Multi-objective Optimisation of Building Design Variables and its impact on Office Building Performance: A Case for Ghana

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List of publications

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1. Appraisal and Implications of design variables in Ghana building regulation on low cooling energy utilization in selected commercial building sector.
2. Economic Assessment of low cooling energy utilization modifications at a Standard Office Building Envelope Design in hot-humid climate: A Case of Ghana.

Abstract

Multi-objective optimisation of building design variables is an appropriate and robust approach in assessing office building performance. Conversely, in developing country contexts like Ghana there is lack of credible building design variables from scientific and technical journals. The main research problem was low building performance assessment by building professionals in Ghana resulting in high cooling energy utilization and indoor environmental discomfort within the commercial building sector. Overall, the aim of the research was to use cost effective low energy technologies to optimize the building design variables to achieve recommended good practice for energy utilization of service equipment and indoor environmental performance in office building. Research questions addressed in this research included the following: 1. How does local building professionals' practices impact on design variables used in performance assessment, and are occupants' comfortable as well as satisfied with building performance in Ghana? 2. Are the building fabrics used in Ghana suitable for enhancing building performance? 3. How can the building performance design variables from survey questionnaires and experimental assessments be optimized? 4. Are the existing economic benefit assessment tools adequate for fast accurate decision making in comparing recommended good practice for cooling load by CIBSE Guides in hot-humid climate?

The following creative and novel methodologies were used for this research: 1. Survey questionnaires using Bristol Online Survey Tool for the administration and acquisition of responses from participants. 2. Experimental assessment of selected fabrics from Ghana and creative parametric fabrics using both TCi Thermal Analyser and AutoPore IV mercury intrusion Porosimeter. 3. Computer simulations for optimised design variables using ESDL Tas. Finally, Design of creative comparator decision making tool for economic benefit assessment of the optimised computer simulations design variables.

The selected significant findings from the application of the creative and novel methodologies in addition to the corresponding implications are summarised as follows:

1. An average of 16% of all building professionals do assess design variables associated with its practices with about 60% building professionals satisfied

with Ghana building regulations, on the contrary, highly recommended for an improvement on the regulations.

2. Experimental assessment of representative selected Ghana building fabrics and enhanced parametric studies meets the thermo-physical properties outlined in the CIBSE Guide standards, with the range of thermal conductivity being 0.2 to 0.7W/m^{2}K.
3. From the creative computer simulation outcomes, the cooling load of the base case is about 10 times more than the recommended good cooling load practice outlined in CIBSE Guides. The optimised computer simulation single wall layer building design model was achieved using optimum low transmittance building fabrics, optimum internal conditions and low chilled beam technology.
4. From the economic benefit assessment, an increasing trend of inverse correlation between difference in modification cost with cooling load reduction was observed. That is, for reduction in cooling load, there is an increasing cost in modification. For example, for reduction of cooling load of 40% from Case 1 to Case 3, there is a corresponding increase in modification cost of 79.4%.
5. Representative office occupants are generally satisfied and comfortable with building performance in Ghana.

The above findings have compounded extreme implications on the local building professionals' practices, leading to subsequently high cooling load, hence the rising energy utilization of service equipment in non-residential buildings. Finally, the overall aim of achieving the recommended good practice for service equipment energy utilization in commercial buildings was not accomplished for the cooling load. This is due to the difference in cooling load calendar used by CIBSE Guide and hot-humid climate, Ghana.

In conclusion, an optimised low cost computer simulation of single wall layer envelope design, with cooling load of 120 kW/m^2 for floor area and acceptable indoor environmental quality has been achieved in this research.

It is strongly, recommended that, performance assessment should be incorporated into building permit issuing process using the designed creative feedback chart designed in this research.

Keywords: Energy utilization, CIBSE Guide, Building performance, Design variables

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List of symbols

$\dot{q}_x$	Heat flux (W/m^2) in the positive x-direction
dT/dx	Temperature gradient (negative) (K/m) in the direction of heat flow
λ	Proportionality constant, thermal conductivity of the material (W/mk)
Q	Heat transfer rate in W
U	Overall transmittance in W/(m^2•K)
ΔT	Change in temperature in K
h	Heat transfer coefficient (W/m^2-K)
Ts	Temperature of the surface (K)
Tf	Temperature of the fluid (K)
A	Area (m^2)
E	Emissivity
ε	Surface's ability to emit radiation
σ	Stefan-Boltzmann Constant ($\sigma = 5.6 \times 10^{-8} W/m^2K^4$)
T_s	Absolute surface temperature in *K*
G	Incident radiation
G_{abs}	Rate of radiant energy absorption
α	Absorptivity
$\dot{Q}_{inf}$	Rate of infiltration
ELA	Effective leakage area
S	Specific infiltration velocity
V	Surface velocity at the envelope
f_s	Stack effect
f_w	Coefficient of wind effect
$\overline{ELA}$	Average effective leakage area
ρ	Density of air (kg/m^3)
V_r	Ventilation rate (m^3/s)

C	Specific heat of air (J/kg.K)
N	Number of air changes per hour
V	Volume of room space
SC	Shading coefficient
WO_3	Tungsten oxide
CO_2	Carbon dioxide
T_1, T_2, T_3, T_4 and T_5	Mixing design ratios for mortar and concrete block
k	Thermal conductivity
W	Electrical power input to the main heater
A	Main heater surface area
dT	Temperature difference across the specimen
d	Specimen thickness
M	Mortar block,
bs	Builders sand type
Tn	Test series of mixing ratio from n = 1, 2,3, 4 and 5.
ws	Washing sand type
bws	Mixed builders and washing sand type
C	Concrete block
m	Number of surfaces in room
$q_{i,\theta}$,	Rate of heat conducted into surface *i* at inside surface at time
Ai	Area of surface *i*
hci	Convective heat transfer coefficient at interior surface *i*
gij	Radiation heat transfer factor between interior surface *i* and interior surface *j*
$t_{a,\theta}$	Inside air temperature at time θ
$t_{i,\theta}$	Average temperature of interior surface *i* at time θ

$t_{j,\theta}$	Average temperature of interior surface *j* at time θ
$RS_{i,\theta}$	Rate of solar energy coming through windows and absorbed by surface *i* at time θ
$RL_{i,\theta}$	Rate of heat radiated from lights and absorbed by surface *i* at time θ
$RE_{i,\theta}$	Rate of heat radiated from equipment, occupants and absorbed by surface *i* at time θ
Z_{tbb}	Total cost of base building
z_b	Cost of base building envelope
z_{bo}	Electricity operating cost for base case
z_o	Base cooling load per meter square floor area * tariff.
B	Base cooling load per meter square floor area
Zbo	Base cooling
Z_{tmb}	Total cost of modified building
z_m	Cost of modified building envelope
M	Modified building cooling load per meter square floor area
z_{mo}	Electricity operating cost for modified building
Z_d	Difference in cost of modification
Z_{se}	Savings in electricity cost per annum after modification
Z_p	Payback

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Appendix C: Selected economic benefit graphs

List of Abbreviations

EIA	Energy Information Administration
IEA	International Energy Agency
DOE	Department of Energy
SE4ALL	Sustainable Energy for All
GNI	Gross National Income per capita
VRF	Variable Refrigerant Flow
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
UK	United Kingdom
ANSI	American National Standards Institute
IES	Indian Engineering Services
CIBSE	Chartered Institution of Building Services Engineers
ISO	International Organization for Standardization
EN	European
NF	French
ESDL	Environmental Design Solution Limited
TRNSYS	Transient System
VBA	Visual Basic for Applications
EES	Engineering Equation Solver
TAS	Thermal Analysis simulation Software
BLAST	Building Loads Analysis and System Thermodynamics
TRACE	Trane Air Conditioning Economics
eQUEST	The Quick Energy Simulation Tool
GHG	Greenhouse gas
ECG	Electricity Company of Ghana
CAR	Central African Republic

LWC	Lightweight Concrete
HVAC	Heating, ventilation and air conditioning
VAV	Variable Air Volume
FC	Fan Coil
EMCS	Energy Management and Control System
PT	Programmable Thermostat
AIM-2	Alberta Air Infiltration Model
CONTAM	Contaminant Transport Model
ABIMS	Acoustic Building Infiltration Measurement System
ASTM	American Society for Testing and Materials
ELA	Effective Leakage Area
TETD/TA	Total Equivalent Temperature Differential/Time Average
CLTD/CLF	Cooling Load Temperature Difference/Cooling Load Factor
TFM	Transfer Function Method
HB	Heat Balance
RTS	Radiant Time Series
TA	Time Averaging Method
SCL	Solar Cooling Load Factor
SC	Shading Coefficient
PV	Photovoltaic
VT	Visible Transmittance
SHGC	Solar Heat Gain coefficient
SC	Solar Control Technology
TI	Thermal Insulation technology
EWC	Efficient Windows Collaborative
EC	Electrochromic
IC	Ionic Conductor
CE	Counter Electrode

TC	Transparent Conductor
DC	Direct Current
TC	Thermochromic
PVB	Polyvinyl Butyral
IGU	Insulated Glass Unit
DFEG	Dynamic Facades Evaluation Group
LCD	Liquid Crystal Device
SPDS	Suspended Particle Device
PCM	Phase Change Material
TES	Thermal Energy Storage
LHES	Latent Heat Energy Storage
CTES	Cool Thermal Energy Storage
A/C	Air Conditioning
ERV	Energy Recovery Ventilation
HRS	Heat recovery system
BS	British Standards
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfaction
PURC	Public Utilities Regulatory Commission
GHP	Guarded Hot Plate
WBT	White Box Technologies
CBECS	Commercial Buildings Energy Consumption Survey
FTP	File Transfer Protocol
XML	extensible Markup Language
HTTP	Hypertext Transfer Protocol
DIFAX	Digital Facsimile
NCEI	National Center for Environmental Information
IWEC2	International Weather Experience Center 2
ISD	Integrated Surface Database
EPW	EnergyPlus Weather File

CSV	Comma Separated Values
USA	United States of America
CTZ2	California Climate Zones 2
CWEC	Canadian Weather for Energy Calculations
CityUHK	City University of Hong Kong
CSWD	Chinese Standard Weather Data
TMY	Typical Meteorological Year
TMY2	Typical Meteorological Year version 2
TMY3	Typical Meteorological Year version 3
GPSIA	GPS Innovation Alliance
ACH	Air Changes per Hour
DG	Double Glazed
LCC	Lowest Life Cycle Cost
LTC	Low Thermal Conductivity Building Fabric (Opaque And Transparent)
AIC	All internal condition variables
SPA	Savings per Annum
SNROLC	Simple Net Return over Life Cycle
DC	Difference in Cost
EPCs	Energy Performance Certificates
TPS	Transient Plane Source

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1 CHAPTER ONE: INTRODUCTION OF THE RESEARCH

1.1 Research Background

According to EIA (2016), world total primary energy consumption has risen steadily from 408.04 in 2002 to 524.08 in 2012 Quadrillion Btu as shown in Figure 1a. The total primary energy consumption in Figure 1a composes of petroleum, dry natural gas, coal, net nuclear, hydroelectric, and non-hydroelectric renewable electricity. In Figure 1b, there is a corresponding rise of world carbon dioxide emission from the total consumption of energy.

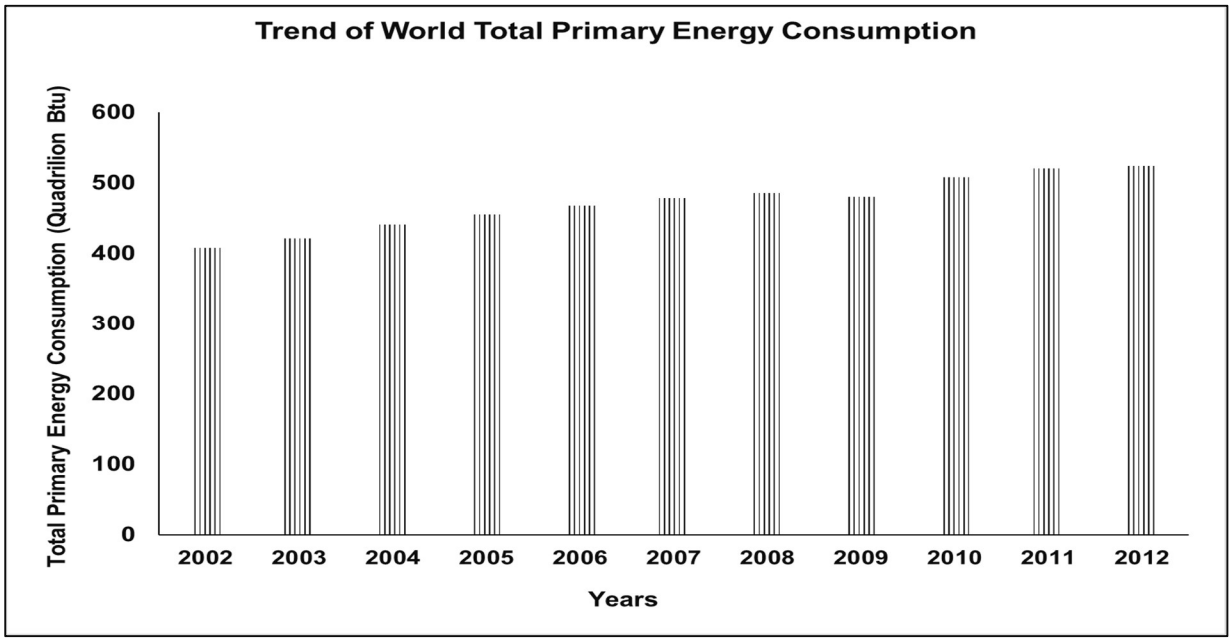

Figure 1.1a: Trend of World Total Primary Energy Consumption.
Source: (EIA, 2016)

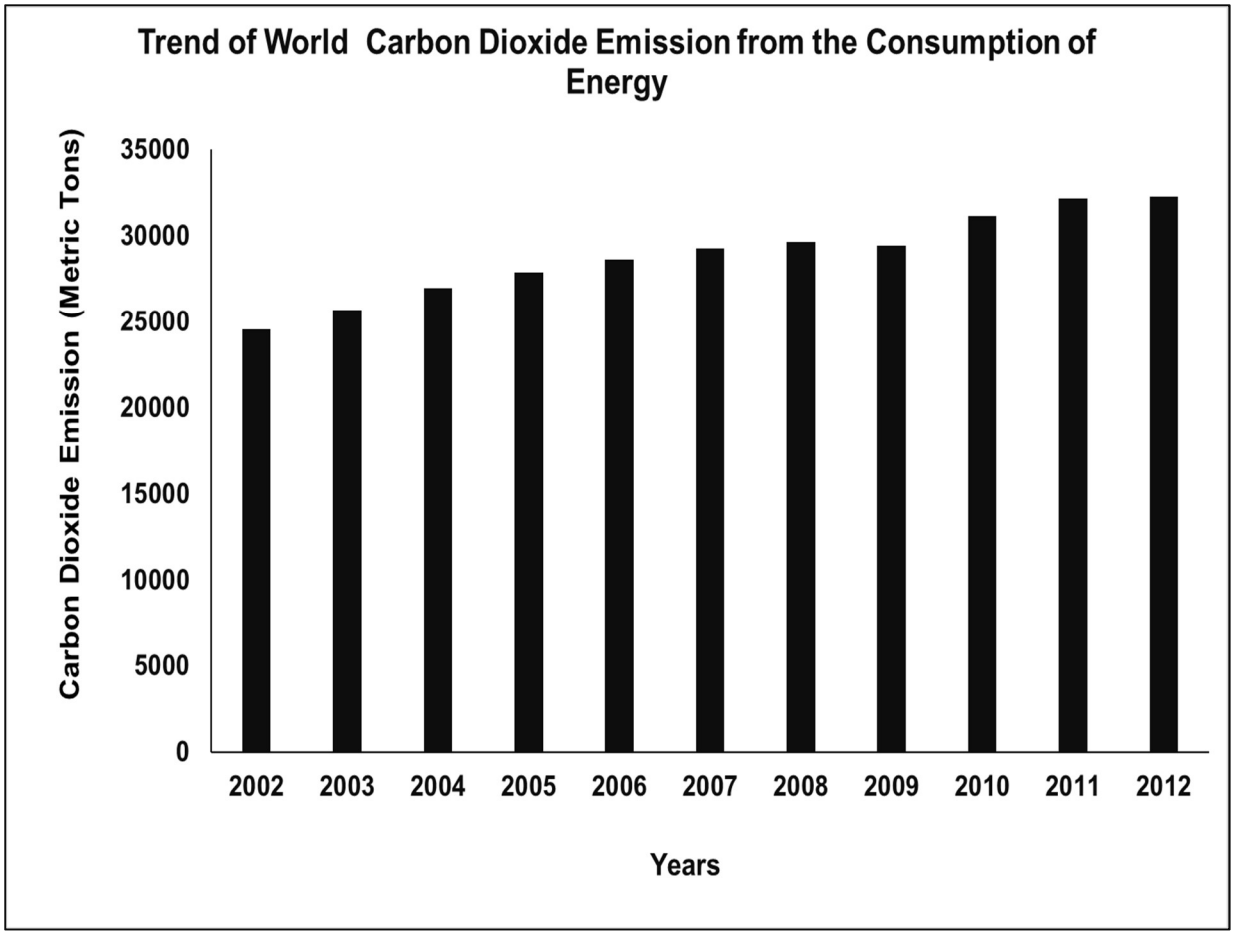

Figure 1.1b: Trend of World Carbon Dioxide emission from the consumption of Energy.
Source: (EIA, 2016)

Electricity remains the second highest form of energy utilized in the world (International Energy Outlook, 2013). On the contrary, according to World energy outlook (2014), electricity is the fastest-growing final form of energy. Conversely, the electricity-growth is highly sensitive to regional differences, countries' income levels, urbanization rates and supply risks (Karanfil and Yuanjing,2015).

The world Total Electricity Net Consumption has risen from 13,949.94 Billion Kilowatt hours in 2002 to 19,710.36 Billion Kilowatt hour in 2012 representing a rise of 29.2% in a decade (International Energy Statistics,2013). Figure 1.2 shows the trend of the world Total Electricity Net Consumption within the decade (2002 to2012).

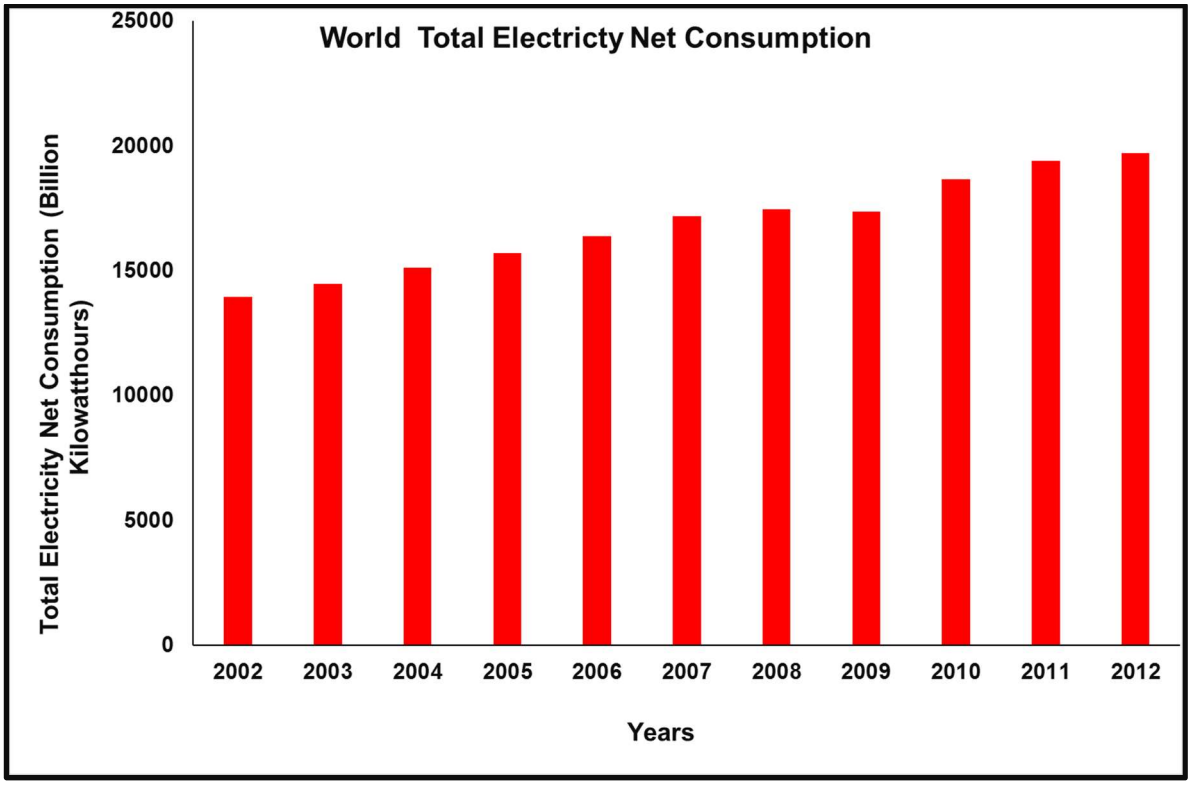

Figure 1.2: World Electricity Net Consumption

Source:

From Figure 1.2, the world electricity net consumption increased progressively about 20% from 2002 to 2008. However, between 2008 and 2009 there was no significant change in consumption. There was an increased growth of about 5% from 2010 to 2012. In overall, there was an increase of 29.2% of electricity net consumption from 2002 to 2012.

An increasing trend of rise in electricity utilization has been predicted by IEA (2013a) in reference case projections on world total electricity consumption by End-use sector for 2010 to 2020 as shown in Figure 1.3.

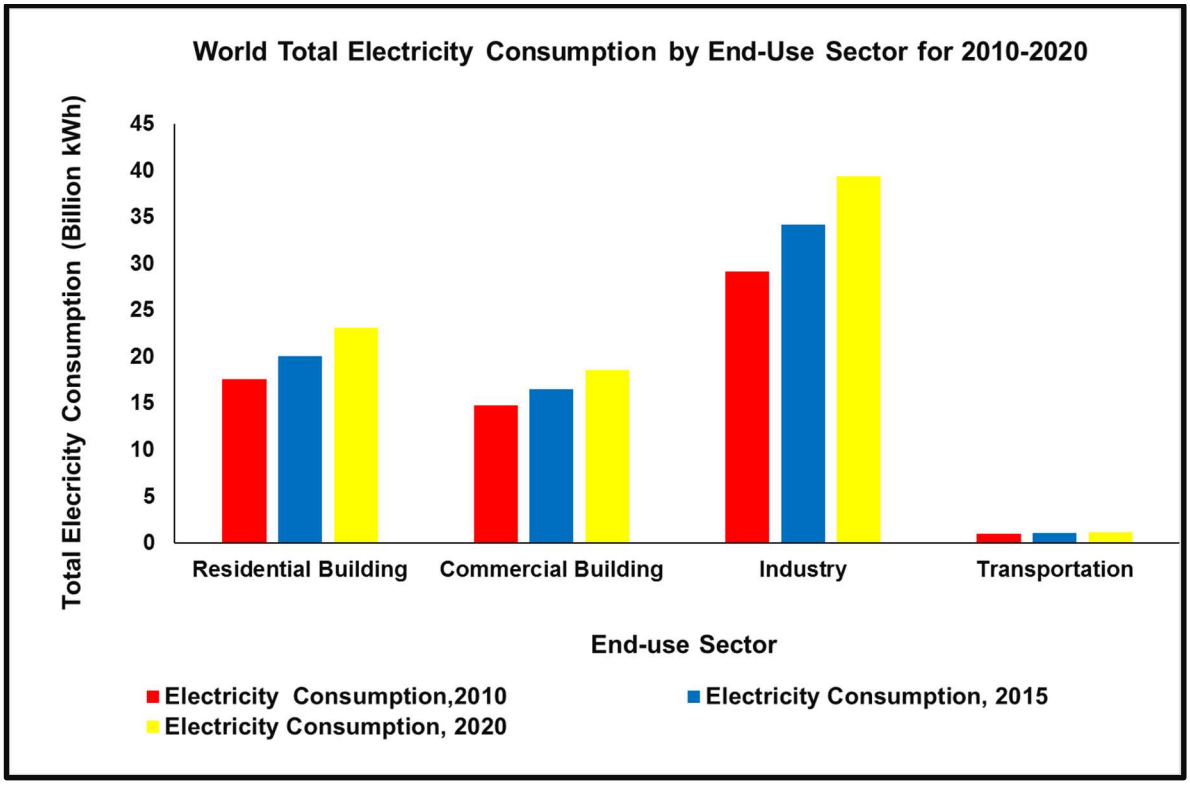

Figure 1.3: World Total Electricity Consumption by End-use sector for 2010-2020
Source: (IEA, 2013)

World electricity consumption by the building (residential and commercial) sector would increase slightly higher than the Industrial sector from 2010-2020 as illustrated in Figure 1.3. On other hand, the predicted consumption of electricity in residential building from 2010- 2020 is higher than commercial building sector. Contrary, to IEA (2011), by 2050, in the building sector, the global number of households (residential) will grow by 67% and the floor area of the service sector (commercial and institutional) buildings by almost 195%. This implies that electricity utilization in the commercial building sector would be about triple of that consumed by households (residential).
The main energy sources use in buildings ranges from electricity, natural gas, coal, wood, solar, renewables among others. Energy end-use in buildings include cooling, heating, cooling, lighting, equipment usage etcetera depending on the country's climate. Conversely, electricity is the dominant energy source for building (DOE, 2008). The assertion of DOE,2008 is in consistent with International Energy Outlook, 2013 and it is summarized in Figure 1.4.

Figure 1.4 shows world total primary energy end-use for commercial building sector from 2010-2020.

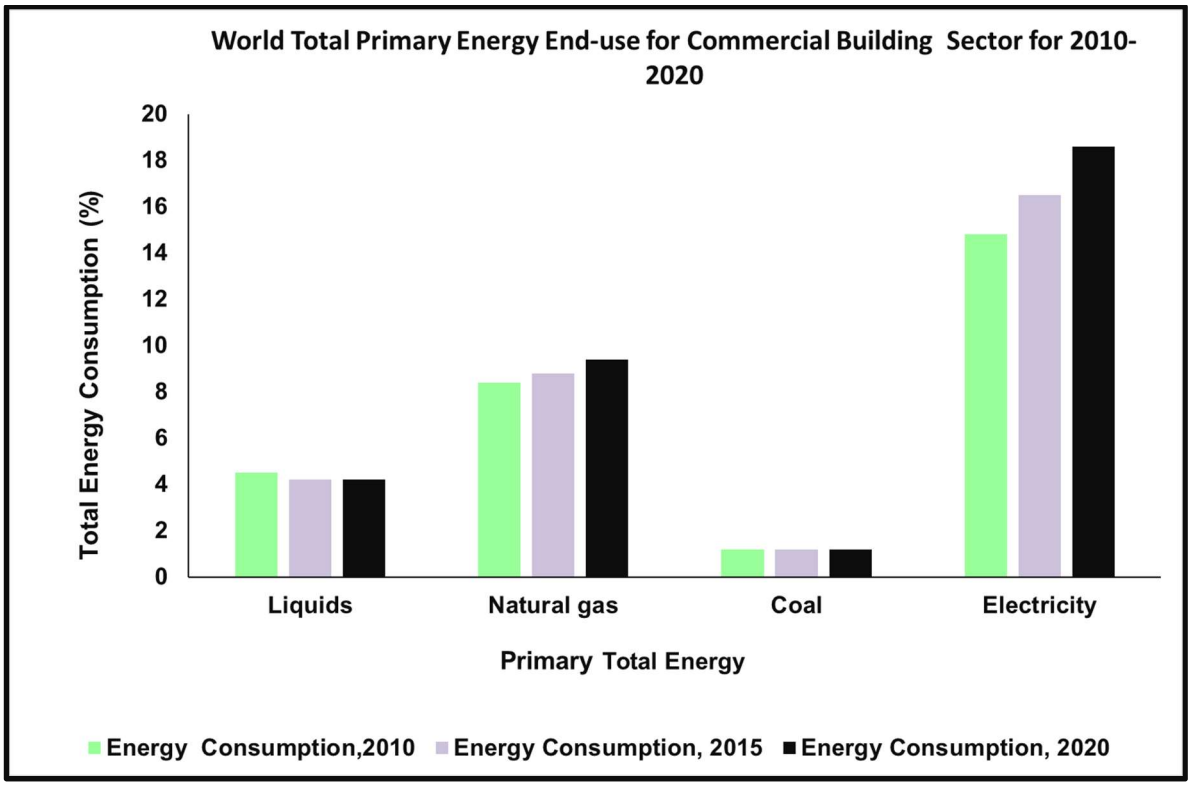

Figure 1.4: World Total Primary Energy End-use for Commercial Building Sector end-use
Source: International Energy Outlook, 2013

In Figure 1.4, electricity consumption projection for 2010 to 2020 is increasing significantly compare to natural gas. On other hand, the consumption of liquid and coal remains constant.

Many studies indicated that energy consumption is mainly driven by the country's economic growth, population, demographic, building size and service equipment demand (IEA, 2008a; Kwok and Rajkovich, 2010; Fumo et al., 2010 and Eggoh et al., 2011).

To confirm the drivers influencing the world increasing energy consumption as indicated by other researchers above, a case of 3 African countries among the 40 world largest electricity consumers in 2010 were reviewed and compared to Ghana as in Figure 1.5.

IEA (2014) has indicated that Energy sector remains significant to Africa's development, on the contrary it remains most poorly understood parts of the global energy system. Implications of SE4ALL (2013), IEA (2014) and World Bank (2013) statistics shows that there is a major issue with energy specifically electricity in Africa.

The selected countries and its indicators from World Bank (2016) are describe below.

1. Algeria's population has grown from 36.7 million in 2011 to 37.4 million in 2012 and Gross National Income per capita (GNI) rose in the same period from US $ 4,590 to US $ 5,200 with corresponding electricity power consumption from 1,121.60 to 1,236.10 kWh per capita (World Bank, 2016).
2. Egypt population has grown from 83.8 million in 2011 to 85.7million in 2012 and Gross National Income per capita rose in the same period from US $ 2,590 to US $ 2,810 with corresponding slight decline of electricity power consumption from 1,700.7 to 1,700.4 kWh per capita (World Bank, 2016).
3. Nigeria's population has grown from 163.8 million in 2011 to 168.2 million in 2012 and Gross National Income per capita rose in the same power from US $ 1,720 to US $ 2,470 with corresponding electricity power consumption from 149.3 to 155.9 kWh per capita (World Bank, 2016).

The data from (World Bank, 2016) on the selected countries development indicators are summarised in Figure 1.5.

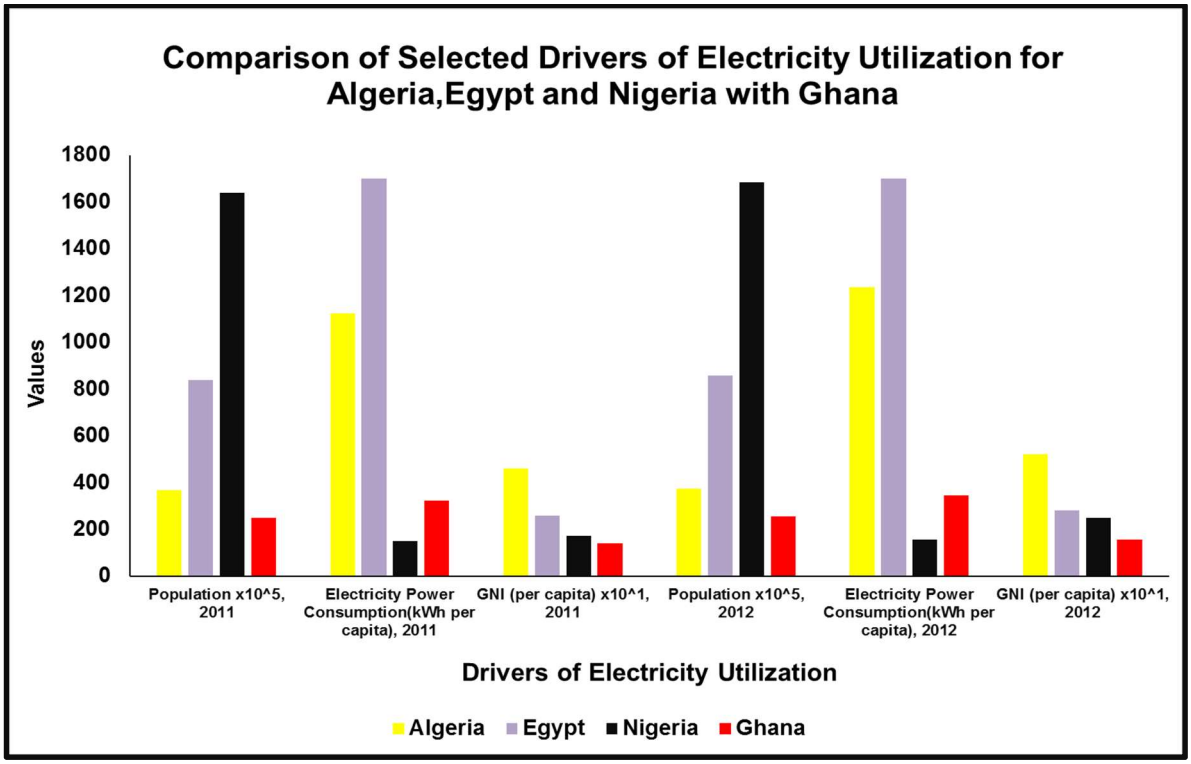

Figure 1.5: Drivers of Electricity Utilization . Source: (World Bank, 2016)

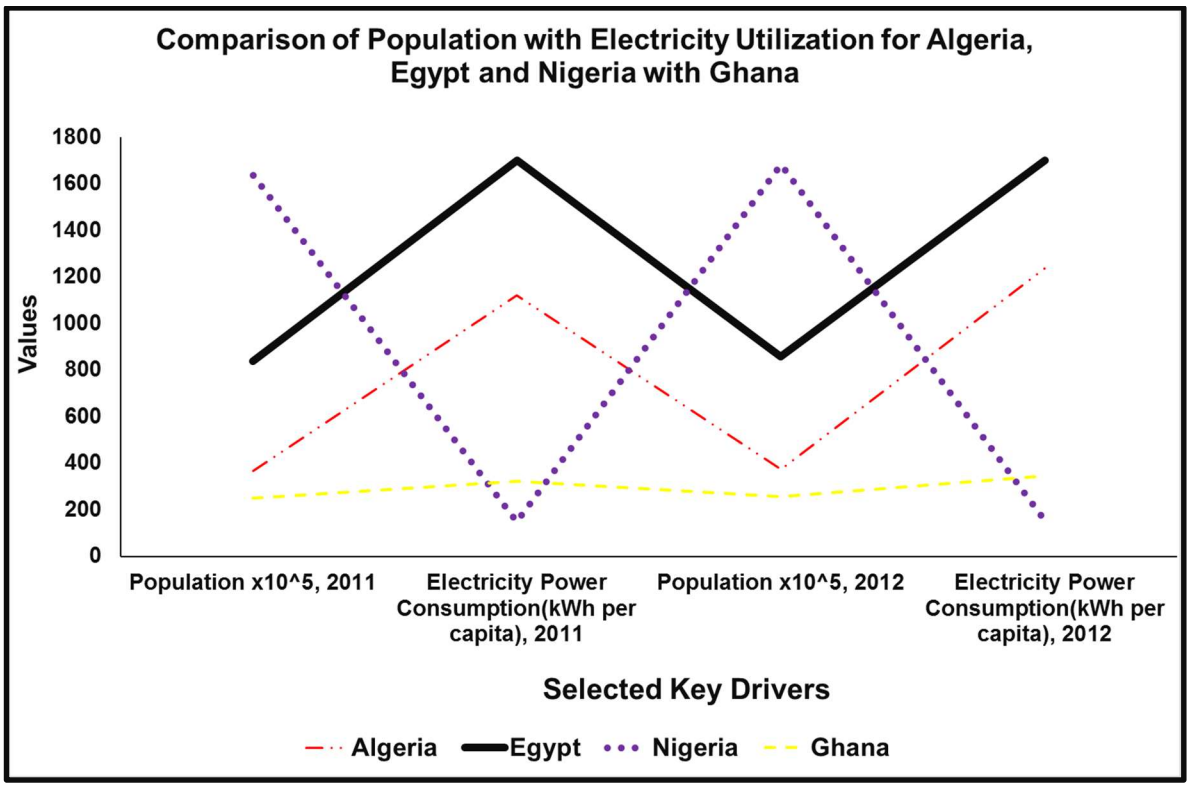

Figure 1.5a: Drivers of Electricity Utilization .Source: (World Bank, 2016)

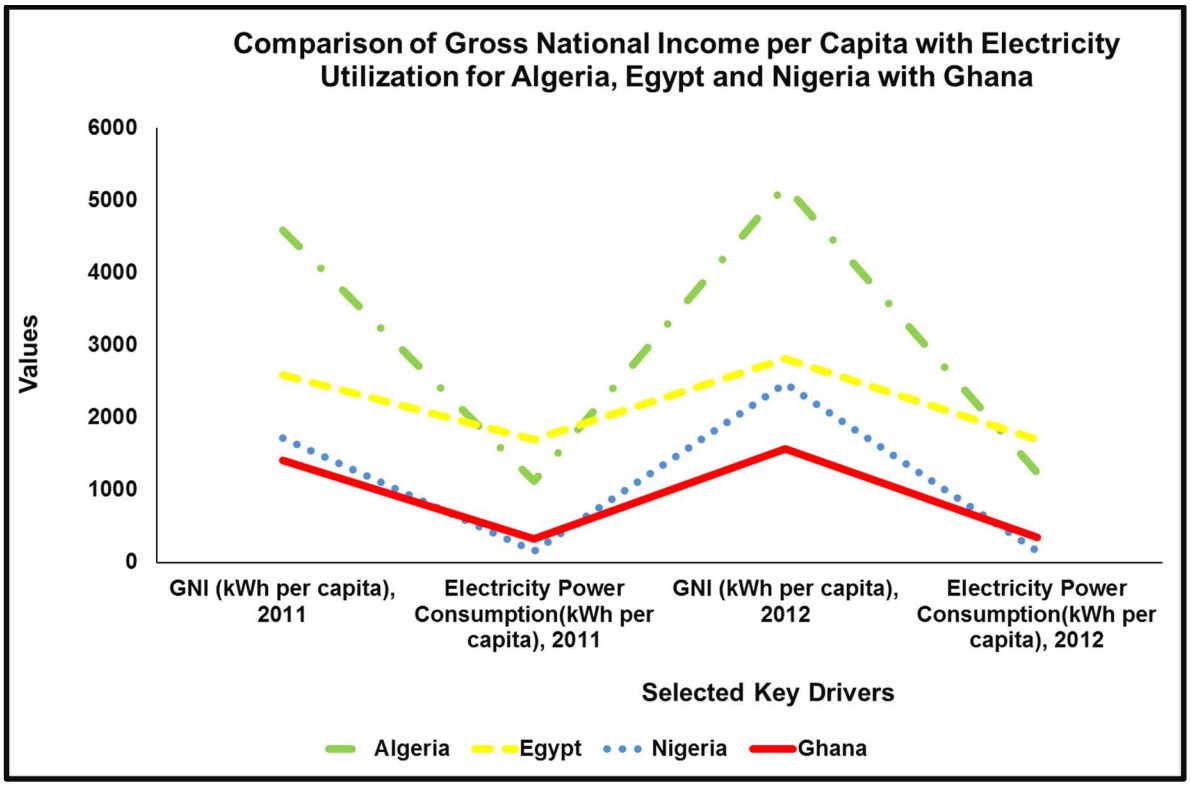

Figure 1.5b: Drivers of Electricity Utilization

Source: (World Bank, 2016)

As above in Figure 1.5 a & b, the following deductions can be made:

1. Commencing 2011 to 2012, a trend of increasing electricity power consumption with increasing GNI and population were observed among all the countries except for Egypt. Within the same period, although there were increases of GNI and population; the electricity power consumption per capita reduced insignificantly.
2. Nigeria has the lowest electricity power consumption per capita and this is as the result of the high population among the selected countries.
3. Ghana has the lowest population among the selected countries, but has relatively low electricity power consumption per capita compared to Algeria and Egypt. This is as the result of the country's low total of power production losses.
4. Ghana has the lowest Gross National Income per capita among the selected countries. This is because of the low Gross National Income.
5. Complex correlation between electricity power consumption per capita is observed between GNI and population.

