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The Effect of Building Orientation on Energy Cost in Air Conditioning Systems

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ABSTRACT

This study investigates the impact of building orientation on energy consumption in a building. It includes the analysis of cooling load using Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) method with standard design considerations and stipulated guidelines by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The study takes the design of Nigeria Liquefied Natural Gas (NLNG) Corporate Head Office building in Port Harcourt, Nigeria as a case study, to assess the energy saving potential through building orientations that minimize the solar radiation heat gain of the walls. This would reduce the need for auxiliary cooling and consequently reduce the capacity of the air conditioning system required in the building, thereby resulting in lower energy consumption. The cooling load analysis carried out using CLTD/SCL/CLF method modelled in MATLAB program shows that the maximum load of the building occurred at 13:00 hours (1:00pm). The total cooling load of the building was found to be 359804.4W when the building is oriented North-East while it is 292993.72W when the building is oriented North. Thus, the north is a better orientation for less energy consumption and would achieve an annual energy savings of 252394.047kWh, which translates to potential energy cost savings of ₦12, 670,181.16 annually. The study validated appropriate building orientation selection as an energy efficiency strategy and architectural solution to optimized energy consumption and cost in buildings.

KEYWORDS: Energy Consumption, Energy Saving, Cooling Load, Building Orientation, Solar Radiation Heat Gain.

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1.0 INTRODUCTION

Energy used in buildings is mostly for the provision of heating and cooling to maintain the conditions that are required for indoor products, processes and to provide thermal comfort, this accounts for a large amount of energy consumption (Oktay *et al.*, 2020). The persistent energy crisis in Nigeria is affecting all sectors of the economy, thus requires prudent management of our energy resources, which involves energy- efficient operations and energy consumption reduction plans (Lombard *et al.*, 2007). One way of achieving this is to have more energy efficient building designs (Odunfa *et al.*, 2015).

This study is set out to validate building orientation as an energy efficiency strategy and as an architectural solution, using NLNG Corporate Head Office in Port Harcourt, Nigeria as a case study. It has been reported in the literatures reviewed that the ratio of the total radiation entering a building for a given side per unit area depends on the compass direction of the side. Thus, orientation has direct impact on the building cooling load and consequently determines the sizes of the air conditioning system components required in the building.

Odunfa *et al.* (2015) studied the energy efficiency of buildings at the University of Ibadan, Nigeria. The study took the designs of three buildings orientated north-south and east-west into consideration with the view to assess the energy saving potentials through building orientation. It was concluded that energy efficiency was guaranteed with the north-south building orientation.

Abanda *et al.* (2016) investigated the impact of building orientation on energy consumption in a domestic building using Emerging Building Information Modeling. They concluded that orientation determines the internal solar gain, affecting the requirements for heating, cooling and lighting, and that a properly oriented building could minimize the energy required for heating, cooling and lighting.

Marin (2017) studied the impact of building orientation on energy usage, using a simulation software IDA ICE. The energy behavior of a real dwelling located in Madrid, Spain was studied for different orientations. It was concluded that the most efficient orientation from an energy use perspective was south, due to the decrease of heating demand.

Kontoleon *et al.* (2017) analyzed heat flows through building zones in the aspects of their orientations and glazing proportions, under varying conditions in North Greece. The analysis was done with the aid of a Lumped Thermal-Network Model. They concluded that glazing area increased heat gain or heat loss, depending on the orientation of the wall where windows were installed, highest heat losses being observed on walls facing North and the opposite on walls facing South.

Yuksek and Karadayi (2017) investigated the energy-efficient methods applied in building life cycles. The study gave information about the life cycles of buildings and explained energy-efficient guiding principles in life cycle stages, which included orientation of buildings.

Elghamry and Azmy (2019) presented a paper on building orientation and its impact on energy consumption. They employed Energy-Plus simulator to estimate the energy consumption annually and during critical months in summer and winter in Cairo, Egypt. To obtain the best orientation for maximum energy saving, different orientations were tested and they reported that an air-conditioned building that has a southern facade consumed less energy while the western facade was found to cause a higher annual energy consumption by 26% over the southern. Also, in the case of a two-facade building, it was found that the lowest energy consumption was obtained between the northern and southern orientations.

Thus, a significant number of researches have been conducted in reviewing different air conditioning systems, energy consumption and energy efficiency in buildings. Various methods are used in analyzing, modeling and simulating those systems. Reviews and comparisons of these different methods show that there were discrepancies in the results due to differences in input parameters and control strategies. The present study optimizes energy consumption in air conditioning systems by using cooling load calculations which serve as the basis for determining air conditioning equipment sizes and energy cost.

