  |  | 28.86 °C |

**Table 12. Simulation data of building openings and fenestration showing the effects of architectural principle of rhythm on building "D" (topmost floors)**

| Building opening sizes | Simulation | Building opening | Results (Celsius) |
|---|---|---|---|
| 1200 × 900 mm<br>(4ft × 3ft)<br>1.0m$^2$ |  |  | 28.9 °C |
| 1200 × 1200 mm<br>(4ft × 4ft)<br>1.44 m$^2$ |  |  | 28.7 °C |
| 1500 × 1500 mm<br>(5ft × 5ft)<br>2.25 m$^2$ |  |  | 28.95 °C |
| 1200 × 1800 mm<br>(4ft × 6ft)<br>2.16 m$^2$ |  |  | 28.66 °C |

## 3.2. Effects of Poor Design Process of the Building Openings and Fenestration and Architectural Features

### 3.2.1. Heights of Individual Space Head Room

Table 14 shows the individual heights of various headroom spaces as provided by the respondents in the questionnaire. Out of the 394 respondents that were surveyed, 85 (22%) of them indicated the head room height of their rooms from floor to the soffit of the deck is 1.5m–2.1m, 159 (40%) respondents indicated it is 2.4m–3m, 111 (28%) of them indicated that it is 3.3m–3.9cm, while 32 (8%) respondents indicated it to be 4.2m–4.8m, and 7 (2%) of the respondents indicated other specifics. Hence, a greater percentage (62%) of respondents indicated that the height of their head rooms is below the normal accepted standard of a minimum of 3m. This shows the possibility of not having thorough circulation of ventilation, cross ventilation, or movement of air, which will lead to conducive indoor thermal comfort in the various room spaces in the buildings.

**Table 13. Heights of Individual Space Head Room**

| | Awada Layout n (%) | Ozalla Layout n (%) | Ugwuagba Layout n (%) | Total n (%) |
|---|---|---|---|---|
| 1.5 m– 2.1 m | 44(28.75) | 24(23.52) | 17(12.23) | 85(21.57) |
| 2.4 m – 3 m | 48(31.37) | 30(29.41) | 81(58.27) | 159(40.35) |
| 3.3 m – 3.9 m | 35(22.870 | 41(40.19) | 35(25.17) | 111(28.17) |
| 4.2 m – 4.8 m | 22(14.37) | 4(3.92) | 6(4.31) | 32(8.170 |
| Other specific | 4(2.61) | 3(2.94) | - | 7(1.77) |
| **Total** | 153(100.00) | 102(100.00) | 139(100.00) | 394(100.00) |

### 3.2.2. Openable Window Types in the Designated Buildings of Study

Table 15 shows the common window types in the designated buildings in the study area. Out of 394 respondents, 220(56%) indicated sliding window types, while 39(10%) respondents reported a projected window type. 135(34%) of the respondents indicated louver types of windows in their buildings. There was no indication of casement window types in the responses. This might be because casement windows had not been introduced to the building industry or market when these buildings were constructed. Casement, louvre, and projected windows have tropical advantage of allowing much airflow for indoor thermal comfort in buildings, unlike double sliding windows, which effectively provide 50% of their opening space for ventilation purposes.

**Table 14. Openable Window Types in the Buildings of Study**

| | Awada Layout n (%) | Ozalla Layout n (%) | Ugwuagba Layout n (%) | Total n (%) |
|---|---|---|---|---|
| Sliding windows | 52(33.98) | 75(73.52) | 93(66.90) | 220(55.83) |
| Projected windows | 18(11.76) | 10(9.80) | 11(7.91) | 39(9.89) |
| Louvres | 83(54.24) | 17(16.66) | 35(25.17) | 135(34.26) |
| **Total** | **153**(100.00) | **102**(100.00) | **139**(100.00) | **394**(100.00) |

### 3.2.3. Opening of Doors as Alternative to Airflow Movement in Room Spaces

The response of respondents' experiences to the opening of doors as alternatives to openable windows for air circulation in room spaces is shown in Table 16. Out of the 394 respondents, 342(87%) were in the affirmative that for effective ventilation in rooms, both doors and windows need to be opened, while 52 (13% of respondents) were not in the affirmative. Hence, this result showed that either there was not proper orientation of the buildings/openings or there was obstruction of airflows, or existence of a heat island in the area of study as a result of poor building setbacks from the perimeter walls. Ordinarily, doors are meant to be closed when not in use for internal movements within the building, and still, effective ventilation through openable windows will be achieved through design strategies.

