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The Effect of Aspect Ratio of Compact Forms on Thermal Comfort in a Telecommunications Office Building in Hot-Dry Region

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ABSTRACT

Telecommunications office buildings have become important to the development of every nation's economy, and on the other hand, they mostly have large workspaces, thereby, making thermal comfort a necessity. Unfortunately in the hot-dry regions, achieving this comfort has always been through mechanical means with excessive use of energy. The study aimed at investigating the suitable aspect ratio of building forms (compact forms) in a telecommunications office building in a hot-dry climate of Maiduguri. It therefore focused on, firstly, examining the thermal performance of different building forms of the same floor area against their volume to surface ratio (V/S) and secondly, the forms were further optimized with different aspect ratios elongated along east-west orientation. ECOTECT program was used to experimentally study the energy performance and solar radiation on exposed surfaces of the forms using weather data files of hot-dry region. The study showed that forms with higher V/S performs better, and also 20% solar radiation on the west surface could be further reduced during summer period when optimized with an optimum aspect ratio of (1:2.5) as compared to aspect ratio (1:1).

Keywords: Aspect ratio, Building forms, Hot-dry climate, Volume to surface ratio, large workspace, Thermal comfort.

INTRODUCTION

Thermal comfort is recognized as a key parameter for healthy and productive workplaces. Some of which are found in telecommunications building. At the same time, lowering energy use in office buildings' workspaces is vital if a significant reduction in greenhouse gas emissions is to be achieved. Traditionally thermal comfort has been achieved at the expense of significant energy use for heating and/or cooling (Ismail etal., 2010). In a major study, Taylor *et al*; (2008) found that a well-designed building should be able to provide good thermal comfort, while simultaneously having low energy consumption. The excessive energy used to attain occupants' comfort has caused decrease in the productivity of companies, If the decrease in productivity is lasting for a longer period and many employees have to deal with these circumstances, the effect to the productivity can be enormous. The loss of each worker will affect the others and add up. The condition of the environment of a company seems to be very important with respect to the productivity and hence the success (Ismail etal., 2010). Studies have shown that employee satisfaction with the thermal comfort of their workplace plays a significant role in both employee retention and productivity. One study even revealed that employees consider workplace comfort second only to compensation in terms of benefits (American Society of Interior Designers, 1999).

Therefore, primary design parameters of building should be developed as providing the climatic comfort conditions and minimum energy consumption during the construction and use of the building. Building form is one of the important design parameters affecting the heating and cooling energy consumption in the building. (Erdim & Manioglu, 2011). Studies by (Marks, 1997) and (Chia *et al*; 2007) show that different geometrical forms have the ability to react to thermal comfort differently, due to differences in its geometrical characteristics. It was based on these that the study aimed at examining different aspect ratios of building forms in an attempt to suitably enhance the thermal comfort, with minimum amount of energy in a telecommunications office large workspaces in a hot- dry region.

Building Form Compactness

A study by (Gratia & De Herde, 2002) defined the volume to surface area ratio (V/S) as 'compactness' (C) of a form. Here the surface area of a building includes wall surfaces, roof surface, and ground surface. As heat losses are proportional to the surface area of envelope, the more compact a form, the less will be the heat loss. Buildings with non- rectangular plan (or with complicated configurations) are prone to thermal bridges and losses; as the junctions of structural components do not lie on the same plane. As demonstrated by the study, building with a V/S of 1.24 (highly compact) requires less space heating /cooling energy while compared to a building with a V/S of 0.84 (the least compact form studied).

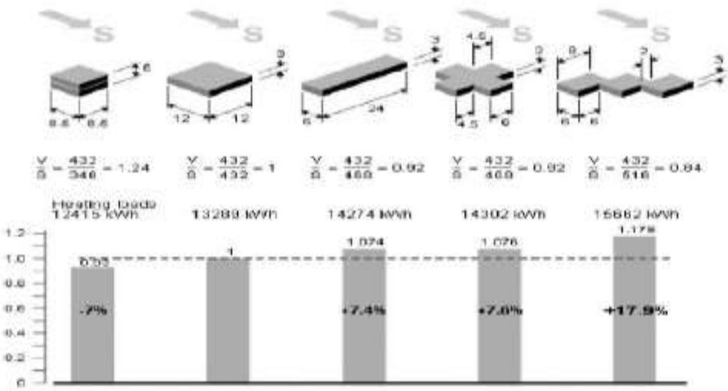

Figure 1.1: Impact of building shape on heating load
Source: Gratia & De Herde, 2003

(AlAnzi, Seo, & Krarti, 2009) have proposed a different metric to measure the compactness of a form in Kuwait as shown in figure 1.2 . Relative compactness (RC) is used in their study as an indicator while assessing the impact of shape on the building energy performance. According to their result, it is observed that as the RC increases, the exterior wall area exposed to ambient conditions decreases and consequently the building energy decreases.