2.0 MATERIALS AND METHODS

The materials used in this study are the architectural drawings of the NLNG Corporate Head Office, Port Harcourt, design information of the building, standard design codes and stipulated guidelines by ASHRAE (2013). The methods that used in the study are discussed in the following sections:

2.1 Building Survey

An accurate survey of the load components of the space to be air conditioned is a basic requirement for a realistic estimate of cooling load (ASHRAE, 2017). Thus, a survey was carried out at the building site to obtain comprehensive design information. The building is mainly used as an office complex. It is of 5 floors with a floor area of 1555.2m^2 and floor-to-floor height (average ceiling height) of 2.7m. The windows are double- glazed and the area is 80% of the concrete wall area. The building is occupied by 6 persons per 50m^2 and the recommended ventilation is 34m^3/h per person.

2.2 Sizing of Air Conditioning System

Cooling load calculations serve as the basis for determining air conditioning equipment sizes.

2.2.1 Cooling load

Cooling load is the summation of the heat gained and lost by the building which can be categorized as either external or internal cooling loads. The external cooling loads include the conduction and radiation heat loads transferred through roofs,

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walls, skylights and windows, through ventilation requirements or infiltration. Internal cooling loads include the heat loads from people, both latent and sensible, loads from lighting and miscellaneous equipment like computers, televisions, motors, etc. (Mao, 2016). The Cooling Load Temperature Difference/Solar Cooling Load /Cooling Load Factor (CLTD/SCL/CLF) method is employed in this study. The study was carried out in March within the hot and humid season peculiar to the Niger Delta of Nigeria due to her location in the tropic (Adejuwon, 2012).

2.2.2 CLTD/SCL/CLF Method

CLTD/SCL/CLF is the most popular method used by heating, ventilation, and air conditioning (HVAC) design engineers for cooling load calculations due to the reduced complexity of applying the method while still providing acceptable cooling load prediction accuracy, compared to the other methods (Mao, 2016). The CLTD/SCL/CLF method covers the building envelope conduction heat gain calculations and calculates the solar heat gain by using the maximum Solar Heat Gain Factor (SHGF), Cooling Load Factor (CLF), Shading Coefficient (SC) and Solar Cooling Load (SCL) concept to account for solar heat gains through fenestration (Spitler *et al.*, 1993).

2.2.3 Design Temperatures

The tabulated CLTD needs to be corrected if the actual outdoor and indoor conditions do not match with the default conditions using the formula (Mao, 2016)

$$CLTD_c = CLTD + (25.5 - t_r) + (t_m - 29.4) \quad (1)$$

$$t_m = T_o - \frac{DR}{2} \quad (2)$$

where $CLTD_c$ = corrected cooling load temperature difference (°C), $CLTD$ = cooling load temperature difference (°C), t_r = indoor temperature (°C), t_m = mean outdoor temperature (°C), T_o = maximum outdoor temperature (°C), DR = daily range (°C)

2.2.4 Cooling Load from Conduction Heat Gains

The conduction heat gains come from walls, roof, etc, and heat transfer by radiation through fenestration such as windows and skylights. All these are external cooling loads and sensible heat transfers. The heat gain is converted to cooling load using the Room Transfer Functions (Mao, 2016).

(i) Wall

The conduction heat gains from walls (Q_{wall}) is given as (ASHRAE, 2017)

$$Q_{wall} = U \times A \times CLTD_{Wall} \quad (3)$$

where U = overall heat transfer coefficient (W/m^{2}K), A = Area of walls (m^2)

(ii) Roof

The conduction heat gains from roof (Q_{roof}) is given as (ASHRAE, 2017)

$$Q_{roof} = U \times A \times CLTD_{roof} \quad (4)$$

2.2.5 Cooling Load through Fenestration

Cooling Load through fenestration consists of the transmitted by conduction (Q_c) and solar radiation (Q_R) and are calculated as follows (ASHRAE, 2017):

$$Q_c = U \times A \times CLTD_{glass} \quad (5)$$

$$Q_R = A \times SC \times SCL \quad (6)$$

where SC = shading coefficient, SCL= Solar cooling load (W/m^2)

2.2.6 Cooling Load through Partitions, Ceilings and Floors

According to ASHRAE (2017) the conduction heat gains for interior partitions, ceiling and floor can be calculated as a steady state conduction heat transfer using the formula (ASHRAE, 2017)

$$Q = U \times A \times (T_b - T_i) \quad (7)$$

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where T_b = average air temperature in adjacent space (°C), T_i = air temperature in conditioned space (°C)

2.2.7 Internal Cooling Loads

The various internal loads consist of sensible and latent heat transfers due to occupants, products, processes, appliances and lighting. The conversion of sensible heat gain (from lighting, people, appliances, etc.) to space cooling load is affected by the thermal storage characteristics of that space and is thus subject to appropriate cooling load factors (CLF) to account for the time lag of the cooling load caused by the building mass (ASHRAE, 2017).