From the findings above, there was inadequate data on the corresponding building sector growth in relation to the key drivers of electricity consumption. This makes it a challenge to conclude on the contribution of building sector growth to the drivers of electricity utilization. On the contrary, a similar data on key drivers for the world buildings sector was used as correlation and presented in Figure 1.6a and 1.6b.

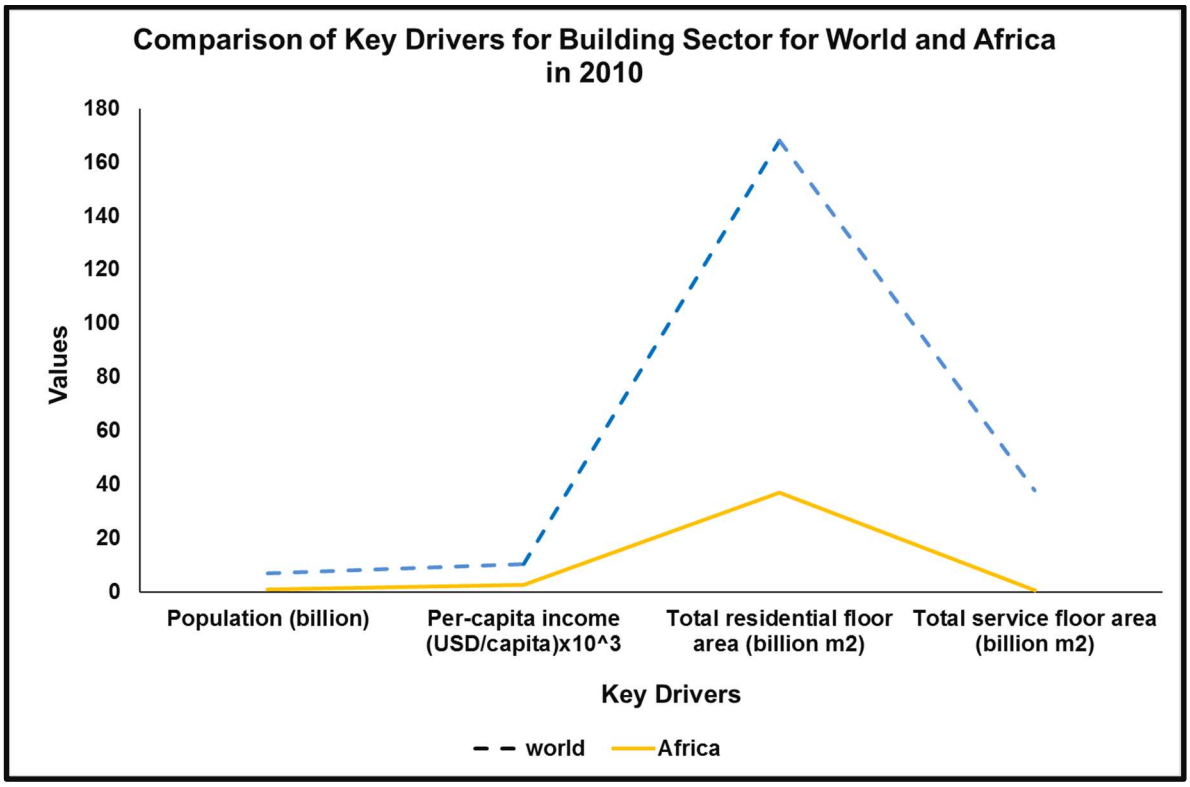

Figure 1.6a: Key drivers for Building Sector comparison for World and Africa in 2010

Source: (IEA, 2013b)

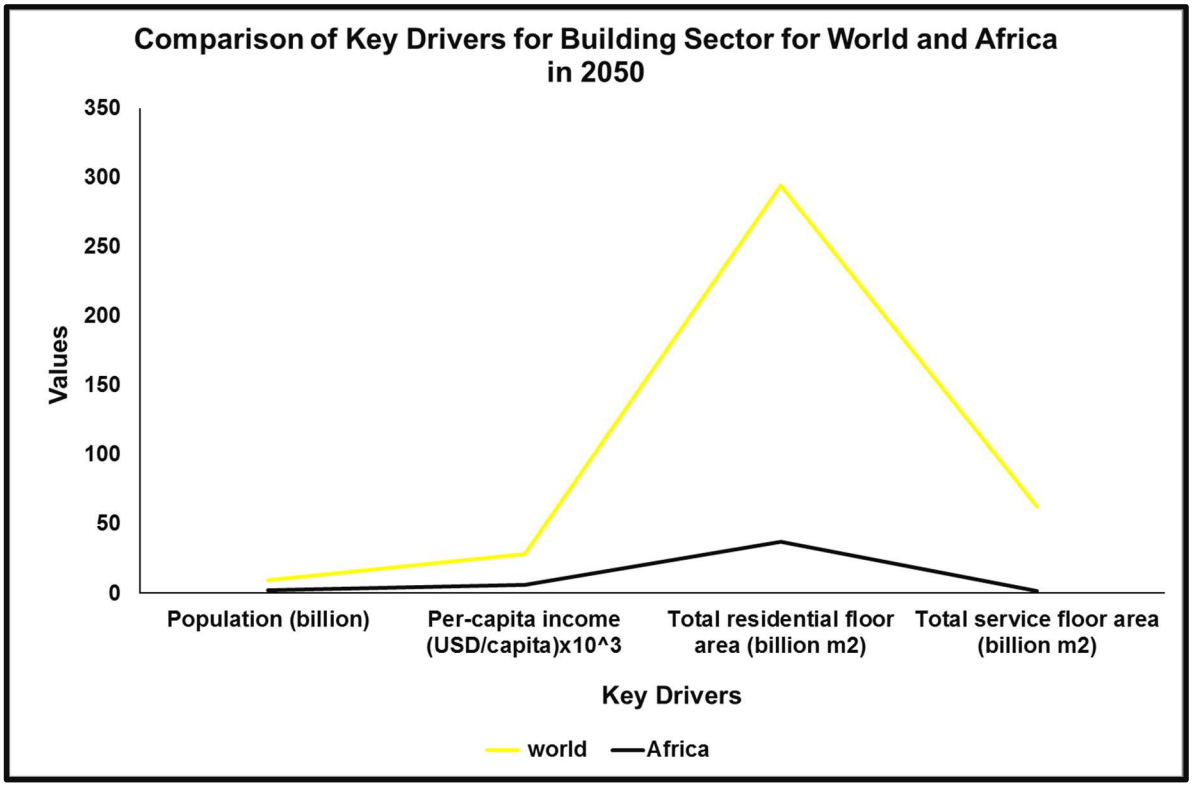

Figure 1.6b: Key drivers for Building Sector comparison for World and Africa in 2050
Source: (IEA, 2013b)

In Figure 1.6 a & b, the world population increase from 2010 to 2050 as the per-capita income (USD/capita), number of households (millions), total residential floor area (billion m^2) and total service floor area (billion m^2) increases. The same trend of increasing building floor space with population and economics is seen in Africa, of which the four countries.

Many researchers have concluded that, there is rise in energy consumption in building sector above other end-use sectors like industrial, transportation, and the other sectors in the world (Lombard et al.,2008; Iwaro and Mwashan, 2010; Sadineni et al.,2011 and Devabhaktuni et al., 2013). It has been estimated that buildings (both commercial and residential) accounts for up to about 40% of world energy end-use (IEA, 2008a and World Energy Council, 2013).

In conclusion to the research background, there is a trend of increasing energy utilization in the world.

Electricity consumption in Africa follows the same trend of selected drivers (economic growth and population) as concluded by the researches in other parts of the world (Perrez-Lombard et al.,2008; Kwok and Rajkovich, 2010; Fumo et al., 2010 and Karanfil and Li, 2015). Building (residential and commercial) sector energy utilization is above other end-use sectors in the world with electricity being the highest type of energy use. Heating Ventilation and Air Conditioning is the dominant electricity usage service equipment in building sector.

The scope of this research is focused on the rising of electricity utilization in Ghana because of service equipment demand in commercial and institutional building sector.

1.2 Building Performance

Building on its own does not consume electricity; but the usage of the service equipment by the occupants. Performance of the commercial and institutional building has a key influence on electricity utilization of service equipment demand as well as on the quality of the indoor environment (Enteria and Mizutani,2011; Korolija et al.,2011 and Vakiloroaya et al., 2014).

The demand for indoor environmental comfort in modern building designs in hot-humid tropical climate leads to reliance on mechanical cooling; usually vapour-compression air conditioning systems Chua et al., 2013.

It is well known fact that, building performance is influenced by several factors, example, architecture, service equipment, building regulation, technology among others (Yildiz et al.,2012; Ekici and Aksoy, 2011; Choi et al.,2012; Olofsson and Mahlia,2012; Zhao and Magoules, 2012; Pacheco et al., 2012 and Santamouris and Kolokotsa, 2013). Conversely, though building professionals' practices influence building performance, it is least discussed during most researches. Brief descriptions of building performance factors are as follow:

i). Architecture

Lot of research have been conducted on the impact of architectural factors on improving building performance specifically electricity utilization, indoor environment quality and emissions.

All these researchers concluded that, electricity utilization and indoor environmental quality are directly linked to architectural factors like building design, building fabric, building tightness, orientation and construction
(Stegou-Sagia et al., 2007; IEA, 2010; Stavrakakis et al., 2012; Prajongsan et al., 2012; Huang et al., 2013 and Jradi et al.,2013).

ii). Building Service System

As stated above in research background and building performance, service equipment is one of the major drivers of electricity utilization as well as indoor environmental quality. Several researchers have concluded that, equipment type selections, designing and sizing by building service engineer have significant implication on building performance (Uihlein and Eder, 2010; Enteria and Mizutani,2011; (Korolija et al., 2011 and Chua et al., 2013).

iii). Occupants

Many researchers have concluded that occupants' behaviour have substantial influence on building performance. Indoor environmental quality of the working area has impact on occupants' productivity and general well-being. Typical occupants' behaviour connected to building performance include window opening of air-conditioning space, window curtains operation, floor carpet, the choice of indoor temperature and humidity set point for air-conditioning systems, increasing time spent in the space, high comfort requirement among others (Poel et al.,2007; Herkel et al., 2008; Yun et al.,2009; Lee and Guerin,2010; Yu et al.,2011; Fabi et al., 2012; Jin et al., 2012; Agha-Hossein et al., 2013 and O'Brien and Gunay, 2014).

iv). Climate

Several researchers have shown that, climatic conditions (Solar radiation, ambient temperature, air humidity, precipitation, wind and sky condition) have strong correlation with building performance (Lam et al., 2010; Zhao and Magoulès, 2012; Lu et al.,2012 and Survey questionnaire in 2014).

On the contrary, increased human activities have led to elevated temperatures hence high service demand for indoor environmental quality (IEA, 2007; Crawley and Drury, 2008; Mansura et al., 2008; Lam et al.,2010; Wang et al., 2010; Kolokotroni et al., 2012 and Santamouris,2014).

v). Technology

In view of the increasing electricity consumption arising from air conditioning systems in buildings, several integrated building approaches have been used to enhance performance. Among them the active and passive technologies are: phase change materials for building fabric, building demand management systems, moisture permeability retarders, ejector refrigeration, heat recovery technology, variable refrigerant flow (VRF) system, heat exchangers, desiccant materials, desiccant dehumidifiers, cooling towers, rotary desiccant wheel and many more (Yu et al., 2011; Zhao and Magoulès, 2012; Chua et al., 2013; Devabhaktuni et al., 2013; Lamnatou et al.,2015; Buker and Riffat,2015 and Cuce and Riffat,2015) . Majority of researchers have concluded that technology either active or passive possess a more viable approach in enhancing building performance and minimizing the associated effect (Hughes et al., 2011; Sadineni et al., 2011; Santamouris and Kolokotsa, 2013; Buker and Riffat, 2015; Buker et al., 2015 and Cuce and Riffat, 2015).

vi). Building Code/Regulation/ Policy

Building code/regulation/policy introduces minimum performance requirements for building envelope and finishing. Building practices, technologies and construction are constantly evolving; hence building codes, regulations and policies are constantly being revised to reflect efficiency, up-to-date (scientific, technology and technical details) and effective minimum building envelop specifications to enhance performance. For example, ASHRAE series, UK building regulations, ANSI, ASHRAE standards, IES Standard 90.1, CIBSE Guides, ISO standards, British standards and many more.

Many research conducted on building code/regulation/policy concluded that it's one of the most cost-effective approaches in enhancing performance (Lowe and Oreszczyn, 2008; Uihlein and Eder, 2010; Pacheco et al., 2012). On other hand, building compliance continues to remain a challenge (IEA, 2008; Iwaro and Mwasha, 2010 and Pan and Garmston, 2012).

1.2.1 Building Performance Assessment

Building performance assessment is an innovative multi-disciplinary process which is usually carried out on new or existing building to enhance part or whole function of a building envelope and finishing (Preiser and Vischer, 2005). Considerable number of researchers normally use the following tools for building performance assessment: computer simulation, environmental chamber experiments, theoretical calculation, energy audits, survey questionnaire, spot measurements, indoor measurements, test cells and others (Clarke and. Yaneske, 2009; Kruger et al., 2011; Dascalaki et al., 2011; Synnefa et al., 2012; Barbhuiya and Barbhuiya, 2013; Guerra-Santin et al., 2013; Wilde, 2014; Nguyen et al., 2014; Gibbs and O'Neill, 2015; Han and Srebric, 2015; Eicker et al.,2015; Elmeret al., 2015; Lamnatou et al., 2015; Clarke and Hensen, 2015; Olivia and Christopher , 2015 and Cattarin et al., 2016).

Building performance assessment offers benefits from design stage to post occupancy stage. Dominant benefits include: estimations, cost effective design options, enhancements to building energy efficiency, indoor environmental climate, assist in meeting building standards and minimising emissions (Schlueter and Thesseling,2009; Pati et al.,2009; Breesch and Janssens,2010; Hall et al.,2013; Santamouris and Kolokotsa,2013; Rodrigues et al 2013 and Jradi and Riffat,2014).

Computer simulation has been proven as an effective approach to assessing the performance of building envelops (Clarke, 2001; Chowdhury et al., 2008; Koranteng et al., 2010; Kolarika et al.,2011; Kolarika et al., 2011 and Rysanek and Choudhary, 2012).

Representative building performance simulation tools include Trynsys, ESDL Tas, EnergyPlus (Alwaer and Clement-Croome,2010; Celen and Yalcin,2012; Schwartza and Raslaan, 2013; Melo et al., 2014 and Angrisani et al., 2014). Different simulation tools result in different energy consumptions for the same input variables (Schwartza and Raslaan, 2013).

A representative output variables of building performance assessment include: energy utilization (equipment, lighting, cooling etc.), indoor environmental quality, CO_2 emissions, user satisfaction, economics, sizing equipment and among others. The output variables of building performance assessment are normally systematically measured against the following performance indicators: building codes/regulations/policy, CO_2 emission targets, electricity bills, ISO standards, CIBSE Guides, ASHRAE standards and others (CIBSE Guide A,2005; ASHRAE,2005; Celen and Yalcin,2012; Alwaer and Clements-Croome, 2010 and Melo et al.,2014).

In conclusion, all the reviewed factors influence the various elements of building performance significantly. Building performance factors outlined above have key potentials for mitigating high electricity utilization and indoor environmental discomfort. On the contrary, the percentage levels of improvements as outlined by researchers varies due to the building purpose, climate, building designs among others. In view of this, the building design variables in the simulation were optimized using the outlined building factors performance to electricity utilization and indoor environmental quality.

1.3 Rationale for the Case Study: Ghana

Ghana had a population growth from 24,928,503 in 2011 to 25,544,565 in 2012 and the Gross National Income per capita rose in the same period from 1410 to US $1,570 GNI. In the same period, electricity power consumption rose from 321 to 348.3 kWh per capita (World Bank, 2016).

Ghana's country profile as above, it is clearly seen that it is not among the 40 highest electricity power consuming countries in the world. On other hand, Ghana's economy is highly dependent on the electric power sector as any other African country (IEA, 2014).

Selected key rationales for selecting Ghana as case study include:

1. Insufficient research into electricity consumption trend in commercial building and improvement into building fabric used in envelope design Survey questionnaires, 2014.
2. Inadequate building professionals (government agencies, architects, building service engineers and building fabric manufacturers) do conduct building performance assessment (Koranteng 2010 and Survey questionnaires,2014)
3. High end-use inefficiency contributing to high electricity consumption (Ghana Energy Commission outlook, 2006-2020).
4. Rapidly growing demand for energy by all sectors of the economy and growing Population (Ghana Energy Commission outlook, 2006-2020).
5. Ghana government's policy to reduce electricity consumption in institutions by 50% by 2015, as well as the Energy Efficiency and Conservation Act (Ghana Energy Commission outlook ,2006-2020).
6. The electricity in Ghana is basically generated from hydro and thermal plants. Based on data from Grid Company and the Volta River Authority the total electricity generated from hydro and thermal plant was 67.5% and 32.5%, respectively, in 2011. Due to the unsustainable nature of these two primary energy sources, the country continues to experience power cuts.
7. Lack of energy efficient technologies in Ghana local market, clear policy and regulations on performance of commercial equipment as well as appliances (Ofosu-Ahenkorah, 2007).
8. In 2007 and 2011 the country has embarked on a nationwide exercise to improve on the energy efficiency of lighting and refrigerator, which are high electricity consumption equipment used in most residential buildings (Buskirk et al., 2007 and Ghana energy outlook, 2012).

9. Most of the buildings in Ghana were built before the building regulation of the country was developed or was passed into law (Field study,2014)
10. Ghana follows the same drivers of factors which influences electricity utilization in buildings.
11. According to IEA (2011), present trends in energy supply and use are unsustainable economically, environmentally and socially. Without critical action, global energy-related greenhouse gas (GHG) emissions will more than double by 2050 and accelerated oil demand will amplify concerns over the security of supplies.

1.4 Research Problem Statement: Ghana*'s* Case

Reviewed scientific journal, technical journal and survey questionnaires indicate that, about 16% of building professionals in Ghana do assess building performance from design stage to post occupancy stage (Koranteng et al., 2009; Amos-Abanyie et al., 2012 and Survey questionnaires, 2014). This low building performance assessment has led to high building service equipment electricity utilization and indoor discomfort in representative cooling spaces. Specific problems identified among building professionals regarding performance assessment from the survey questionnaires are detailed below and summarised in Figure1.7.

1. Ghana building regulation and policy is prescriptive with no technical guidance to achieving the thermo-physical properties of the building fabric and detail design variable specification.
2. 70% of building professionals design and finish buildings with client's choices of fabric specifications without prior knowledge of its impact on the overall performance.
3. Ghana building policy on the use of local building construction materials states 60% of local materials should be used in constructing public buildings by 2015. On the contrary, the survey shows less than 20% of public buildings are built using local building fabric in 2014.

4. From the building regulation, there is a section on building insulation. However, from the field study, only 1 % of building professionals do insulate their building; contributing to high electricity utilization.
5. Thermo-physical properties of materials specified in the building regulations are not strictly complied with prior to the issuance of building permit by appropriate authorities.
6. From critical review of scientific and technical journals on Ghana, there is scanty information on building design variables.
7. New trend of high window-to-wall ratio for multi-storey office buildings with intensive dependency on air conditioning as well as indoor environmental discomfort.
8. Insignificant building technologies integration into building envelope and finishing Survey questionnaires, 2014.
9. Selection of subjective adjustment factors based on individual experience.
10. Average of 14% of building professional participants excluding building fabric manufacturers undertakes performance assessment Survey questionnaires, 2014.

Figure 1.7 summarises the building performance factors relating to main causes and effects of this research problem.

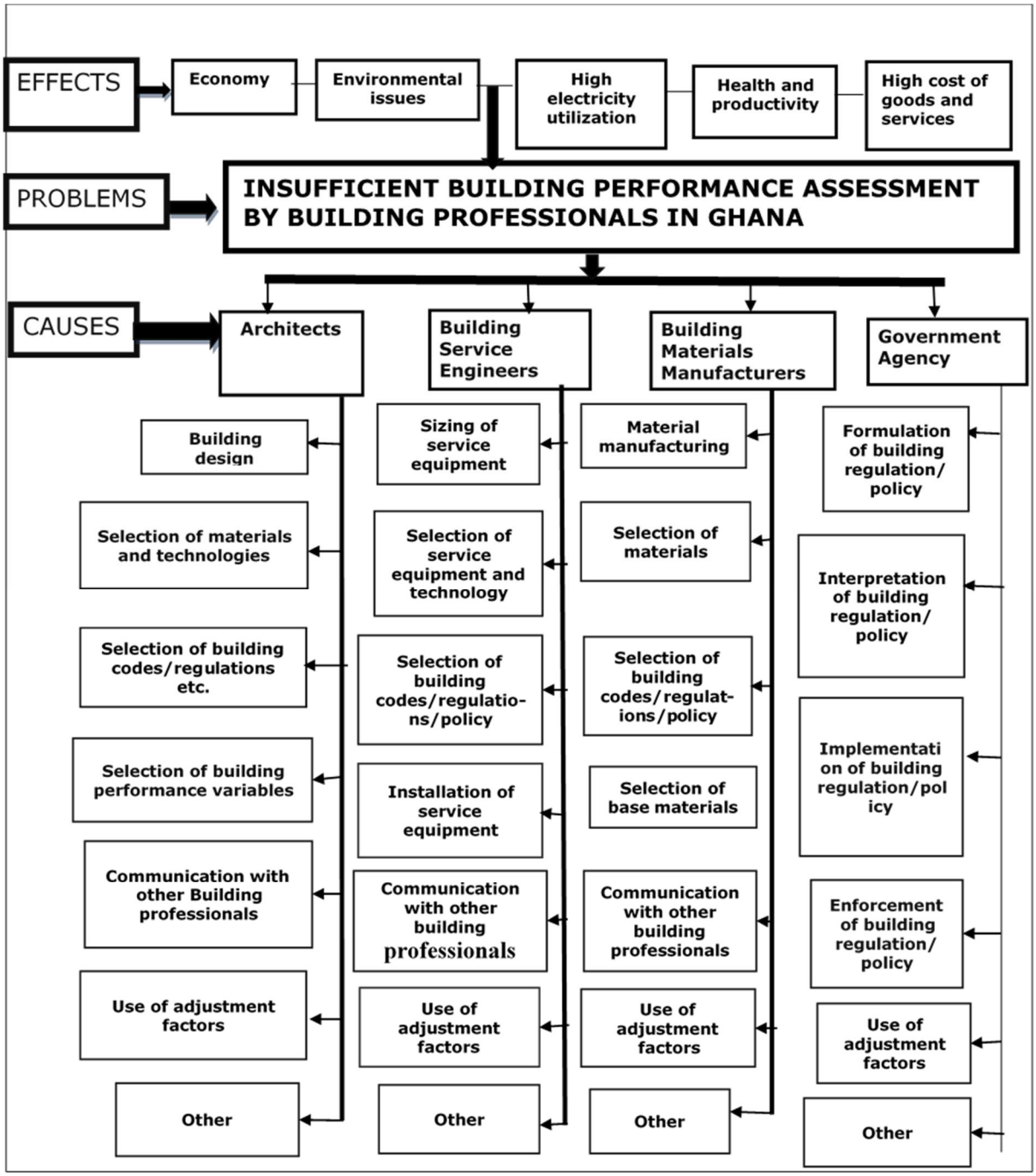

Figure 1.7: Summarized Causes and Effects of Building Performance Factors in Ghana.

Source: Field Study

- **Architects**

The representative practices of Architects in Ghana include: designing of buildings, selection of building materials and technologies, selection of building regulations/codes/policies, selecting of building performance variables, communicating with other building professionals and use of adjustment factors and others. From the listed practices of Architects in Ghana, it is seen that architectural factors are of importance to electricity utilization and indoor environmental comfort. On the contrary, with the prescriptive Ghana building regulation, subjective based adjustment factors and insignificant building performance assessment would mainly contribute to high electricity utilization of service equipment and indoor environmental discomfort.

- **Building service engineers**

The typical practices of building service engineers include: sizing of service equipment, selection of service equipment and technology, installation of service equipment, communicating with other building professionals, use of adjustment factors and others. As seen from the research background, the rising electricity utilization is partly contributed by service equipment, hence any factor relating to its selection or usage remains crucial to tis research. Service engineers use several adjustment factors compared to other building professionals in Ghana. This has risen because of unavailable design variables for sizing service equipment from Ghana building regulation. Therefore, the use of international standards with subjective adjustment factors to suit Ghanaian climate leading to over sizing of service equipment subsequent poor building performance.

- **Building material manufacturers**

Characteristic building material manufacturers' practices include material manufacturing, selection of materials, selection of building regulations/codes/policies, communicating with other building professionals, adjustment factors and others. Even though, building material manufacturers dominantly use Ghana building regulation, adjustment factors are still applied to the selection of building fabric specifications during production. This practice has led to high thermal conductivity of cement-based building fabric and causing high heat gains.

- **Government Agency**

Government Agency comprises of Building and Housing Ministry, building permit issuing bodies and Ghana Standards Boards. Characteristics practices of Government Agency can be categorised into formulation of building regulation /policy, interpretation of building regulation /policy, implementation of building regulation /policy, enforcement of building regulation /policy, use of adjustment factors and others. Government Agency predominantly use Ghana building regulation in its operation. Conversely, from the survey, the basis of the prescriptive regulation was mainly from experience and applied adjustment factors to international codes. This has led to unachievable building fabric u-values under the current building design of Ghana as concluded by Survey questionnaires, 2014.

In conclusion, there is fundamental challenges in building performance assessment among all building professionals in Ghana. Although all the building professionals indicated that there is communication with other building performance right from design to post occupancy stage of the building.

1.5 Research Knowledge Gaps

Substantial solutions exist in scientific and technical journals on improvement of building performance (electricity utilization and indoor environmental quality) in the world. Among them are technologies, models, codes, regulations, policies, improved building fabric, strategies, building tightness, ASHRAE standards, CIBSE Guides and many more (Uihlein and Eder, 2010; Jaber et al., 2011; Sadineni et al., 2011; Zerefos et al., 2012; Rysanek and Choudhary, 2012; Mardiana-Idayu and Riffa, 2012; Evins, 2013; Hall et al., 2013 and Santamouris and Kolokotsa,2013). On the other hand, microclimatic conditions and local building professional practices impact on building design variables differs from country to country in the world; therefore, one solution is not applicable to all countries.

From critical review of technical and scientific primary data resources as well as causes and effects study in Figure 1.7, the identified knowledge gaps are as follows:

1. Inadequate empirical data and practical advice on thermal performance of building envelope fabrics use in Ghana (Amos-Abanyie et al., 2009 and (Survey questionnaires, 2014).
2. Lack of performance based building regulation in Ghana.
3. Inadequate scientific and technical data on occupant's perception on representative building performance comfort and satisfaction in Ghana.
4. Insufficient literature on building fabric to achieving u-values for wall, roof and other building elements using the present single layer wall system and 6-7inches thickness of all opaque fabrics.
5. Lack of technical guidance on achieving the prescriptive assessment tool for Ghana building regulation in enhancing building performance in Ghana.
6. Insufficient literature on selection of adjustment factor basis applied to International building regulation/ code in Ghana.
7. Insignificant research on typical building performance of air-conditioned buildings in Ghana.
8. Lack of building performance comparator tool in assisting decision making on cost effective enhancement approach.

1.6 Research Aim and Objectives

Overall research aim was to optimize the building design variables to achieve recommended good practice for electricity utilization of service equipment and indoor environmental performance in office building using low energy technology.

1.6.1 Research Objectives

1. To critically review the implication of the trend of building design variables, use in Ghana since the worst electricity crisis in 2007. This was achieved through mixed research methods, i.e. survey, simulation and experimental study.

2. To assess and modify thermo-physical properties of selected representative cement-based building fabrics use in Ghana. This was accomplished using cost effective parametric (sand types, mixing ratio design, test method and impact of drying) experimental studies.
3. To appraise dominant building regulation/policy guiding building professional practices in Ghana. Bristol Online Survey Tool was used to ascertain the basis of design variables and adequacy in enhancing building performance in Ghana.
4. To model and perform creative parametric dynamic numerical simulations of selected whole air-conditioned office building in Ghana. ESDL Tas building simulation software was used for modelling, parametric simulation, incorporation of low energy technology and optimization of the design variables for enhanced building performance.
5. To create a novel comparator tool to facilitate decision making of optimized (energy, indoor environmental quality and cost effectiveness) building performance. This was achieved by designing a tool for comparing the cost effectiveness of modification, electricity savings on cooling, comparison of electricity usage of floor area per meter square against recommended good practice of CIBSE Guide.
6. To create a novel two-way feedback tool for enhancing implementation thermo-physical properties during building permit issuing. This was achieved through designing a creative flow chart and technical guidance on achieving thermo-physical properties of cement-based fabric.

1.6.2 Research Questions

The research questions are summarised into four major areas as the following:

1. How does local building professionals' practices impact on design variables used in performance assessment, and are occupants' comfortable as well as satisfied with building performance in Ghana?
2. Are the building fabrics used in Ghana suitable for enhancing building performance?

3. How can the building performance design variables from survey questionnaires and experimental assessments be optimized?
4. Are the existing economic benefit assessment tools adequate for fast accurate decision making in comparing recommended good practice for cooling load by CIBSE Guides in hot-humid climate?

1.7 Research Methods

A mixed research methods approach was adopted in this study. Brief descriptions of the mixed research methods (survey, experiment and dynamic numerical simulation) are as follows.

a) Survey Method

Survey questionnaire was used to establish the basis of the research problem and identify typical design variables use by building professionals in Ghana to enhance performance. Bristol Online Survey tool was for the designing, distribution of questionnaire links as well as collection of completed survey.

b). Experimental Method

Experimental study was used to test the thermo-physical properties of building fabric from Ghana and the parametric experimental studies of cement-based building fabric for enhancement of thermo-physical properties. TCi thermal analyser and Autopore IV were the equipment used for the experiment.

c). Dynamic Simulation Method

Dynamic numerical simulation was carried out to optimize the design variables to enhance a typical air-conditioned office building performance in Ghana. ESDL Tas building simulation software was used.

1.7.1 Constraints of the research

Major constraints of this research include:

1. Identification of non-registered association of building professionals in Ghana for example, building fabric manufacturers and building service engineers
2. Distribution of login details by administrators, secretaries and key participant in associations, organisations and companies as a result of security concerns in giving out emails or contact information.
3. Cost of air shipment of selected building fabrics.
4. Non-availability of cost estimates of proposed modified building fabric in Ghana.
5. Average response rate
6. Lack of equipment for on the spot measurement of the base case and lack of electricity bills for base building.

1.8 Contribution to knowledge

1. Optimum material properties and building fabric specifications to enhance building performance quality in Ghana climate.
2. Novel energy performance and cost benefit comparator tool for and facilitating decision process on modification of building design variables
3. Technical guidance on achieving recommended thermo-physical properties on in Ghana building regulation
4. Empirical database of thermo-physical properties of cement-based building fabrics in Ghana.
5. Practical database of design variables for building performance assessment in Ghana.
6. Propose potential cost effective technology to be integrated into hot humid climate for minimizing dehumidification load at acceptable indoor environmental comfort.