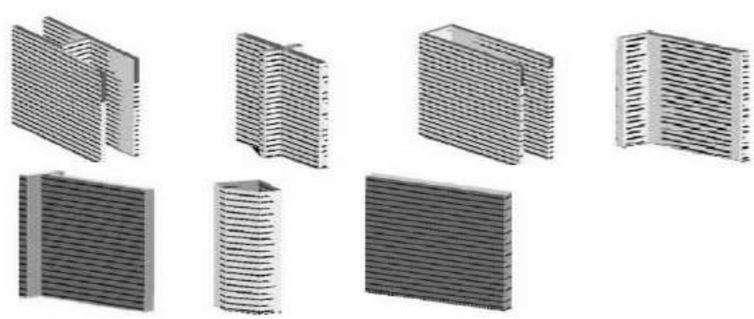

Figure 1.2: L-type, T-type, H-type, cross shape, U-shape, cross shape, and rectangular office buildings
Source: (AlAnzi, Seo, & Krarti, 2009)

A simplified method was developed in the study to predict the impact of shape on the annual energy use for office buildings in Kuwait. Basically, the study depended on the relative compactness (RC) of the building and correlated it with the annual energy use. The relative compactness based on the ratio between the volume of a built form and the surface area of its enclosure compared to that of the most compact shape with the same volume. The results of this study indicated that the effect of building shape on total building energy use depends on the relative compactness, RC, the window- to-wall ratio, WWR and glazing type. Also, it is found that the total energy use is inversely proportional to the building relative compactness independent of its form (AlAnzi, Seo, & Krarti, 2009). Using the relative compactness in evaluating the energy efficiency was criticized as it does not capture the specific three-dimensional massing of a building's shape which can affect the thermal performance via self-shading for example. Also, changing orientation and distribution of glazing which changes the building morphology, shading potential and its thermal performance without changing the relative compactness (Pessenlehner & Mahdavi, 2003).Another study by Gelekta & Sedlakova (2012) selectively compared different forms with dintinct relative compactness (cube, rectangle) and other shapes with varying aspect ratio. The results of the simulation show that the energy use decreases as relative compactness increases. Also, as the relative compactness increases, exterior wall area exposed to ambient conditions decreases. Therefore, in this case the compactness of a form (V/S) area is the main factor that reduces energy load. A study in support of the findings by Gelekta & Sedlakova (2012),AlAnzi, *et al;* (2009) proposed different metric to measure the compactness of a form. Relative compactness (RC) is used in their study as an indicator while assessing the impact of shape on the building energy performance. Their results finally gathered that, as the relative compactness increases, exterior wall area exposed to ambient conditions decreases. Therefore, (Muhaisen & Abed, 2013) concluded that the main proportions affecting geometric shape are surface-to-volume ratio and width to length ratio. Forms with different geometric shapes of the same contained volume have different surface area. This is usually expressed by surface to volume ratio (Behsh, 2002) . However, according to(Ratti, Raydan, & Steemers, 2003), an indication contrary to a high surface to volume ratio is the increase in heat loss during winter season and heat gain due to exposure to solar radiation during summer season. Surface-to-volume ratio (S/V ratio) for geometric shape depends on width to length (W/L) ratio. Geometric shapes with higher value of (W/L) ratio contained lower value of (S/V) ratio [8].

Aspect Ratio (Width to length ratio)

A study by Szokolay (2004) recommends an aspect ratio of 1: 1.3 to 2.0 for elongated buildings depending on the climate and walls with major openings (on the elongated side) to face within 45° of the prevailing wind direction. This is 15° more than what (Lauber, 2005), suggested on the above issue. On the other hand, this implies an optimum orientation of the elongated sides facing north or south, and a thermally inappropriate direction of openings facing the western sun.

(Koranteng &Abaitey, 2010) assert that for a shape that is spread out, the use of ambient energy and orientation is an important issue; whiles compact forms tend to minimize the influence of the external environment, thereby ignoring orientation. The more a form is spread out, the larger the surface area and area that could be exposed to solar radiation. Therefore, for such forms, orientation has to be away from the east and west.

A ratio of 1: 1.64 is also recommended by (Watson & Labs, 1983), but orientation ceases to be an issue when thermal resistance of the building envelope increases.

According to the study of (Chia et al , 2007)W/L ratio are based on studies from Olgyay (1963) and Yeang (1994) which suggested that building form with W/L ratio 1:1.7 and 1:3 are the optimum ratio for tropical climate. They investigated different configuration of forms of high-rise buildings in tropical hot-humid region in Malaysia. This study therefore established a range of aspect ratios on the basis of the above studies.