(i) Lights

The lighting load (Q_{el}) is only sensible and given as (ASHRAE, 2017)

$$Q_{el} = W \times F_{ul} \times F_{sa} \times CLF \quad (8)$$

where W = total light wattage (W), F_{ul} = lighting use factor, F_{sa} = lighting special allowance factor CLF = cooling load factor by hour of occupancy

(ii) People

The sensible heat transfers (Q_s) and latent heat transfers (Q_l) due to occupants are given, respectively, as (ASHRAE, 2017)

$$Q_s = N \times SHG \times CLF \quad (9)$$

and $$Q_l = N \times LHG \quad (10)$$

where N = number of persons, SHG = sensible heat gain per person (W/person), LHG = latent heat gain per person (W/person),

(iii) Power Loads

Industrial and commercial buildings use various equipment such as fans, pumps, machine tools, elevators, escalators and other machinery, which add significantly to the heat gain. The heat gain of the equipment is given as (ASHRAE, 2017)

$$Q_{em} = P \times E_F \times CLF \quad (11)$$

where Q_{em} = heat equivalent of equipment operation (W), P = motor power rating (W), E_F = efficiency factors

(iv) Appliances

In a cooling load estimate, heat gain from all appliances either electrical, gas, or steam should be taken into account. The heat gain of an appliance is both sensible and latent, and are given, respectively, as (ASHRAE, 2017)

$$Q_s = Q_{input} \times F_U \times F_R \times CLF \quad (12)$$

and $$Q_l = Q_{input} \times F_U \quad (13)$$

where Q_{input} = name plate energy input from appliances (W), F_U = usage factor, F_R = radiation factor.

2.2.8 Cooling Load from Infiltration Air

Cooling load from infiltration air is both sensible and latent and are given, respectively, as (ASHRAE, 2017)

$$Q_s = 1.08 \times CFM \times (T_o - T_i) \quad (14)$$

and $$Q_l = 4840 \times CFM \times (W_o - W_i) \quad (15)$$

where CFM = infiltration air flow rate at standard air conditions (m^3/s), T_o = outside dry bulb temperature (°C), T_i = inside dry bulb temperature (°C), W_o = outside humidity ratio (kg/kg), W_i = inside humidity ratio (kg/kg).

2.2.9 Cooling Load from Ventilation Air

Ventilation air is the amount of outdoor air required to make up for air leaving the space due to equipment exhaust and exfiltration as required to maintain indoor air quality for the occupants. The heat is usually added to the air stream before entry to the cooling coil and has no direct impact on the space conditions. The additional cooling coil load is calculated as follows:

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$$Q_s = 1.08 \times CFM \times (T_e - T_c) \quad (16)$$

and $$Q_l = 4840 \times CFM \times (W_e - W_c) \quad (17)$$

where T_e = dry bulb temperature of air entering the cooling coil (°C), T_c = dry bulb temperature of air leaving the cooling coil (°C), W_e = humidity ratio of air entering the cooling coil (kg/kg), W_c = humidity ratio of air leaving the cooling coil (kg/kg)

2.2.10 Cooling Load Summary

The total cooling load is determined as follows (Bhatia, 2020):

$$Q_{space} = Q_{roof} + Q_{walls} + Q_{windows} + Q_{people} + Q_{light} + Q_{appliance} \quad (18)$$

$$Q_{Total} = Q_{space} + Q_{\inf} + Q_{vent} \quad (19)$$

where Q_{Total} = total cooling load (W), Q_{space} = space cooling loads (sensible and latent) (W), Q_{vent} = ventilation load (W), Q_{inf} = infiltration load (W) (Bhatia, 2020).

2.3 Designing of Thermal Zones

A thermal zone is a region of the building with one thermostatic control (Institute of Civil Engineers, 2017). The building envelope is divided into 5 thermal zones having 30 rooms using the Exposure Zoning Method recommended by Carrier Corporation (2016). The North-East orientation and North orientation of the building considered in this study are divided in to thermal zones as shown in Figure 1 and Figure 2, respectively.