7. Creative 2-way feedback chart for enhancing compliance assessment using existing method and on site final approval check for commercial building

1.9 Thesis structure

The thesis structure comprises of abstract, acknowledgement, table of contents, nomenclature, list of figures, list of tables and ten chapters. The following are the details of the ten chapters:

Chapter One is the overall introduction of this thesis. It covers the research background, research problem statement, research questions, overall aims and objectives with brief description of methodology, contribution to knowledge and the thesis structure.

Chapter Two is the critical literature review of this thesis. It comprises of building energy utilization, brief history of electrical power crisis in Ghana, trend of energy end-use in Ghana, building performance assessment factors and conclusion of literature review.

Chapter Three comprises of the detail review of building performance assessment factors, theoretical framework for building performance assessment and evaluation of representative whole building simulation software.

Chapter Four is a detail review of selected representative technologies used in buildings worldwide. It consists of related research gaps on building technologies used in Ghana, rationale for the selection of low energy technology for this project as well as detail descriptions of the selected technologies.

Chapter Five is the details of the overall mixed research methodologies for this thesis. It consists of detail explanations of purpose, data collection procedure as well as the analysis procedure for the survey questionnaires, experimental assessments, computer simulations and economic benefit analysis.

Chapter Six is the detail results from the survey questionnaires administered. The data consist of both quantitative and qualitative types with descriptive and statistical analysis of all the findings from representative building professionals and occupants.

Chapter Seven comprises of the results and analysis from the experimental assessments of selected representative Ghana building fabrics as well as the parametric experimental assessments. The results of the experimental assessments include the foam and polymer test methods for concrete blocks, mortar blocks, bricks and concrete roofing tiles.

Chapter Eight is the results, discussions, analysis and implications of the novel computer simulations findings. The computer simulations include the preliminary simulations for base case before and after the enactment of Ghana building regulations, parametric simulations and combinations of optimum building fabrics as well as the internal condition variables and the integrated technology scenario.

Chapter Nine is the creative economic benefit assessment of the proposed optimum computer simulations. It includes the design of the comparator decision making tool, findings as well as the discussions from the parametric scenarios of both low and high electricity tariffs scenarios.

Finally, Chapter Ten is the overall findings, conclusions and recommendation for further research.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Brief History of Electrical Power Situation in Ghana

Currently, Ghana is experiencing the fifth critical national power crisis since 1984. The subsequent power crisis occurred in 1998-1999, 2002-2003, 2006-2007 and 2012-present. The problem underlying power crisis is multifaceted. Among them are reduced electricity generation resulting from exceptional rainfall drought, increased in consumption, transmission losses among others (Brew-Hammond and Kemausuor, 2007 and ECG, 2012). The main electricity generation mix is hydro and thermal. Table 2.1 is the installed electricity generation capacity at Ghana as of 2011.

Table 2.1 Installed Electricity Generation Capacity as of December 2011

GENERATION PLANT	FUEL TYPE	INSTALLED CAPACITY MW
Hydro Power Plants		
Akosombo	Hydro	1,020
Kpong	Hydro	160
Sub-Total		*1,180*
Thermal Power Plants[14]		
Takoradi Power Company (TAPCO)	LCO/NG/diesel	330
Takoradi International Company (TICO)	LCO/NG/diesel	220
Sunon–Asogli Power (SAPP)	NG	200
Tema Thermal Plant1 (TT1P)	LCO/NG/diesel	110
Mines Reserve Plant (MRP)	NG/diesel	80
Tema Thermal Plant2 (TT2P)	NG/diesel	49.5
Sub – Total		*989.5*
Total		**2,169.5**

Source: (Ghana, 2012)

As shown in Table 2.1, it can be seen that, hydro and thermal electricity generation represents 54.39% and 45.6% respectively. Hydro power plant is renewable source whiles the thermal is from fossil fuel. The main concern arises when there is rain drought coupled with high electricity demand, then the mix shift from hydro to increased thermal. These aforementioned problems lead to low power generation as a result of the high operating cost involved in thermal power generation hence the power crisis ascends.

Consequently, there is the need for a sustainable electricity generation to complement the current generation mix for example solar, wind, biomass, among others. On the contrary, due to the capital intensiveness of sustainable electricity generation in Ghana; its contribution to the total electricity generated is insignificant.

In conclusion, several factors have contributed to the electric power crisis in Ghana. Among them are shortfall of electricity generation, drought, cost of sustainable electric power generation, increase electric power usage among others. The scope of this research is focusing on increase electric power usage arising from the building sector.

2.2 Trend of Electricity Consumption in Ghana

Detail electricity consumption of sector end-use in Ghana is represented in Figure 2.1.

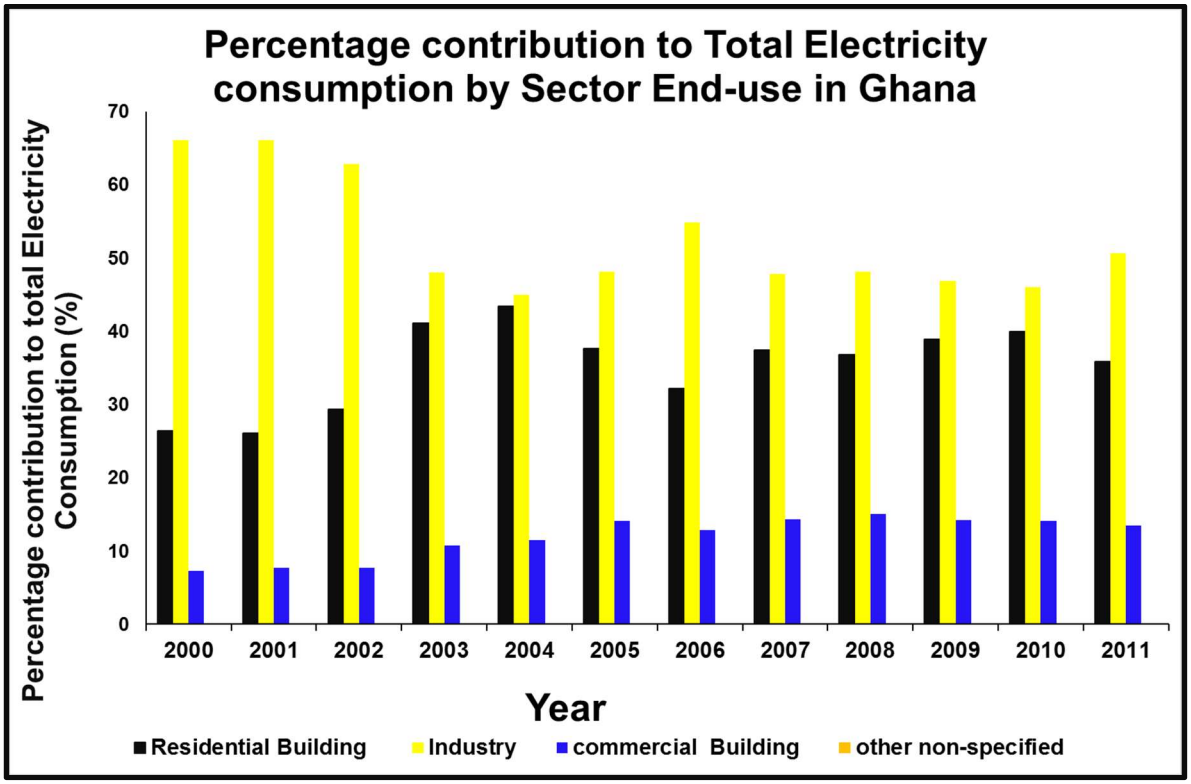

Figure 2.1: Electricity consumption by Sector end-use.

Source: International Energy Agency, 2011

From Figure 2.1, in 2000 and 2001, the percentage share contribution of sectors end-use to the total electricity consumption in Ghana remained constant for all sectors with the Industrial sector being the highest above other sectors. Conversely, the percentage share of building (residential and commercial) sector to total electricity consumption increased from 2002 to 2005 with decreased Industrial sector. Although there was a reverse trend in 2006, however from 2007 to 2010 there was rise and fall pattern observed in all the sectors. In 2011, there was a significant growth in the industrial sector with a decline in the building (residential and commercial) sector. This notwithstanding, there is an increasing percentage share of the building (residential and commercial) sector to industrial sector in Ghana.

Conclusion from Figure 2.1, the percentage share of building (residential and commercial) sector to total electricity consumption increases with decreasing percentage share in industrial sector. This observed trend is inconsistent with the results obtained for the world electricity end-use sector in Figure 2.1.

Comparison of the predicted world total electricity consumption by end-use sector in Figure 1.4 to actual electricity consumption by sector end-use of Ghana in Figure 2.1 show a similar trend across all sectors.

2.2.1 Impact of electrical power crisis on sector end-use electricity consumption

In view of this complex situation of inadequate and unreliable electricity supply, World Bank has been prompted to access the situation and offer recommendations (Crookes, 2013). Figure 2.2 shows a duration of electrical outages and impact on business sales in selected countries.

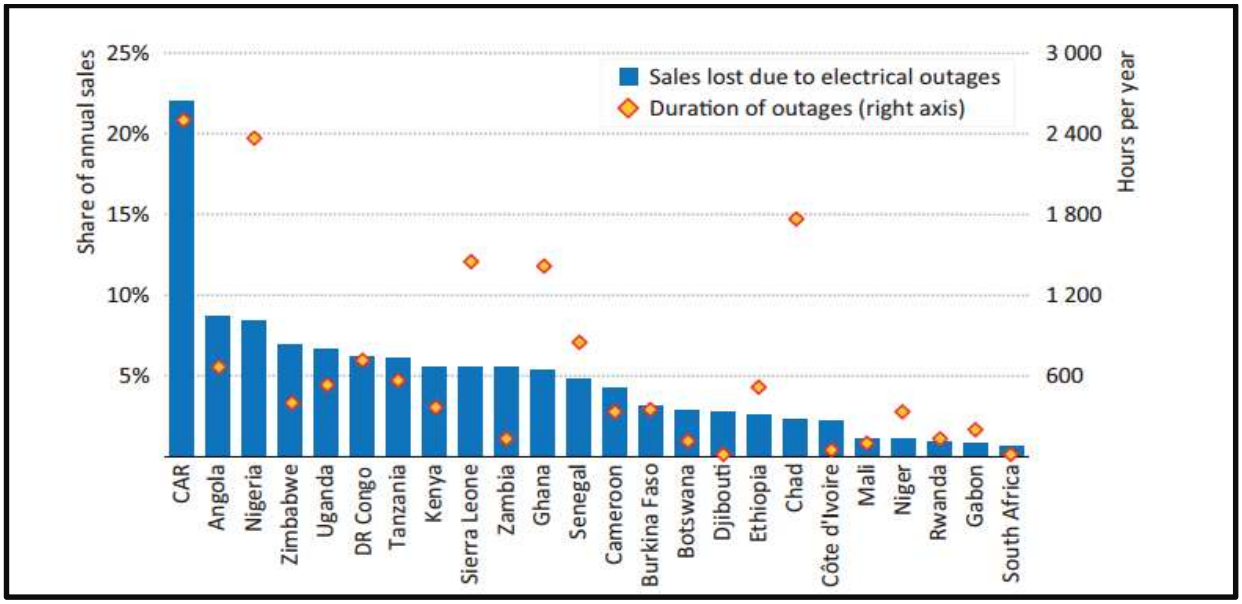

Figure 2.2: Duration of electrical outages and impact on business sales in selected countries. Note CAR = Central African Republic.

Sources: ((World Bank, 2014b) and IEA analysis)

From Figure 2.2, it can be inferred that there is a correlation between electricity outages (power cut or loading sharing) and countries economy. As shown in Figure 2.2, Ghana electricity outages is about 1,400 hours per year with about 700 hours per year sales lost due to electrical outages and a corresponding 6% share of annual sales. As it can be seen from the data on Central African Republic, as the hours of sales lost due to electrical outages increases; the greater the percentage share of annual sales.

In conclusion, electricity crisis in Ghana has significant impact on all sector end-use; hence the World Bank Energy group for Africa assessment and recommendation in 2013 was commendable.

2.3 Dominant office building End-use Service Equipment

A typical office building in Ghana uses several equipment; however, based on the emphasis of the tropical climate in the research, the equipment is categorized into weather sensitive and non-sensitive.

Among the climate sensitive equipment are mechanical air-conditioning, fan for space cooling as well as internal and external lighting.

Among the weather non-sensitive equipment are television, refrigerator; computer, smoke and fire detection, telecommunications, security monitoring systems, elevators, and other auxiliary equipment (Field study, 2014).

Several researchers have concluded that, in hot humid climate, air-conditioning remains the dominant electricity end-use system for indoor environmental comfort. It contributes to about 40 to 60% or more of total electricity consumed in commercial building depending on the climate (Perrez-Lombard et al., 2008; Chan et al., 2010; Fracastoro and Serraino,2011; Luck, 2012; Spyropoulos and Balaras, 2011; Chua et al., 2013; Rasouli et al.,2013; Wrobel et al., 2013 and Vakiloroaya et al.,2014).
From summarised literature, electricity end-use and indoor environmental quality in building is dependent on building performance factors (Yu et al., 2011 and Zhao and Magoules, 2012; Yildiz et al., 2012; Ekici and Aksoy, 2011; Choi et al., 2012; Olofsson and Mahlia, 2012 and Pacheco et al., 2012).

2.4 Building Performance Factors

Building on its own does not consume electricity; but the usage of the service equipment by the occupants. Nevertheless, the performance of the building has a key influence on electricity utilization of service equipment as well as on the quality of the indoor environment. Improving the performance of building remains key area on which to focus when reducing energy consumption (Raftery et al., 2011). The energy performance of buildings, their needs and consumption, have long been an issue in the debate among construction and real estate sectors. Energy saving and environmental sustainability will be the next challenge in architecture, especially as far as technologies and energy plant system solutions are concerned (Fabbri et al.,2012).

The demand for indoor environmental comfort in modern building designs in hot-humid tropical climate leads to reliance on mechanical cooling; usually vapour-compression air conditioning systems (Enteria and Mizuutani,2011; Korolija et al., 2011; Chua et al., 2013 and Vakiloroaya et al.,2014).

It is well known fact that, building performance is influenced by several factors as summarized in the conceptual frame work in Figure 2.3.

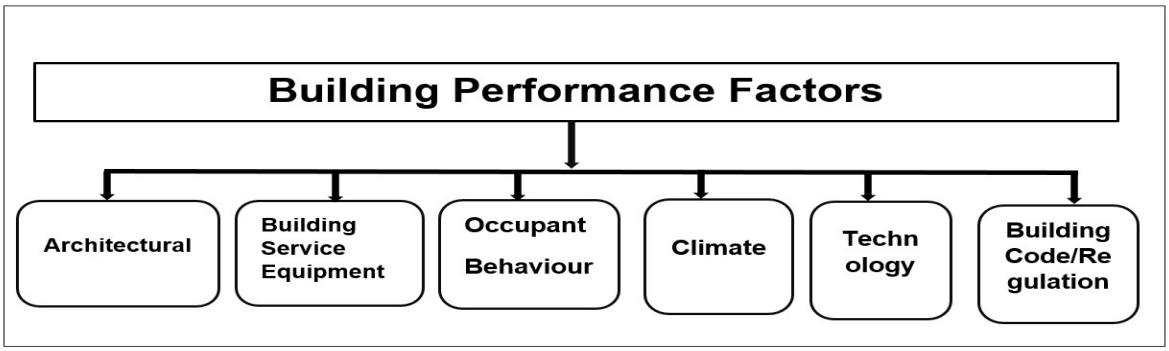

Figure 2.3: Conceptual frame work of Building performance factors

2.4.1 Architectural Factors

Lot of researches have been conducted on the causes and effect of architectural factors on building performance. From these, it has been concluded that, significant electricity utilization and the quality of the indoor environment is directly linked to Architectural factors i.e. building design, building fabric, building control, building form among others as shown in Figure 2.3a. Therefore, the architectural factors of buildings have the potential of reducing energy utilization, improving indoor environment quality and emissions significantly (Stegou-Sagia et al., 2007; (IEA, 2010); Stavrakakis et al., 2011; Prajongsan and Sharples, 2012 and Huang et al., 2013).

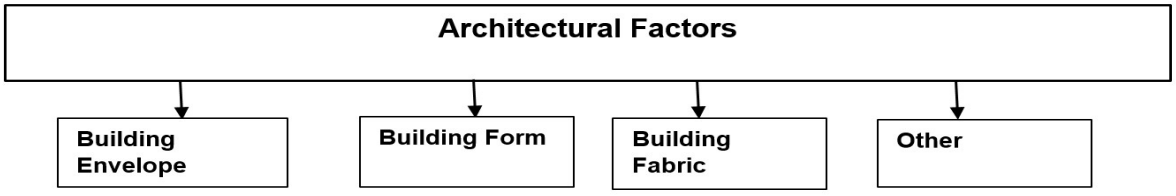

Figure 2.3 a: Architectural Factors

In this research, the following architectural factors have been considered:

i. building envelop design
ii. building fabric

iii. building control
iv. Building Form

2.4.1.1 Building Envelop design

Building Envelope is the exterior dimensions of a building that comprise its visible form and mass, including its height, width, depth, and shape. Building envelope elements are vital determinate of the amount of heat/moisture gain or loss in the building. The integrated elements of the building envelope include:

i. Wall system
ii. Roof system
iii. Window and other openings system,
iv. Foundation/floor system
v. Surface finishing

i. Wall system

Wall is an upright structure made of different building materials to enclose, divide, or protect an area and normally forms the siding of a building.

Wall forms a major part of the building envelope exposed to external weather conditions (solar radiation, outside air temperature, precipitation wind among others). The wall system has vital impact on indoor environment quality and the cooling energy usage because of its thermo-physical properties.

The wall material, thickness and finishes should be selected according to the climate zone and buildings comfort requirements. As stated by Alvarado et al. (2009) in warmer climates, buildings made of cement-based materials often demonstrates thermal discomfort characteristics of high indoor temperature, especially in the absence of an active cooling mechanical system.

Conventionally, based on the materials used in construction, walls can be classified as wood-based walls, metal-based walls and masonry-based walls (Sadineni et al., 2011). There are other types of advanced building wall systems designs that are applied to improve the energy efficiency and indoor environment quality.

Some existing advanced wall systems integrated into designs are, passive solar walls, lightweight concrete (LWC) walls, ventilated or double skin walls, and Walls with latent heat storage.

Many researchers have concluded that u-value of a wall is crucial in influencing the building energy consumption (Sadineni et al., 2011; Givoni, 2011 and Baglivo et al., 2014).

ii. Roof system

Roof is the structure that covers or forms the top of a building and is one of the critical element of the building envelope. Roofs are highly susceptible to solar radiation and other environmental changes, thereby, influencing the indoor environment quality and energy consumption. Roofs account for large amounts of heat gain/loss, especially, in buildings with large roof area such as sports complexes, auditoriums, exhibition halls among others (Sadineni et al., 2011) According to Wong et al. (2003) although the total heat gain for a conventional dark colour roof can be as high as 366kJ/m^2, the heat loss through the same roof is about 4.2 kJ/m^2. Additionally, Soubdhan et al. (2005) reported that 60% of the thermal transfer occurs through the roof. For example, in accordance with the UK building regulations, the upper limits of u-value for roofs have evolved from 0.25 W/m^2 K in 2000 to 0.13 W/m^2 K in 2010.This reduction in the u-value over the years emphasizes the significance of thermal performance of roofs in the effort to reducing the overall thermal performance of buildings.

The representative roofs use for buildings include vaulted and domed roofs, solar-reflective/cool roofs, green roofs, ventilated and micro-ventilated roofs, lightweight roofs, masonry roofs, solar-reflective/cool roofs, photovoltaic roofs (Sadineni et al., 2011).

Modified passive cooling techniques in roof architecture such as compact cellular roof layout with minimum solar exposure, domed and vaulted roofs, naturally or mechanically ventilated roofs, micro ventilated roofs, high roofs and double roofs can be incorporated in tropical climate (Jo et al 2010; Faghih and Bahadori, 2011; Faghih and Bahadori,2011 and Zerefos et al., 2012).

Other methods such as white-washed external roof surfaces to reduce solar absorptivity, roofs covered with vegetation to provide humidity and shade, and usage of high thermal capacity materials such as concrete to minimize peak load demand are also gaining popularity (Alvarado et al., 2009 and Sadineni et al., 2011).
Some researchers have concluded that replacing flat roof with doomed, slanted, reflective cool roof surface material, lightweight roofs among others have significant impact on enhancing building performance (Han et al., 2009; Jo et al 2010; Faghih and Bahadori,2011 and Zerefos et al., 2012).

iii. Window and door system

A window is a transparent or translucent opening usually in a wall or roof. Door is the space in a wall with normally large flat piece of wood, glass among others that opens and closes a building. Windows and doors are key components in building envelope thermal design. Windows and doors affect energy use through radiative transmission, conductive heat transfer (often lumped together as solar heat gain), infiltration, and day lighting which affect the amount of artificial lighting based on the type of material used. The size, position, composition, thickness of glass panes, and type of shading devices strongly impact the indoor environmental quality and energy utilization in the building (Yaghoobian and Kleissl, 2012). Windows are typically classified on the basis of materials used, types of shutters, types of openings of shutters and the position of windows. From summarize reviewed literature, typical window pane used in buildings include: Double, Triple, Quadruple, Electrochromic windows,
Thermochromics windows, Gas fill windows, Heat-absorbing tint, Insulated window, Low-emissivity (low-e) coatings and Reflective coatings (Quansah and Koranteng, 2012; Jelle, 2013; Fernandes et al., 2013; Hoffmann et al., 2014; Arici et al., 2015 and Cuce and Riffat, 2015).
Some researchers have concluded that window-to-wall ratio use in Ghana is increasing (Ampadu-Asiamah and Adjei, 2011; Quansah and Koranteng, 2012; Survey questionnaires, 2014). As stated by Quansah and Koranteng (2012) new buildings in Ghana are being constructed with insufficient knowledge on glazing properties of window pane. Their studies used calculations and survey method to study glazing properties of window pane use in Ghana.

Tabulated heat gains and effective solar coefficient values for characteristic buildings in Ghana is presented in Table 2.2.

Table 2.2: Tabulated heat gain and effective solar coefficient values for usual buildings in Ghana

Building	U-Value [W/m²K]	Area[m²]	Heat gain [W/K]	P[m]	H[m]	PF	SHGCsd	SCsd	SCg	SCe
ICB	5,272	50	263,6	0	7	0	1	1,16	0,59	0,69
AHB	5,243	50	262,15	0	15	0	1	1,16	0,55	0,64
KPB	5,272	50	263,6	0	13	0	1	1,16	0,55	0,64
DUT	0,350	50	17,5	0	16	0	1	1,16	0,4	0,47
ADB	5,272	50	263,6	0,3	7,5	0,04	1	1,16	0,8	0,93
OAB	5,243	50	262,15	0	15	0	1	1,16	0,734	0,85

Source: Quansah and Koranteng, 2012

Doors are normally classified based on arrangement of shutters, method of constructions, principles of working operations and materials used. Commonly used doors include battened and ledged, ledged and braced, framed and panelled, http://lecture.civilengineeringx.com/building/bce/Flush-door.jpgflush doors, swing, sliding, and collapsible doors.

Several researchers have concluded that, u-value, windows size, location, shape and orientation areas in a building have a critical effect on both the heat gains and solar gains of a building depending on the window type used (Jaber and Ajib, 2011; Quansah and Koranteng, 2012; Jelle, 2013; Fernandes et al., 2013; Arici et al., 2015 and Cuce and Riffat, 2015).

Many researches have concluded that buildings cooling load which affect the energy consumption is correlated with the building envelope heat gain (Alvarado et al., 2009; Eicker et al., 2010; Wan et al., 2011; Faghih and Bahadori, 2011; Sadineni et all., 2011; Givoni, 2011; Jaber and Ajib, 2011; Zerefos et al., 2012; Yang et al., 2012; Evins, 2013 and Santamouris and Dionysia,2013). As a result, minimizing heat transfer through the building envelope is crucial for reducing the need for space heating or cooling.

2.4.1.2 Building form

Building Form is the overall shape and axis of a building; with the axis been either symmetrical and/or asymmetrical. The form of a building is one of the most arguable areas of design, with architectural, aesthetic, structural and sustainability influences. Regarding sustainable design, form affects solar gains, daylight and fabric heat loss. Unlike constructions, it is often difficult to represent building forms as straightforward parameters. Much work is ongoing in the architectural domain regarding means of generating complex forms in a manner suitable for adjustment and optimisation.

Some researchers have concluded that, building form can be a barrier to heat, light, air, and must be carefully designed to achieve high performance (Okeil,2010; Zerefos 2012 and Evins,2013).

Effect of building shape factor on energy

The shape factor of a building is a measure of the building's compactness and expresses the ratio between the building's thermal envelope area and its volume.
The thermal envelope area is the area that separates between the conditioned and unconditioned areas or alternatively, the indoor and the outdoor environment. As a result, the heat losses through the thermal envelope account for large percentage of the total final energy use of a building in cold climates. Buildings with a higher shape factor are less compact and therefore have a larger thermal envelope area in proportion to their volume and therefore larger heat losses. The shape factor of the building influences the amount of solar energy it receives hence the total energy it consumed.

2.4.1.3 Building Fabric

Generally, building fabric is any material used for building purposes comprising of roof, floor, walls, windows, and doors. Building fabric plays vital role in building performance assessment as well as protecting its occupants'.

In line with the field study conducted, there are two main building fabrics in Ghana;

i. Conventional
ii. Traditional or Non-conventional

Conventional building fabric: Representative building fabric used for industrial, commercial, military, some residential, quasi-government buildings, university buildings, ports, civil service, foreign missions and embassies as well as mining buildings. Examples of building fabric use include: mortar blocks, concrete blocks, corrugated metal sheets, slate or asbestos, long span aluminium, reinforced concrete roof, roofing tiles, timber, among others.

Traditional or non-conventional building fabric include: Usual building fabric used for selected residential buildings, tourism buildings, museums, selected agricultural buildings among others. Examples of traditional building fabric include mud bricks, landcrete blocks, stabilised adobe, thatch, palm leaves, bamboo, straw, wood among others. Representative building envelope elements fabrics use in Ghana is shown in Table 2.3.

Table 2.3: Representative building envelope elements fabrics used in Ghana

	Wall	Roof	Window Pane and Frame	Floor and Finishing	Door	Ceiling
	Mortar blocks	Concrete Tiles	Aluminium Framed Glass Windows	Concrete Slab	Wood Panelled	Wood
	Bricks	Brick Tiles	Aluminium-Clad Wood Framed Glass Windows	Laterite	Aluminium Framed, Glass Doors	Plywood
	Concrete Blocks	Shingles	Wood Framed Glass Windows	Reinforced concrete	UPVC Framed , Glass Doors	Acoustic ceiling tiles
	Laterite blocks	Long span aluminium roofing sheets	Wood Panelled Windows	Floor tiles	Steel Doors	
	Stabilised blocks	Tiles	UPVC Framed Glass Windows	Terrazzo		
		Corrugated sheets		Porcelaine tiles		
		Slates/asbestos		Ceramic tiles		
				Marble tiles		
				Cement/Sand Screed		
				Carpet		
Fabric						

Source: (Field Study, 2014)

Several researchers have concluded that building fabrics have substantial influence on building performance, hence careful consideration should be taken during selection (Ulatam and Gheewala, 2009; Franzoni,2011; Oppong and Badu, 2012 and Anais et al., 2013).

2.4.14 Building Fabric Properties

There are several properties of building materials, but those that have a direct effect on energy utilization and indoor environmental performance impact are:

- Thermal properties
- Optical properties

- **Thermal Properties**

Thermal properties of materials mainly affect the rate of heat transfer in a building and consequently, the energy and indoor environment requirements. Table 3 shows thermal properties of some building material properties.

It depends mainly on the orientation, size, windows to wall ratio, also on the thermo-physical and optical properties of the building material, and on the external environmental conditions. Table 2.4 is thermo-physical properties of representative building fabric.

Table 2.4: Representative Thermo-Physical Building Fabric Properties

Material	Condition/test (where known)	Source	Thermal conductivity /W·m^{-1}·K^{-1}	Density /Kg·m^{-3}	Specific heat /J·kg^{-1}·K^{-1}
Asbestos-related materials:					
- asbestos cement		S	1.02	1750	840
- asbestos cement building board		D	0.6	1920	840
- asbestos cement decking		C	0.36	1500	1050
- asbestos cement sheet	Conditioned	C	0.36	700	1050
- asbestos cement fibre	At 50°C	I	0.06	640	840
- asbestos mill board	At 50°C	I	0.25	1400	840
Brick		D	0.72	1920	840
		D	1.31	2080	921
-aerated		S	0.30	1000	840
-brickwork, inner leaf		C	0.62	1700	800
-brickwork, outer leaf		C	0.84	1700	800
-burned		S	0.75	1300	840
		S	0.85	1500	840
		S	1.00	1700	840
-mud	At 50°C	I	0.75	1730	880
-paviour		E	0.96	2000	840
-reinforced	At 50°C	I	1.10	1920	840
-tile	At 50°C	I	0.8	1890	880
Cement/plaster/mortar:					
-cement		D	0.72	1860	840
-cement blocks, cellular		T	0.33	520	2040
-cement fibreboard, magnesium oxysulphide binder		A	0.082	350	1300
-cement mortar		S	0.72	1650	920
	Dry	T	0.93	1900	840
	Moist	T	1.5	1900	840
-cement/lime plaster		S	0.8	1600	840
-cement panels, wood fibres	Dry	T	0.08	350	1890
	Moist	T	0.12	350	3040
		T	0.12	400	1470
	Dry	T	0.35	1650	840
-cement plaster		S	0.72	1760	840
		S	1.50	1900	840
-cement plaster, sand aggregate		A	0.72	1860	840
-cement screed		E	1.40	2100	650
-gypsum		E	0.42	1200	840
-gypsum plaster		S	0.51	1120	960
-gypsum plaster, perlite aggregate		A	0.22	720	1340
-gypsum plaster, sand aggregate		A	0.81	1680	840
-gypsum plasterboard		D	0.16	800	840

Source: CIBSE Guide A

- **Optical Properties**

Details of optical properties are presented in Chapter 4.

Several researches have been conducted on both optical and thermal properties of building fabrics. The researchers concluded that, enhanced building fabric properties have important potential in minimizing heat and moisture transfer through building elements for improved performance (Alvarado et al., 2009; Koranteng 2010; Sadineni et al., 2011; Kendrick et al., 2012; Bal et al., 2012; Amos-Abanyie et al., 2013; Anais et 2013; Yun et al., 2013 and Chabannes et al., 2014)

Conversely, certain properties are more significant in enhancing performance base on the climate under consideration, for example thermal mass.

In conclusion, optimizing the performance of building envelope is a promising way to reduce the energy consumption of HVAC system, therefore a key research area with many researchers involved in (Huang et al., 2013).

2.4.2 Building Service System

Building services engineers are often in charge for both electrical and mechanical systems. Some researchers have concluded that building service engineers have a significant role in sizing, using positive effects of microclimate and selecting efficient service equipment as shown in Figure 2.3b.

With the main of achieving minimum energy utilization at an acceptable indoor environmental quality and low emissions (Uihlein and Eder, 2010; Korolija et al., 2011; and Chua et al., 2013). Building Services equipment represents 30-50% of the construction costs and it is the major source of energy consumption in buildings (Field study, 2014).

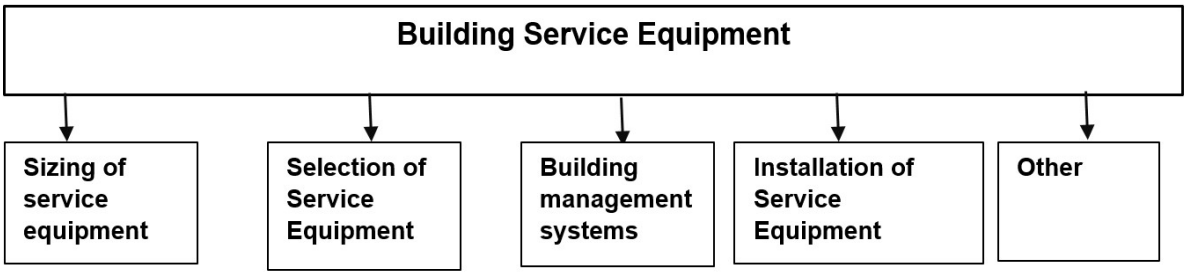

Figure 2.3b: Representative Building Service practices

Korolija et al. (2011) concluded that representative different HVAC system incorporated in the same buildings will have different consumption for the same occupant behaviour. Among the representative different HVAC system are Variable air volume (VAV), fan coil (FC) and solar assisted liquid desiccant cooling (Korolija et al., 2011 and Qi, 2012). Korolija et al. (2011) and Qi (2012) concluded that the use of solar assisted liquid desiccant cooling system with thermal storage has significant electricity savings potential compared to conventional vapour compression system for cooling.

Some researchers have estimated high cooling load per meter square floor area above recommended good practice by CIBSE Guide A around other parts of the world (Koranteng et al., 2010; Qi et al., 2012; Pino et al., 2012; Survey questionnaires, 2014). In conclusion, building service equipment is one of the major drivers of electricity utilization; therefore, it's imperative to optimize its usage in minimizing emissions arising from service equipment usage.

2.4.3 Occupant Factors

According to Oxford dictionary occupant is a person who lives or is present in a house, vehicle, seat, etc., at a given time. Occupant types are can be use as means of classifying buildings. According to Fabi et al. (2012) energy utilization in buildings is influenced by several factors; on the contrary, most of these factors are highly connected to the behaviour of the occupants. Occupants' factors are key in determining performance buildings as seen in Figure 2.3 with detail representative occupant behavior presented in Figure 2.3c

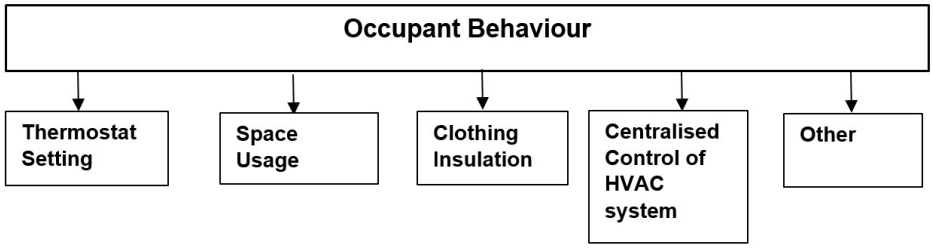

Figure 2.3c: Typical Occupant behaviour

It is widely accepted that there is a gap between design and real world operational energy consumption. This is a result of over simplification of occupants' behaviour which is an important factor influencing building performance (Tetlow et al., 2015).

Some researchers have concluded that typical occupant's behaviour which influences building performance are window opening of air-conditioning space, window curtains operation, floor carpet, the choice of indoor temperature set point for air-conditioning systems, increasing time spent in the space, high comfort requirement, activity level, clothing insulation, among others as summarized in Figure 2.3c. In contrast realistic building user-behaviour patterns are more complicated (Poel et al., 2007; Herkel et al., 2008; Lee and Guerin, 2010; Fabi et al., 2012; Zalejska-Jonsson, 2012; Azar and Menassa, 2012 and Hirning et al 2013).

Several researchers have concluded that, indoor air quality, thermal quality, and lighting quality are the most qualities that affect occupant's environmental satisfaction and job productivity (Lee and Guerin, 2010; Zalejska-Jonsson,2012 and Hirning et al 2013).
In conclusion change of occupant's behaviour can reduce energy and improve environmental performance, if the building performance is well designed Yun et al., 2009.