**Table 15. Doors as alternative Source of airflow movement into room spaces**

| | Awada Layout n (%) | Ozalla Layout n (%) | Ugwuagba Layout n (%) | Total n (%) |
|---|---|---|---|---|
| Yes | 140(91.50) | 92(90.19) | 110(79.13) | 342(86.80) |
| No | 13(8.49) | 10(9.80) | 29(20.86) | 52(13.45) |
| I don't know | - | - | - | - |
| **Total** | 153(100.00) | 102(100.00) | 139(100.00) | 394(100.00) |

### 3.2.4. Window Sizes and Airflow Pattern on Building in the Study Area

The various window sizes of the rooms occupied by the respondents are shown in Table 17. From the result, 155 (39% of the respondents) reported window sizes of 900 mm × 1.2 m, 118(30%) respondents indicated window sizes of 1.2 m × 1.2 m, while 49(12%) of the population indicated window sizes of 1.5 m × 1.5 m. In addition, 59 (15%) of the respondents indicated window sizes of 1.8 m × 1.2 m, while the remaining 13(3%) respondents indicated no window specifications.

**Table 16. Window sizes and Airflow pattern on building in the study area**

| | Awada Layout n (%) | Ozalla Layout n (%) | Ugwuagba Layout n (%) | Total n (%) |
|---|---|---|---|---|
| 3ft × 4ft (900 mm × 1.2 m) | 70(45.75) | 44(43.13) | 41(29.49) | 155(39.34) |
| 4ft × 4ft (1.2 m × 1.2 m) | 39(25.49) | 27(26.47) | 52(37.41) | 118(29.94) |
| 5ft × 5ft (1.5 m × 1.5 m) | 18(11.76) | 14(13.72) | 17(12.23) | 49(35.25) |
| 6ft × 4f (1.8 m × 1.2 m) | 26(16.99) | 10(9.80) | 23(16.54) | 59(14.97) |
| Specify others | - | 7(6.86) | 6(4.31) | 13(3.29) |
| **Total** | 153(100.00) | 102(100.00) | 139(100.00) | 394(100.00) |

### 3.2.5. Keeping Longer Outdoor Activities at the Balconies than Indoors due to Poor Thermal Comfort

Table 18 indicated the various responses by the respondents in the study area regarding keeping longer outdoor activities on the balconies instead of staying more indoors due to un-conducive indoor thermal comfort in the rooms. Out of 394 respondents in the survey, 222 (56% of them) were in the affirmative, whereas 163 (41% of respondents) preferred being indoors, while 9(3%) indicated no specific response. From the foregoing, it is suggested that poor indoor thermal comfort due to inadequate ventilation can cause more outdoor activities, especially on balconies.

**Table 17. Keeping longer outdoor activities at the building balconies than indoors due to un- conducive indoor thermal comfort**

| | Awada Layout n (%) | Ozalla Layout n (%) | Ugwuagba Layout n (%) | Total n (%) |
|---|---|---|---|---|
| Yes | 83(54.24) | 58(56.86) | 81(58.27) | 222(56.34) |
| No | 61(39.86) | 44(43.13) | 58(41.72) | 163(41.37) |
| I don't know | 9(5.88) | - | - | 9(2.28) |
| **Total** | 153(100.00) | 102(100.00) | 139(100.00) | 394(100.00) |

## 4. Hypothesis Testing

The hypothesis was formulated to test whether there is a significant relationship between rhythm as an architectural design principle and passive airflow patterns in low-rise residential buildings in the study area. The Analysis of Variance (ANOVA) of regression produced the sum of squares of regression = 116.076. df = 15, mean square = 7.738, n F= 10.525, and significance = 0.000 for regression, while residuals of the test produced a sum of squares=277.924, df = 378, mean square 0.735, F = 0, and sig =0. The total values for sum of squares = 394.000 and df = 373. Predictors include orientation, type of window, size of window, front setback and side setback, floor of the building, and room level.