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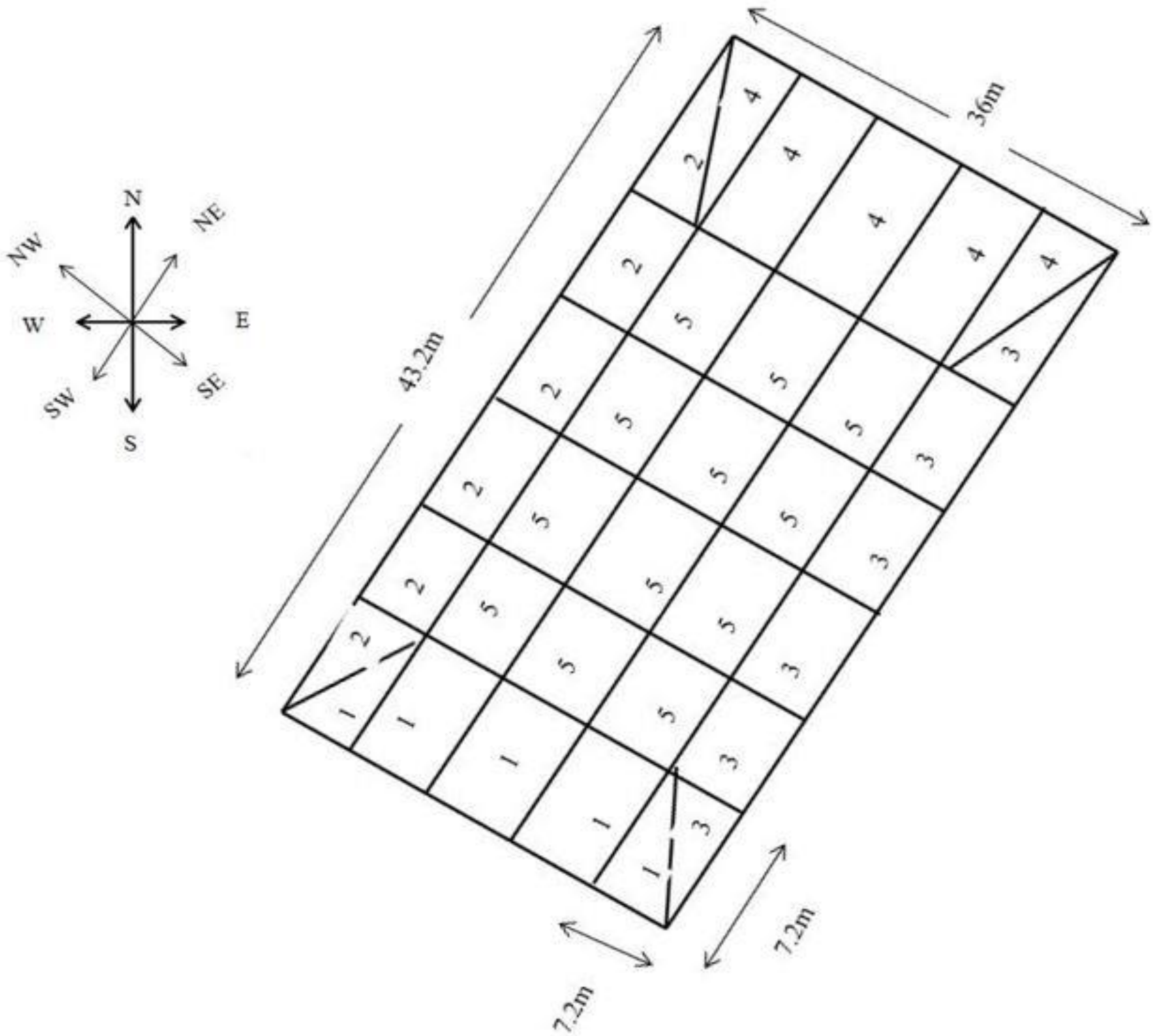

Figure 1: Schematic Diagram of Thermal Zone Divisions from Architectural drawing in North-East orientation

Table 1: Thermal Zone Description in North-East orientation

Zone Number	Number of Walls per room	Wall Side	Number of Room	Area of Concrete Wall (m^2)	Area of Glass wall and Window (m^2)	Area of Roof (m^2)
1	1	SW	4	10.37	41.47	51.84
2	1	NW	5	10.37	41.47	51.84