2.4.4 Climate Factors

The fundamental requirements of building envelope are protection and comfort it offers to occupants who resides/work within them from the weather.

The objective of environmental building design is the creation of a comfortable yet energy efficient indoor environment. The successful design of buildings relies on understanding of the climate as shown in Figure 2.3d; that is, to be able to analyse the interaction between the energy supply and energy demand of a building, which results from different climate influences.

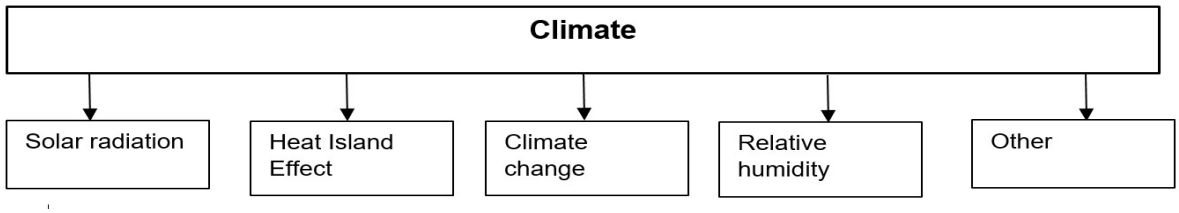

Figure 2.3d: Characteristic Climate elements

Hence depending on the climate and season, positive climatic elements can be used to enhance building performance. For example, in temperate climate, during winter, solar radiation can be used for heating and lighting. Whiles in tropical climate, wind and solar radiation can be used for ventilation, cooling and lighting respectively. However, the negative effects of climatic elements need to be controlled; for an example, heat losses due to low ambient temperature in winter; heat gain from ambient temperature and air moisture transfer in the tropical climate.

Contrary, recent human activities have risen causing high concentrations of greenhouse gases in the atmosphere leading to global warming and extreme weather pattern conditions worldwide. This has contributed to high service demand for indoor environmental quality with its associated negative impacts (Crawley, 2008; Kolokotroni et al., 2012; Lu et al., 2014 and Santamouris, 2014). From Chalmers (2014), in 2010, the world's buildings sector accounted for 32% of global final energy use and 19% of all greenhouse gas (GHG) emissions.

According to Oxford dictionary, climate can be defined as the weather conditions prevailing in an area in general over a long period. Weather describes the state of the atmosphere at a particular place and with regards to heat, cloudiness, dryness, sunshine, wind, rain among others. According to Zhao and Federic (2012), the weather conditions have elements such as:

i. Solar radiation
ii. Ambient temperature
iii. Air humidity
iv. Precipitation
v. Wind
vi. Sky condition

An example of typical annual weather elements for Accra is represented in Figure 2.4.

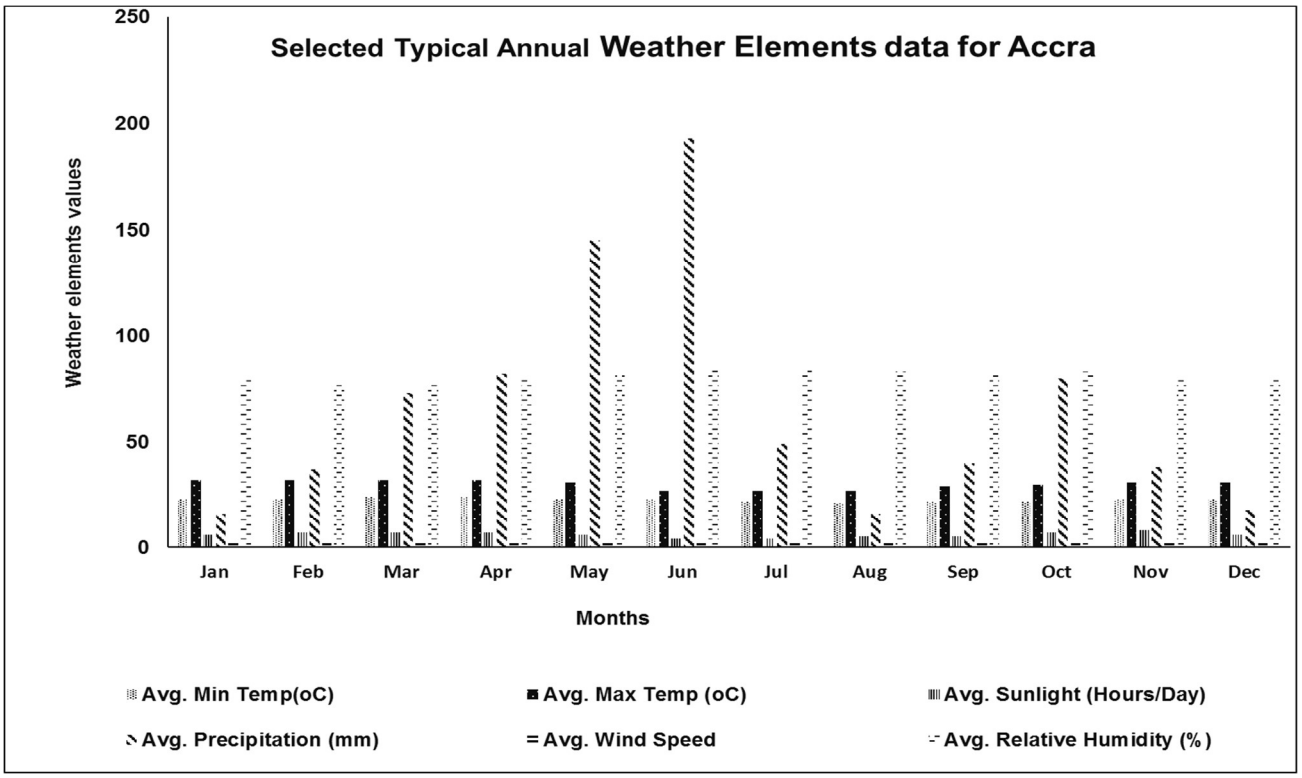

Figure 2.4: Selected typical annual weather elements data for Accra
Source: (climatemps, 2016)

Many researchers have shown that climatic conditions (Solar radiation, ambient temperature, air humidity, precipitation, wind and sky condition) have strong correlation with building performance (Wan et al., 2011; Lam et al., 2011; Zhao and Magoules 2012 and Santamouris, 2014).

Some researchers have concluded that, ambient temperature rises with global warming and this have significant impact on thermal performance of buildings leading to high cooling demand. Weather data forms an integral part of building envelope design and simulation for performance assessment, therefore the need for accurate weather data (Qin et al., 2009; Hong et al., 2013; Guan et al., 2014 and Santamouris, 2014).

In conclusion, all the reviewed researchers on climatic factors indicated that energy utilization and related CO_2 emissions from heating and cooling are increasing due to climate change hence the need for more microclimatic architectural building designs. Again, building design varies with geographical area climate. The extent to which overall energy use for space conditioning to be affected would depend significantly on the prevailing local climates and the actual climate change in future years.

2.4.5 Building Code/Regulation/ Policy Factors

Building practices, technologies and construction are constantly evolving; hence building codes, regulations and policies are constantly being revised to reflect efficiency, up-to-date (scientific, technology and technical details) and effective minimum building envelop specifications to enhance performance. Representative specifications in building codes/regulation/standards is represented in Figure 2.3e.

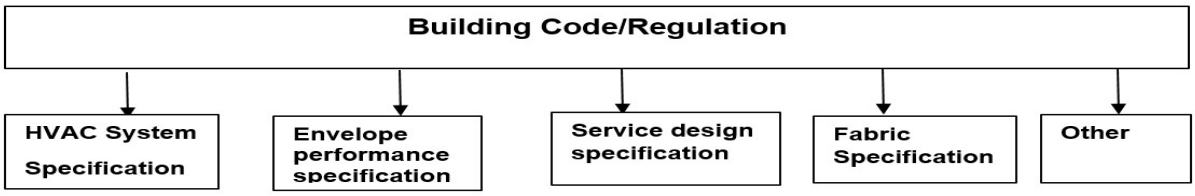

Figure 2.3e: Characteristics factors under building code/regulation

For example, ASHRAE series, UK building regulations, ANSI, ASHRAE standards, IES Standard 90.1, CIBSE Guides, ISO standards, British standards and many more. Building code is any set of standards usually series of documents enacted by government authorities, organisations, institutions in establishing minimum/maximum requirements for building design, construction and maintenance.

Building policy is rules, guidelines or framework for building design, construction and maintenance. Building regulations contain rules, standards or guidelines for building design, construction and maintenance. Representative types of building regulation include: Prescriptive, Trade-off, Model building, Energy frame and Performance.

Representative constituent of regulations/codes/policies are building envelope, HVAC system, lighting, energy conservation measures among others.

Many researchers have concluded that building code/ regulation and policy over the years have been used as one of the effective measures to control building envelope performance (IEA,2008; Iwaro and Mwasha,2010; IEA,2011; Uihlein and Eder,2010; Perez-Lombard et al 2011 and Pacheco et al.,2012). Conversely, researches conducted by IEA (2008), Iwaro and Mwasha (2010) and Pan and Garmston (2012) building code/regulation/policy compliance continues to remain a challenge as a result of the following:

- Inadequate information for building professionals
- insufficient finance for efficiency improvement
- Insignificant incentives
- users' lifestyle choices
- Insufficient efficiency awareness among clients
- Cost implications

IEA (2008), Iwaro and Mwasha (2010) have indicated that building code/ regulation/policy compliance check is carried out by:

1. Prescriptive Approach where all individual requirements for Building Envelope, HVAC systems, Service Water Heating, Power, Lightning and Other Equipment are achieved.
2. The Energy Cost Budget, where the energy consumption must be below a value calculated based on a calculation for the building and fixed values for efficiency.
3. The Design Energy Cost where all parts of the building and the installations have the same energy or better energy efficiency than the figures used for the calculation of the Energy Cost Budget.

2.4.6 Building regulation of Ghana

Ghana Building regulation was enacted into law in 1996 as result of several structural failures and collapses. The intent was to provide minimum safety standards about structures with regards to fire, structural issue, and plumbing work electrical and mechanical.

The Regulation has been in use almost 20 years without amendment until 2012 when the Ministry of Housing announced the development of new Ghana building code. Yet since the announcement of the new building code in 2012 up to now, the state of the code development is unknown. Subsequently, Global Building Code Implementation and Stringency report on 2014 of the world, characterised Ghana as No codes or unknown.

2.4.52 Building permit Issuing Process in Ghana

From the building regulation in Ghana, the detail of the building permit application is purely based on the Architectural factors as shown in Table 2.5 and Ghana Building regulation. It is imperative in building permit issuing process to get satisfactory minimum requirement within the regulation. For example, within the building permit process, there is a requirement to declare the description of building materials to be used. Table 2.5 shows the requested list for building permit issuing process.

Table 2.5: Requested list for building permit issuing process.

Element	Description
Foundation	materials and proportions
Walls	materials and proportions
Ground floor	materials and proportions
Upper floors	materials and proportions
Windows	type and dimension
Doors	type and dimension
Roof	type, covering and spacing of trusses

Significant researchers have concluded that, codes/ regulation/ policies/ standards are an effective approach in modifying as well as controlling performance and CO_2 emissions arising from buildings (Hitchin,2008; Radhi,2009; Audenaert et al., 2010; Iwaro and Mwasha,2010; Chua and Chou, 2011; Noailly, 2012; Pan and Garmston,2012; Tulsyan et al., 2013)

2.4.7 Technology

There is growing demand for energy saving technologies in buildings due to global warming and environmental impact issue arising from high demand of vapour compression air-conditioning systems. As a result, energy-efficient technologies are becoming more popular amongst researchers and designers (IEA, 2011; Devabhaktuni et al., 2013 and Mardianaldayu and Riffat, 2012).

According to Oxford dictionary, technology is the application of scientific knowledge for practical purposes. There are several technologies integrated into building for comfortable indoor environment and efficient energy at cost-effective way. Representative technologies incorporated in this research is summarised in Figure 2.3f.

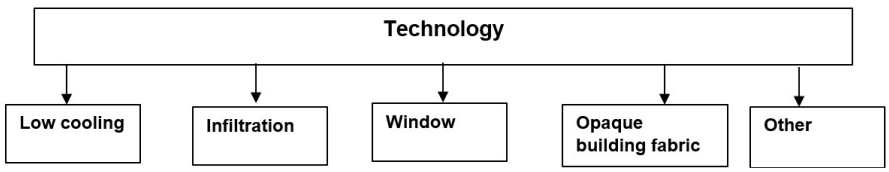

Figure 2.3f: Representative technologies incorporated in buildings

It is well known that technologies integrated in buildings which have direct impact on building performance can be classified into passive and active.

Active technologies include: active solar thermal technology, smart grids, photovoltaics, building control, building demand management system, occupancy control, lighting control, liquid desiccant air-conditioning, heat recovery, thermo-active, heat exchanger, thermal energy storage, among others (Parameshwaran et al., 2012; Lamnatou et al., 2015; Goyal et al.,2015 and Buker et al.,2015.

Passive technology includes: Insulation, Air tightness, Natural light, Solar gain, Natural Ventilation, building fabric technologies (Phase change materials, Nanomaterial technology etc.), shading, thermal mass, renewable energy technologies (solar power, wind power and fuel cell), climatic building response design, among others (Pan,2010; Givoni,2011; Sinnott and Dyer,2012; IEA,2013 and Santamouris and Kolokotsa,2013).

Majority of researchers have concluded that technology either active or passive integrated into building possess a more viable approach in enhancing building performance and minimizing negative environmental impacts (Day et al., 2009; Givoni, 2011; Hughes et al., 2011; Mardiana and Riffat, 2012; IEA, 2013; Devabhaktuni et al., 2013 Hall et al 2013; Kameni et al., 2015 and Buker and Riffat, 2015).

2.4.8 Building Professional Practices

Some researchers have concluded that, building professional practices have a major impact on building performance. Building professionals' practices include designing of building and service systems, selection of materials technologies, adjustment factors and others, sizing of equipment, interpreting codes/regulation, implementation of codes/regulations/ policies, among others. On contrary, though building professionals' practices are guided by standards, as seen in the building regulation section, the level of compliance is low (Akadiri, 2011; Cao et al., 2015; Clarke and Hensen, 2015; Survey questionnaires, 2014; Asaadani and Souza, 2016; Survey questionnaires,2014 and Nielsen et al.,2016).

Conversely, it is not often included in the representative factors influencing building performance (Sovacool, 2014).

2.4.9 Identified Gaps in Building Performance Factors

From Figure 2.4, there are several factors which affect building performance. The following gaps were obtained from the detailed building performance factors outlined above:

1. Lack of empirical data and practical advice on thermal performance of building envelope fabric used in Ghana (Amos-Abanyie, 2012).
2. There is a lot of existing literature on residential housing types and type of building ownership, however there is a limited coverage of the literature on commercial building in Ghana (Nyame-Tawiah et al., 2011; Damptey, 2006 and Amos-Abanyie et al., 2009).
3. Decision making on building design in Ghana is inadequately informed on building performance factors (Koranteng and Mahdavi, 2011).
4. Lack of technical guidance on Ghana building regulation on achieving the prescriptive minimum standards for building envelop design
5. From Ghana building regulation section on building fabric properties, it is impossible to achieve the u-values of building envelope elements using the local building professional practices.
6. Lack of detail building design variables in Ghana building regulation leading to adoption of international standards with subjective adjustment factors.

2.5 Representative Thermo-Physical Test Methods

Many methods for determining thermal properties do exist in both scientific and technical journals. Among them are, transient plane source, modified transient plane source, hot wire method, hot plate method, heat flow meter, laser flash analysis method and many more. The individual methods are suitable for a limited range of materials, depending on the thermal properties and the medium temperature. The methods of testing are mainly classified into steady-state and transient techniques. In steady state techniques during the measurement, temperature of the material does not change with time.

The steady-state methods are represented by (ISO, 8302:1991) and (ASTM, C177-04). In steady state techniques, during the measurement, temperature of the material does not change with time. Steady state measurements offer simple measurements methods without any complex means of analysis, conversely, it has relatively long time in reaching stationary conditions for fabrics with great thermal inertia.

Transient technique incorporates one or more heat flux meters in the stack of plates calibrated against standard samples whose conductivity was previously measured using the absolute approach. Transient measurement methods have advantages in relatively detailed measurements and fast readings, on the other hand, it requires a complex data processing and high expertise in the heat source (Bairi et al., 2007). Transient technique represented by (ASTM, D7984-16). Currently, modified transient plane source technique exist in test measurement and it is represented by (ASTM, D7984-16).

2.5.1 Representative Thermal (Conductivity and Effusivity) Test Methods

Testing is how the properties of a material are routinely evaluated and compared with the appropriate specification requirements. Based on the identified gap, this research focused on thermal properties. Thermo-physical properties of permeable materials are affected by several factors, for example thermal contacting agent, porosity, compactness among others (C-Therm, 2007; Bal et al., 2012; Darkwa et al., 2012 and Yu et al., 2015). Detail description of measurement test methods listed above are as follows.

i. Transient Hot Wire Method

Transient hot wire method uses a heating wire or cylindrical heating element and a temperature sensor for observing the variation in temperature over time. The thermal conductivity and the thermal diffusivity of the material is then calculated from the mathematical solution of heat conduction equation, the known heat liberation and the temperature history of the wire or the probe. Transient hot wire method is conducted under (NF EN ISO 8894; Chabannes, 2014 and Laaroussi et al., 2014).

ii. Modified transient plane source

This research used C-Therm Tci analyser which is based on modified transient plane source. C-Therm Tci analyser was selected based on the following: i. C-

Therm Tci analyser offers a comprehensive testing range capabilities that is, thermal conductivity (0.0 to 220 W/mK) and temperature (–50˚ to 200˚C). ii. Testing is non-destructive (leaves the sample intact). iii. C-Therm Tci analyser measure the thermal properties (thermal conductivity and effusivity) of materials in liquid, powder, paste and solid (example ceramic and metal) states simultaneously per reading.

The C-Therm Tci thermal analyser comprises of a sensor, power control device and data acquisition system as seen in Figure 5.4. The sensor has a central heater/sensor element in the shape of a spiral surrounded by a guard ring. The guard ring generates heat in addition to the spiral heater, thus, approximating a one-dimensional constant heat flow from the sensor into the one side of the specimen under test in contact with the sensor. The voltage drop on the spiral heater is measured before and during the transient. The voltage data is then translated into the effusivity value of the specimen. The conductivity is calculated from the voltage data by C-Therm's patented iterative method. Results are then displayed on the system's laptop or computer in real-time.

iii. Hot wire method

The hot wire technique makes use of a thin hot wire, which is heated with a constant current producing a heat flow per unit length q and an increase of the hot wire temperature. A small part of the supplied heating current is used to heat the wire; the major part is used to heat the surrounding medium via thermal conduction. The variation of wire and medium temperature with time depends directly on the heat conductivity of the medium and the supplied thermal energy. The hot wire method described in (BS EN 993-15 and Al-Sibahy and Edwards, 2012).

iv. Guarded hot plate method

Consists principally of a hot plate and a cold plate. In a HGP test, the test specimen is placed on a flat plate heater assembly consisting of an electrically heated inner plate (main heater) surrounded by a guard heater. The guard heater is carefully controlled to maintain the same temperature on both sides of the gap separating the main and the guard heaters. This prevents lateral heat flow from the main heater and ensures

that heat from the electric heater flows in the direction of the specimen. On the opposite side of the specimen are additional flat plate heaters (cold plate) that are controlled at a fixed temperature selected by the operator. For a given heat input to the main heater, the hot plate assembly rises in temperature until the system reaches equilibrium. The final hot plate temperature depends on the electrical power input, the thermal resistance of the specimen, and the temperature of the cold plate. The average thermal conductivity, k, of the specimen is determined from the Fourier heat flow

$$k=W/A\ [1 \times d/\Delta T] \qquad \text{Eqn 2.1}$$

where W is the electrical power input to the main heater,
A is the main heater surface area,
DT is the temperature difference across the specimen, and
d is the specimen thickness (Othuman and Wang, 2011).

v. Laser flash method

A laser flash delivers short pulse of heat to the front of the sample and an infrared scanner observes the temperature change at the rare face as a function of the time. Laser flash method is use for the measurement of the thermal diffusivity and thermal conductivity of various kinds of solids, powders and liquids just as modified plane source method.

2.5.2 Representative Density Test Methods

AutoPore IV mercury Porosimeter characterizes a material porosity by applying various pressure levels (high and low) to the specimen immersed in mercury.

The pressure required to intrude mercury into the specimen pores is inversely proportional to the size of the pores. AutoPore IV provide high-quality enhanced data for easy system characterisation.

In conclusion, this research used TCi Thermal Conductivity Analyzer and AutoPoreIV mercury intrusion porisimeter for the measurement of thermal conductivity and density respectively based on the level of accuracy of both equipment.

2.6 Building Performance Optimization

Optimization is mostly defined as the procedure/ procedures of making something (as a design, system, or decision) as efficient, fully perfect, functional or as active as possible. Simulation-based optimization is an efficient measure to achieve several rigorous requirements of high performance buildings for example, low-energy buildings, passive houses, green buildings, net zero-energy buildings, zero-carbon buildings, among others (Zhu et al.,2013; Nguyen et al., 2014 and Stevanovic,2015).

According to Nguyen et al. (2014), optimization process can be basically classified into 3 phases, that is, pre-processing phase, an optimization phase and a post-processing phase. The pre-processing phase plays an important role in the success of the optimization. The most vital task of formulating the objective functions are carried out for example, minimization of cost, energy savings, improvement of thermal comfort, indoor air quality psychological comfort, visual comfort among others. The optimization phase deals with the analysts of the objective functions to monitor convergence of the optimization and to detect errors which may occur during the entire process. The term convergence is usually used to indicate that the algorithm has reached the final solution. Sometimes, it is necessary to note that a convergent optimization process does not necessarily mean the global minimum (or minima) or maxima has been found. The post-processing phase deals with the analysis and interpretation of optimization data into charts, diagrams or tables to draw useful conclusions from the optimal solutions achieved from the optimization.

Representative simulation based software used for optimization are TRNSYS, Energy Plus, DOE-2, ESP-r, EQUEST, ECOTECT (Hwang et al.,2012; Lazos et al., 2014 and Nguyen et al., 2014).

Representative algorithms used in building performance optimization are Hooke–Jeeves algorithms, coordinate search algorithm, Mesh adaptive search algorithm, Generating set search algorithm, generic algorithm, Simplex algorithm, genetic programming, evolutionary programming, differential evolution, cultural algorithm, bounded BFGS, Levenberg–Marquardt algorithm, discrete Armijo gradient algorithm, CONLIN method nvasive weed optimization algorithm, Branch and Bound methods, Exact algorithm, Simulated annealing, Tabu search, Hill climbing method, CONLIN method (Turrin et al.,2011; Suganthi and Samuel ,2012; Bigot et al.,2013; Evins,2013; and Nguyen et al., 2014)

Several researches have concluded that using optimization for enhanced building performance leads to improved performance, enhanced comfort, lower utility bills, reduced operating costs, longer equipment life, among others (Kusiak et al.,2010; Wang et al., 2010; Hamdy et al.,2011; Fesanghary et al., 2012; Starvrakakis et al., 2012; Zhu et al., 2013; Baglivo et al., 2014 and Gang et al., 2015).

2.7 Conclusion on representative approaches for solving building performance problems

Selected representative research on mitigation measures use in enhancing building performance include controlling solar gain through window, thermostat set point, use of design parameters (ventilation rates, building aspect ratio and weather design variables), building standards/regulation/codes/policy , building control technologies (energy management and control system(EMCS), programmable thermostat (PT)), building form , daylighting harvesting , building fabric selection, phase change materials, architectural design, window properties, thermal insulation level , energy efficient building design, passive cooling techniques, high-reflectivity coating on building walls in cooling dominate areas, air tightness, control of building envelope heat gain/loss, low energy cooling technologies, energy efficient technologies, climate responsive design, reduction of u-values, low cooling technologies among others

(Radhi,2009; Iwaro and Mwasha,2010; Givoni,2011; Wan et al., 2011; Chua and Chou,2011; Dunois and Blomsterberg,2011; Escriva- Escriva,2011; Leskovar and Premrov,2011; Darkwa et al., 2012; Tsikaloudaki et a.,2012;Ballarini and Corrado, 2012; Pacheco et al., 2012; Futhcher and Mills, 2013; Chen et al., 2013; Santamouris and Kolokotsa,2013; Survey questionnaires, 2014; Buker et al 2015 and Survey questionnaires, 2014).

Finally, all the building performance factors outlined above are key potentials for mitigating high electricity utilization and indoor environmental comfort.
On other hand, the percentage of the level of improvements as outlined by researchers varies due to the building purpose, climate, building designs among others. In view of that, this research would conduct a parametric study on integrating all the above factors to identify the most sensitive mitigating approaches.

3 CHAPTER THREE : BUILDING PERFORMANCE

3.1 Introduction

Building performance assessment is multi-disciplinary process which usually carried out on new or existing building to enhance part or whole function of a building envelope and finishing. Considerable number of researchers normally use the following tools for building performance assessment: computer simulation, environmental chamber experiments, theoretical calculation, energy audits, survey questionnaires, indoor measurements, test cells and others (Clarke and Yaneske,2009; Kruger et al., 2011; Dascalaki and Sermpetzoglou, 2011; Synnefa et al., 2012; Barbhuiya and Barbhuiya ,2013; Guerra-Santin et al., 2013; Wilde,2014;Nguyen et al., 2014; Gibbs and O'Neill,2015; Han and Srebric,2015; Eicker et al.,2015;Elmer et al., 2015;Lamnatou et al., 2015; Clarke and Hensen, 2015; Olivia and Christopher, 2015 and Cattarin et al.,2016). A representative output variables of building performance assessment include: energy utilization (equipment, lighting etc.), indoor environmental quality, CO_2 emissions, user satisfaction and economics, among others. The output variables of building performance assessment are normally systematically measured against the following performance indicators: building codes/regulations/policy, CO_2 emission targets, electricity bills, ISO standards, CIBSE Guides, ASHRAE standards and others.

3.2 Theoretical Framework for Building Performance Assessment

This research is multi-disciplinary approach which focuses on the whole building performance assessment. The main theoretical framework of building performance assessment is heat and moisture transfer. These theories as applied to this research requires independent variables arising from the following tools used in assessing the building performance: laboratory experiment, computer simulation and survey questionnaires. The resulting dependent variables been energy utilization (cooling, equipment and lighting), thermal comfort and economic.

3.2.1 Heat Transfer

Heat transfer is an exchange of thermal energy between systems depending mainly on temperature, pressure and the medium of transfer. Also, heat transfer is governed by both First and Second Laws of Thermodynamics. Heat transfer in systems occur in three modes mainly conduction, convection and radiation. The heat flow by conduction is the process of heat exchange from one part of a body at a higher temperature to another at a lower temperature and mainly arises in solid systems. For example, heat conduction in building elements include walls, roof, ceiling, floor, etc. The heat flow by convection is the process heat transfer from one part of a fluid (gas or liquid) to another part at a lower temperature by mixing of fluid particles. Heat transfer by convection takes place at the surfaces of walls, floors and roofs. The heat flow by radiation is the process by which heat is transferred from a body by virtue of its temperature and increases as the body temperature increases. It does not require any material medium for propagation. For example, heat radiation in building elements are paint on wall surfaces, roof surface and emission from window, among others. The details of the three modes of heat transfer are as follows.

a) Heat conduction in building envelope

Heat conduction in building envelope calculation is governed by Fourier's law. Fourier law states that, the heat flux resulting from thermal conduction through a material is proportional to the negative gradient of temperature. Fourier's Law provides the definition of thermal conductivity and forms the basis of many methods of determining its value. Fourier Law can be written mathematically in one-dimensional form i.e. *x*-direction as

$$\dot{q_x} = -\lambda \frac{dT}{dx} \qquad \text{Eqn 3.1}$$

Where

$\dot{q}_x$ is the heat flux (W/m^2) in the positive x-direction.

dT/dx is the (negative) temperature gradient (K/m) in the direction of heat flow (i.e., conduction occurs in the direction of decreasing temperature and the minus sign confirms this thermodynamic axiom)

λ is the and the proportionality constant**,** thermal conductivity of the material (W/mK).

Conduction heat transfer through building can simply be written as

$$Q_{conduction} = U \ \ \Delta T \qquad \text{Eqn 3.2}$$

Where

Q= heat transfer rate in W

U= overall transmittance in W/(m^2•K)

ΔT = change in temperature in K

A= Area (m^2)

b) Convection

Convection heat transfer is also mainly governed by Fourier's law, except that it occurs in fluids.

$$Q_{convection} = hA(T_s - T_f) \qquad \text{Eqn 3.3}$$

Where

h = heat transfer coefficient (W/m^2-K)

Ts = temperature of the surface (K)

Tf = temperature of the fluid (K)

A= area (m^2)

The numerical value of the heat transfer coefficient depends on the nature of heat flow, velocity of the fluid, physical properties of the fluid, and the surface orientation.

c) Radiation

Radiation is governed by Stefan-Boltzmann law and it describes the rate of transfer of radiant energy for an object in a vacuum. The law states that the total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature. Mathematically, Stefan-Boltzmann law can be expressed as;

$$E = \varepsilon\sigma T_s^4 \, , 0 \leq \varepsilon \leq 1 \qquad \text{Eqn 3.4}$$

Where
E = Emissivity
ε = is a surface's ability to emit radiation
σ = is the Stefan-Boltzmann Constant ($\sigma = 5.6 \times 10^{-8} W/m^2K^4$)
T_s = is the absolute surface temperature in *K*

The building envelopes surfaces also absorb radiation. Incident radiation G, does not necessarily equal the rate of radiant energy absorptionG_{abs}. Absorption is limited by the absorptivity 'α', a property of the surface irradiation. Absorbed irradiation increases the matters' thermal energy; the unabsorbed portion is reflected; that is $G_{abs} = \alpha G \, , 0 \leq \alpha \leq 1$.

3.2.2 Moisture transfer

Moisture transfer in air conditioned building is the dominant contributing load to the overall cooling load in hot-humid climate (Solupe and Krati, 2014 and Survey questionnaires 2014).

Determination of moisture transfer in buildings are complicated Main sources of moisture in air conditioned buildings are occupants, diffusion through the building envelope elements, infiltration, ventilation and outdoor climate (Woods and Winkler, 2016).

a) Diffusion

Diffusion arises as a result of pressure difference across indoor and outdoor air through permeable building envelope elements. Methods for determining diffusion in building are experimental, theoretical calculations for example Fick's laws, modelling using 2-D cartesian and cylindrical Fourier equation, 3-D mesostructure, aggregate shapes (Bairi et al., 2007; Kurumisawa et al.,2012; Abyaneh et al.,2013; Liu et al.,2015; Bezerra et al., 2015).

Experimental methods of measurements are based on either steady or transient state conditions for example laser flash analysis, TCi Thermal Analyser, hot wire etc. Each experimental method offers major advantages in terms of accuracy as well as various levels of complexity in analysis (Kurumisawa et al., 2012; Laaroussi et al., 2014; Bezerra et al., 2015 and Bajja et al., 2016). Conversely, the overall effect of diffusivity in energy simulation of ESDL Tas was not adequate (Survey questionnaires, 2014).

b) Infiltration

Infiltration basically is uncontrolled inward air leakage to conditioned spaces through unintentional openings as a result of pressure difference Infiltration is also known as air leakage and it has significant impact on building energy utilization for cooling or heating to depending on the tightness of building envelope as well as heating ventilation and air conditioning system operation. Dominant sources of infiltration include cracks in building envelope, permeability of building fabric, leakages arising from (doors, windows, ducts, fan, vents, plumbing work, Wall or window-mounted air conditioners, installations etc.) (Lin and Chuah,2010; Sadineni et al., 2011; Hana et al.,2015; Ng et al., 2015; ANSI/ASHRAE,2016 and Chen et al., 2016).

The extent of infiltration be influenced by local climate conditions, predominantly wind conditions and microclimates surrounding the building. Air tight and sealing approaches are mainly use to control infiltrations in cooling or heating demand buildings. Infiltration can be determined experimentally, theoretically through the use of models, constant infiltration rates, air change rate method, straightforward empirical techniques and detailed multi-zone numerical methods, among others.

Theoretical models use internal airflows in the buildings for infiltration estimation. Major models use in calculating infiltration are simplified model, empirical infiltration models, Sherman -Grimsrud infiltration model, Alberta air infiltration model (AIM-2), AIRFLOW NETWORK model, contaminant transport model CONTAM, 3D lattice Boltzmann modelling among others (ASHRAE,1989; Qiu and Haghighat,2007; Wang et al., 2009; ASTM,2010; Hana et al., 2015; Brinks et al.,2015; and Ng et al., 2015).

Example of experimental measurements use by researchers to determine infiltration rate include: acoustic Building Infiltration Measurement System (ABIMS), Curtain blower method, tracer-dilution method and blower door test method (Dols and Persilyl,1995; Relandera et al., 2012; Wanga and Zhong,2014; Solupe and Krati,2014 and Hayati et al., 2014). Experiments are mainly conducted using standard test method for measuring rate of infiltration through building envelope under selected specified pressure differences across the specimen(ASTM E 283-04, 2012 and ASTM E283-04,2012). Detail of a sample model is presented below.

Sherman -Grimsrud infiltration model

Sherman infiltration model was developed by Lawrence Berkeley Laboratory includes stack and wind effect. The model considers the leakage areas at the leakage points as orifices at the building envelope. As a result, the infiltration rate due to different effects can be estimated using the effective leakage area across the orifice, expressed as ELA, multiplied by the specific infiltration velocity S, m/s, as shown in Eq.3.5

$$\dot{Q_{inf}} = EL \ . S \qquad \text{Eqn 3.5}$$

Where

$\dot{Q_{inf}}$ =rate of infiltration

ELA = effective leakage area

S = specific infiltration velocity

Specific infiltration velocity and effective leakage area are determined using equations

$$\overline{ELA} = \frac{1}{n}\sum_{i=1}^{n} ELA \quad \text{Eqn 3.6}$$

$$S = (f_w^2 v^2 + f_s^2 |\Delta T|)^{1/2} \quad \text{Eqn 3.7}$$

Where V=surface velocity at the envelope

ΔT= temperature difference for outdoor and indoor

f_s = stack effect

f_w = coefficient of wind effect

$\overline{ELA}$= Average effective leakage area

Details of this model can be find in (Sherman, 1987 and Lin and Chuah, 2010).

c) Ventilation

Ventilation is the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity or temperature within the space (ANSI/ASHRAE, 2016). Major methods of ventilation in buildings are natural, mechanical and mixed mode. Natural ventilation occurs without any mechanical means but it's driven by climatic forces of wind (wind effect) and temperature (stack effect) through window or ventilation panel (CIBSE Guide A).

Mechanical ventilation is controlled by mechanically powdered equipment such as motor-driven fans and blowers (CIBSE Guide A). Mixed mode ventilation uses both natural and mechanical ventilation technology. Mixed mode ventilation offers considerable reduction of load arising from ventilation gain when compared completely mechanical systems (CIBSE Guide A).

Ventilation gain can be determined using standard formulae, models and experiment (CIBSE Guide A; Ai and Mark, 2014; Lai et al., 2015 and Tominaga and Blocken, 2015).