METHODOLOGY

The experiment in the first phase involves simulation of different built forms in terms of their volume-to-surface ratio for energy consumption. Simulation models of (Cube, cylindrical, L-shaped, U- shaped, H-shaped, and cross shaped) with the same floor area and volume are created using Autodesk revit. Revit is also used to create bounded 'rooms (zones) to be identified by ECOTECT. The mass models are then exported to ECOTECT analysis as 'gbxml' file.

The criteria used for assessing the building forms is based on the reliable findings of the extensive study from literature. Each of the building form is studied based on the main factors that led to the minimum energy consumption. The second phase of the simulation involves further optimization of the cylindrical and the cube form (which results showed to be the most compact forms) with aspect ratios.

ECOTECT was therefore, used to simulate data for cumulative incident solar radiation on the vertical surfaces of the forms on a daily and monthly basis. The simulation displays the graphical distribution patterns and availability of solar insolation over the surfaces of the entire building. All simulations are calculated based on the available hourly direct and diffuse horizontal solar irradiance data from ECOTECT Weather Tool for Maiduguri, Nigeria (11°N, 13°E).

Dependent and Independent Variables

Both dependent variables are adjusted by the independent variables which are the comfort conditions (air temperature, relative humidity, air velocity, activity level, clothing insulation and radiant heat gain), building forms and aspect ratios. This is as shown below:

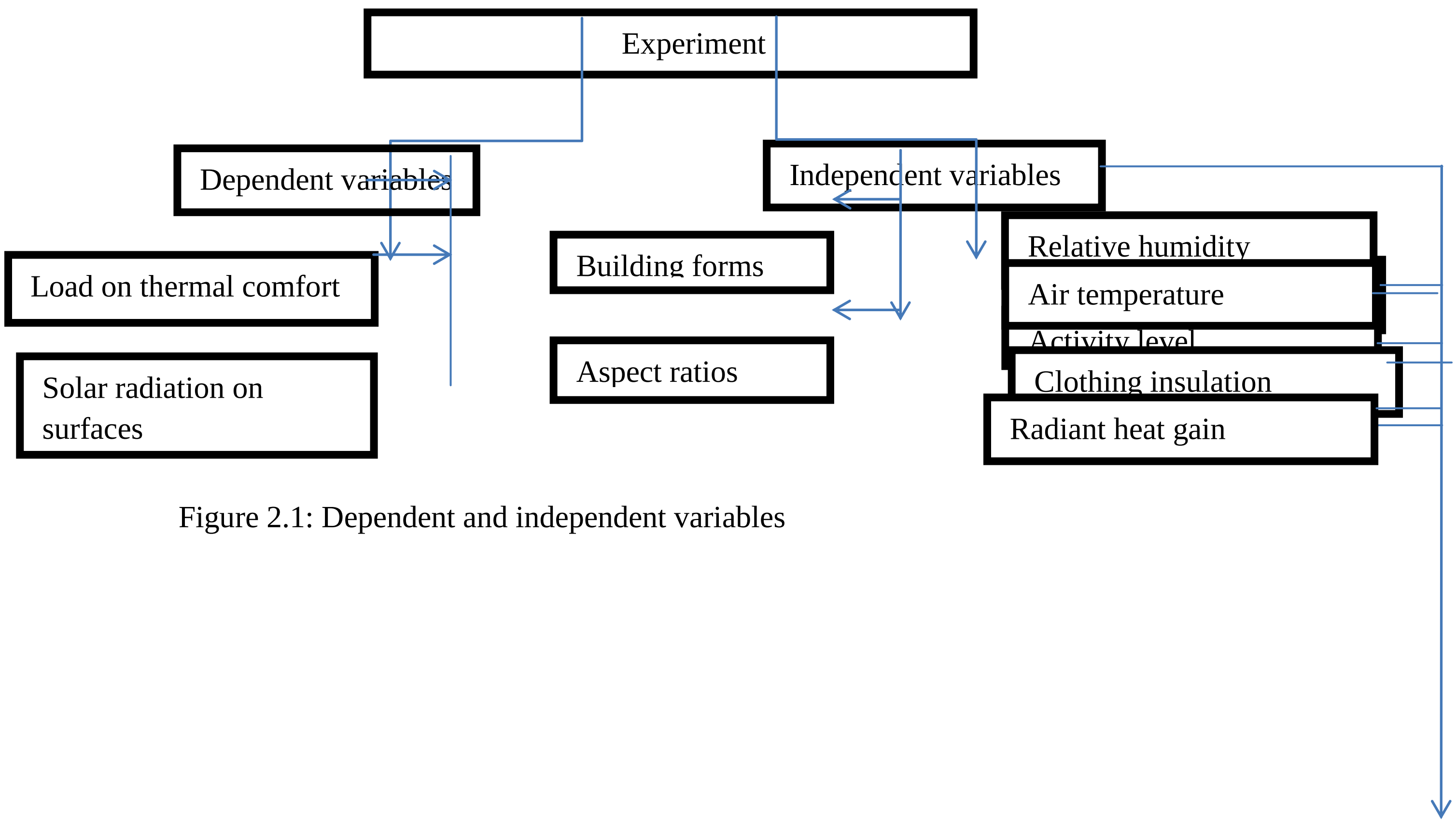

Figure 2.1: Dependent and independent variables

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SIMULATION INPUTS AND ASSUMPTIONS