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3	1	SE	5	10.37	41.47	51.84
4	1	NE	4	10.37	41.47	51.84
5	-	Interior	12	-	41.47	51.84

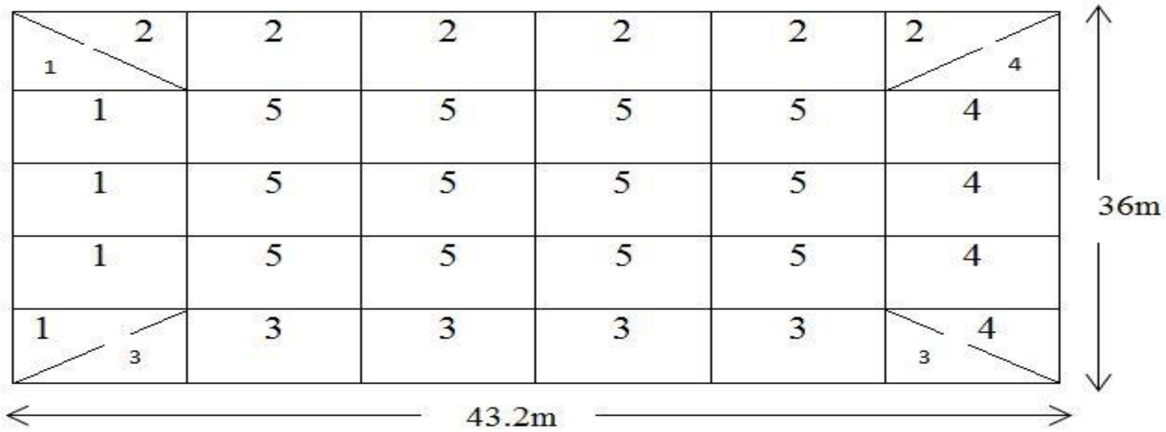

Figure 2: Schematic Diagram of Thermal Zone Divisions from Architectural Plan in North orientation

Table 2: Thermal Zone Description in North Orientation

Zone Number	Number of Walls per room	Wall Side	Number of Rooms	Area of Concrete Wall (m^2)	Area of Glass Wall and Window (m^2)	Area of Roof (m^2)
1	1	W	4	10.37	41.47	51.84
2	1	N	5	10.37	41.47	51.84
3	1	S	5	10.37	41.47	51.84
4	1	E	4	10.37	41.47	51.84
5	-	Interior	12	-	41.47	51.84

2.4 Energy Consumption

Energy used in AC systems is a major proportion of the total energy consumption in a building and depends on the total cooling load and the operation schedule of the building. Annual Energy Consumption (AEC) in the building is measured in kilowatt hour (kWh) and is calculated using the formula (Roslizar *et al.*, 2014):

$$AEC = Q_{Total} \times H \times LF \quad (20)$$

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where H = operation schedule (h), LF = loading factor of equipment

2.5 Energy Savings

Energy saving is an amount of saved energy determined by measuring consumption before and after implementation of an energy efficiency improvement measure. Energy saving is translated to cost saving which is calculated by the formula (Suna & Haas, 2013)

$$CES = AES \times ER \tag{21}$$

where CES = energy saving cost (₦), AES = annual energy saving (kWh), ER = electricity utility bill (₦/kWh)

3.0 RESULTS AND DISCUSSION

The results of the study are presented and discussed as follows:

3.1 Analysis of Total Cooling Load in North-East Orientation

The analysis of the sensible loads, latent loads and total cooling load of the building in North-East Orientation is obtained from the MATLAB program code developed.