The heat flow rate due to ventilation of air between the interior of a building and outside depends on the air exchange. It is given by:

$$Q_V = \rho_{V_r} C \Delta T \quad \text{Eqn 3.8}$$

Where

ρ = density of air (kg/m^3)

V_r= ventilation rate (m^3/s)

C= specific heat of air (J/kg.K)

ΔT = temperature difference (To-Ti) (K)

However, if the number of air changes is known then,

$$V_r = \rho C \frac{NV}{3600} \Delta T \qquad \text{Eqn 3.9}$$

Where

N=number of air changes per hour

V=volume of room space (m^3)

p=density (kg/m^3)

C= Specific heat of air (J/kg.K)

3.2.3 Comparison of Cooling Load Calculation Method

Cooling load is the rate at which heat is removed from conditioned space to maintain a constant air temperature and relative humidity. Cooling load methods uses several components which utilizes heat in addition to moisture transfer equations for its calculations and forms the basis of designing service equipment (Rees et al., 2000; Gang et al., 2015 and Ward et al., 2016).

It's generally known that the predicted cooling load calculation will normally deviate from the actual load as a result of uncertainties. Some of the uncertainties in predictions include occupants' behaviour, outdoor weather variations, changes in heat gain data, method use, among others. Accurate prediction of cooling load calculation offers several benefits. Among them are, right HVAC sizing, costs, operating energy efficiency, occupant comfort, indoor air quality, emissions etc (Spitler, 2014; Kwok et al., 2011; Adil and Yumrutas,2015 and CIBSE Guide A). Representative cooling load calculation methods include: i. rule of thumb sizing (simple calculation)

ii. Manufacturers sheet/forms iii. Total Equivalent Temperature Difference/Time Average (TETD/TA), iv. Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) v. Transfer Function Method (TFM). vi Heat Balance (HB) vii. Radiant Time Series (RTS) viii. Admittance method ix. Steady-state periodic admittance method x. Cyclic dynamic model (CIBSE Guide A; Uba et al., 2013; Duanmu et al., 2013; Zainal and Yumrutas, 2015; and Ozel, 2016).

These different methods yield different results for the same input data (Rees et al., 2000 and Feng et al., 2013). This is primarily due to the way; each method handles the solar effect and building dynamics. Brief description of the various representative cooling calculations is as below.

i. Rule of thumb sizing

Rule-of-thumb method is a simple and mostly use for initial system design calculation. However, the accuracy level of this calculation method is low.
Rule-of-thumb method has advantage of producing a quick load calculation to assist designers to define mechanical spaces and cost modelling particularly in the phase of design-build competitions

ii. Manufacturers sheet/forms

Typical manufacturers sheet/forms consist of sections which requires user inputs with a resulting summation to form the overall output load. Some of the sections include conductive heat through the building elements and corresponding load factor, light and equipment, infiltration and ventilation and number of occupants and the corresponding load factor. The load of each section is calculated and finally summed to obtain the total cooling load (Uba et al., 2013).

iii. Total Equivalent Temperature Difference/Time Average (TETD/TA)

Total Equivalent Temperature Differential (TETD) simply multiplies u-values of various components by the equivalent temperature differentials to obtain the conduction gains. The sum of conduction gains is added to internal heat gain elements to obtain an instantaneous total rate of space heat gain. This space heat gain is converted to an instantaneous total cooling loads by the time averaging method (TA). Time averaging method (TA) averages the radiation portion of the heat gain load components for the current hour, with respect to the values from an appropriated period of immediately preceding hours. Conversely, various ad hoc corrections are needed to be made for conditions that varied from those under which the tabulated data had been calculated. For example, Conduction gains (Walls, Roofs and doors) by eqn 3.10

$$Q = U \times A \times TETD \qquad \text{Eqn 3.10}$$

Where TETD is the Total Equivalent Temperature Differential, which accounts for temperature difference, mass, colour and solar gain.
A= Area (m^3)
U=Overall transmittance in W/(m^2•K)

iv. Cooling Load Temperature Difference/ solar cooling load factor/Cooling Load Factor (CLTD/SCL/CLF)

The CLTD/CLF/SCL method applies predetermined set of data tables resulting from transfer function method in calculating cooling load. The data tables are categorized into different sections based on several different variables. Among the variables are, building fabric, building fabric thicknesses, day of the year, latitude time of day, orientation of the surface, etc. The main limitation of this method is the use of predetermined tabulated data and approximations resulting from extrapolations. The details of the individual methods are as below.

Cooling load temperature difference (CLTD) is a theoretical temperature difference that accounts for the combined effects of inside and outside air temperature difference.

CLTD factors are applied to building elements like roof, wall, floor etc. to adjust the conduction heat gains. The calculation of individual building element is based on eqn 3.11:

$$\dot{q}_t(t) = UA\ CLTD \qquad \text{Eqn 3.11}$$

Where

CLTD= Cooling load temperature difference, which is calculated as a function of time.

A= Area (m^3)

U=Overall transmittance in W/(m^2•K)

solar cooling load factor (SCL) are used to adjust transmission heat gains from glass in the building envelope.

Solar load through glass is calculated using,

$$q = A(SC)(SCL) \qquad \text{Eqn 3.12}$$

Where

A= area

SC= shading coefficient

SCL= solar cooling load factor

Cooling Load Factors (CLF) accounts for the fact that all the radiant energy that enters the conditioned space at a particular time and does not become part of the cooling load instantly. The CLF values for various surfaces have been calculated as functions of solar time, orientation and are available in the forms of tables in ASHRAE Handbooks. CLF factors are used for adjusting heat gains from internal loads, for example lights, occupancy, power appliances and others (Rees. et al., 2000).

For example, internal heat gain of appliances are calculated as

$$q_{sensible} = q_{input} \times usag \quad factors\ (CLF) \qquad \text{Eqn 3.13}$$

$$q_{latent} = q_{input} \times load\ factor\ (CLF)$$ Eqn 3.14

v. Transfer Function Method (TFM).

Transfer Function Method (TFM) is a complex method proposed by ASHRAE and requires the derivative of the Heat Balance Method. The Heat Balance equations are used to derive Transfer Function coefficients (heat gain and cooling load), and the coefficients are used repeatedly to calculate load. The calculation requires the use of a computer program or advanced spreadsheet (Rees. et al., 2000).

vi. Heat Balance (HB)

Heat Balance method is one of the utmost accurate calculation methods. On the other hand, it involves complex iterative calculations process which solves a set of simultaneous equations. The calculation of cooling load for a space comprises of calculating a surface-by-surface conductive, convective and radiative heat balance for each room as well as convective heat balance for the room air. Hourly step zone heat balance equations are needed to be assembled and solved via suitable computer program (Rees. et al., 2000).

vii. Radiant Time Series (RTS)

Radiant Time Series (RTS) method is a simplified method related to and derived from Heat Balance (HB) method (Spitler et al., 1997). It takes advantage of 24-hour periodic response factors of the wall/roof to compute the conductive heat gain and periodic radiant time factors to convert the instantaneous heat gain to simple cooling load calculation procedure. Radiant Time Series Method is suitable for spreadsheet implementation, in view of this iteration loops are avoided.

Conversely, the RTS method is based on continuous operation of the air-conditioning system because all the design information provided for cooling load calculations is under the condition of constant space air temperature.

Hence, it is unable to give the accurate design cooling load in intermittent operation where the air-conditioning system is usually not working during night.

If the heat gains of the building exceed the heat loss at the off-work hours, the room air temperature will increase, which will result in heat storage in the building envelope and furniture.

The RTS Method uses the same approximations as the heat balance procedure, but effect of the radiative portion of the heat gain on the cooling load is estimated with the radiant time series, rather than the surface heat balances (Rees. et al., 2000).

The RTS is a simplified method derived from heat balance (HB) method and effectively replaces all other simplified (non-heat balanced) methods (Rees et al.,2000).

viii. CIBSE Admittance method

CIBSE admittance method uses idealised (sinusoidal) weather and thermal response factors (admittance, decrement factor and surface factor) that are based on a 24-hour frequency. The admittance procedure for cooling load calculation recognises that a person's feeling of thermal comfort depends on the heat exchanges between the body of a person to the indoor environment by convective heat loss to the indoor air and by radiant heat loss to the indoor environment.

The application creates the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is calculated simultaneously to generate air temperatures, surface temperatures and room loads. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation exchange is modelled using the Stefan-Boltzmann law. Long-wave radiation from the sky and the ground is treated using empirical relationships (EDSL Tas, 2007).

Although the Admittance Method uses heat balance equations to find the load components, the main component of the conduction gains can be pre-calculated for each hour. This is because these gains are calculated based on an analytical solution to sinusoidal excited conduction heat flow.

ix. Cyclic dynamic model

Cyclic models are only suitable for applications that require an assessment of conditions after a long period of identical periods. For example, the calculation of design sensible cooling load, hence best suited for space cooling. Cyclic models can also be used for assessment of peak summertime temperatures and preheat requirement. Cyclic model analysis is based on the assumption of using a sequence of identical days for the external weather conditions which vary on a 24-hour repeated period. A typical example is CIBSE admittance method. Cyclic models are only suitable for applications that require an assessment of conditions after a long identical period. For example, the calculation of design sensible cooling load, hence best suited for space cooling. Cyclic models can also be used for assessment of: Peak summertime temperatures and Preheat requirement

Limitations of Cyclic model

1. Cyclic model is simple model hence its application must be treated with caution
2. Cyclic model analysis predicts a limit state, which under some circumstances may never be reached. For example, for unoccupied weekends and holidays, the predicted peak may not occur since the model cannot predict this type of event hence the actual benefit of mass cannot be assessed.
3. The cooling load may be overestimated as a result of high proportions of convective gain.

In conclusion According to CIBSE Guide A, radiant time series (RTS) method is a simplification of heat balance method. Heat balance and radiant time series methods are established on the basics of building physics and are refer to as the most reliable means of estimating cooling loads. Conversely, these two methods do not undermine the validity of earlier ASHRAE methods such as the transfer function method (TFM) and total equivalent temperature differential method with time averaging (TETD/TA) when used correctly. CIBSE admittance method is similar to cyclic dynamic method.

Due to the fact that, the simulation results would be compared to CIBSE guide A and B, it is expedient to use a similar software which uses CIBSE admittance method for cooling load calculation, hence the use of EDSL Tas.

3.3 Evaluation of representative Whole Building Simulation Software

Several building simulation software is available commercially and in literature. Notable among them include ESDL TAS, EnergyPlus, Trnsys, Ecotect, ESP-r, DOE-2, e-QUEST, Opt-E-Plus, BEopt and many more. As indicated in the research problem, average of 14% undertakes performance assessment using ESDL TAS, EnergyPlus and TRNSYS software in Ghana. The characteristic building simulation software considered in this research, is in consistent with the research tool used for assessment in Ghana by (Koranteng et al., 2009 and Amos-Abanyie 2013). In view of this, the detail evaluation was based on ESDL TAS, EnergyPlus and TRNSYS.

Table 3.1: Summary of evaluated building simulation software

Software	Adequacy	Accuracy	Output results	Optimization	Availability
ESDL TAS	1.Limited user integration files 2. life cycle assessment 3.Limited weather data	1.Cyclic Admittance calculation method 2.Complaince and standards assessment	1.3D Model 2. Thermal comfort 3. Heating 4. Cooling 5.Ventilation 6.Lighting 7.Equipment 8.CO_2 emissions	No	Commercially and at University of Nottingham
TRNSYS	1.Unlimited user integration files 2. Unlimited weather data 3. Life cycle cost analysis Tool	1.Heat Balance and Transfer Function Method 2.	1.HVAC analysis 2. Equipment 3.Thermal performance 4. Assessment control 5.Renewable and emerging technologies 6.Sizing 7. Building envelope model 8.Daylighting controls	Yes	Commercially and not at University of Nottingham
EnergyPlus	1.No life cycle cost analysis tool 2. Unlimited user	1.Heat Balance Calculation method	1.Heating 2.Cooling 3.Ventilation 4.Lighting 5.Plug load	No	Commercially and at University of Nottingham

	integration files 3.Building envelope modelling is carried out in a different software 4.Unlimited weather data	2.Complaine and standards assessment	6.Atmospheric pollution calculations 7.Daylighting controls 8.		

Source: (ESDL Tas, 2007; TRNSYS, 2000 and EnergyPlus,2000)

3.3.1 ESDL Tas

Tas building performance software was developed by Environmental Design Solution Limited to perform hourly computation of cooling load on buildings using cyclic dynamic admittance cooling load calculation method. Tas building simulation software uses dynamic building simulation package with 3D modeller, building simulator and result viewer. Tas accurately predicts key features of building performance.

Tas application creates the sensible heat balance for a zone by setting up equations representing the individual energy balances for air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is calculated simultaneously to generate air temperatures, surface temperatures and room loads. Conduction in the fabric of the building is treated dynamically, using two methods for the analysis of wall heat flows. For state-representation, finite difference methods are applied whereas conductive heat flows at the surfaces of walls and other building elements are calculated with a response factor method. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation ex-change is modelled using the Stefan-Boltzmann law. Long-wave radiation from the sky and the ground is treated using empirical relationships (EDSL 2007).

The main module is Tas Building Designer, which performs dynamic building simulation with integrated natural and forced airflow. It has a 3D graphics-based geometry input that includes a CAD link. Tas System has HVAC systems/controls simulator, which may be directly coupled with the building simulator. It performs automatic airflow and plant sizing and total energy demand. Tas Ambien's, is a robust and simple to use 2D CFD package which produces a cross section of micro climate variation in a space. Tas combines dynamic thermal simulation of the building structure with natural ventilation calculations, which include advanced control functions on aperture opening and the ability to simulate complex mixed mode systems. The software has heating and cooling plant sizing procedures, which include optimum start. Tas has about 20 years of commercial use in the UK and around the world.

Tas main output application include thermal performance, environmental performance, prediction of energy utilization (cooling, light, equipment), plant sizing, energy conservation and energy rating target.

3.3.2 TRNSYS Software

TRNSYS is a transient system simulation program with a modular structure which implements a component-based simulation approach. Components may be simple systems like pumps or fans, or complex systems such as multi-zone buildings.

TRNSYS components (referred to as ''Types'') may be as simple as a pump or pipe, or as complex as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, while building input data is entered through a dedicated visual interface (TRNBuild). The simulation engine then solves the system of algebraic and differential equations that represent the whole energy system using heat balance calculation methood. In building simulations, all HVAC-system components are solved simultaneously with the building envelope thermal balance and the air network at each time step. In addition to a detailed multizone building model, theTRNSYS library includes components for solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, etc.

The modular nature of TRNSYS facilitates the addition of new mathematical models to the program. New components can be developed in any programming language and modules implemented using other software (e.g. Matlab/Simulink, Excel/VBA, and EES) can also be directly embedded in a simulation. TRNSYS can generate redistributable applications that allow non-expert users to run simulations and parametric studies.

3.3.3 EnergyPlus Software

EnergyPlus is an advanced whole building energy simulation tool, developed on the basis of work carried out on DOE-2.1E. It incorporates the same functionality as DOE-2, producing hourly (or sub-hourly) energy costs of a building given system input information. It also incorporates many advanced features not available in DOE-2, such as multi-zone airflow and extensive HVAC specification capabilities. EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.

Some EnergyPlus building energy simulation program outcome include modelling building heating, cooling, lighting, ventilation, plant sizing, occupant comfort and occupant health among other energy flows. EnergyPlus uses heat balance method for conduction transfers and radiant time series method for convection transfers. It is a simulation engine with input and output of text files. Loads calculated by a heat balance engine at a user-specified time step.

The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response.

Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

Some of the notable features and capabilities of EnergyPlus include:

- **Integrated, simultaneous solution** of thermal zone conditions and HVAC system response that does not assume that the HVAC system can meet zone loads and can simulate unconditioned and under-conditioned spaces.

- **Heat balance-based solution** of radiant and convective effects that produce surface temperatures, thermal comfort, and condensation calculations.
- **Sub-hourly, user-definable time steps** for interaction between thermal zones and the environment, with automatically varied time steps for interactions between thermal zones and HVAC systems. These allow EnergyPlus to model systems with fast dynamics while also trading off simulation speed for precision.
- **Combined heat and mass transfer** model that accounts for air movement between zones.
- **Advanced fenestration models** including controllable window blinds, electrochromic glazings, and layer-by-layer heat balances that calculate solar energy absorbed by window panes.
- **Illuminance and glare calculations** for reporting visual comfort and driving lighting controls.
- **Component-based HVAC** that supports both standard and novel system configurations.
- **A large number of built-in HVAC and lighting control strategies** and an extensible runtime scripting system for user-defined control.
- **Functional Mockup Interface** import and export for co-simulation with other engines.
- **Standard summary and detailed output reports** as well as user definable reports with selectable time-resolution from annual to sub-hourly, all with energy source multipliers.

4 CHAPTER FOUR: SELECTED TECHNOLOGIES USED IN BUILDINGS

4.1 Introduction

There are significant technologies used in buildings for enhanced building performance in scientific and technical journal as enumerated in Chapter 2. From scientific and technical journals, typical Investment costs for installing efficient technology for improvement of building performance remains a major obstacle to professionals (Tan et al., 2016; Cuce and Riffat 2015 and Hameer and Niekerk,2015). Representative total cost of technologies integrated into buildings depends mainly on the countries subsidy policies/regulations, cost of the technology, installation cost, operating cost, capacity, efficiency, maintenance, among others. For example; McLarty et al. (2016) and McLarty et al. (2016) research concluded that fuel cells are economically viable alternative in California, New York and Connecticut at installed costs of $7000–10,000/kW. From Andreadis et al. (2013), total budget for a 9.6MWp PV installations could cost round Euros 14,680,800. Again, Cucchiella et al. (2012) indicated that installation of PV of 16.5 MWh/y capacity has an initial cost of 98,675 Euros. Though there are several building technologies as stated above, the research critically reviewed low energy building technology.

Low energy building technologies uses a combination of passive and active technologies to improve building performance at a reduced associated greenhouse gas emission. Representative low energy building technologies consist of insulation, energy efficient windows, low levels of air infiltration, heat recovery ventilation, energy recovery, bioclimatic, sustainable, night ventilation, among others (Persson and Gronkvist,2015; Salvalai et al., 2013 and Risberg et al., 2015).

Selected main benefits for integrated low energy building technologies include:

- Minimizes greenhouse gas emissions.

- Offers better psychological occupant comfortable through proper use of daylight than conventional artificial light, thereby increasing productivity in certain climates.
- Improved operational energy use
- Economic benefits through reduced energy bills.

4.2 Related Research Gaps on Technologies use in Ghana Buildings from developed mixed research methods

The identified research gaps from developed mixed research methods obtained from representative building professionals in Ghana include:

1. Insignificant technology is integrated in buildings.

2. Several building professionals in Ghana indicated high cost remains a barrier in integrating technologies into buildings.

3. Dehumidifying load is the dominant contributing load to total cooling load and represents about 60%.

4. Building envelope elements especially the window panes and cement-based elements have high u-values due to the building designs as well as practices in Ghana.

In conclusion, based on the identified gaps from developed mixed research methods, cost effective low energy cooling technologies solutions for minimizing heat gains and dehumidifying load are reviewed.

4.2.1 Rationale for low energy cooling technologies

Rationale for selecting low energy cooling technologies being:

1. Cost effectiveness
2. High potential to minimize dominate dehumidifying load

3. Minimization of heat gain used in the building fabric

4.3 Selected Low Energy Cooling Technologies

The representative low energy cooling technologies include:
Passive cooling design technologies for example, evaporative cooling, radiative cooling, slab cooling, evaporative cooling, night ventilation, earth to air heat exchangers, Groundwater/sea/river/lake water cooling, cooling towers, minimization of heat gain, shading, control of infiltration and ventilation, daylighting, among others
Delivery systems to maximise potential of low energy cooling for example, water cooled slabs, chilled beams and chilled ceilings and displacement ventilation, etcetera.

Desiccant cooling technology includes solid-desiccant wheel dehumidifier and liquid-desiccant dehumidifier system.

Several low cooling energy technologies have been listed as above with significant potential to improve dehumidifying load and heat gain. This research focused on passive cooling design technologies and Delivery systems to maximise potential of low energy cooling. Under passive cooling design technologies, minimization of heat gain as well as control of infiltration and ventilation were considered whiles chilled beam/ceiling was selected for Delivery systems to maximise potential of low energy cooling considered. The main selections were based on the following:

a. Rationale stated in section 4.1. 1.
b. Availability of the technology toolbox in the selected simulation software.
c. Survey questionnaires (2014) indicated that, shading both internal and external technologies are extensively use in Ghana.
d. Air sealing technology has the potential of reducing electricity for cooling/heating by 20% to 30% (IEA, 2013).

4.3.1 Minimization of heat gain

Cooling load calculation methods uses heat gain and heat losses within the building envelope extensively, hence integrating technologies to minimize heat gain is important. Minimization of the heat gain was categorized into transparent and opaque building fabrics. From the survey questionnaires (2014), transparent building fabrics were used basically for all the fenestration elements in the building envelope amounting to 30-50% of the whole building envelope i.e. window-to-wall ratio. Whiles the opaque building fabrics were used for the remaining building envelope elements. In Ghana, the transparent building fabrics that is, the window panes are mainly imported whiles the opaque building fabrics that is the cement-based as well as wooden fabrics are dominantly manufactured in the country. As indicated in Survey questionnaires, the main window technology use in Ghana is double glazing. From the computer simulations carried on earlier with Ghana case study, shows that the various types of double glazing technologies considered reduced the solar gain load contribution to the overall cooling load by about 8%. In contrast to the reviewed window panes in Chapter 2, there is more improved technologies available in literature other than double glazing.

As stated by Survey questionnaires (2014) the experimental results of cement-based building fabric from Ghana show that, thermal conductivity of majority of mortar and concrete blocks are within the range of 0.21-0.36 W/mK and 0.3-0.7 W/mK respectively. These experimental thermal conductivities are within the range of the recommended CIBSE Guide A. Conversely, the thermal conductivities are outside the range of the proposed thermal conductivities of Survey questionnaires, 2014) in achieving the u-value of 0.3 W/m^2K as stated in Ghana building regulation. From the identified gaps on opaque cement-based building fabric, typical technologies incorporated to lower thermal conductivity were reviewed. Among the characteristic technologies are additives (admixtures), aerated autoclaved, cellular, lightweight, reinforce concrete example, fibre-reinforced, polymer composites among others. Brief descriptions of window pane technologies are outlined in 4.2.11.

4.3.2 Window Pane Technologies

Window pane technologies were categorized into static and dynamic technology. Static glazing technologies have fixed thermal and optical properties whiles dynamic technology offers additional advanced glazing properties on both interchangeable thermal and optical abilities. Selection of a window technology is mainly based on thermal and optical properties capabilities for example solar transmittance, solar reflectance, visible transmittance, u-value, shading constants and solar heat gain coefficient. Representative commercially available static and dynamic window technology comprise of: highly insulated window, smart windows, glazing types, gas fill, low-emissivity (low-e) coatings, solar heat gain control films, among others. Description of the various window technologies are outlined below.

- **Glazing Types Technology**

Typical glazing types used in buildings include: single, double, triple and multiple glazing types. Description of glazing types are below.

i. Single glazing

Clear single glazing is the simplest glazing type. Clear single glazing has the highest visible transmittance with large thermal gain or losses leading to higher cooling energy. On other hand, clear single glazing panes offers a better visual comfort leading to enhanced psychological comfort subsequently high productivity. Conversely, the properties of clear single glazing window can be modified using tints and low-emission coating to enhance both thermal and optical transmission through the panes (Kiss and Neij,2011; Torok,2014; Haglund,2015 and Arici et al., 2015). Figure 4.1a and 4.1b shows a representative clear single pane window and Heat as well as light transmission through single glazing pane respectively. Table 4.0 is an outline of classical thermal and optimal properties of various glazing types as the enhanced properties.

ii. Double glazing

Double glazing has two panes. Clear double glazing pane have enhanced thermal and optical properties over single glazing pane technology. Although U-factor is reduced significantly, the VT and SHGC for a double-glazed unit with clear glass remain relatively high.

Conversely, enhanced double glazing pane with technologies like tint, low-emittance coating, gas fill, among others have better thermal and optical properties than an enhanced single glazing pane. Depending on the technology used for the enhancement, visual comfort is compromised and additional artificial lighting may be required (Ismail et al.,2009; Kiss and Neij,2011; Torok,2014; Haglund,2015 and Arici et al., 2015). Figure 4.1a shows a representative clear double pane window. Table 4.0 is an outline of classical thermal and optimal properties of various glazing types as the enhanced properties.

iii. Triple glazing

Triple glazing has three panes as seen in Figure 4.1a. Clear triple glazing window pane have better thermal and optimal properties compared to double glazing and single pane. Glazing performance can be altered using tints, gas fill, low-emissivity coatings, different colours, among others (Torok,2014; Arici et al.,2015 and Haglund,2015). Figure 4.1a shows a representative clear triple pane window. Table 4.1 is an outline of classical thermal and optimal properties of various glazing types as the enhanced properties.

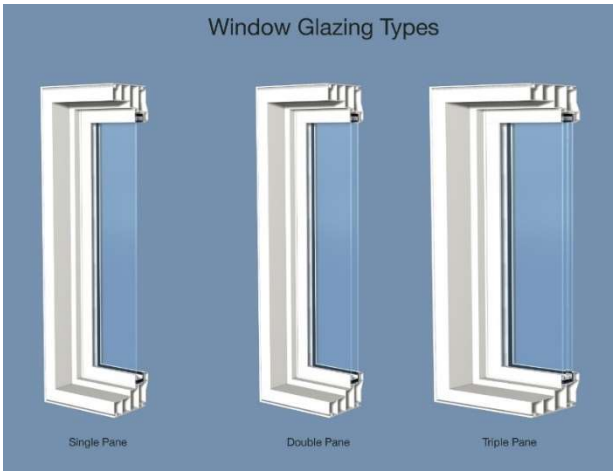

Figure 4.1a: Representative glazing type window
Source: (Torok, 2014)

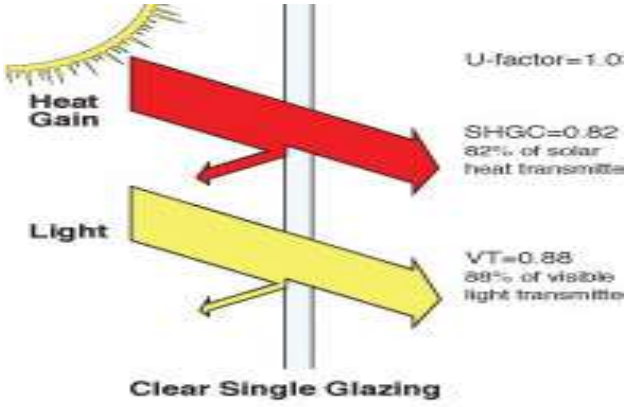

Figure 4.1b: Heat and light transmission through single glazing pane.
Source: (Haglund, 2015)

Table 4.1: Classical thermal and optimal properties of various glazing types as the enhanced properties.

		Visible		Solar					Thermal U-value ($WK^{-1}m^{-2}$)	
No	Type of glazing	T_{vis}	R_{vis}	T_{sol}	R_{sol}	A_{sol}	g-value (SHGC)	SC	Air filled	Gas filled
	Single Glazing									
1	Clear, 6 mm thick	88	8	79	7	14	0.82	0.95	5.7	
2	Tinted, 6 mm thick	50	5	47	5	48	0.60	0.68	5.7	
3	Reflective	31	42	24	47	29	0.38	0.44	5.6	
4	TI Low-e 6 mm thick, indoors	67	25	58	19	23	0.62	0.71	3.8	
5	TI Low-e, 10 mm thick, indoors	65	24	53	17	30	0.58	0.66	3.7	
6	Self-cleaning, 6 mm thick	83	14	79	13	8	0.81	0.93	5.9	
	Double glazing (all panes 6-mm thick)									
	OUTDOORS | INDOORS									
7	Clear | Clear	79	14	64	12	24	0.72	0.82	2.9	2.8
8	Tinted | Clear	44	7	38	7	55	0.48	0.55	2.7	2.6
9	Reflective | Clear	49	39	28	43	29	0.31	0.36	2.7	2.6
10	TI Low-e | Clear	73	17	55	15	30	0.69	0.79	1.7	1.5
11	SC Low-e | Clear	70	10	38	28	34	0.43	0.49	1.4	1.1
12	Self-cleaning/SC Low-e | Clear	67	16	36	32	32	0.40	0.46	1.4	1.1
13	Tinted SC Low-e | Clear	49	39	28	42	30	0.31	0.36	1.4	1.3
14	SC Low-e | TI Low-e	53	22	29	34	37	0.34	0.40	1.3	1.1
15	TI Low-e | TI Low-e	56	31	42	23	35	0.53	0.60	1.5	1.3
	Triple glazing (all panes 6 mm thick)									
16	Clear | Clear | Clear	70	19	52	15	33	0.63	0.73	1.8	1.7
17	TI Low-e | Clear | Clear	55	32	39	24	37	0.50	0.57	1.3	1.2
18	SC Low-e | Clear | Clear	62	14	33	29	38	0.39	0.45	1.0	0.9
19	Self-cleaning/SC Low-e | Clear | TI Low-e	54	20	28	35	37	0.35	0.40	0.8	0.7
	Quadruple glazing (all panes 6 mm thick)									
20	Clear | Clear | Clear | Clear	63	23	43	17	40	0.57	0.65	1.3	1.2
21	TI Low-e | Clear | Clear | Clear	50	35	33	25	42	0.45	0.52	1.0	0.9
22	SC Low-e | Clear | Clear | Clear	56	17	28	31	41	0.36	0.45	0.9	0.7
23	SC Low-e | Clear | Clear | TI Low-e	52	18	26	31	43	0.34	0.39	0.7	0.6

Source: (G. Leftheriotis and P. Yianoulis, 2012)

Where > SC= Solar control technology, TI = Thermal Insulation technology and (I) =Gaps between window pane arrangement.

Below is a brief description of the technologies used to enhancing the glazing types.

- Tints

Glass is available in many tints which absorb a portion of the solar heat and block daylight. Tints changes the colour of the window and can increase visual privacy. The

main uses for tinted glass are reducing glare from the bright outdoors and minimizing the amount of solar energy transmitted through the glass.

Tinted glazing retains their transparency from the inside, although the brightness of the outward view is reduced and the colour is changed. The most common colours are neutral grey, bronze, and blue-green etc. Traditional tinted glazing, bronze and grey, often force a trade-off between visible light and solar gain. There is a greater reduction in visible transmittance than in solar heat gain coefficient (see figure to the right). This can decrease glare by reducing the apparent brightness of the glass surface, but it also diminishes the amount of daylight entering the room. For windows where daylighting is desirable, it may be more satisfactory to use a high-performance tint or coating along with other means of controlling glare. On the contrary, at night the effect is reversed and it is more difficult to see outdoors from the inside, especially if the tint is combined with a reflective coating.

- **Low-emission (low-e) coating**

Low-e coating is an extremely thin, nearly invisible film of metal or metal oxide layers deposited on a window or skylight. Low-e coatings are classified into hard and soft coating.

The hard low-e coating is thin oxide based with low solar transmittance and higher infrared reflectance.

Soft low-e coating is thin silver, zinc or vacuum layer based with lower solar transmittance and higher infrared reflectance compared to hard thin oxide-based coatings. The glass enters a vacuum chamber filled with an inert gas which is electrically charged. The electricity combined with the vacuum allows molecules of metal to sputter onto the glass. The coating is fairly delicate or "soft" (Hammarberg and Roos, 2003 and P.P.G,2016).

Benefits of low-e coatings include:

i. Low-emission coatings applied to window glass reduce inside heat loss without reducing outside solar gain.
ii. Low-e coatings offer significant improvement on overall performance of a window relating to heating, lighting, cooling and is cost effective.

iii. Low-emittance coating mainly minimize u-value, amount of ultra-violet and infrared light transmission through glass without compromising the amount of visible light.

- **Gas Fill Technology**

Gas fill technology are typically integrated in double, triple or multi glazing windows. The typically gases use are argon, krypton and others. These gases are filled and sealed in the air spaces between the layers of glass. The gas is viscous and allows less convection than ordinary air. Filling the space with denser gases reduces both heat loss and heat gain significantly (Ismail et al., 2009 and Kiss and Neij,2011) Figure 4.2 shows double glazing window with an indicating gas filling

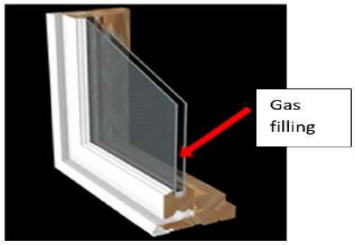

Figure 4.2: Double glazing window with an indicating gas filling
Source: (EWC, 2016)

Benefits of gas fill technology include:

1. Less expensive and efficient window technology
2. Improve thermal performance of insulating glazing units by reducing the conductance of the air space between the layers

In conclusion, glazing type window panes are:

1. Increasing of the clear window pane numbers reduces the u-values for both air filled and gas filled.
2. The enhanced glazing window panes with solar and low-emission technologies minimizes a u-values significant.

3. Adding a low-e to a surface of the double-pane unit will increase the energy performance. Depending on the type of Low-E coating, the SHGC and VT will also be affected. Adding a gas fill between the layers of glass will also improve energy performance
4. Adding a gas fill between the layers of glass will also improve energy performance.
5. Every change in colon or combination of different glass types affects visible transmittance, solar heat gains coefficient and reflectivity.

- Switchable glazing (smart) windows technologies

Switchable glazing incorporates technologies that control the amount of light, glare, and heat transmitted through the glass while providing a high level of insulation. Switchable glazing is also referred to as ‘‘smart window’’. Switchable glazing technologies have chromogenic materials in the glazing. Chromogenic phenomenon is when material changes its reflectivity and absorptivity. The main categories of switchable glazing include electrochromic (EC), liquid crystal, suspended particle, gasochromic, thermochromic, photochromic (Papaefthimiou et al., 2009; Asdrubali and Baldinelli, 2009; Jelle,2013; Hoffmann et al., 2014; Cuce and Riffat,2015 and Piccolo and Francesca,2015).

Benefits of Smart windows:

i. Improves building energy performance that is, by increasing heat gain in cold weather and decreasing it in hot weather by adopting windows radiative and thermal properties dynamically.
ii. Switchable glazing enables the user to change the optical or thermal properties of sealed glazed units.
iii. Switchable glazing can change the light transmittance, transparency, or shading of windows in response to an environmental signal such as sunlight, temperature or an electrical control.

Details of the various smart windows are described below.

- **Electrochromic windows**

Electrochromic coatings are multilayer thin films that are controlled via a low voltage signal. Electrochromic window normally consists of an electrochromic (EC) material or coating, an ionic conductor (IC) and a counter electrode (CE) interposed between two glass panes each with a transparent conductor (TC) as represented Figure 4.3. By applying a voltage over the two transparent conductors, ions will go through the ionic conductor between the electrochromic coating, counter electrode, and thereby change the colour of the electrochromic layer. The counter electrode acts as an ion storage, supplying the necessary ions for the electrochromic reaction, which, via the ionic conductor, are injected into or withdrawn from the electrochromic layer depending on the polarity of the applied voltage. The counter electrode may also have electrochromic properties complementary to the electrochromic coating, thus enhancing the colour changes (Hong and Selkowitz,2010; Hughes et al., 2011; Fernandes et al., 2013; Piccolo and Francesca,2015 and Haglund, 2015).

Typical EC windows have an upper visible transmittance (VT)range of 0.50–0.70 and a lower range of 0.02–0.25. The Solar Heat Gain coefficient (SHGC) ranges from 0.10–0.50. A low transmission is desirable for privacy during the day for control of direct sun and glare, potentially eliminating the need for interior shading. A high transmission is desirable for admitting daylight, during the time of the day that the sun is not shining directly into the space, during overcast periods and for passive solar heating in winter.

The most promising switchable window technology today is electrochromic (EC) windows. The electrochromic thin film stack is deposited on a glass substrate and is typically about one micron thick. The stack consists of ceramic metal oxide coatings with three electrochromic layers sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film through the ion conductor (electrolyte) and into the electrochromic film. The effect is that the glazing switches between a clear and transparent blue-grey tinted state with no degradation in view, similar in appearance to photochromic sunglasses.