Analysis of Internal Heat Gain

Internal gains are considered from people, fluorescent lighting, and equipment. At first, occupancy density for the office space is determined according to the default values listed in Standard 62.1- 2007 (ASHRAE, 2007) as 20person/m2. No occupancy is chosen for auxiliary spaces.

i) Heat gain from people for 24 °C room dry bulb temperature, an adult male will produce 75 *W* sensible heat and 55*W* latent heat performing moderately active office works (ASHRAE, 2009). Following this Guideline, sensible heat gain and latent heat gain are set as 75*W*/person and 55*W*/person respectively.

ii) Heat gain from equipment

Heat gained from servers and UPS (uninterrupted power supply) in telecommunication rooms, equipment rooms and other equipment facilities are set as obtained from ASHRAE thermal guidelines for telecommunication facilities, 2009 as shown in table below. And for the assumed office spaces in the experimental procedure, In a medium to heavy load density office the recommended load factor for equipment is 16.1 *W*/m2. Here equipment refers to computers, monitors; laser printer, and fax machines (ASHRAE, 2009).Therefore, equipment gains are set as 16.1 *W*/m2 for open plan offices in current project.

Table. 2.1: Illustration of primary parameters for the simulation

Equipment Heat Dissipation			**2.3kw Power Consumption**			
			744w/m^2 heat dissipation			
Functions Assumed	Comfort temperatures (°C)		Equipment Sensible Heat gain (w/m^2)	Lighting sensible heat gain (w/m^2)	Occupants latent heat gain (w/m^2)	Air change rate (per hr)
	Heating set point	Cooling set point	Heat dissipated per rack=744 Racks per telecom room= 5			
Equipment area	18.3	32.2	3720.0	22.0 (Data center white paper,2004)	55.0 (ASHRAE, 2009).	15.0 -20.0 (Engineering toolbox,)
Open office plan	18.0	26.0	16.0 (ASHRAE, 2009).	12.0 (ASHRAE, 2009).	55.0 (ASHRAE, 2009).	3.0 (Engineering toolbox,)

RESULTS AND DISCUSSIONS

About 12 simulations are performed corresponding to simulation of 6 different varieties of form which gave clear preference of the forms in terms of energy required for thermal comfort and HVAC load consumption. And thereafter, another simulation for 6 varying aspect ratios of the cube and cuboid form was performed to check the amount of solar insolation on west and south surfaces. Below are results of the simulations based on the internal heat gain input information.

Table 3.1Description of forms that were simulated

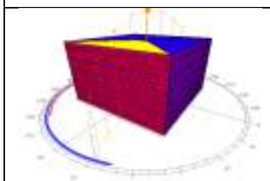
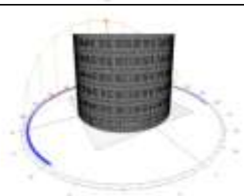
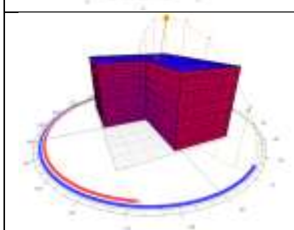
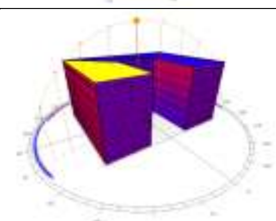
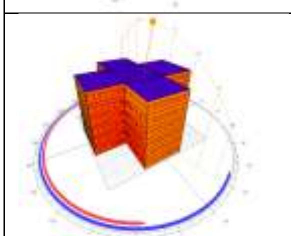
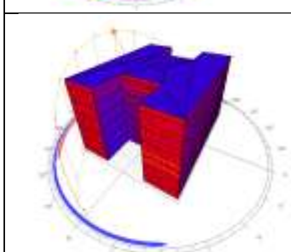
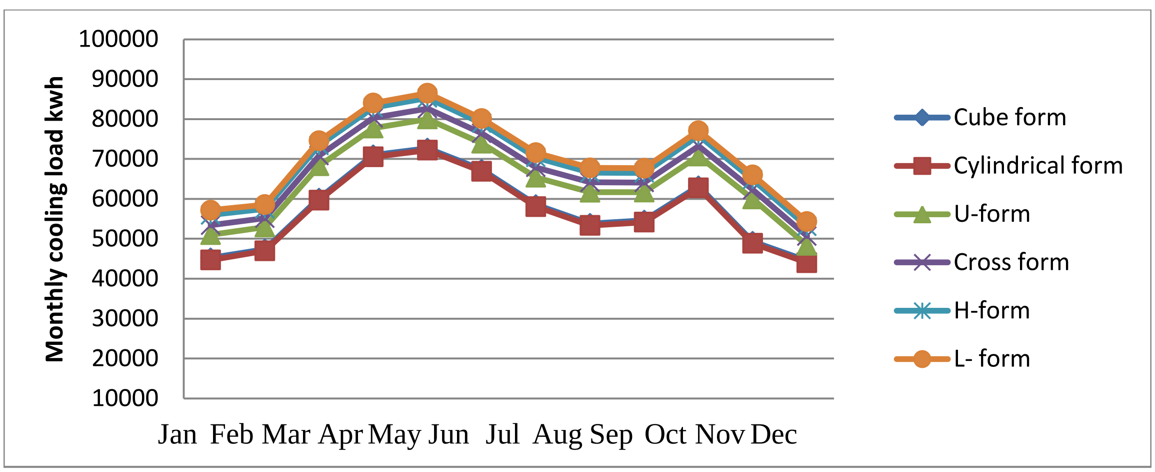
Building Forms	Volume	Volume /surface area Ratio (V/S)	Total floor areea	Total Surface area	Exposed surface area
	29326.4m^3	1.56	7350.0m^2	18828.0m^2	4582.3m^2
	29326.4m^3	1.57	7350.0m^2	18810.0m^2	4784.6m^2
	29326.4m^3	1.54	7350.0m^2	19098.3m^2	5010.3m^2
	29326.4m^3	1.54	7350.0m^2	19082.0m^2	5821.6m^2
	29326.4m^3	1.51	7350.0m^2	19406.6m^2	5413.4m^2
	29326.4m^3	1.45	7350.0m^2	20180.5m^2	5989.3m^2