Table 3: Total Cooling Load of the Building in North-East Orientation

Time of Day	8	9	10	11	12	13	14	15	16
				Zonal Load					
Zone-1 (4 Rooms)									
Sensible (W)	11406.57	18426.51	22812.10	27553.76	37722.28	71052.88	69843.38	61845.80	51472.388
Latent(W)	1669.745	1669.745	1669.745	1669.745	1669.745	1669.745	1669.745	41669.74	1669.74
Zone-2 (5 Rooms)									
Sensible (W)	13978.29	23033.24	28562.86	33882.41	39420.2	80670.26	61173.73	48272.35	43673.65
Latent(W)	1650	1650	1650	1650	1650	1650	1650	1650	1650
Zone-3(5 Rooms)									
Sensible (W)	49900.18	66700.81	72778.54	72692.13	67336.69	48394.54	51617.66	55085.06	60428.8
Latent(W)	2087.181	2087.181	2087.181	2087.181	2087.181	2087.181	2087.181	2087.181	2087.181
Zone-4(4 Rooms)									
Sensible (W)	42613.88	45431.72	39801.97	36626.14	36606.07	48781.08	54051.56	38406.91	37783.71
Latent(W)	1669.745	1669.745	1669.745	1669.745	1669.745	1669.745	1669.745	1669.745	1669.745
Zone-5(11 Rooms)									
Sensible (W)	10291.49	22834.57	26403.85	30304.87	34713.03	36745.94	38923.17	39022.17	37500.54
Latent(W)	4591.797	4591.797	4591.797	4591.797	4591.797	4591.797	4591.797	4591.797	4591.797
Zone-5 Kitchen Room									
Sensible (W)	3131.59	4271.87	4596.35	4950.99	5351.73	5536.54	5734.47	5743.47	5605.14
Latent(W)	1000.44	1000.44	1000.44	1000.44	1000.44	1000.44	1000.44	1000.44	1000.44
Zone-5 Office Services									
Sensible (W)	3131.59	4271.87	4596.35	4950.99	5351.73	5536.54	5734.47	5743.47	5605.14
Latent(W)	417.44	417.44	417.44	417.44	417.44	417.44	417.44	417.44	417.44
Total(Sensible)(W)	**134453.6**	**184970.6**	**199552.0**	**210961.3**	**226501.7**	**346718.1**	**287078.4**	**192273.4**	**190596.9**
Total(Latent)(W)	**13086.34**	**13086.34**	**13086.34**	**13086.34**	**13086.34**	**13086.34**	**13086.34**	**13086.34**	**13086.34**
Total Cooling Load(W)	**147539.9**	**198056.9**	**212638.4**	**224047.6**	**239588.1**	**359804.4**	**300164.7**	**275359.7**	**253683.2**

Table 3 shows the summary of these loads. The maximum sensible load, maximum latent load and maximum total cooling load obtained from the analysis are 346718.1W, 13086.34W and 359804.4W, respectively.

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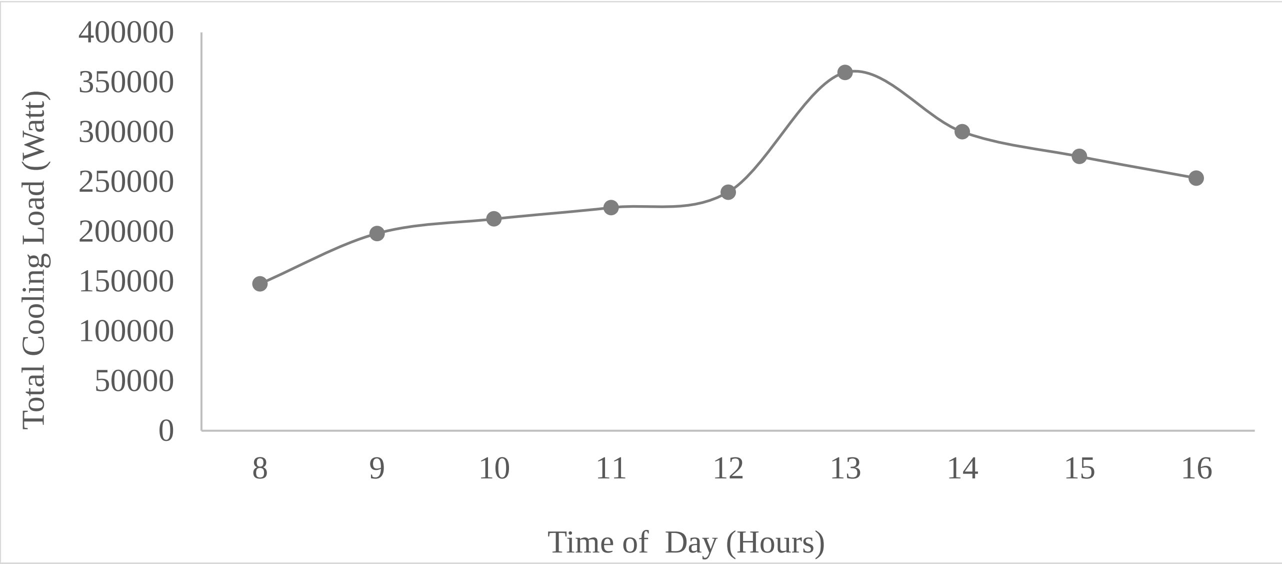

Figure 4: Graph of the Total Cooling Load Against Time for North-East Orientation

Figure 4 shows the variation of the total cooling load with time which clearly shows that the maximum cooling load of 359804.4W in the North-East orientation occurred at 13.00 hours.