The ANOVA of the Categorical Regression Analysis (Table 19) showed that *p*=0.000, i.e. $p<0.05$. This indicated that there was a significant relationship between the type and sizes of windows (elements used in measuring rhythm) and wind velocity (intensity or force of breeze), a measure of passive airflow pattern in the study. In addition, Table 20 of the Coefficients of Regression also showed that the type of window ($p<0.001$) and size of window ($p<0.000$) had P-values less than 0.05. These results are indications that there is a significant relationship between rhythm, an architectural design principle, and passive air flow patterns in low-rise residential buildings in the study area. Therefore, the null hypothesis was rejected.

**Table 18. ANOVA of Regression Analysis**

| ANOVA | | | | | |
|---|---|---|---|---|---|
| | **Sum of Squares** | **df** | **Mean Square** | **F** | **Sig.** |
| Regression | 116.076 | 15 | 7.738 | 10.525 | 0.000 |
| Residual | 277.924 | 378 | 0.735 | | |
| **Total** | 394.000 | 393 | | | |

Independent Variable: Intensity or force of breeze (Wind velocity).

Predictors: Orientation Type of window Size of window Floor of the building Height of room level

**Table 19. Coefficients of Regression**

| Coefficients | | | | | |
|---|---|---|---|---|---|
| | Standardized Coefficients | | df | F | Sig. |
| | Beta | Bootstrap (1000) Estimate of Std. Error | | | |
| Orientation of building | 0.515 | 0.240 | 1 | 4.605 | 0.033 |
| Type of window | 0.191 | 0.123 | 2 | 2.410 | 0.001 |
| Size of window | 0.470 | 0.196 | 4 | 5.768 | 0.000 |
| Floor of the building | 0.776 | 0.270 | 4 | 8.278 | 0.000 |
| Height of rooms | 0.328 | 0.244 | 2 | 1.804 | 0.166 |

Independent Variable: Intensity or force of breeze: wind velocity.

From the results of Beta (β) coefficients, all five identified predictors had significant positive effects on passive airflow patterns in the buildings investigated in the study area. The floor location of the building recorded the highest effect (β= 0.776). Next was the orientation of the buildings (β= 0.515), followed by the size of the window (β= 0.470) and then the type of window (β= 0.191). These results mean that the intensity or force of breeze in the buildings will change by 0.776, 0.515, 0.470, and 0.191 unit increase in standard deviation in the building's floor location, orientation, window sizes, types, and lengths.

## 5. Discussion

Based on the results of this study presented in the previous section of the study, it showed that there was a significant relationship between the architectural design principle of rhythm in building openings and fenestration and the airflow pattern on outdoor airflow and indoor thermal comfort of low-rise residential buildings in the study area. This was explained using simulation processes using data collected from the designated buildings A–D. The simulation involved the evaluative effects of rhythm in the process, as seen in the details of the data collected from the process, which indicated differences in sizes of building openings and window openings from each of the designated building spaces, typical in principle of rhythm in the architectural design process of the buildings. These results showed variations in temperature levels (indications of differences in indoor thermal comfort) of various indoor spaces of the investigated designated floors and buildings, especially the ground floors and top-most floors of the buildings. Specifically, the ground floor has a higher temperature than the top floor. With the rhythm (repetitive placement) of windows on each floor level, the temperature range has been constant within the range of 27.7–30.0 ºC. This supports the submission of [39] that contemporary structures in warm, humid tropics have an indoor air temperature (29.4°C) but traditional buildings' indoor air temperature (28.8 °C). The results also corroborate previous studies that investigated the relationship between airflow pattern and thermal comfort [6, 46–48]. They confirmed in their studies the correlation between the effect of airflow pattern and indoor thermal comfort. In collaboration with Jamaludin et al. [30] that for non airconditioned buildings, it is also necessary to calculate the temperature variation of the indoor climatic condition of the building over a relatively specific period of the season. This is to know the duration of uncomfortable thermal periods in the building [48].