Table.1.2 :Monthly and annual cooling loads

Months	Cube form	Cylindrical form	U-form	Cross form	H-form	L- form
Jan	45186.5	44686.5	51020.4	53377.2	55952.3	57142.7
Feb	47422	46970.4	52937	55137.4	57488.7	58563.9
Mar	60155.7	59655.7	68277	70827.6	73367.2	74557.6
Apr	71009.2	70525.3	77724.9	80259.3	82852.7	84004.7
May	72696.3	72196.4	80011.9	82618	85277	86467.4
Jun	67367.6	66883.7	73926.2	76433.4	78958.6	80110.6
Jul	58532.7	58032.7	65398.6	67896	70378.9	71569.3
Aug	53842.2	53342.2	61639.7	64126.6	66555.9	67746.3
Sep	54649.7	54165.9	61686	64095.6	66511.1	67663.1
Oct	63238.2	62738.2	70706.9	73212.8	75860.3	77050.7
Nov	49344.3	48860.5	59958	62280.6	64842.1	65994.1
Dec	44483.1	43983.1	48327.1	50658	53116.6	54307
TOTAL	687927.3	682040.6	771613.7	800922.4	831161.3	845177.3



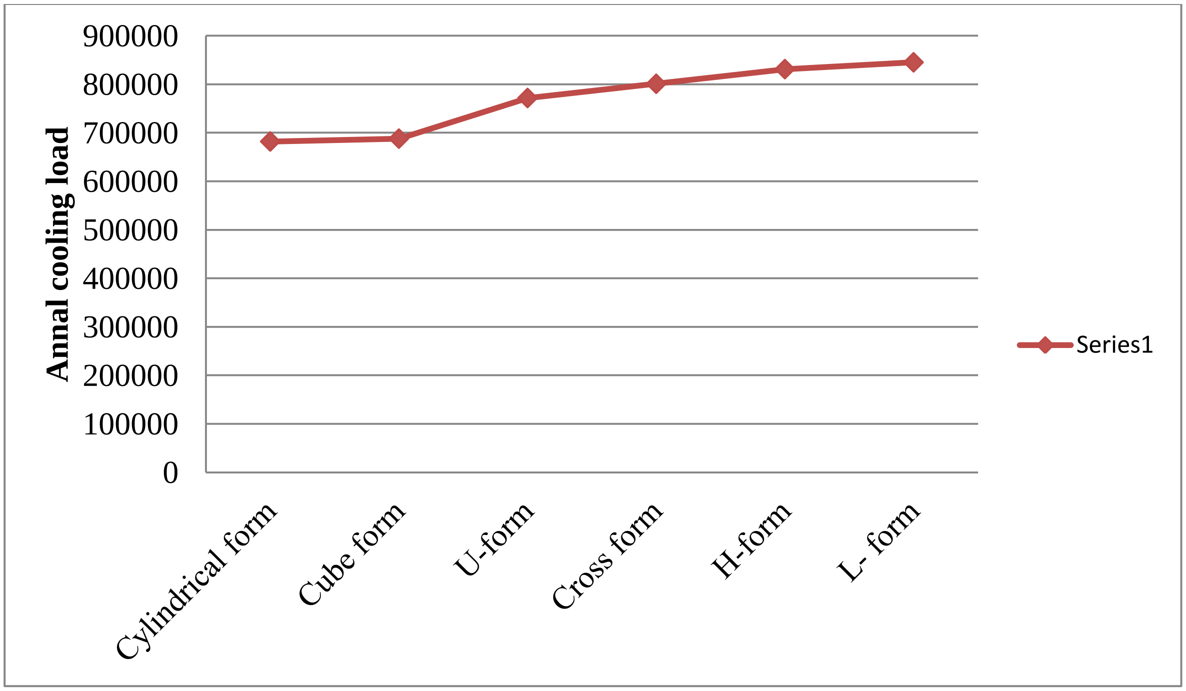
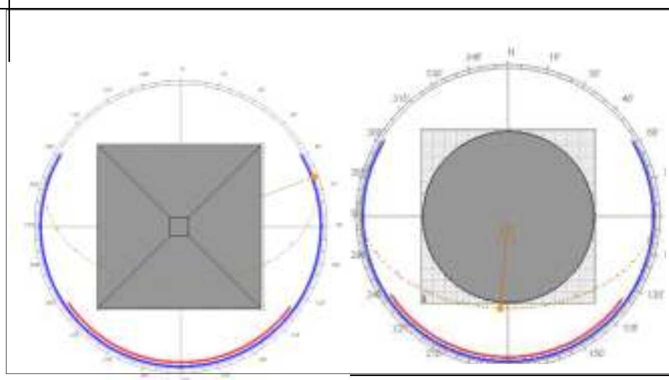


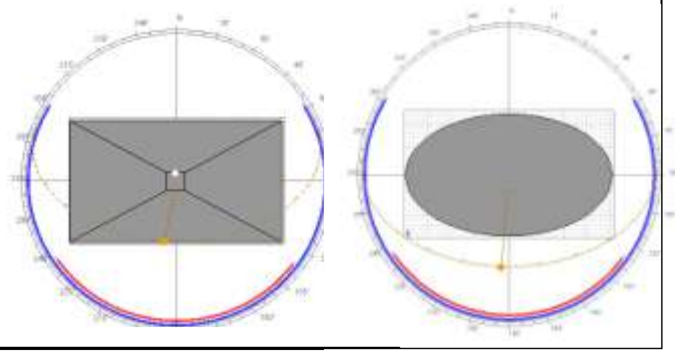
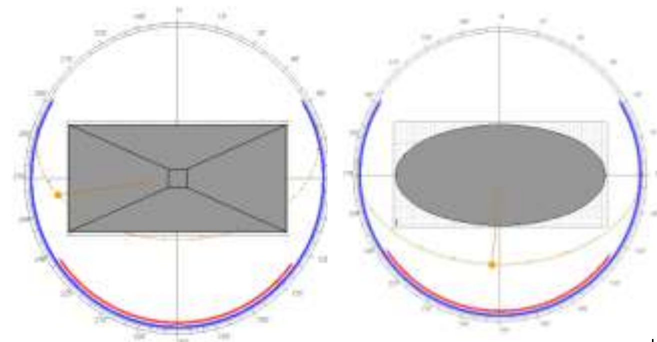
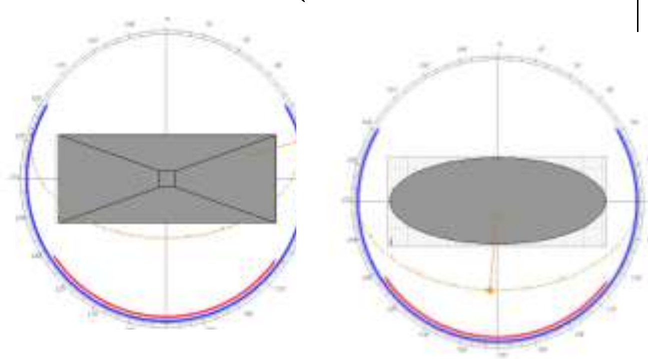
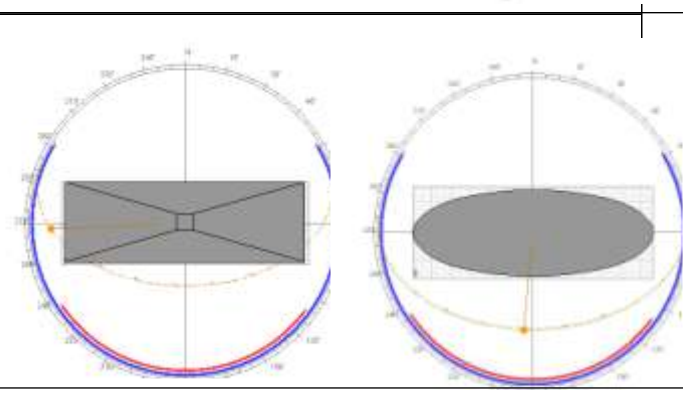
Figure 3.2: Comparison of annual cooling load of the forms