3.2 Analysis of Total Cooling Load of the North Orientation

Analysis of the total cooling load in North orientation was done in like manner to the North-East orientation.

Table 4: Total cooling load of the Building in North Orientation

Time of Day	8	9	10	11	12	13	14	15	16
				Zonal Load					
Zone-1 (4 Rooms)									
Sensible (W)	11630.52	18949.04	23298.16	27553.76	33019	75206.56	69932.24	55454.68	40980.12
Latent(W)	1669.745	1669.745	1669.745	1669.745	1669.7	1669.745	1669.745	1669.745	1669.745
Zone-2 (5 Rooms)									
Sensible (W)	16594.92	23888.82	27937.47	33536.92	40275	61959.47	45368.82	44480.47	43328.19
Latent(W)	1650	1650	1650	1650	1650	1650	1650	1650	1650
Zone-3(5 Rooms)									
Sensible (W)	13259.62	26501.42	40119.32	51118.72	60930	52636.17	60693.52	65484.97	66665.42
Latent(W)	2087.181	2087.181	2087.181	2087.181	2087.1	2087.181	2087.181	2087.181	2087.181
Zone-4(4 Rooms)									
Sensible (W)	55473.72	63146.54	61678.04	54237.92	46543	38686.16	40224.36	41076.48	43121.48
Latent(W)	1669.745	1669.745	1669.745	1669.745	1669.7	1669.745	1669.745	1669.745	1669.745
Zone-5(11 Rooms)									
Sensible (W)	10291.49	22834.57	26403.85	30304.87	34713	36745.94	38923.17	39022.17	37500.54
Latent(W)	4591.797	4591.797	4591.797	4591.797	4591.7	4591.797	4591.797	4591.797	4591.797
Zone-5 Kitchen Room									
Sensible (W)	3131.59	4271.87	4596.35	4950.99	5351.	5536.54	5734.47	5743.47	5605.14
Latent(W)	1000.44	1000.44	1000.44	1000.44	1000.4	1000.44	1000.44	1000.44	1000.44
Zone-5 Office Services									
Sensible (W)	3131.59	4271.87	4596.35	4950.99	5351.7	5536.54	5734.47	5743.47	5605.14
Latent(W)	417.44	417.44	417.44	417.44	417.44	417.44	417.44	417.44	417.44
Total (Sensible)(W)	**113513.4**	**163864.1**	**188629.54**	**206654.17**	**226186**	**279907.4**	**266611.2**	**257005.7**	**242806.0**
Total (Latent)(W)	**13086.34**	**13086.34**	**13086.348**	**13086.348**	**13086**	**13086.35**	**13086.34**	**13086.35**	**13086.34**
Total Cooling Load(W)	**126599.7**	**176950.4**	**201716.3**	**219740.51**	**239272**	**292993.7**	**279697.6**	**270092.1**	**255892.4**

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Table 4 shows the summary of the results of the sensible loads, latent loads and total cooling loads for the building in North orientation. The maximum sensible load, maximum latent loads. and maximum total cooling load obtained from the analysis are 279907.38W, 13086.34 W and 292993.72W, respectively.