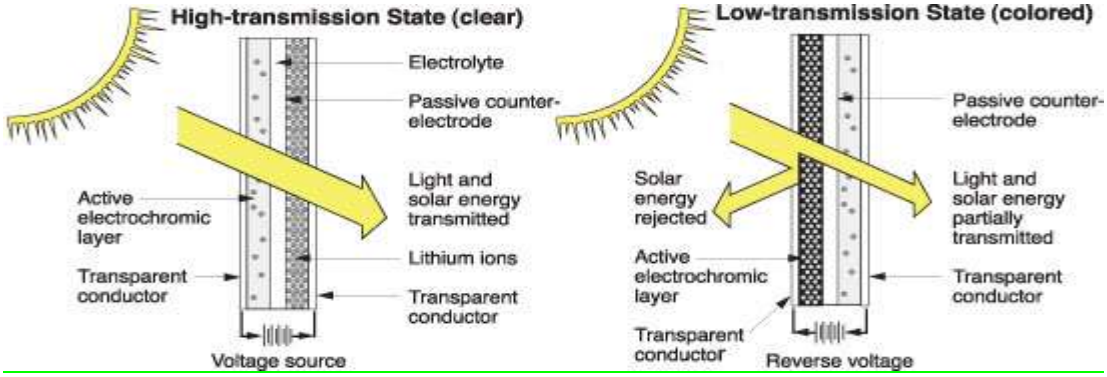

Figure 4.3: Schematic diagram of a five-layer electrochromic coating

Source: (Haglund, 2015)

A reversible low-voltage source moves ions back and forth between an active electrochromic layer and a passive counter electrode. When the lithium ions migrate into the active electrochromic layer, an electrochemical reaction causes that layer to darken. When the voltage is reversed and the ions are removed, the electrochromic layer returns to its clear state.

Benefits of Electrochromic Switchable Window Technology

i. Significant energy savings potential from cooling and lighting with improve glare without daylight compromise.
ii. Heat gain modulation with improved shading
iii. Typically requires low-voltage power (0–10 volts DC)
iv. Remains transparent across the switching range, and can be controlled to intermediate states between clear and fully coloured.
v. Small voltage is required for switching

❖ Gasochromic

Gasochromic windows is similar to electrochromic windows but it colour's the window and change transmission. Gasochromic windows consist of a thin layer (less than one-micron tick) of tungsten oxide (WO_3) covered by thin layer of platinum. When this coat exposes to the diluted hydrogen or oxygen gas WO_3 will be reduced, causing to create colour.

A gasochromic glazing is composed of two glazed panes with a coating on one of the two inner surfaces. The coating consists of a WO_3 film whose colour changes to blue when exposed to a low concentration of hydrogen. When the coating is exposed to oxygen it resumes its initial colour. Experiments have shown that the transmittance varies from 11-74%.

Small amount of gas is needed for switching process, and water needed in WO_3 layer for rapid transport of hydrogen. Gasochromic glass switches by alternate exposure of hydrogen-containing gas and oxygen containing gas. Gasochromic glass has a simple structure and suitable for large-scale window (Georg et al.,2000; Wittwer et al.,2004; Yoshimura et al., 2009 and Feng et al.,2016).

Benefits of Gasochromic:

1. Glare control and reduction of transmittance level with short time for switching.
2. Reduction of energy utilization for lighting and cooling of the space.
3. Improved u-value
4. Responds appropriately to the environmental changes.

- **Thermochromic**

Thermochromic window (TC) comprise of a common safety interlayer, made from extruding special thermochromic materials into polyvinyl butyral (PVB), laminated between two pieces of heat strengthened or tempered glass and placed into an insulated glass unit (IGU) with a low emissivity coating as shown in Figure 4.4. Thermochromic (TC) windows passively switches colour and optical properties in response to varying thermal conditions. The thermochromic is characteristically applied to the outer glass layer of an insulating glass unit. At a critical temperature range as a result of the high incident solar radiation/ high outdoor temperature, the thermochromic switches from clear to tinted transparent state. The switching process is reversible and leads to reduction of solar as well as visible transmittance of the window. The switching process from tinted to clear occurs at a lower temperature compared to switching from clear to tinted (Seeboth et al., 2010; Kamalisarvestani et al., 2013; Hoffmann et al., 2014 and Ye et al.,2014). A representative commercialised

thermochromic window switching temperature is in the range of 24°C-76°C (DFEG, 2014-2015).

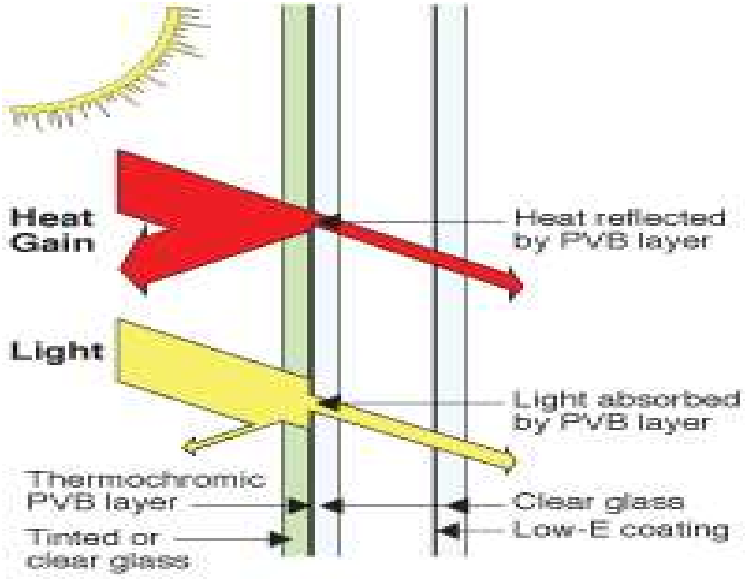

Figure 4.4: Diagram of heat reflectance and light absorption through the thermochromic film.
Source : (Haglund, 2015)

Benefits of Thermochromic window:

1. Thermochromic windows are designed to block solar gain.
2. Reduction of cooling load.
3. Self-regulation control of light and heat.
4. Thermochromic windows do not require wires, power supplies or control equipment and can be installed by glazing contractors as conventional window hence cost effective.
5. Thermochromic windows reflect transmission of infrared light and heat gain

❖ **Photochromic windows**

Photochromic windows change transparency in reaction to light intensity. Photochromic windows respond to the illumination level by colouring and whitening reversibly. When photochromic materials change transmittance, the absorptivity is

increased, thus causing glass to absorb more heat. On sunny, colds days, they absorb solar heat and room source heat and then radiate some heat back to the surroundings. On sunny, hot days, photochromic window does not reject as much solar heat as reflective glass. The molecules are transparent to visible light in the absence of UV light, which is normal for artificial lighting. But when exposed to UV rays, as in direct sunlight, the molecules undergo a chemical process that causes them to change shape. The new molecular structure absorbs portions of the visible light, causing the lenses to darken. The number of molecules that change shape varies with the intensity of the UV rays. Photochromatic windows darkens automatically with sunlight and lighten up at sunset on the contrary it does not control heat gain (Kamalisarvestani et al., 2013; Connavale et al., 2013 and El-Zaiat et al., 2016). Conversely, although photochromic windows are cost-effective, it is not available in commercially quantities (Haglund, 2015) .

Benefits of Photochromic window:

Photochromic windows reduce glare from sun but do not control heat gain.

1. Photochromic reacts to ultraviolet radiation and visible light.
2. Photochromic window saves energy on hot, sunny summer days.
3. Photochromic window can combine with daylighting for lighting purposes to minimize electricity utilization.

- **Liquid Crystal Device Windows**

Liquid crystal device (LCD), contains molecular particles suspended in a solution between plates of glass. In their natural state, the particles move randomly and collide, blocking the direct passage of light. When energized, the particles align rapidly and the glazing becomes transparent. This type of switchable glazing can block up to about 90 percent of light. Liquid crystal glazing is controlled electronically. It is changed from translucent manner to transparent. A very thin layer from liquid crystal is covered by transparent conductive metal, which is wired to power supply and laminated between two layers of glass. When power is off liquid crystals are in a random out of position with light scatter. This phase gives opaque window glass with high privacy. On the

contrary, when the power is on the liquid crystals are aligned by electricity, the light passes through the window and there is a transparent glass with clear view in both directions. The variation occurs in less than a second. On the contrary liquid Crystal windows cannot reduce heat gain.

In Liquid crystal device technology, the glass is either clear or translucent with no intermediate settings. Liquid crystal windows do not provide significant energy savings since the window lets in nearly the same amount of light and solar heat whether it is on or off. A constant electrical charge is required to maintain a transparent state. Liquid crystal glazing currently adds about $90/ft2 to the glazing

Benefits of Liquid crystal device

1. Liquid crystal device provide privacy and reduce glare.
2. Transmit incident light
3. Reflect transmission of infrared light and heat gain

- **Suspended Particle Device (SPDS) Windows**

SPDs are microscopic molecular particles which are suspended in a liquid solution and then placed on a conductive sheet or film. When no electrical voltage is present, the particles absorb light and block it from passing through the film. When an electrical voltage is applied, the particles align so that light can pass through. By regulating the voltage with a simple switch or other control device, users instantly regulate the amount of light, glare, and heat coming through products such as window. On the other hand, cost remains an issue (Kamalisarvestani et al.,2013; Barrios et al.,2015 and Ghosh et al., 2016). Figure 4.5 represents the principle of operation for suspended particle device.

Benefits of Suspended Particle Device (SPDS) Windows:

1. Suspended Particle Device (SPDS) Window blocks significant amount of ultraviolet light.
2. Suspended Particle Device can act as window blinds or light valves
3. Suspended Particle Device can be use as light control in which the colour of glass changes from clear to dark.

4. Depending on the voltage, users can continuously adjust light transparency in less than two seconds manually or automatically regardless of the size of the window.
5. Have wide range of transmittance
6. Reduces transmission of infrared light.
7. It also has energy saving capabilities.

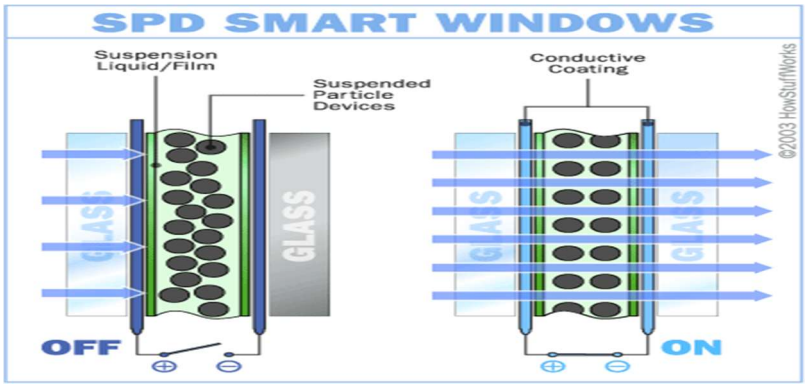

Figure 4.5: Principle of operation for suspended particle device
Source: (Bonsor, 2016)

In conclusion, majority of technologies incorporated into windows minimizes the heat gain subsequently improves the energy efficiency. The reviewed smart windows show that, its technology have switching capabilities to adjust to either ultra violet light, heat gain or visible light. Comparably, clear glass allows highest heat gain depending on local climate conditions while permitting the highest daylight transmission. Tinted glass has advantage in controlling glare, however solar heat gain and visible light transmission performance may be minimized depending on local climate conditions. Selection of window technology is mainly dependent on climate and purpose of usage. Window technologies suitable for energy savings as well as indoor environmental comfort at cost effective prices in commercial quantities are inadequate in the market.

4.3.3 Opaque building envelope technology

Several technologies exist in enhancing opaque building envelope fabric. Among the representative technologies are thermal insulation, phase change material, light weight concrete, thermal energy storage technologies among others. Below are descriptions of the representative technologies.

- **Thermal Insulation Technologies**

Thermal insulation in buildings is vital for minimizing unwanted heat loss or gain in achieving acceptable building performance. Thermal insulation can be integrated in all elements of building envelope. Typical insulation technologies incorporated in building fabrics are cellulose, glass wool, rock wool, polystyrene, urethane foam, ash, vermiculite, perlite, wood fibre, plant fibre, reflective insulation, cement, plant straw and many more. The incorporation of insulation technologies has yielded several enhanced thermal property products for building envelope elements, for example autoclaved aerated concrete, glazing, insulated concrete block, insulated concrete foam, lightweight concrete, among others). Thermal insulation technologies mainly increase the resistance of the material to control the temperature difference across the building element. Thermal insulation technologies are mainly selected based on climate, mechanical properties requirements, thickness etcetera (Sadineni et al., 2011; Alam et al., 2011 and Kosny et al., 2014).

- **Phase Change Materials**

The phase change material (PCM) is incorporated in light weight wall structures to enhance the thermal storage capacity. PCM material is impregnated commonly in gypsum or concrete walls. Porous material such as plasterboard has better PCM impregnation potential than pumice concrete blocks. The microencapsulation of PCM material in wall construction material has allowed this PCM weight ratio to about 30% in gypsum. Recent years have seen the advent of composite materials that can encapsulate PCM up to 60% by weight (Sadineni et al., 2011 and Chen et al.,2015)

- **Thermal energy storage technologies**

In recent years, the magnitude of energy consumption in buildings seems to crest from the normal demand and that has to be carefully addressed through implementing energy conservative and energy management techniques. In the class of having several energy efficient schemes, thermal energy storage (TES) technologies for buildings are increasingly attractive among architects and engineers. In the class of having several energy efficient schemes, thermal energy storage (TES) technologies for buildings are increasingly attractive among architects and engineers. In the scenario of growing energy demand worldwide, the possibility of improving the energy efficiency of TES systems can be achieved from break-through research efforts. The prime intention of this paper is to review the potential research studies pertaining to a variety of latent heat energy storage (LHES) and cool thermal energy storage (CTES) systems solely dedicated for building heating, cooling and air conditioning (A/C) applications. Technical revelations regarding the integration and performance evaluation of heat storage materials in building fabric elements as well as using separate heat storage facility to satisfy the space thermal load demand have been gleaned from numerous research contributions and presented (Parameshwaran et al.,2012 and Ouedraogo, 2012).

4.3.4 Chilled ceilings/ beams

Chilled ceilings/beams can be used incorporation with other low cooling technologies such as slab cooling, ground cooling air, displacement ventilation among others.

- **Chilled ceilings**

The cooling units are mainly integrated with false ceilings. Cooling is provided by circulating cool water (~16^{o}C) through the units for removal of heat gains, leaving ventilation and humidity control to the air distribution system.

Chilled ceilings primarily, have flat panel units which transfer cooling to the space primarily by radiation (Barnard and Jaunzens,2001; Florides et al., 2002 and Kim and Leibundgut, 2014) Chilled ceilings have approximately, 40W/m^2 typically assuming 50% active area with cooling water @ 16^{o}C and occupied space @ 26^{o}C (Barnard and Jaunzens,2001).

According to Vakiloroaya et al. (2014), chilled ceiling systems have potential for significant can energy savings, on the contrary, it has a risk of water condensation gathering on the system's chilled panels resulting in water dropping on the ceiling. Kim and Leibundgut (2014), finding on condensation arising from chilled ceiling is inconsistent with Vakiloroaya et al. (2014), hence it is challenging implementing this technology in hot and humid climates. A characteristic sketch of chilled ceiling is shown Figure 4.6.

- **Chilled beams**

Chilled beams directly cool room air with exposed water coils supplied with chilled water through beams and can be characterised into passive and active (Barnard and Jaunzens,2001; Riffat et al.,2004 and Chen et al., 2015; Nelson et al., 2016).

Passive chilled beam consists of a fin and tube heat exchanger with cooled water running through it. The passive system relies entirely on the convective air motion to cool the zone it is assigned to.

An active chilled beam, on the contrary, utilises an internal air supply. This air is passed through the beam which, in turn, induces air from the zone to flow past the cooling coil, and assist in the cooling of the space. The active chilled beam provides significant cooling to the designated zone compared to passive type.

Chilled beams are mostly open structure and rely on convective air movement as the principle mechanism for heat transfer. Chilled beams have approximately, 60W/m^2 characteristically with cooling water @ 16^{o}C and occupied space @ 26^{o}C (Barnard and Jaunzens,2001). A characteristic sketch of chilled beam is shown Figure 4.6.

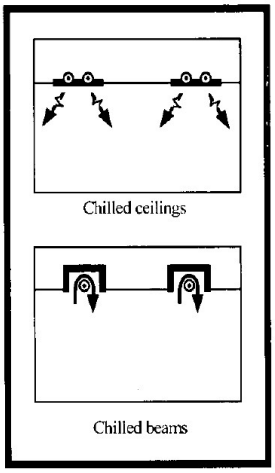

Figure 4.6: Sketch of Chilled ceiling/beam
Source: (Barnard and Jaunzens,2001)

Benefits Chilled ceilings/ beams

1. **Chilled ceilings/ beams** can be used in conjunction with a low-quality source of cooling due to the relatively high cooling water temperature.
2. Cooling supplied within the space limit the requirements of the ventilation system to providing fresh air, so reducing plant and ductwork space requirements and fan energy consumption.

4.3.5 Control of Infiltration and ventilation

Control of infiltration is mainly focused on sealing and insulation. There is insignificant infiltration control technology identified in literature. On the contrary, representative ventilation control technology in literature are energy recovery ventilation (ERV) and Heat recovery ventilation technology. Brief energy recovery ventilation (ERV) and heat recovery ventilation technology

- **Heat recovery ventilation technology**

Heat recovery technology recovers energy (heat/mass) from a stream at a high temperature to a low temperature. Heat recovery ventilation technology uses the exhaust air as either a heat source or sink depending on the climate conditions, time of the year and requirements of the building. In cooling the exhaust air is used a heat sink for thermal energy in the warmer incoming fresh air thereby reducing cooling demand. Heat recovery systems are mainly classified into sensible and enthalpy heat recovery systems. A representative heat recovery systems consist of a heat exchanger core unit, ducts for fresh and outgoing air, exhaust air and blower fans (Fouih et al., 2012; Mardiana-Idayu and Riffat, 2012; Cuce et al., 2015 and O'Connor et al., 2016).

Benefits of Heat recovery ventilation technology

1. Heat recovery ventilation technology is use for HVAC energy reduction
2. Heat recovery system (HRS) provides cost-effective and environmentally friendly energy.
3. Improve indoor environmental quality

In conclusion, integrated technologies in buildings improves performance significantly although, there is general perception of high cost being a hindrance to building professionals

5 CHAPTER FIVE: RESEARCH METHODOLOGY AND DESIGN

5.1 Introduction

The research aim is multi-disciplinary requiring knowledge from architecture, building service, facility management, mechanical among others, hence the need for mixed research methods approach. Detailed flow chart for this research is represented in Figure 5.1.

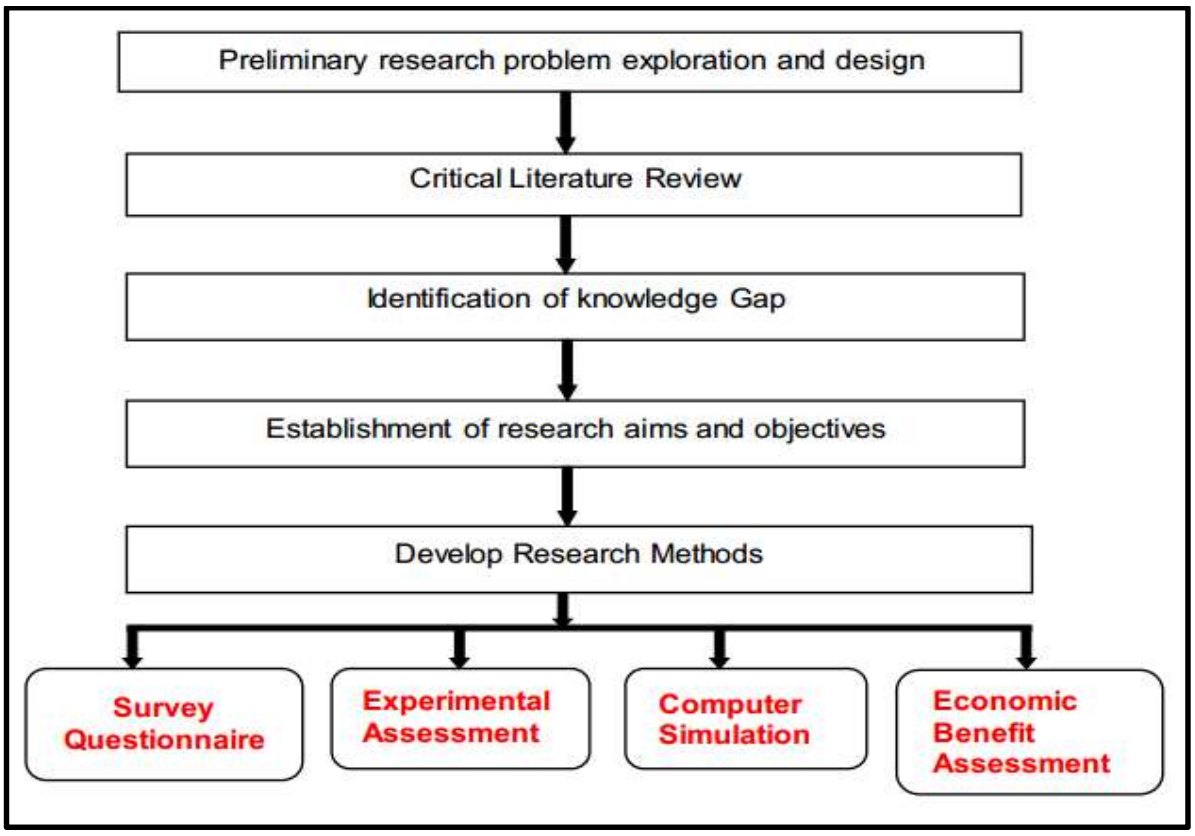

Figure 5.1: Detailed flow chart for this research

Preliminary research problem exploration and design was carried out to explore the actual building performance situation in Ghana and to establish the research topic. Based on the identified research topic, critical literature review was undertaken to find the knowledge gap in scientific and technical journals. From the knowledge gap, the overall research aims and objectives were outlined. It was concluded that mixed

research methods would be required based on lack and adequacy of the design variables required to accomplish the overall research aim.

5.2 Research Methods

To meaningfully conclude and achieve the overall aim, mixed research methods were adopted as shown in Figure 5.1. The mixed research methods involved survey data, experimental assessment and computer simulation. The data acquisition was accomplished using dominant and less-dominant design. The dominate methods were dynamic computer simulation and experimental assessment whiles the less dominant method was survey questionnaire.

Survey research method is the most appropriate tool for acquisition of data involving participants. Survey research methods can be classified into interview and questionnaire. Both methods have their own capabilities and suitable application areas. Questionnaire survey research method was adopted in this research base on the required sample size and the mixed research questions. Questionnaires were used to acquire data on representative:

i. Building professional's practices,
ii. Building performance design variables,
iii. Characteristic trend in solving rise in electricity consumption in Ghana
iv. Occupants comfort as well as satisfaction of

Experimental research method was used to:

i. Assess the thermo-physical properties of building fabric from Ghana
ii. Creative parametric experiment to enhance thermo-physical properties
iii. Validate the survey data from building fabric manufacturers participants.

Computer Simulation was used to:

i. Assess data acquired from survey and experiments
ii. Optimize the design variables for enhanced building performance

5.2.1 Justification of research design and methods

1. Mixed research methods applied in this research enhanced the data validity since the survey findings were assessed and compared with both experimental and computer simulations.
2. Mixed research methods assisted in solving all the identified gaps in scientific and technical journals.

In summary, survey data showed that an average of 14% of representative building professionals undertake performance assessment in Ghana. On the contrary, this percentage is inadequate in generalising the building performance in Ghana; hence the need for computer simulation and experimental assessment.

5.3 Data Collection for Mixed Research Method

As indicated above, mixed research method was used for this research, hence data acquisition was acquired through survey, experimental study and dynamic simulation. The significance of the acquired data is dependent on the purpose, process and outcome of the research. Brief description of each method of data acquisition is as below.

5.3.1 Data collection through Survey Questionnaires

Survey questionnaire is the dominant practical data collection technique in literature for human factors related research (Frontczak et al. ,2012 and Zalejska-Jonsson and Wilhelmsson 2013). The survey questionnaires were designed for building professionals and occupants. The building professionals consist of Building Service Engineers, Architects, Building Materials Manufacturers and Government Agencies (Building Permit Issuers, Ghana Standard Boards and Building Regulation Institutions). The occupants compose of representative air-conditioned institution buildings and other public offices.

The survey questionnaires were administered and completed questionnaires were collected through Bristol Online Survey Tool.

Limitations of the study

1. Due to the online administration of the questionnaires, the response rate was a little above average.
2. Disperse nature of Building Service Engineers and Building Fabric Manufacturers, snowball sampling technique was used. Hence, majority of the participants were not reached.
3. Average Sample size.

In conclusion, the survey questionnaires formed the robust fundamental knowledge for the experimental study, whole building modelling and simulation.

5.3.11 Purpose of Survey Questionnaires Data

The main purpose of this survey questionnaires was to explore, describe, obtain information and explain the causative effect of the local building professional's practices on design variables. This aim was accomplished through the following specific objectives:

1. To acquire detailed knowledge and skills into what, why, how, when and where local building professional practices impacts on building performance in Ghana.
2. Use participant's responses in supporting the research problem and to identify typical design variables used in performance assessment.
3. To carry out appraisal of Ghana building regulations and compliance check by building professionals.
4. Explore building professional's representative practices for enhancing the design variables and subsequently building performance.

5. To identify occupant's perception on indoor environmental comfort and satisfaction of office building envelope design, building finishing as well as building fabrics
6. To establish cost effectiveness and affordability of propose optimize solutions to the research problem.

5.3.12 Survey Data Collection Process

The questionnaires were designed with knowledge of standard building performance and literature on building professionals as well as occupants in Ghana. Different questionnaires were designed for each building professional and occupants. On the contrary, all building professionals in Ghana use the building regulation. Hence the seven-level Likert scale questions for appraisal of Ghana building regulation was repeated across all the questionnaires for building professionals. Among the subsections in the questionnaires for building professionals and occupants are as follows:

- ✓ Ghana Building regulations
- ✓ International Building Codes, Regulation and Standards
- ✓ Sizing Building Service Equipment and Client know-how
- ✓ Building Performance and Life Cycle
- ✓ Building Envelop Design
- ✓ Building Envelop improvements
- ✓ General Occupants information
- ✓ Indoor Environmental Comfort
- ✓ Overall Occupants Satisfaction
- ✓ International Building Standards and Regulations
- ✓ Products Specification
- ✓ Sustainable Building Materials

The designed questionnaires were mixed open-ended and close-ended format.

Open-ended set of questions were employed to allow participants to share their representative knowledge and skills regarding the subject. The closed ended questions were composed of the following:

- dichotomous questions e.g. (Yes /No),
- Characteristic seven-level Likert scale e.g. (Highly satisfied, satisfied, Turn to be satisfied, Neither satisfied nor dissatisfied, Turn to be dissatisfied, Dissatisfied and Very Dissatisfied) for the Ghana building regulation appraisal.
- Filter questions to direct participants to the correct subsequent questions e.g. (If yes, proceed to 1b).

Some selected mixed questions in the survey questionnaire include:

1. To what extent are you satisfied with the **empirical basis** (derived from observation, experience, experiment and not theory) of the building regulations of Ghana?

- ○ Highly satisfied
- ○ Satisfied
- ○ Turn to be satisfied
- ○ Neither satisfied nor dissatisfied
- ○ Turn to be dissatisfied
- ○ Dissatisfied
- ○ Very Dissatisfied

2. Do you **typically** conduct field inspection of office buildings for regulation compliance after the building permit has been issued?

- ○ Yes
- ○ No

Other *(please*

Detailed questionnaires are represented in Appendix A.

Both question types offer a unique advantage to the research. Among them are:

1. Reduction of thinking load by participants

2. Participants responses were made easier to sort out and analyse.

3. Participants could express their personal experience on questions to enhance the knowledge and skills of the researcher.

Subsequently, from the designed questionnaires, an application of ethical certificate was sort for, from the ethical board within University of Nottingham. As part of the survey approval process, the designed questionnaire, consent letter and methodology for the administering of the questionnaires were attached.

On receiving the approval of the ethical certificate, samples of the questionnaires were administered to the research supervisors and colleagues via Bristol Online Survey Tool, to test administration method selected, appropriateness and clarity of the questions. The feedback from the trail sample questionnaires were effected into the main questionnaires for modification before launching online.

Multistage sampling technique by Frontczak et al. (2012) and Zalejska-Jonsson and Wilhelmsson (2013) was modified for data acquisition across the building professionals and institutional as well as public office occupants in Ghana.

The multistage sampling techniques were categorised into four major stages; being identifying cluster of institutions and associations, sample size of participants in each institutions and associations, distribution of questionnaires and corresponding with Administrators and Secretaries in each institution, as follows:

Stage 1: Identifying cluster of Institutions and Associations

The cluster of institutions was selected using the knowledge from the critical literature review, snowball sampling technique and list of building professional institutions and registered associations obtained from official websites. Aside the Architecture, and Government agencies who have a registered Institutions; the remaining clusters (Building Material Manufactures and Building Service Engineers) are disperse all over Ghana.

Rationale for the selected approach for data sampling technique was because of the disperse nature of some associations, occupants in the public office buildings. Finally, all institutions in Ghana have their Headquarters in Accra, hence any data acquired in Accra (study area) would be a representative data for generalisation in the whole Ghana.

Stage 2: Sample size of participants in each institutions and associations

The administrators and secretaries of registered institutions stated above, known large-scale companies of Building Service Engineers, known large-scale companies of Building Manufacturing Companies and administrators of public office buildings educational, judicial, finance, minerals and mining, health, among others were contacted. Emails and telephone conversations were sent out to all administrators and secretaries identified above. However out of 150 emails sent; 55% of an affirmative response were received with constraints.

The constraints included:

1. Due to security reasons for participants, no details (name or email address) can be given to me.
2. Username and passwords should be submitted to the administrators for distribution to participants using stratified random sampling i.e. based on the participant speciality or section relating to the study.
3. Restriction on numbers of username and password logins requested to be sent by the institutions.

Stage 3: Distribution of Questionnaire

Five different emails corresponding to each questionnaire link for inviting and introducing the purpose of study were sent to the administrators and secretaries of the respective clusters. The generated integrated user login controls for each questionnaire link was sent to the administrators and secretaries of the respective clusters email separately based on the requested logins for distribution to individual respondents for the specific questionnaire link.

Stage 4: Corresponding with Administrators and Secretaries

There was continuous correspondence with administrators and secretaries through email and telephone conversation to address any concern arising from the distribution of the login details.

5.3.13 Procedure for Survey Analysis

Reliability and data accuracy were insured using integrated login details restricting access to the questionnaire link by participants outside the clusters identified. On the contrary, it should be noted that, the data are susceptible to the non-sampling errors associated with non-response, incomplete filling of questionnaires, and data processing. Excel spreadsheet was used to eliminate data processing errors arising from calculated data entry. Completed and compiled questionnaires data for each building professional link as well as occupant were downloaded from Bristol Online Survey Tool. The various subsections within the questionnaires as listed above were examined, sorted and regrouped along the following clusters for analysis:

- Building Professionals Practices and Building Regulation Appraisal
- Typical design variables for whole building simulation
- Occupants comfort and satisfaction perception
- Cost benefit analysis

The process of sorting out the questions for the various subsections within the questionnaires were done base on the objective of each question.

In view of the mixed qualitative and quantitative data received from the questionnaires, the analysis was classified into three. Namely, descriptive statistics analysis, analytical models and statistical analysis. Brief description of the three-analysis used in the questionnaires are as follows.

a). Descriptive statistics analysis was applied on all the exploratory data within the following subgroups:

- Building professionals' practices
- Typical design variables for whole building simulation
- Occupants comfort and satisfaction perception
- Cost benefit analysis

b). Analytical analysis was used for Ghana Building Regulation Appraisal. There were 9 characteristic factors for the appraisal. The factors are, cost effectiveness, proportionality, consistency, ease of implementation, flexibility, government effectiveness in implementation, empirical basis, adequacy and modification. The analytical analysis of the 9 characteristic factors for the appraisal are:

Table 5.1: Analytical Analysis of characteristic factors

Analytical Analysis	**Characteristic Factors**
1. Cost effectiveness analysis	cost effectiveness
2. Equality impact assessment	proportionality and consistency
3. Outcome evaluation	ease of implementation, flexibility and government effectiveness in implementation
4. Opportunity analysis	empirical basis, adequacy and modification

c). Statistical Analysis

Statistical variance analysis was used to assess the representative design variables obtained from the survey questionnaire with standard CIBSE Guide.

5.3.2 Data collection through Experimental study

The data collection through experimental study were from two different building fabric sources; namely selected building fabric from manufacturers in Ghana and creative parametric building fabric by the researcher. The main independent variables involve in the experiment include: mixing design ratio and sand type. The main dependent variables include thermal conductivity, thermal effusivity and density. Detail description of the two different building fabric sources are as below.

- **Selected building fabric from manufacturers in Ghana**

From Survey data in 2014, there is lack of well-established association/institution of building fabric manufacturers in Ghana, where representative production details of thermal properties can be acquired. The findings of 2014 survey shows that,

- Insignificant percentage of building fabric manufacturers do undertake test measurements of the manufactured products.
- Lack of equipment by government agencies to test thermo-physical properties of the materials.

Taking into consideration of the above challenges, building fabric manufacturers were categorized into three main sections based on their method of production and quantities produced. Considering the above constraint and cost of shipping to United Kingdom, snow ball sampling technique was used to identify 10 leading large-scale building manufacturers in Ghana.

According to Survey data in 2014, the dominant building fabrics use in Ghana are concrete blocks, mortar cement blocks and bricks. Hence, building fabric randomly selected from the stock of each 10 companies were concrete blocks locally called quarry dust blocks, mortar cement blocks, bricks, and concrete roofing tiles.

Four stages were carried out prior to the main thermo-physical test measurement as summarized in Figure 5. 2(a, b, c, d, e and f). Stage one: measurement of weight and dimension of selected cement-based samples from companies were taken as shown in Figure 5.2a and 5.2b. Stage two: blocks were divided into at least 6 parts, relabelled with anonymous names and radioactive test was carried on samples by Atomic Energy of Ghana before Customs clearance was granted for shipping as shown in Figure 5.2c. Stage three: moisture control of the specimen in UK was carried out as a result of moisture transfer and temperature variation from Ghana to UK. Finally, in stage four: further reduction of specimen sizes and surface finishing were carried out before the experimental measurements were undertaken as represented in Figure 5.2f and Figure 5.3.