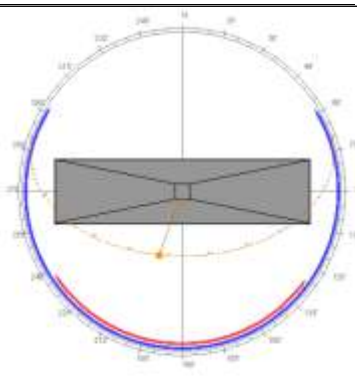
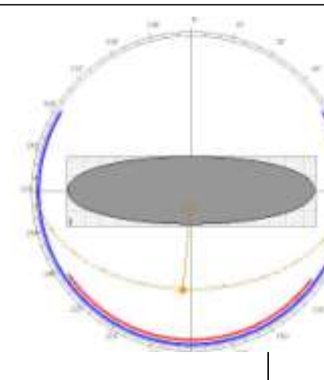
The above charts and table illustrate the monthly energy consumption on thermal comfort for each of the building forms. From the analysis performed, the cubic form and the cylindrical form showed minimum energy required for cooling annually. Although the cylindrical form shows slight reduction than the cubic form as it dropped by 5886Wh representing 1.1 % less energy consumed. This was because of the slight increase of volume / surface the former has over the latter. However, the cube depicts the definition of compactness of a form in terms of highest value of volume/surface ratio (V/S) over the other rectilinear forms which are the ,L-shape, U-shape, and H-shape.(see table 3.1 above). The cube form dropped by 836864kwh representing 10.8% as compared to the U- form, the U- form dropped by 29308 kwh representing 3.7% as compared to the cross-shape, the cross-shape dropped by 30238kWh representing 3.6% as compared to the H-shape, and the H-shape dropped by 14016kwh representing 1.7% as compared to the L-shape. This significant high reduction in energy consumption from cube and cylindrical-shape compared to H-shape is caused by the fact that the H-shape has the least V/S in terms of compactness (see table 3.1 above). It shows high decrease in V/S compared with the other forms which translates to the high increase in its energy consumption as shown in the table and graphs below. The percentage drop in energy consumption from the cube/cylindrical forms (most suited form) to the H-form (least suited form) is 157250kwh which represents 18% total reduction.

Analysis of Varying Aspect Ratios for the Compact Forms

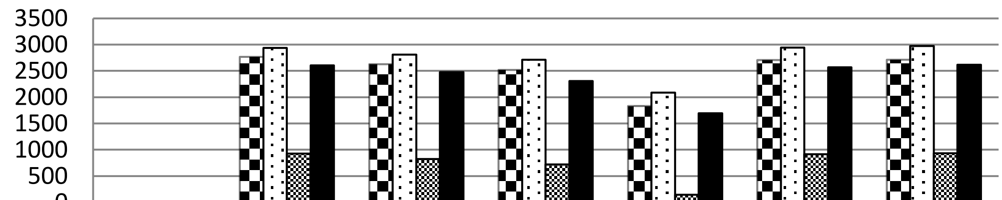
From result above, it is evident that the cylindrical and the cubic form are the most compact form and have the minimum energy consumption. However, this section further experiment the extent to which solar radiation on exposed west surfaces could be reduced during summer and maximized on south surfaces during winter. According to (Hachem, Athienitis, & Fazio, 2011). The south facade can receive more than twice the heat gain of east and west facades in the winter. Yet, the east and west facades have significant impacts on overall heat gain in the summer months. Solar radiation can be harnessed to reduce the consumption for heating by altering the building aspect ratio. Based on this, ratios 1:1, 1:1.7, 1:2, 1:2.5, 1:3 and 1:4 are proposed to further optimize these forms.

Aspect Ratios (X:Y)	Total floor area	West exposed area	South exposed area	Forms on east –west orientation
1:1 B x L = 34.8m x 34.8m	1200 m^2	100.94m^2	100.94 m^2	

1:1.7 B X L = 26.6m x 45.2m	$1200m^2$	77.62 m^2	131.04 m^2	
1:2 B X L = 24m x 50m	$1200m^2$	70.63 m^2	143.67 m^2	
1:2.5 B X L = 22m x 55.2m	$1200m^2$	63.66 m^2	157.46 m^2	
1:3 B X L = 20m x 60m	$1200m^2$	59.74 m^2	173.17 m^2	

1:4 B X L = 17.2m x 70m	1200m^2	51.22 m^2	202.21 m^2	 

Incident solar radiation (w/m2)



	Aspect ratios	Ratio 1:1	Ratio 1:1.7	Ratio 1:2	Ratio 1:2.5	Ratio 1:3	Ratio 1:4
south sufaces		2771	2632	2518	1831	2705	2717
west surfaces		2938	2812	2714	2088	2944	2974
North surfaces		929	829	723	148	918	934
East surfaces		2603	2479	2306	1692	2571	2615

Figure 3.1: Chart showing high solar radiation on west and south surfaces on a daily basis on 15th May in summer and 7th January in winter respectively, for different ratios.