The objective and hypothesis of the study were discussed based on the responses to the questionnaire by the respondents, who indicated their various individual reaction to the dependent and independent variables (intensity of the force of the breeze on their experiences inside the building) due to variation in the height of the floor levels of the buildings, architectural openings, and balconies. These are fundamental elements discussed in its objectives as significant architectural elements that form the rhythm of the architectural design principle of the designated buildings in the study area, typical of the various designated low-rise residential buildings in the study area. These correspond with other previous studies investigated by Lin et al. [46] that indicated that the achievement of good indoor thermal performance in residential buildings involved the process of modeling the transfer of heat energy between the indoor environment of the building and its surrounding environment. As a suggestion, then, the increase in intensity of the force of the breeze indoors depends on adequate considerations of design variables of geometrical dimensions of various building elements such as height of walls, roof, types and sizes of windows, orientation of the building, and appropriate placement of building shading devices [46]. Meakhail [49] was in agreement with the result when we decided that, typical of a room, there could be some geometrical complexity in building design that could produce airflow turbulence, differences in airflow, differences in circulation of wind speed, and air buoyancy.

Based on the Categorical Regression Analysis (CATREG) used to analyze the responses from the questionnaire, the dependent variable is the intensity of the force of the breeze, determined by variations in building heights, the floor of the building, the sizes of building openings and fenestrations, and window elements. The floor location of the building recorded the highest effect on influencing indoor thermal comfort. Being typical of the building rhythm of the low-rise residential buildings in the area, the analysis further explained architectural and environmental/climatic synergy in the determination of indoor thermal comfort (change in temperature) due to the impact of airflow velocity allowed through building openings. This result further collaborates with other previous studies [50, 51], which opted that the enhancement of indoor air quality and thermal comfort depends on the architectural environmental/climatic synergy which allowed naturally ventilated indoor environmental spaces of the building and indirectly thermal comfort condition of the space. Wang et al. [52] made a case in line with the result for natural ventilation as an adequate passive cooling process in the summer season to offer efficient ways of reducing energy consumption in buildings while maintaining acceptable indoor thermal comfort conditions. Other authors, like Ayata & Yildiz [53], observed that the use of natural (passive airflow pattern) and hybrid ventilation strategies can make the building more environmentally sustainable and more energy efficient, especially under the influence of climate change [7, 51, 54–57].

The interpretation of values and variables of hypotheses results in emphasizing the intensity of the force of the breeze and its effectiveness in maintaining indoor thermal comfort through building openings, which underscores the relevance of using rhythm as an architectural design principle for low-rise residential buildings in the provision of adequate indoor thermal comfort at various levels of the building if adequately placed. The result underscores the previous studies of Chan [1] that inferred rhythm as a phenomenon that provides quality of design and the process of design development towards scientific theories and contributions in fields of design studies and concepts [58]. This is evident in the result of the hypothesis that showed the usefulness of rhythm in maintaining vertical indoor thermal comfort of low-rise residential buildings in the study area through adequate inference of the intensity of wind velocity on the buildings to maintain a sustainable and healthy indoor thermal comfort environment. This view was further buttressed by these authors [17–20].

Consequently, the interpretation shows the justification of previous studies that added to the improvement of indoor airflow to enhance indoor air quality and thermal comfort. Other authors [53, 59, 60] postulated in their studies that the efficiency of enhanced passive airflow process depends on the location and design of the buildings, and the natural ventilation strategies used [61-63] which involves, cross-ventilation for controlling airflow in and around the buildings, opening of windows and drawing of blinds, and automatic or manual control of the openings and as such, emphasized the use of rhythm as architectural design principle in repetition of architectural building openings like balconies, windows or door elements that can improve the effect of airflow pattern in low-rise residential building, wherein the building floor heights, sizes of windows, doors and balconies maintain adequate heights, proper positioning and not interfered by other existing buildings blocking the airflow pattern. So, it becomes an important outcome of the analysis of the objective that building openings and fenestrations with regard to improving airflow pattern in low-rise residential buildings in the study area must be adequately applied through rhythm as an architectural design principle in such low-rise residential buildings, especially in the study area, considering the tropical climatic environment.

Based on the findings of its objective, it underscores the relevance of rhythm as repetition of architectural design elements for low-rise residential buildings in the study area. This enhances the aesthetics of the buildings and provides relevant building openings for various building floors for the occupants of the buildings. The investigation also advocates that the extent to which the relevance of rhythm has been applied and the improvement of its functionality in increasing airflow pattern in buildings, especially in the tropics, to enhance indoor thermal comfort in terms of temperature, humidity, and air circulation in room spaces depends on these other factors: heights of building floors, sizes of windows or building openings and fenestrations, and operational techniques in the usage of such building openings. This was buttressed by previous studies in collaboration, with the results of this study stressing the challenging nature of the tropics [64].