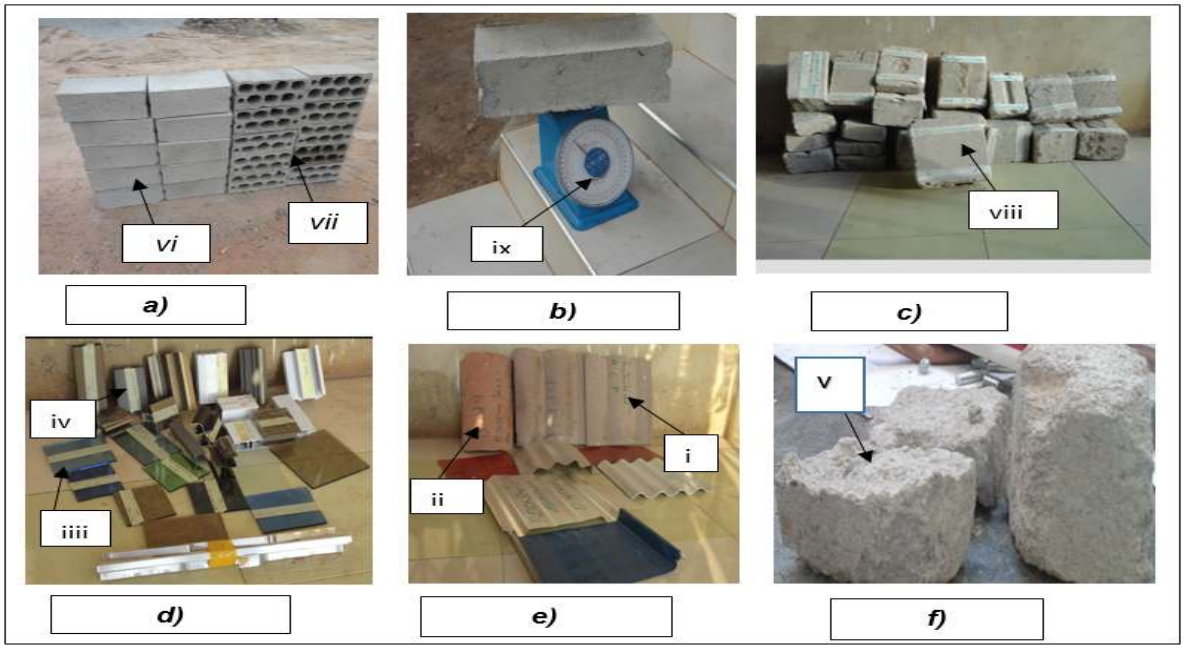

Figure 5.2: Representative Buiding Fabric samples from Ghana

Where

a)= Selected cement-based blocks products

b)= Weighing of select cement-based blocks

c)= Prepared cement-based samples for shipping sample size

d) = Selected fenestation

e)= Selected roofing fabric

f) = moisture controlled

i= concrete roof tile

ii= Brick roof tile

iii=window pane *iv= Window frame*

v= reduced sample size *vi =solid cement-based samples*

vii= hollow cement-based samples *viii= Anonymous named samples for shipping*

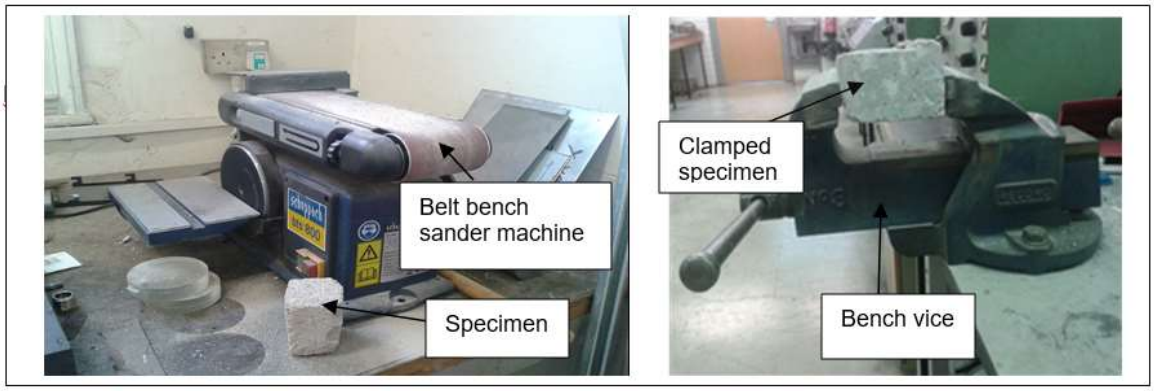

Figure 5.3 Surface Finishing

In conclusion, test measurements were carried out on all the surface finished specimen. Details of the test measurements are outlined in section 5.3.23.

- **Creative Parametric building fabric**

Creative parametric cement-based building fabrics were designed at University of Nottingham using cement, mixed 10mm-20mm size gavels, builders sand and washed sand. The overall aggregates for the creative parametric blocks were selected in accordance of BS EN 13139:2002 and BS EN 13055-1.

- ✓ **Creative Parametric Experiment Design**

The preparation of specimen moulds, casting of the concrete samples and compaction operations were performed according to BS EN12390-1 and BS EN12390-2 in conjunction with characteristic participant's response of survey questionnaires.

The casting wooden boxes were 50mm x 50mm each as shown in Figure 5.4a. One set of casting wooden box was used for the parametric mortar blocks whiles the other set was used for the parametric concrete blocks. The creative parametric blocks consisted of 15 different mortar and 15 concretes. Five dominant representative mixing design ratio used in Ghana were selected for both mortar and concrete blocks. The mixing design ratio for mortar and concrete block were labelled as T1, T2, T3, T4 and T5.

In mortar block 'T' was defined as Cement: Sand type ratio of the following:

T_1 = 1:5

T_2= 1:6

T_3= 1:3

T_4= 1:2

T_5= 1:4

In concrete block 'T' was defined as Cement: Gravels sizes: Sand type of the following ratio:

T_{11} = 1:3:1

T_{22} =1:4:1

T_{33} = 1:5:1

T_{44} = 1:1:3

T_{55} = 1:1:4

In view of the three different sand types used (washed, builders as well as mixed washed and builders sand types) for the creative parametric mortar and concrete blocks, the following were carried:

1. 5 parametric mortar blocks using washed sand type with the 5 different outlined mixing ratios. The blocks were labelled $MwsT_1$, $MwsT_2$, $MwsT_3$, $MwsT_4$ and $MwsT_5$.

2. 5 parametric mortar blocks using builders sand type with the 5 different outlined mixing ratios. The blocks were labelled $MbsT_1$, $MbsT_2$, $MbsT_3$, $MbsT_4$ and $MbsT_5$.
3. 5 parametric mortar blocks using mixed washed and builders sand types with the 5 different outlined mixing ratios. The blocks were labelled $MbwsT_1$, $MbwsT_2$, $MbwsT_3$, $MbwsT_4$ and $MbwsT_5$.
4. 5 parametric concrete blocks using washed sand type with the 5 different outlined mixing ratios. The blocks were labelled $CwsT_{11}$, $CwsT_{22}$, $CwsT_{33}$, $CwsT_{44}$ and $CwsT_{55}$.
5. 5 parametric concrete blocks using builders sand type with the 5 different outlined mixing ratios. The blocks were labelled $CbsT_{11}$, $CbsT_{22}$, $CbsT_{33}$, $CbsT_{44}$ and $CbsT_{55}$
6. 5 parametric concrete blocks using mixed washed and builders sand types with the 5 different outlined mixing ratios. The blocks were labelled $CbwsT_{11}$, $CbwsT_{22}$, $CbwsT_{33}$, $CbwsT_{44}$ and $CbwsT_{55}$. Samples of the creative parametric blocks are shown in Figure 5.4b and 5.4f.

Note:

Builders is a general-purpose sand type with fine aggregate mostly suitable for rendering plaster and mortar blocks. Builders sand type was selected in accordance of BS 1199 and 1200:1976 standards.

Washed sand is a general-purpose sand type with mixed larger aggregates mostly suitable for concrete blocks. Washed sand was selected in accordance of ASTM C33 standards.

The Cement used was Portland

Limitation of the Creative Parametric Experimental Study

The initial test were carried out after 28 days of casting the blocks. Unfortunately, since it was air dried under ambient conditions; the moisture content of the blocks were suppose to be tested. Convesely , there was no equipment for moisture testing, hence the blocks were assumed to be dry based on the 28 days of the ambient drying period in BS EN1367-4.

To overcome this limitation,the labeled parametric mortar blocks were weighed before the initial test measurement and were left in the ambient conditions for another one month drying. After the one month, the extra dried parametric mortar blocks were weighed and tested to generate the repeat results.

5.3.21 Purpose of Experimental Assessment

The experimental study of building fabric from Ghana was carried out, as a result of insignificant thermo-physical properties in scientific and technical literature. A follow-up parametric experiment was carried out due to high range representative thermal conductivity values and the identified findings on typical mixing ratio, sand type and standards use for practice. The overall aim of the experimental study is to determine the thermo-physical properties of a representative building fabric from Ghana and enhance the resulting properties using parametric sand type as well as mixing ratio design approach. The specific objectives in achieving the aim include:

1. To investigate the use of local materials thermal properties to establish the most suitable material to minimize heat and moisture transfer.
2. To enhance thermo-physical properties of a representative building fabric from Ghana using sand type and mixing design ratio design.

5.3.22 Selected Experimental Test Measurements

The individual methods are suitable for a limited range of materials, depending on the thermal properties and the medium of temperature source. Laser flash method and Modified transient plane source (C-Therm Tci) were the dominant and accurate methods for measuring both thermal conductivity as well as thermal effusivity concurrently. On the other hand, laser flash equipment is not available at University of Nottingham.

In view of this, modified transient plane source which is in accordance of ASTM D7984 was used. Modified transient plane source (TCi Thermal Conductivity Analyzer) which conforms to ASTM D7984 and AutoPore IV intrusion mercury Porosimeter were used in determining thermal conductivity, thermal effusivity and density. On the contrary, density of each building fabric is derived from a calculation of a model from C-Therm manufacturer manual and it is dependent on the measured thermal conductivity as well as thermal effusivity. This implies that, any error made in the use of C-Therm (TCi Thermal Conductivity Analyzer) measurements would affect the density. In view of this challenge, AutoPore IV intrusion mercury Porosimeter equipment was used to determine the density of the building fabrics. Details of TCi Thermal Conductivity Analyzer and AutoPore IV intrusion mercury Porosimeter are described as below.

- **TCi Thermal Conductivity Analyzer**

The TCi Thermal Conductivity Analyzer comprises of a sensor, power control device and data acquisition system as represented in Figure 5.4. The sensor has a central heater/sensor element in the shape of a spiral surrounded by a guard ring. The guard ring generates heat in addition to the spiral heater, thus, approximating a one-dimensional constant heat flow from the sensor into the one side of the specimen under test in contact with the sensor. The voltage drop on the spiral heater is measured before and during the transient. The voltage data is then translated into the effusivity value of the specimen. The conductivity is calculated from the voltage data by C-Therm's patented iterative method. Results are then displayed on the system's laptop or computer in real-time. Figure 5.4 is the experimental setup of TCi Thermal Conductivity Analyzer.

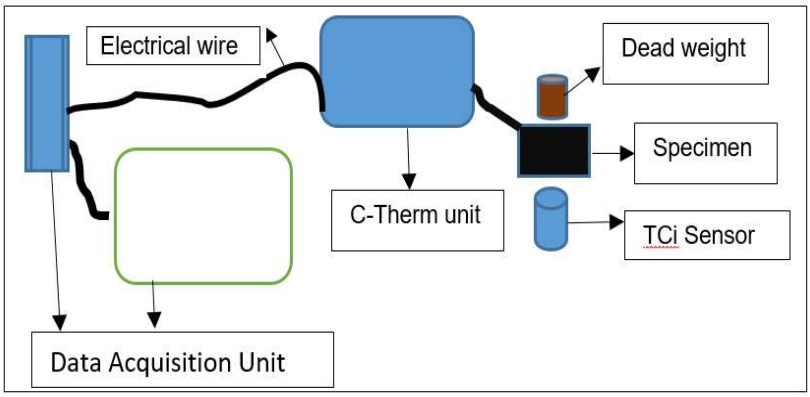

Figure 5.3: Experimental setup of TCi Thermal Conductivity Analyzer

❖ AutoPore IV intrusion mercury Porosimeter

The Autopore IV intrusion mercury Porosimeter uses pressurized mercury for material characterization. Representative output material characterization of Autopore IV intrusion mercury Porosimeter include pore sizes, pore tortuosity, material compressibility, pore number fraction, pore-throat ratio, pore fractal dimensions, permeability, bulk density, percentage of porosity among others. The mercury intrusion volume at various pressures was used to calculate the material characterization properties listed above. Conversely, as a result of extensive available literature on material characterization properties listed above, only density measurement data was extracted. The Autopore IV intrusion mercury Porosimeter 9500 model series have one low-pressure ports and one high-pressure port as represented in Figure 5.4a.

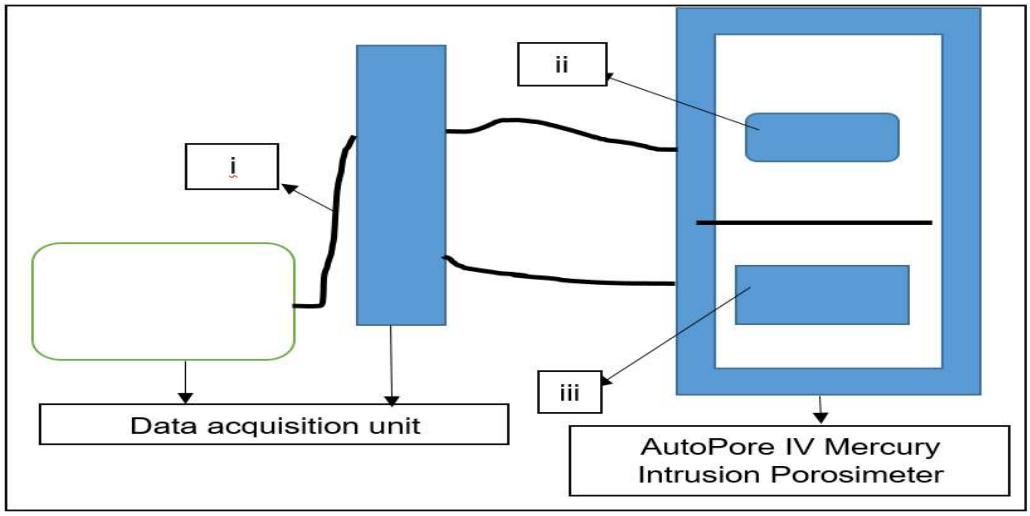

Figure 5.4a: Experimental setup of AutoPore IV Mercury Intrusion Porosimeter

Where

i= Electrical wire ii = Low pressure port iii = High pressure port

The penetrometer consists of a sample cup bonded to a metal-clad, precision-bore, glass capillary stem. The sample is placed in the sample cup; during analysis, mercury fills the cup and capillary stem. As pressure on the filled penetrometer increases, mercury intrudes into the specimen pores, beginning with largest pores diameter. The injected mercury into the specimen is at increasing pressures from 0 to 60,0000 psi. The mercury moves from the capillary stem resulting in a capacitance change between the mercury column inside the stem and the metal cladding on the outer surface of the stem. The AutoPore detects very slight changes in capacitance.

AutoPore IV intrusion mercury Porosimeter is a destructive testing method, hence specimens were appropriately disposed of in the mercury waste after testing. AutoPore IV intrusion mercury Porosimeter offers extremely high-resolution data; better than 0.1 µL for mercury intrusion and extrusion volume.

5.3.23 Experimental Measurement Procedure

The experimental procedure for determining thermal properties were carried out in accordance of BS EN ISO 10456-2007 and BS EN 1745:2012 standards. The experimental procedure was categorised into two, TCi Thermal Conductivity Analyzer and AutoPore IV intrusion mercury Porosimeter. Detail description of each procedure is outlined below.

- **TCi Thermal Conductivity Analyzer measurement procedure**

The experiment procedure was categorized into two different calibration methods, namely foam and polymer. The main distinctions between foam and polymer calibration methods are the range of thermal properties and the use of thermal conductivity. The foam calibration method was used to measure all suitable finished surfaces of each specimen. This is preceded with the application of thermal contact

agent. The procedure is simplified in Figure 5.5 followed by detail description of Foam and Polymer calibration methods.

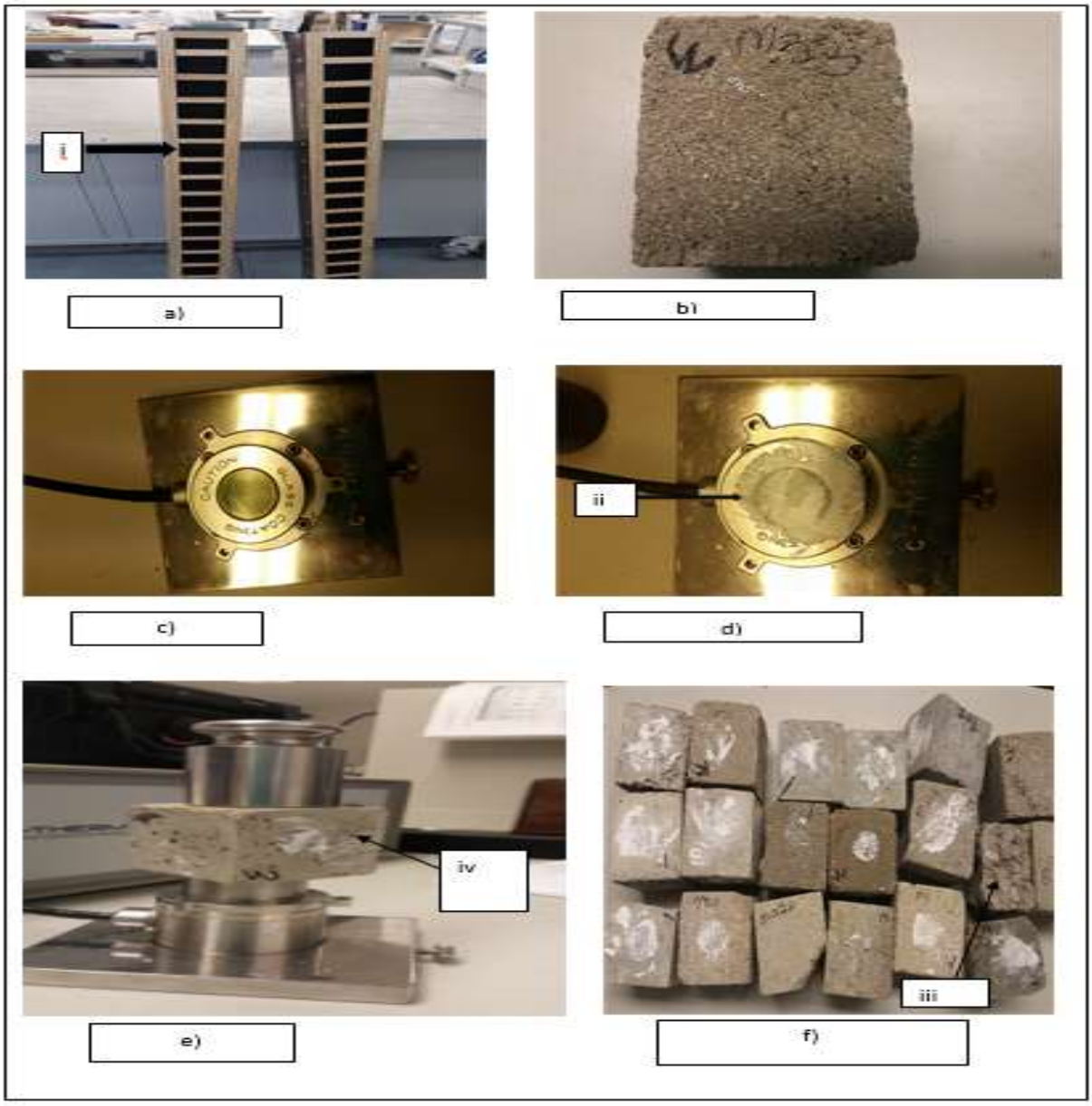

Figure 5.4: Experimental Procedure

Where

a) Parametric Casting Boxes

b) Parametric mortar block

c) C-Therm Sensor

d) C-Therm Sensor with contact agent

e) Polymer test method set-up

f) Some tested samples

i. One parametric block casting box

ii. Contact Agent

iii. Parametric concrete block iv. Specimen

- **Foam Calibration Method**

Steps 2-5 is use for the measurement readings for foam method. Step 1 is performed once, since it involves the starting up of the equipment set-up.

Step 1: Starting up the C-Therm TCi system

Turn on the computer, C-Therm TCi controller and Initiate the C-Therm TCi software by selecting the C-Therm TCi software icon.

Step 2: Measurement Set-up

The experimental set-up in Figure 5.4 was used. All the specimen was surface finished using the equipment set-up in Figure 5.2g. The surface finished specimen was placed on the C-Therm sensor one at a time as shown in Figure 5.5c on the sensor without applying contact agent. Measurement set-up of project name on C-Therm software on the computer was carried out. The measurement set-up includes: material group, calibration methods, the name of the sensor to be used for the testing and finally the number of test measurements to be carried out on that surface.

Step 3: Measurement reading collating

The number of test measurement readings for 1 surface of the specimen displayed on the monitor was copied and collated in an excel spread sheet.

Step 4: Repeated test measurements for other suitable finished surfaces

Repeated test measurements for other suitable finished surfaces of each block was carried out by repeating step 2 and 3.

Step 5: Results Processing

The measurement readings for each suitable surface finish for each specimen in step 3 are collated. For example, each specimen has 6 surfaces. Depending on the suitability of the surface finish, all the six surfaces are measured.

- **Polymer Method**

As stated above, thermal contact agent is used for polymer method. Contact agent is liquid or paste use to enhance contact between the sensor surface and specimen. Steps 1b - step 2 applied for polymer test measurement readings.

Step 1b: Application of thermal contact agent
Thermal contact agent is applied on top of the C-Therm sensor for each surface reading as shown in Figure 5.5d.

Step 2: Repeated steps in Foam method measurement
Step 1b and Steps 2-5 in foam method and were repeated. The processes were continued until the last prepared surface of specimen is completed.

- **AutoPore IV intrusion mercury Porosimeter measurement procedure**

AutoPore IV intrusion mercury Porosimeter experimental procedure is in two sections namely, low pressure port and high-pressure port. The low-pressure port is principally for mercury filling into the penetrometer assembly whiles, the high-pressure port is for the main measurement readings. Figure 5.6 summarizes AutoPore IV intrusion mercury Porosimeter measurement procedure for low and high-pressure port measurements.

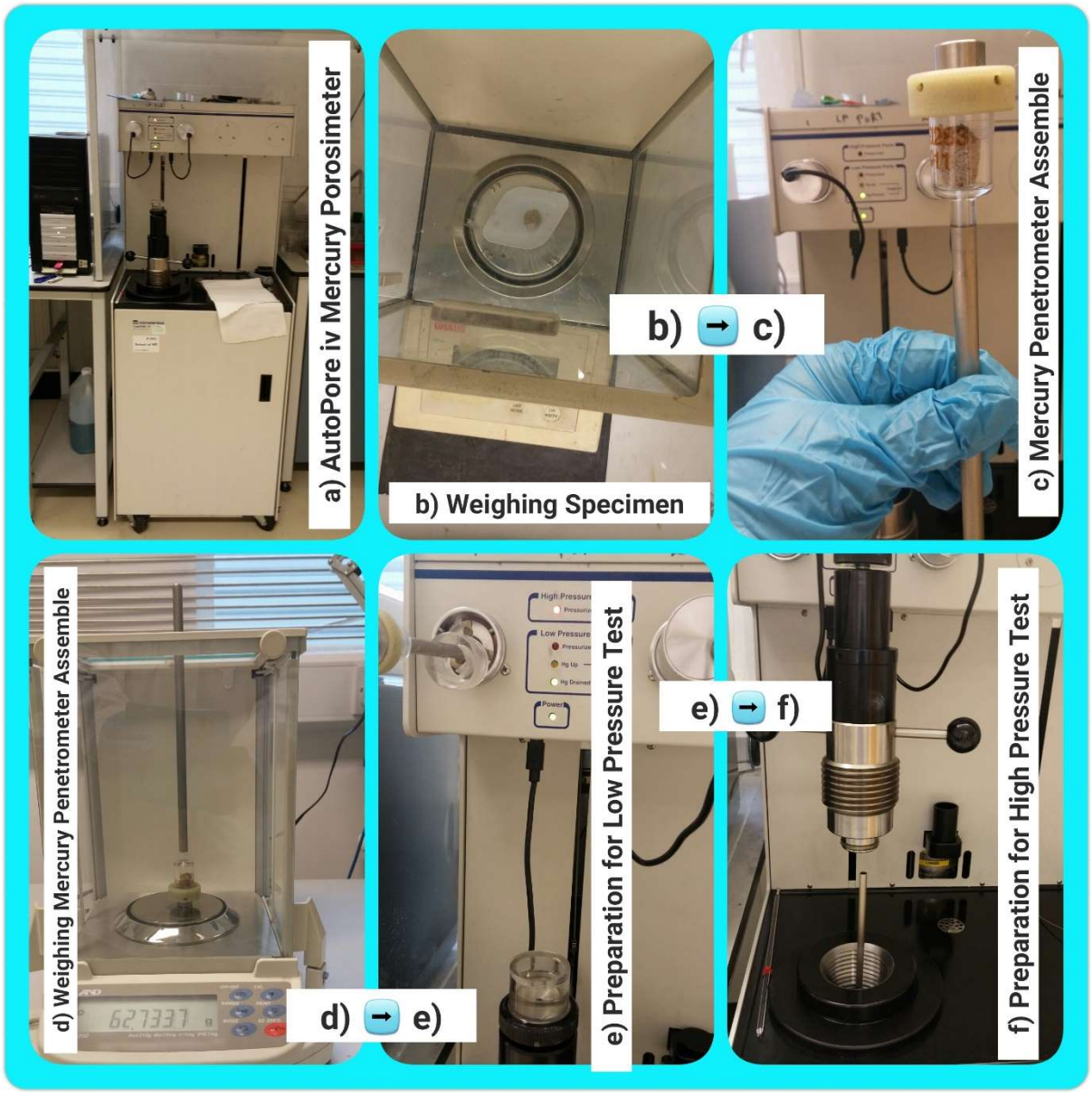

Figure 5.5: Summarized AutoPore IV intrusion mercury Porosimeter measurement procedure.

- **Low pressure port measurement procedure**

Simplified measurement procedure for low pressure port are outline in the following steps.

Step 1: Setting up of measurement on the data acquisition system

A file was created for the specimen to be tested. Information regarding the penetrometer properties, weighed specimen, analysis condition and temperature of the mercury were filled appropriately. Figure 5.6b represents the weighing of the specimen on the digital scale.

Step 2: Penetrometer assembly

The assembly was prepared by inserting the weighed specimen into the penetrometer with a careful application of vacuum grease along its edge to prevent grease penetration into specimen. The penetrometer was placed in its holder, and tightened the locking ring. The penetrometer assembly is weighed before the low-pressure port measurement. The prepared penetrometer assembly and its weighing are shown in Figure 5.6c and 5.6d respectively.

Step 3: Low pressure port measurement

The metal rod in the low-pressure port was removed and placed on the Porosimeter. The penetrometer assembly was then inserted into the low-pressure port and tightened appropriately as represented in Figure 5.6e. The created file in step 1 on the data acquisition unit was updated and started for the low-pressure port measurement. The mercury intrusion volume into the penetrometer assembly at each pressure is measured for the specimen characterisation analysis.

Step 4: Completion of Low pressure port measurement

From the manufacturer's manual, the completion of the low-pressure port measurement analysis is characterised by status of Idle on the data acquisition system.

In conclusion, the low-pressure port measurement takes place at the upper part of the AutoPore IV mercury intrusion Porosimeter as shown on the experimental set-up in Figure 5.4a. The high-pressure port measurement proceeds immediately after the low-pressure port measurement.

- **High pressure port measurement procedure**

Simplified measurement procedure for high pressure port are outline in the following steps.

Step 1a: Set-up for High pressure port measurement

The penetrometer assembly with the filled mercury was removed, grease on the rod was cleaned and weighed for the high-pressure port measurements. The created specimen information used for the low-pressure measurement was subsequently updated. The high-pressure port measurement was carried out in the high-pressure port section as shown in Figure 5.6f.

Step 2a: High pressure port loading

The weighed penetrometer assembly with the filled mercury was loaded into the high-pressure port as represented in Figure 5.6f. The vent valve in the high-pressure port was opened whiles tightening the loaded assembly.

Step 3a: High pressure port measurement

On completion of steps 1a and 2a, high pressure port measurement was initiated on the monitor of data acquisition system. On completion of the high-pressure port measurement, the status on the monitor returned to Idle. The mercury in the penetrometer was carefully poured out and specimen disposed of appropriately.

Step 4a: Repetition of low and high-pressure port measurements

The outlined steps in both low and high-pressure port measurements were repeated for the remaining specimens one at a time until completion. The penetrometer assembly was cleaned and dried following each high-pressure port measurement.

Finally, the data for each specimen was downloaded and collated in an excel spreadsheet.

5.3.24 Procedure for Test Measurement Analysis

The procedure for analysing the measured experiment data was categorised into two sections; the preliminary test and main test results. Figure 5.7 summarizes the procedure for the analysis.

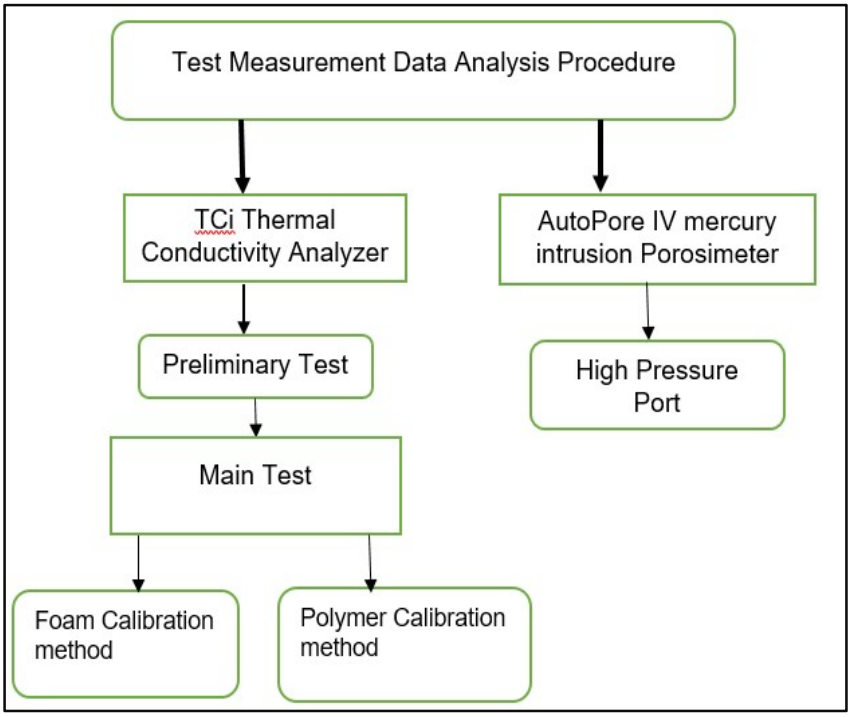

Figure 5.6: Summary for test measurement analysis.

- **TCi thermal conductivity Analyzer analysis**

TCi thermal conductivity analysis was categorized into preliminary test and main test measurement data as shown in Figure 5.7. The preliminary test was used to validate the experimental set-up in Figure 5.4 using the manufacturer's expected measurement of Pyrex glass using polymer calibration method. The main test measurements data were obtained from the selected building fabric from Ghana and the creative

parametric blocks using both foam and polymer calibration methods. Summary of preliminary and main test measurements are as follows.

- **Preliminary test**

Preliminary test was carried out to establish the validity and reliability of the instruments used in the TCi Thermal Conductivity Analyzer experimental setup in Figure 5.4. Preliminary test measurement results of Pyrex glass using polymer test method was compared with Tci Thermal Conductivity Analyzer manufacturer's manual. The expected manufacturer's values for both thermal conductivity and thermal effusivity showed percentage deviation of 7.1% and 0.7% respectively. This implies that, the error arising from the set-up measurement is minor, hence can be neglected in the subsequent readings.

- **Main Test**

The main test data analysis is simplified in Figure 5.7. The collated measurement data for the suitable surfaces of each specimen was examined and analysed using statistics. The examination process of the collated measurement data for the suitable surfaces of each specimen was carried out to remove all incorrect readings from both foam and polymer calibration method until the completion of the. Analysis of variance was used to validate the obtained measurements from main test method against CIBSE Guide.

- **AutoPore IV Mercury Intrusion Porosimeter**

As stated above, the AutoPore IV Mercury Intrusion Porosimeter measurement comes out with detail characterisation of the specimen properties simultaneously per each test. The bulk density data was extracted out of the other properties of the specimen obtained from the high-pressure port. All the densities were collated and converted into SI units.

5.3.3 Data collection through Simulation

Simulation is the dominate method in literature for assessing building performance in both scientific journals and technical documents. The parameters and data required to design the building were selected in accordance of BS EN ISO 9000 and CIBSE Guides. The resulting data from the simulation is numeric models. The detail methodology for the simulation is presented in Chapter 8. Methodologies of characteristic building performance researchers were adopted and modified (Rysanek and Choudhary 2012; Melo et al., 2014; Echenagucia et al.,2015 and Ward et al., 2016).

5.3.31 Purpose of Computer Simulation

The purpose of the simulation is to assess and optimize representative building design variables obtained from experimental study and survey questionnaire.

Specific objectives for accomplishing the main simulation purpose include the following:

1. To investigate the suitability of fabric selection and envelope design in achieving building elements variables in Ghana regulation.
2. To assess the impact of characteristic building professional's practices on design variables before and after the enactment of Ghana building regulation.
3. To optimize typical building design variables in Ghana to achieving recommended good building performance as stated in CIBSE Guides and ASHRAE standards
4. To incorporate chilled beam low cooling technology into the numerical whole building in minimizing dehumidification load arising from:
    i. Infiltration
    ii. Vapour diffusion factor of building material
    iii. Ventilation
    iv. Climate dependent variables

5. To assess the suitability of recommending one good practice for electricity utilisation of service equipment by CIBSE Guide for building types in different climate.

In conclusion, the accomplishment of the specific objectives outlined above would yield a robust cost effective solution in optimizing typical building performance in hot-humid climate in developing countries.

5.3.32 1Computer Simulation Scenarios

The representative rectangular base office building form was selected out of the survey questionnaire as well as building envelope performance design variables before and after the enactment of Ghana building regulation. The identified major difference between building envelope performance design variables before and after the enactment of Ghana building regulation was varying floor to ceiling height and constant floor to ceiling height for multi-storey building respectively.

The selected building envelope form was modelled and simulated using the design variables from survey questionnaire and experimental study in ESDL Tas. Preliminary simulation was carried out to assess the adequacy and suitability of ESDL Tas software in achieving the overall aim of this research. The subsequent simulations were carried out base on four different stages as follows:

Stage One: Based on climate type that is hot-humid and hot-dry climate. NB. Accurate data for the Northern part of Ghana which is hot-dry climate was not obtained, hence not considered in the computer simulations.

Stage Two: Based on performance of envelope design variables for before and the enactment of Ghana building regulation.

Stage Three: Based on performance of envelope design variables for after the enactment of Ghana building regulation

Stage Four: Integration of chilled beam technology into combination optimum practical design variables obtained from the parametric simulation of the subgroups using base

building form from envelope performance design variables after the enactment of Ghana building regulation.

The detail simulations under each of the three stages are as follows:

Stage One

- **Based on climate type that is, hot-humid (Ghana) and hot-dry climate.**

From the Survey questionnaire in 2014 it was concluded that, the parametric simulations for representative building envelope in Ghana did not meet the recommended good practice for service equipment electricity utilization by CIBSE Guide. In view of this, a typical hot-dry climate condition was selected to verify, the suitability of CIBSE Guide recommendation under different climate conditions.

The simulation under Stage One on the base building was carried out in two different scenarios namely:

- Use of Ghana weather data with building envelope performance design variables before the enactment of Ghana building regulations.
- Use of Ghana weather data with building envelope performance design variables after the enactment of Ghana building regulation.

On completion of the Stage One simulations, the detail parametric simulations in Stage Two were based on Ghana climate for design variables before and after the enactment of Ghana building regulation.