From the charts above, result shows that incident solar insolation is more excessive on the west during summer and south during winter. Also, it could be noted that the incident solar radiation decreases progressively from aspect ratio 1:1, followed by 1:1.7, 1.2 and 1:2.5. At aspect ratio 1:3, the incident solar radiation increases rather than decrease and it continued in that direction up to aspect ratio 1:4.Therefore, it could be said that an optimum aspect ratio of 1:2.5 existed for the wide range of ratios from 1:1-1:4. This complied with what Olgyay (1963) and Yeang (1994) obtained as ranges within which aspect ratio should not exceed, that is, 1:1.7-1:3.

From simulation results of the charts below, it is clear that the incident solar radiation is much excessive on the west surfaces for the aspect ratios during the summer periods, which is assumed to be as a result of high sun angle (fig. 3.2). On the contrary, figure 3.3 shows excessive amount of solar radiation on the south surfaces during winter months which are caused by low sun angle during the months. Therefore, the optimum aspect ratio (1:2.5) represents west and south surfaces whereby minimum solar radiation existed during summer corresponding to the maximum solar radiation in winter.

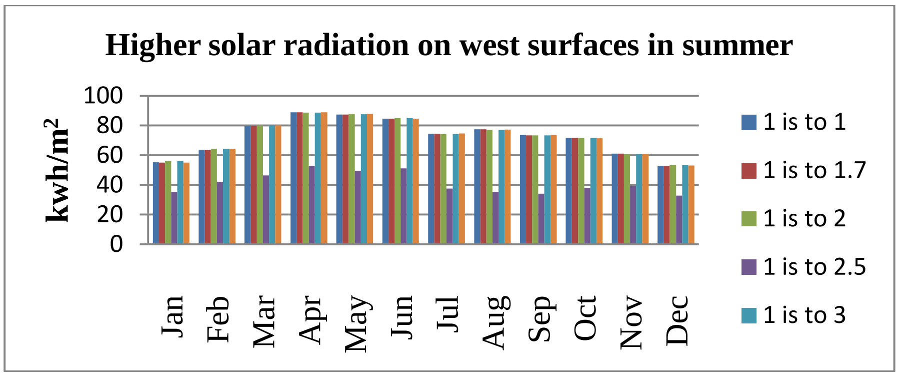


Figure 3.2: Chart showing high solar radiation during summer months on west surfaces for different ratios.

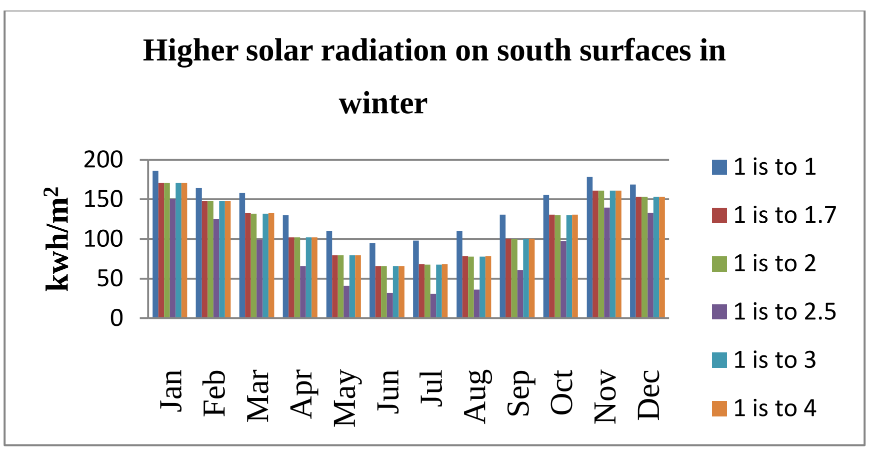


Figure 3.3: Chart showing high solar radiation during winter months on south surfaces for different ratios.

CONCLUSION

A simulation analysis was used to conduct experiment on the effects of varieties of building forms on annual energy consumption on thermal comfort for a large office workspace. Cylindrical and cubic forms appear to consume less energy. Thereafter, different aspect ratios were used to further optimize the extent at which solar radiation could be reduced on west surfaces in summer and maximized on south surfaces in winter. The inclusion of optimal aspect ratios in design criteria will have a lasting impact on the future energy consumption of building.

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