In the tropics, considering the adverse effects of seasonal variables of the region with other climatic variables that are usually increased due to some human activities [65], the non-provision of inadequate fresh air ventilation [66–68] results in poor indoor air quality, and as such, maintenance of its good air quality becomes difficult [69] based on the excessive exposition of buildings to the hot atmosphere of the region. Therefore, the maintenance of indoor thermal comfort demands that properly designed shading devices be used to avoid excessive exposure to solar radiation for interior spaces, with a strategy of optimizing the building envelope, namely the window-wall ratio [70]. All these conditions tend to provide an answer to the research question that indicates an increase in building floors in low-rise residential buildings and demands the implementation of rhythm as an architectural design concept to repeat openings at various floors of the buildings. Furthermore, these various building openings at various building floors demand enhancement of the indoor thermal comfort of the spaces. Consequently, in advocating for rhythm, it has to maintain adequate heights, sizes, and proper placement of building openings in order to improve the indoor thermal comfort of the low-rise residential buildings in the study area.

## 6. Conclusion & Recommendations

One of the essentials and a design requirement of good architectural design is to maintain adequate indoor thermal comfort conditions in spaces. This task has led to various studies, one of which is on architectural design principles and strategies to maintain and improve human thermal comfort in indoor spaces. The study emphasized the examination, determination, assertion, and investigation of the difficulty in maintaining adequate indoor thermal comfort conditions in low-rise residential buildings in the study area.

Building forms and architectural design principles can also contribute to a huge extent to how airflow patterns can improve the indoor thermal comfort conditions of low-rise residential buildings. This study investigated how building openings and fenestrations could enhance the indoor thermal comfort of the buildings in the study area. The study's goal, as detailed in its hypothesis analyzed by categorical regression (CATREG) using the collected data from the field survey and administered questionnaire from the designated layouts, reveals that the floor of the building has the highest significant positive effects on passive airflow pattern. Likewise, the CFD method was also further used to analyze the same objective of the study. Consequently, the results of the test indicated that there is a collaboration between rhythm as an architectural design principle on building openings and fenestrations and the airflow pattern of low-rise residential buildings in the study, in view of sustaining the indoor thermal condition of the buildings.

Besides internal building spaces that facilitate an increase in the rate of airflow circulation, building forms and the extent of the impact of the airflow pattern on buildings determine the magnitude of the airflow force in buildings. Building openings, fenestrations, and the architectural principle of rhythm influence the inlet of airflow, the amount of airflow, and the frequencies and percentages of its impact on low-rise residential buildings. With regard to improving the efficient effects of outdoor airflow patterns on indoor thermal comfort conditions in low-rise residential buildings in hot-humid conditions, the results showed that the more building openings and fenestrations in low-rise residential buildings, the better it contributes to maintaining adequate indoor thermal comfort in the buildings. By implication, rhythm, which is the architectural design principle used for both the design and construction of low-rise residential buildings in the study area, has been shown in this study as an effective design strategy to provide improved thermal comfort on various floor levels of the buildings. However, when buildings are wrongly positioned due to poor orientation or inadequate building setbacks, the resulting architectural atmospheric spaces created through rhythmic design principles do not enhance the indoor thermal comfort conditions of such buildings. Therefore, this study implies the relevant emphasis and consideration of rhythm as an architectural design principle for the enhancement of building openings and fenestrations in order to improve the indoor thermal comfort condition of low-rise residential buildings and urban housing development policies in the tropics. These building openings and fenestrations are important as they affect the improvement of the thermal comfort condition of building spaces; hence, using rhythm as an architectural design principle in low-rise residential buildings becomes a purposeful principle recommendable to architects and building designers.

# 7. Declarations

## 7.1. Author Contributions

Conceptualization, P.I.O.; methodology, P.I.O.; software, F.O.O.; validation, P.I.O.; formal analysis, F.O.O.; investigation, E.J.M.; data curation, F.O.O.; writing—original draft preparation, P.I.O., F.O.O., and E.J.M.; writing—review and editing, F.O.O.; supervision, E.J.M.; project administration, E.J.M.; funding acquisition, P.I.O. All authors have read and agreed to the published version of the manuscript.

## 7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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## 7.4. Conflicts of Interest

The authors declare no conflict of interest.

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