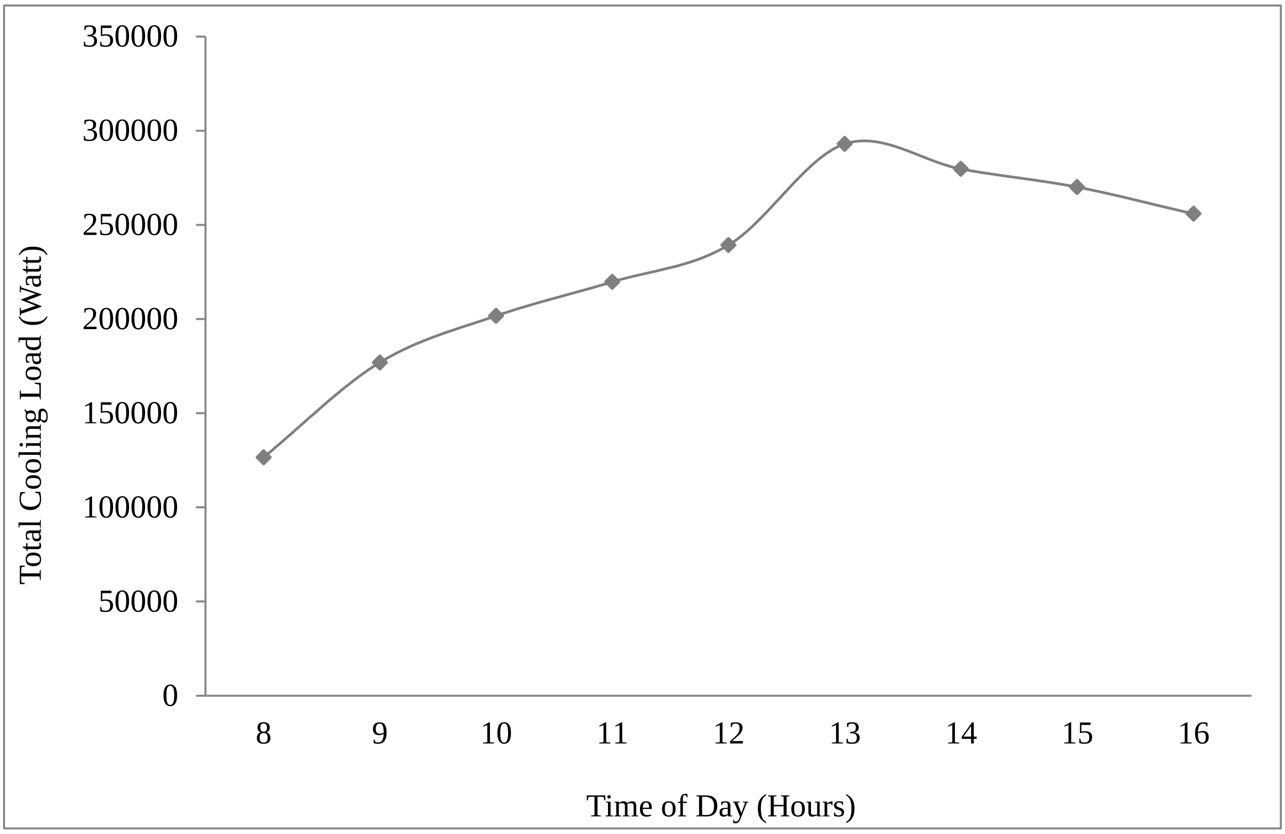

Figure 5: Graph of the Total Cooling Load Against Time for North Orientation

Figure 5 shows the variation of the total cooling load with time which clearly shows that the maximum cooling load of 292993.7W in North Orientation also occurred at 13.00 hours.

3.3 Analysis of Energy Consumption

Applying Equation 20, the energy consumption when the building is oriented North-East and North are determined as follows: H = 9h (Building Survey Report), LF = 1.15 (ASHRAE, 2017), $Q_{Total(NE)}$ = 359804.4W (Table 3), $Q_{Total(N)}$ = 292993.72W (Table 4)

$$AEC_{NE} = 359804.4 \times 9 \times 365 \times 1.15$$
$$= 1359251.072 kWh$$
$$AEC_{N} = 292993.72 \times 9 \times 365 \times 1.15$$
$$= 1106857.025 kWh$$

From the analysis, the difference between the energy consumption for the North-East and North orientations is 252394.047kWh. Thus, when the building is oriented North, an annual energy savings of 252394.047kWh would be achieved over that of the North-East orientation.

3.4 Analysis of Energy Cost Savings

Applying Equation 21, the energy cost savings is determined as follows: *AES* =252394.047kWh, *ER* = 50.20₦/kWh (Port Harcourt Disco. 2015)

Therefore, *CES* = 252394.04 x 50.20

= ₦12, 670,181.16

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This indicates a potential energy cost savings of ₦12, 670, 181.16 annually, if the building is oriented North than North-East.

4.0 CONCLUSION

The findings of the study are summarized as follows:

(i) The cooling load of the building in North-East orientation analyzed using MATLAB program shows that the maximum sensible load, latent load and total cooling load are 346718.06W, 13086.34W and 359804.4W, respectively.

(ii) The cooling load of the building in North orientation shows that the maximum sensible load, latent loads and total cooling load are 279907.38W, 13086.34W and 292993.72W, respectively.

(iii) The maximum load of the building in both North-East and North orientation occurred at 13.00 hours.

(v) An annual energy savings of 252394.047kWh would be achieved, when the building was oriented north, which translates to a potential energy cost savings of ₦12, 670,181.16 annually.

In conclusion, the better of the two orientations, in term of energy consumption, is the North; thus, validating appropriate building orientation selection an architectural solution to optimized energy consumption and cost in buildings.

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