Stage Two

- **Based on building envelope performance design variables for before the enactment of Ghana building regulation.**

The parametric simulation was based on the use of Ghana weather data for building envelope performance design variables before the enactment of Ghana building regulation scenario. The rationale for the selection of this scenario was based on the impact of varying floor-to ceiling height design across the multi-storey building on the overall cooling load.

The details of the novel parametric simulations are in subgroups as follow:

a. Varying Thermostat Setting: temperature setting and relative humidity setting
b. Varying Ventilation Gain
c. Varying Infiltration Gain
d. Varying vapour diffusion factor of cement based building fabric.
e. Varying the thermal conductivity of opaque building fabrics
f. Varying the window pane technologies
g. Varying equipment gain
h. Varying thickness of opaque building fabrics
i. Propose envelope design and fabrics.

Five different values of each design variables in the sub groups were selected and simulated keeping all other variables constant. The results of each simulation at a given value was plotted for all the subgroups. The sensitive variables with respect to hot-humid climates building performance were outlined.

The minimum practical design variables obtained from the novel parametric simulation of the subgroups in Stage two, were then combined into the following main scenarios:

i. Combinations of design variables (before 1996 building regulation) for Ghana weather data.
ii. Combinations of design variables (after 1996 building regulation) for Ghana weather data.

The detail simulations under each combinations of design variables as listed above are as follows:

- **Detail Combination of design variables (before 1996 building regulation) for Ghana weather data scenario include the following:**
    1. Base Case for Ghana using building design variable before 1996 building regulation
    2. Combination of all simulated low practical thermal conductivity building fabric with base internal condition from survey questionnaires, 2014.

3. Combination of all simulated low practical internal condition values with base case building fabric from survey questionnaire.
4. Combination of all simulated low practical values for building fabric and internal conditions variables.

- **Detail Combination of design variables (after 1996 building regulation) for Ghana weather data scenario include the following:**
  - Base Case for Ghana using building design variable after 1996 building regulation
  - Combination of all simulated optimum practical thermal conductivity building fabric with base internal condition from survey questionnaires, 2014.
  - Combination of all simulated optimum practical internal condition values with base case building fabric from survey questionnaires, 2014.
  - Combination of all simulated optimum practical values for building fabric and internal conditions.

Stage Three

In Stage Three, the base case used was the building envelope design after the enactment of Ghana building regulations.

From the completion of the detailed novel parametric simulations in Stage Three, the reviewed chilled beam low cooling technology was incorporated into combination of all simulated optimum practical values for building fabric and internal condition to obtain Stage Four

Stage Four

Chilled beam low cooling technology was integrated into combination of all simulated optimum practical values for building fabric and internal conditions using after 1996 regulation building design scenario for Ghana weather data. Summary of the simulation scenarios is shown at Figure 5.8.

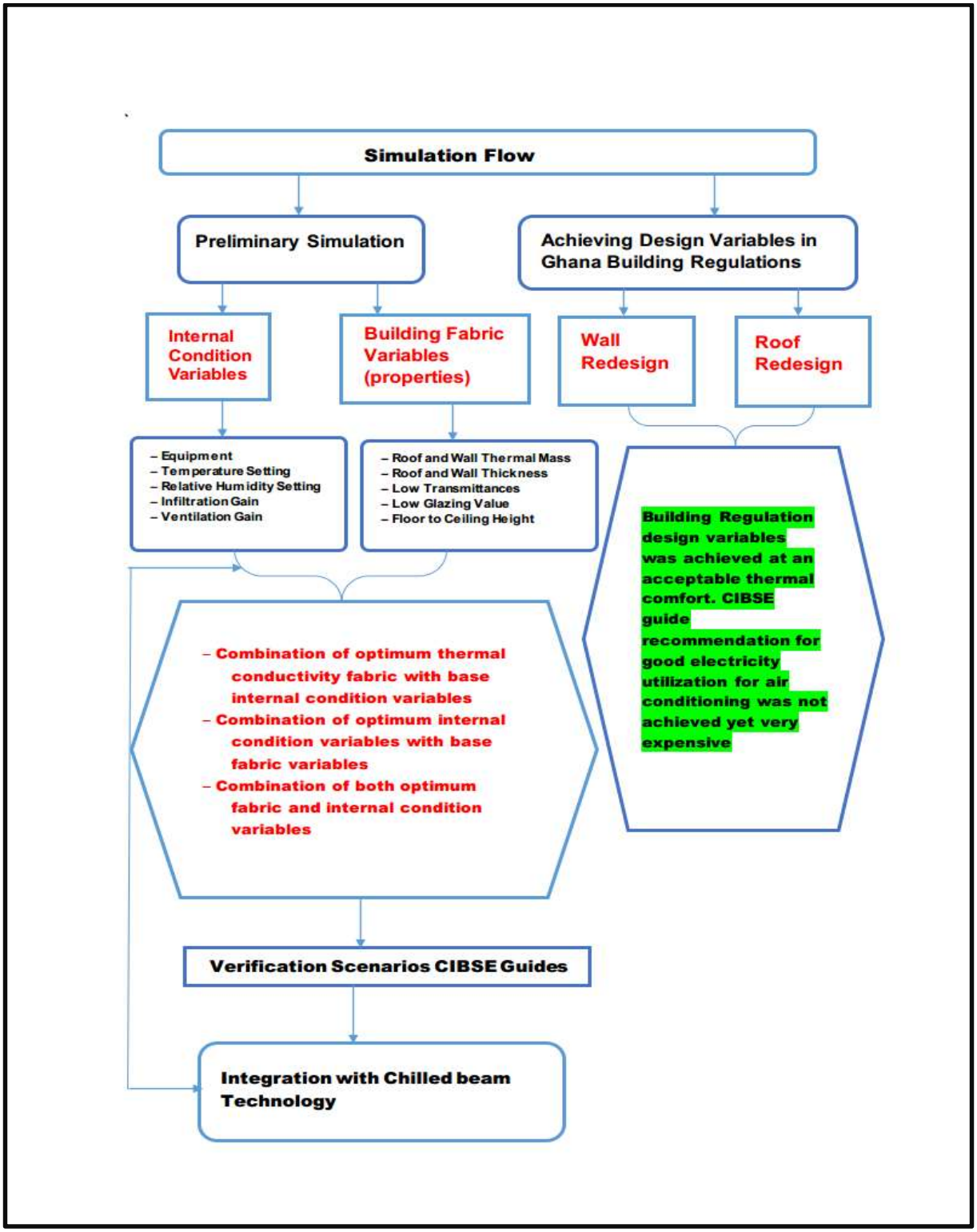

Figure 5.7: summarizes the preliminary and novel parametric simulations.

5.3.33 Procedure for Simulation Analysis

The simulations data were plotted using Microsoft Excel for electricity utilization loads (KWh/m^2) against scenarios for all simulations in section 5.3.32. The resulting correlations between the design variables and resulting electricity utilization loads were estimated. The resulting building performance assessment indicators were compared against recommended CIBSE Guide and the characteristic survey questionnaire. A detailed subsection for simulation analysis include preliminary, novel parametric and integration of chilled beam.

a. Preliminary Computer Simulation

The preliminary simulations included the electricity and thermal performance assessment of the base building scenarios outlined above for Ghana. The resulting cooling loads for HVAC system, equipment and lighting load were discussed and compared with the recommended good practice outlined in CIBSE Guide. The obtained predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) were discussed and compared with ASHRAE 55 standard.

b. Novel Parametric Computer Simulation

The novel parametric simulations were discussed and analysed to observe the sensitive variables as well as the trends of the correlations between electricity utilization and the resulting design variables. The novel parametric simulations are as follows:

i. Thermal Mass (Concrete and mortar block)
ii. Ventilation Gain
iii. Infiltration Gain
iv. Temperature setting
v. Relative humidity setting
vi. Equipment Gain
vii. Window pane technology
viii. Window to wall ratio

ix. Vapour diffusion factor
x. Varying thickness of opaque building fabrics
xi. Propose envelope design and fabrics.
xii. Thermal conductivity of opaque building fabrics

c. Integration of cost effective technology in solving high dehumidifying load

The simulation results for the enhanced building electricity performance using simulated low practical optimum design variables and incorporated chilled beam low cooling technology for Ghana were compared with CIBSE Guide.

In conclusion, the following significant findings on the research methodology were: 1. the mixed research methods and the creative designs outlined above were suitable in achieving the research aim. 2. The predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) from the simulation was acceptable in accordance with ASHRAE 55 standard enhance there was no need for thermal comfort enhancement. 3. From the enhanced building performance using low practical design variables and incorporated chilled beam low cooling technology shows that, the recommended electricity utilization for cooling load in CIBSE Guide is not achievable in different climates using the same building envelope design variables and internal conditions. 4. From the novel parametric experiment using the mixing design ratio and sand type in both mortar as well as concrete blocks proved to be cost effective approach in minimizing thermo-physical propertied of cement-based fabric. 5. Finally, the use of multi-stage sampling techniques is an effective sampling approach for enhancing online response rate.

5.3.4 Data collection through Economic Assessment comparator decision tool

Several modifications have been proposed through this research for enhancing building performance. Due the major concern of cost effectiveness of building professionals in Ghana, it is essential to undertake economic assessment of all proposed approaches for enhancing building performance.

Representative economic assessment tools integrated in some commercial building simulation software are available in the market. Among them are ESDL Tas; EnergyPlus, DesignBuilder; Safaira Architecture; TRACE; Trane 700 Chiller Plant Analyzer; ESP-r; eQUEST; Bsim, TRNSYS and etcetera. On the other hand, there is knowledge gap identified from the review on the existing software listed above on the proposed optimized building performance scenarios considered in this research. In view of this, comparator decision tool has been designed to facilitate the economic assessment. Economic comparator tool was design in accordance to ISO 14040:2006 (E) standards for life cycle assessment.

- ❖ The following are the capabilities of economic comparator assessment decision tool:

1. Comparator tool should validate the user input of annual cooling load with recommended CIBSE Guide for typical good practice for standard airconditioned office building.

Note

Recommended cooling load for typical practice for standard air-conditioned office = 31 (kWh/m^2)

2. Compare the payback of the modified building and the difference in cost for modification with typical short and long term risk free investments.
3. Simple comparison method i.e. easy to understand and interpret by decision maker.
4. Suitable for both early design and retrofit stage.
5. Tool can be applied to calculating heating load, on the contrary, the comparison with CIBSE Guide would have to be carried out manually.
6. Can be integrated into an existing building simulation software.

- ❖ The assumptions made for the cost calculations are:

1. The energy used for cooling is electricity and it is in per kilowatt-hour; this cost will be considered as constant along buildings' life span. That is, Constant Electricity tariff (kWh) per annum for commercial buildings with consumption of 301-600(kWh) = 0.26 'Ghana pesewa' for the life cycle.

2 The building life span is fifty years.

3 The modification effect is on the cooling load only.

4. The difference in modification cost accounts only for the building fabric and service equipment hence maintenance cost through the life cycle is neglected.

Due to the assumptions made, there are some limitations of the tool. The limitations include the following:

1. Cooling loads should be determined by the user using accurate cooling calculation method i.e. simulation or manual calculation.
2. Due to price variation of building fabric and service equipment from different companies, decision maker should estimate the costs associated with the project.
3. Due to the technical difficulties associated with calculating indoor environmental performance, it's recommended that, it should be calculated separately.

❖ The potential users of the tool include the following:

1. Management of organizations
2. Researchers
3. Building Professionals
4. Technical Teaching aid
5. Students

5.3.41 Purpose of Economic assessment

The overall purpose of this economic assessment is to develop a novel multi-variable comparator economic assessment tool to simplify decision making of proposed optimized design variables, compare the resulting modified cooling load with CIBSE Guides and recommend best alternatives.

The main objectives include:

1 To critically review scientific and technical data on multi-variable life cycle cost analysis tools.
2 To acquire representative multi-variable life cycle cost design variables from Ghana through survey questionnaires.
3 To develop novel multi-variable comparator life cycle cost analysis tool using standard equations from economics through visual basic software.
4 To assess and compare the cost effectiveness of the proposed optimized building performance on cooling load electricity savings, simple cost of returns and other factors on modification against recommended good practice of CIBSE Guide

5.3.42 Procedure for Economic Assessment Analysis

Representative multi-variable life cycle cost design variables from Ghana were sorted from architects, building service and building fabric manufacturers survey questionnaires subsequently analysed using statistical description.

The selected parametric percentage modification cost became necessary due to the following challenges encoutered during the costing:

1. The modified transparent (glazing) and opaque building fabric (low thermal conductivity) are not available in Ghana.
2. Emails and telephone calls made to selected companies in UK for cost estimate was not sucessful, since they all indicated that assistance can not be given to proposed buildings.
3. Discrepancies obtained from prices of building fabric from marketing websites like Alibaba, Amazon among others.

In view of the above challenges, parametric pecentage modification cost was in an increment of 5 in the range of 5% to 25% were considered to address the price discrepancies.

Three main scenarios were considered in the parametric case studies in Ghana. Two scenarios were from the computer simulations in Chapter 8 and one hypothetical scenario. The three scenarios for the parametric studies are as follows:

- Building design before 1996 building regulation
- Building design after 1996 building regulation.
- Hypothetical case (Building design before 1996 building regulation cooling load and cost of Building design after 1996 building regulation)

Out of these three scenarios, four different cases were considered as follows:

Case 1: Combination of all optimum internal condition values with base case building fabric

Case 2: Combination of all optimum thermal conductivity building fabric with base internal condition

Case 3: Combination of all optimum values (building fabric and internal conditions)

Case 4: Combination of all low values (building fabric and internal conditions) with chilled beam low cooling technology

Conversely, Case 4 that is, the incorporation of chilled beam low cooling technology into combination of all low values (building fabric and internal conditions) for building design before and after building regulation enactment increased the cooling load for Ghana climate. In view this, it is recommended that different low cooling technology should be incorporated in a different building simulation software package this is because of limited technologies in ESDL Tas used, hence not considered in this assessment. All the above scenarios were considered for both high and low electricity tariffs.

The economic assessment data obtained from the comparator decision tool were plotted using Microsoft Excel for the following:

i. Difference in cost of modification vs cooling load

ii. Difference in cost vs savings per annum

iii. Difference in cost vs savings over life time for all the scenarios

The correlation of difference in cost of modification and annual cooling load for all the scenarios were obtained to predict the cost of modification for achieving the recommended good practice for cooling load outlined in CIBSE Guide. Trends were observed for difference in cost vs savings per annum as well as savings over life time. All the simple payback calculations were below one year hence no detail analysis was carried out on it. In conclusion, the resulting graphs listed above from each scenario were compared to obtain the most appropriate optimized modification scenario for hot-humid tropical climate and the resulting results is in consistent with Fernández-Membrive et al.,2015.

6. CHAPTER SIX: SURVEY QUESTIONNAIRES

6.1 Data Sorting, Analysis and Discussion

The mixed quantitative and qualitative data received from participants of the survey questionnaires were examined, sorted and categorized along the following clusters for analysis with cognizant of the general assumptions above:

- General Information for research problem
- Building Professionals Practices and Building Regulation Appraisal
- Typical Design Variables for whole building simulation
- Occupants Comfort and Satisfaction Perception

The data sorting was undertaking to extract the relevant and appropriate questions into the respective cluster to facilitate easy analysis.

6.2 General Information for research problem

From building professionals' respondents, the trend of office building designs since the worst 2007 electricity crisis in Ghana have being;
57.1% indicated that it has complicated building design with about 70% glass fabric, 23.4% indicated that there have being no change and 9.1% indicated that there have being sustainable building design with bioclimatic and passive technology incorporation. According to 63.2% respondents, fully passive multi-story office building designed and constructed at efficient cost, low energy utilization and comfortable indoor environment cannot be accomplishing in Ghana climate. Typical reasons why this cannot be achieved in Ghana being cost, climate and building materials. 50% of participants indicated that upfront cost of 30-50%of additional expenditure would be incurred if passive building design consideration is chosen above conventional building design, built with the present building regulations. Though there is an extra cost to be incurred for opting passive building designs, 67.5% of clients are interested. There are general assumptions relating to this subject area of the survey questionnaire that the following have significant impact on design variables:

1. Local building professional's practices.
2. Content of the local building regulation
3. Level of implementation and enforcement of the building regulation.

6.2.1 Building Professionals Practices and Building Regulation Appraisal

Building professional's practices and building regulations are sorted, analysed and discussed along the following clusters:

i. Building Envelope and Service Equipment Design
ii. Building Materials Manufacturers
iii. Government Agencies
iv. Typical Technology integrated in Buildings
v. Building Regulation Appraisal
    a. Cost effectiveness analysis (cost effectiveness)
    b. Equality impact assessment (Proportionality, consistency)
    c. Outcome evaluation (ease of implementation, flexibility, government effectiveness in implementation)
    d. Opportunity analysis (empirical basis, adequacy and modification

i. Building Envelope and Service Equipment Design

Building envelope and service equipment design encompasses building professionals' practices with respect to performance assessment, envelope design, selection of building fabric, sizing of service equipment, design decision for natural and mechanical cooling. For clarity of presentation, the following sub groups were considered:

a. Natural and Mechanical cooling design for both building envelope and equipment sizing.

b. Appraisal of building professionals' practices on regulations/codes and performance assessment
c. Application of adjustment factors by building professionals
d. Building performance assessment tools
e. Building Performance validation methods
f. Factors influencing selection decisions of building professionals
g. Typical factors used for sizing service equipment

a. Natural and Mechanical cooling design for both building envelope and equipment sizing.

Substantial building service engineer's participants representing 78% indicated that, mechanical cooling type is used in Ghana office buildings; with 34%, 30% and 29% been the typical mechanical cooling type of central; split and window air-conditioning systems. Figure 6.1 represents characteristic architect and building service engineering participants' opinion on difference in natural and mechanical cooling design strategies for office buildings.

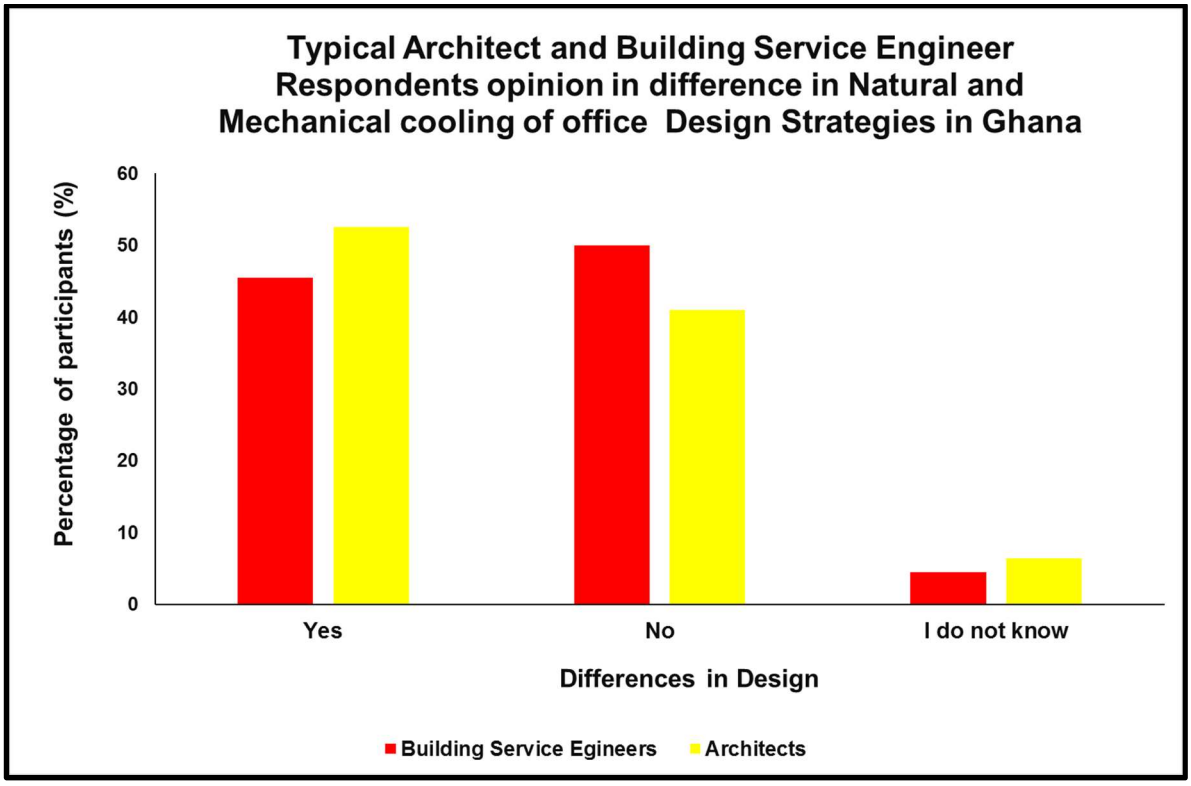

Figure 6.1: Typical difference in natural and mechanical cooling design strategies

In Figure 6.1, significant percentage of architects representing 52.6% did acknowledge that, there is difference in building design for natural and mechanical cooling buildings compared to 45.5% of building service engineering participants. The objective of this question was to ascertain the knowledge and skills of both architects as well as building service engineers on the energy utilization finding of converted natural cooling office buildings to mechanical cooling buildings identified in the field study. The main difference in natural and mechanical cooling building envelope design given by architectural participants were window to wall ratio, floor to ceiling height, air circulation design and clients' specification. In the critical reviewed literature, window-to-wall ratio and floor to ceiling height are the key building performance indices. As indicated by the architectural participants, the main difference between natural and mechanical cooling building designs are the key building performance indices. In view of this, for 50% and 4.5% of building service engineering participants indicating no difference and I do not know respectively hence this calls for further investigation into air-conditioning sizing in Ghana.

As a result of this discrepancy, further investigation into the building envelope design and sizing of air-conditioning system would be undertaking using computer simulation.

In conclusion, the identified discrepancy in knowledge and skills of both architects and building service engineers in Ghana on natural cooling building design converted into mechanical cooling building would be solved through computer simulation. The solution of this discrepancy, would improve air-conditioning sizing and enhance building performance in general.

b. Appraisal of building professionals' practices on regulations/codes and performance assessment

From the field study, building professionals' in Ghana uses several building codes and regulations as part of their practices. Figure 6.2 is the typical building codes/regulation use in Ghana by building professionals for performance assessment of designs, sizing and selection of service equipment.

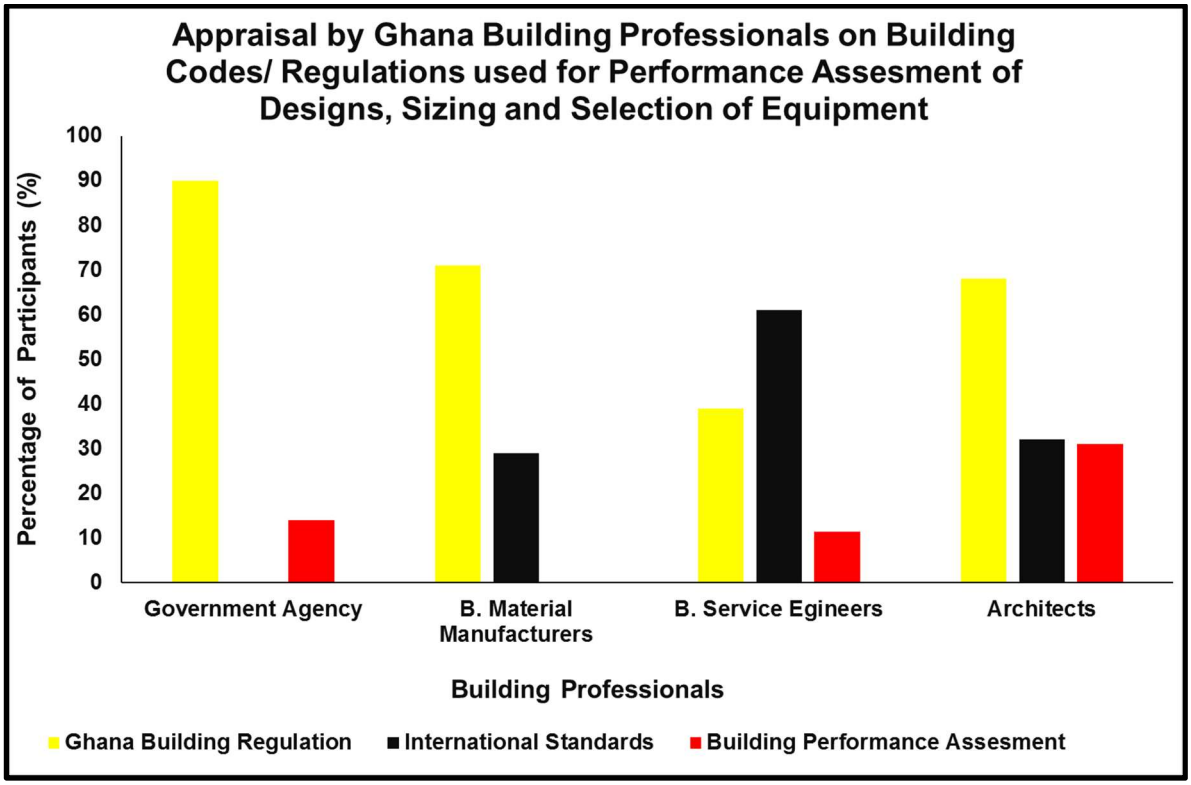

Figure 6.2: Appraisal of building professionals' practices on regulations/codes and performance assessment.

On the use of Ghana building regulation in practice by building professionals, it can be seen that the highest user is government agencies representing 90%, followed by building materials manufacturers followed by architects and finally the building service engineers. The high percentages of architects and building material manufacturers using Ghana building regulations in Figure 6.2 is because of the well-defined description of design variables as well specifications regarding their practices. On contrary, the reverse scenario happens when it comes to the use of international standards. International standards constitute all codes/regulations/ policies enacted outside Ghana example, CIBSE Guide, ASHRAE standards, ISO standards, British standards among others. 61% of Building Service Engineers depend significantly on international standards compared to Ghana building regulations. This has become a necessity as a result of the prescriptive nature of Ghana building regulations and lack of the design variables needed by building service engineers for selecting and sizing service equipment within Ghana. Conversely, it should be noted that government agencies do not use international standards within their practice, this is as a result of the area of concern.

In conclusion, the level of usage of design variables outlined in the respective regulation/codes play significant role in selecting a regulation/codes among professionals for practices.

On building performance assessment 31.1% of architects do assess building performance of their designs compared to 11.4% of building service engineers. Building performance assessment is plays very important role enhancing indoor environmental quality and energy utilization. The key building professionals to assess building performance from design stage to occupancy in Ghana are the architects and building service engineers. On the contrary, from Figure 6.2, the percentages are very poor among architects and building service engineers. This practice has contributed to high energy utilization and discomfort indoor environmental among the selected buildings. Government agencies should have been the highest percentage of professionals to undertake building performance assessment. On the other hand, it is the opposite; this is because of the procedure for issuing building permit. From Ghana building regulations procedure, performance assessment of the design is not a requirement for issuing the permit; rather a signed engineering drawings by an

assigned professional authority. Building material manufacturers do not take on building performance assessment, on the other hand they rather measure properties of the fabrics.

In conclusion, the percentage total of building professionals with the exception of material manufacturers, who undertake building performance is insignificant representing an average of 19%. This low average percentage of building professionals undertaking performance assessment can lead to adverse energy utilization and indoor environmental discomfort. Hence, there is the need for comprehensive research to be carried out on building performance assessment to ascertain the suitability of the characteristic design variables use in section 6.4.2.

c. Application of Adjustment Factors by Building Professionals

Adjustment factors are assumed subjective values applied to standards or parameters for correcting unanticipated errors. In Ghana, adjustment factors are often referred to as 'correcting factor' among professionals. It is applied mainly to standard to adjust variables based on climatic conditions or scenarios different from Ghana practices. Adjustment factors are mainly based on professional experience, experimental assessment, simulation, among others.

Figure 6.3 shows the representative percentages of building professionals adjustment factors used in practice.

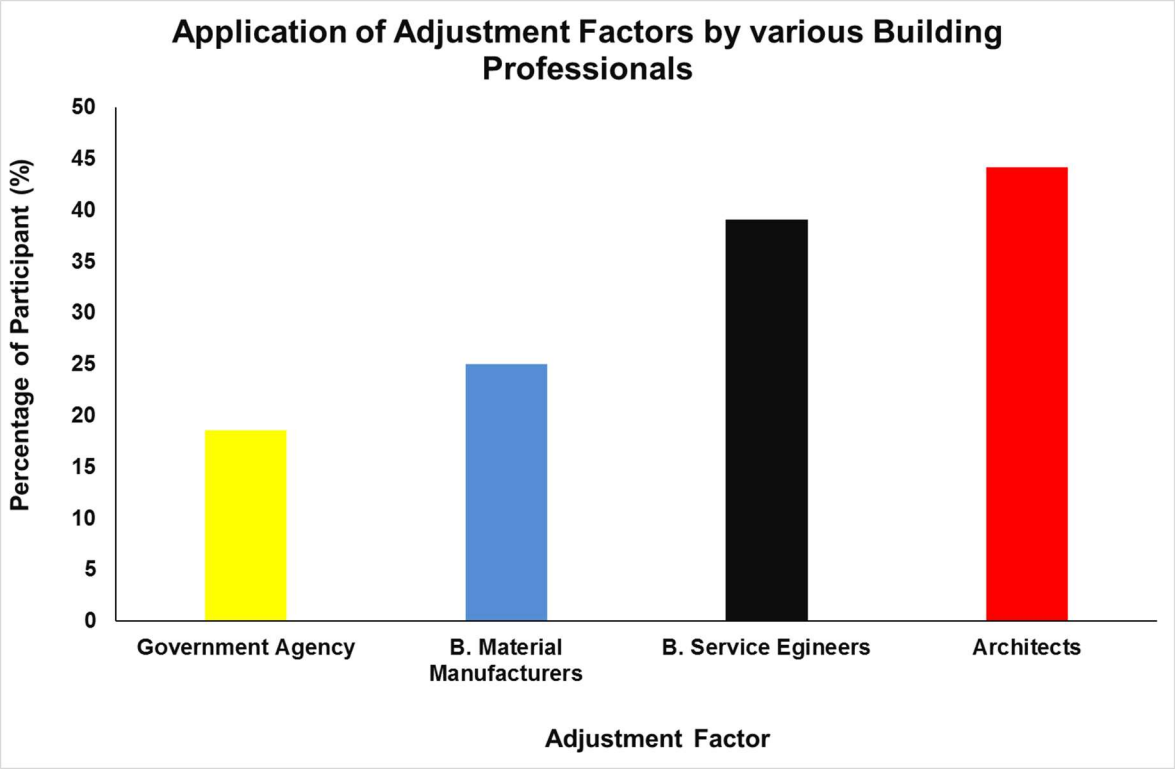

Figure 6.3: Application of Adjustment Factors by Building Professionals

In Figure 6.3, government agencies are the least user of adjustment factors, this is because they are more of service providers in terms of designing codes/regulations/policies and implementation. 25% of building materials manufacturers use adjustment factors this is expected as of the responses obtained in Figure 6.2. The design specifications for manufacturing building materials are adequately presented in the building regulations hence, the less dependency on international standards and application of adjustment factors. On the contrary, the percentage of architectural participants using adjustment factors were 44.5% which is the highest. There is the need for further investigation into the architectural finding. In Figure 6.2, 68% of participants indicated they use Ghana building regulations in practice; for 44.5% to apply adjustment factors to the regulations, then there is the need for practical appraisal of Ghana building regulations. In Figure 6.2. 61% of building service engineers use international standards for practice with 39% percent of participants using Ghana building regulations. For 39% of building service engineers to apply adjustment factors, then detailed assessments of characteristic design variables are required to ascertain its suitability under Ghana's climate.

In conclusion, detailed assessment of practical design variables used by building service engineers would overall be of significance in enhancing building performance especially the energy utilization in buildings.

d. Building performance assessment tools

As found in Figure 6.2, an average of 19% of building professionals do assess performance in Ghana. Out of this percentage, the characteristic computer building simulation software use is represented in Figure 6.4.

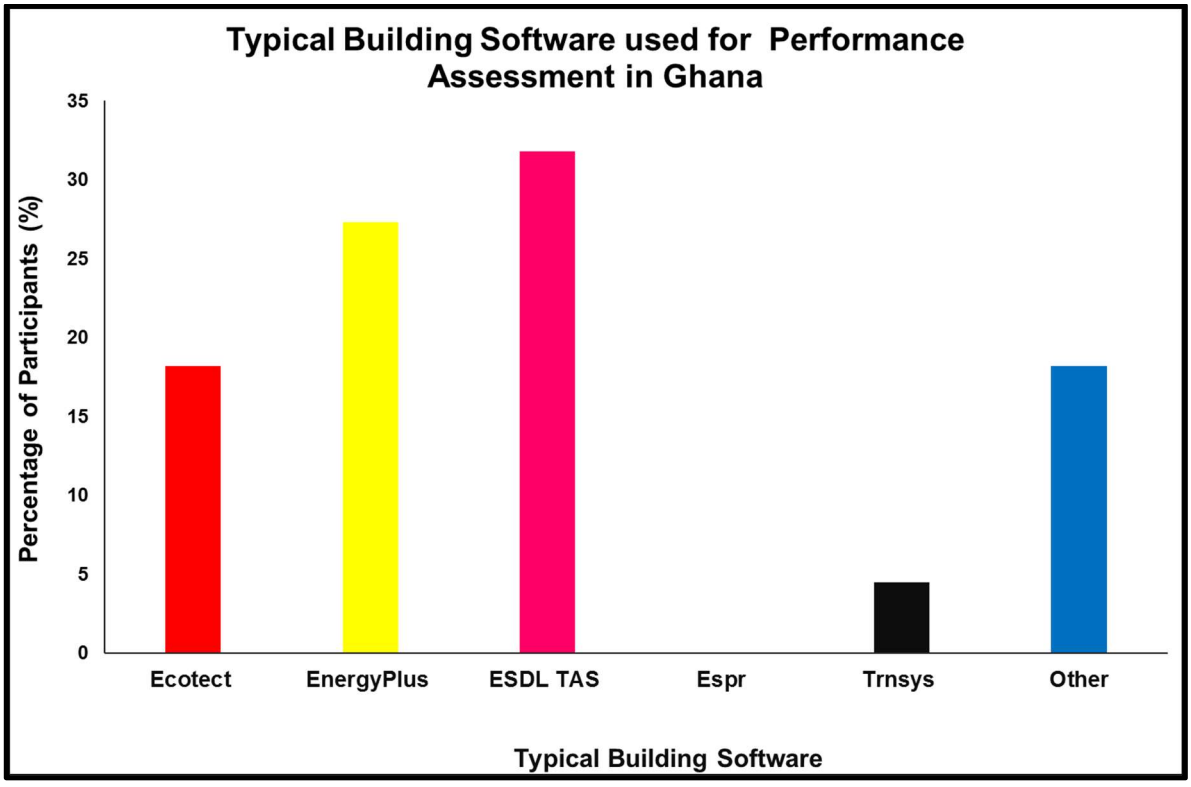

Figure 6.4: Typical Building Software for performance analysis

The major computer building simulation software use among building professionals is ESDL TAS followed by EnergyPlus. No building professional participant indicated using Espr; the main reason for this cannot be explained.

Further research will be recommended to investigate the reason behind the selection of any software for performance assessment in Ghana is due to availability, accuracy, cost, ease of usage, among others. It can also be inferred from Figure 6.4 that, there is little difference between the use of Ecotect and the other software currently use in Ghana. The details of each software are outlined in chapter 4. ESDL TAS was selected for computer simulation due to its dominant use in Ghana.

e. Building Performance Validation Methods

A follow up question was put to the low percentage of participants who undertake building performance assessment from Figure 6.2 and 6.4 to obtain overall understanding of their valuation procedures in practices. Figure 6.5 shows typical performance indicators use in validating performance assessment by building professionals in Ghana.

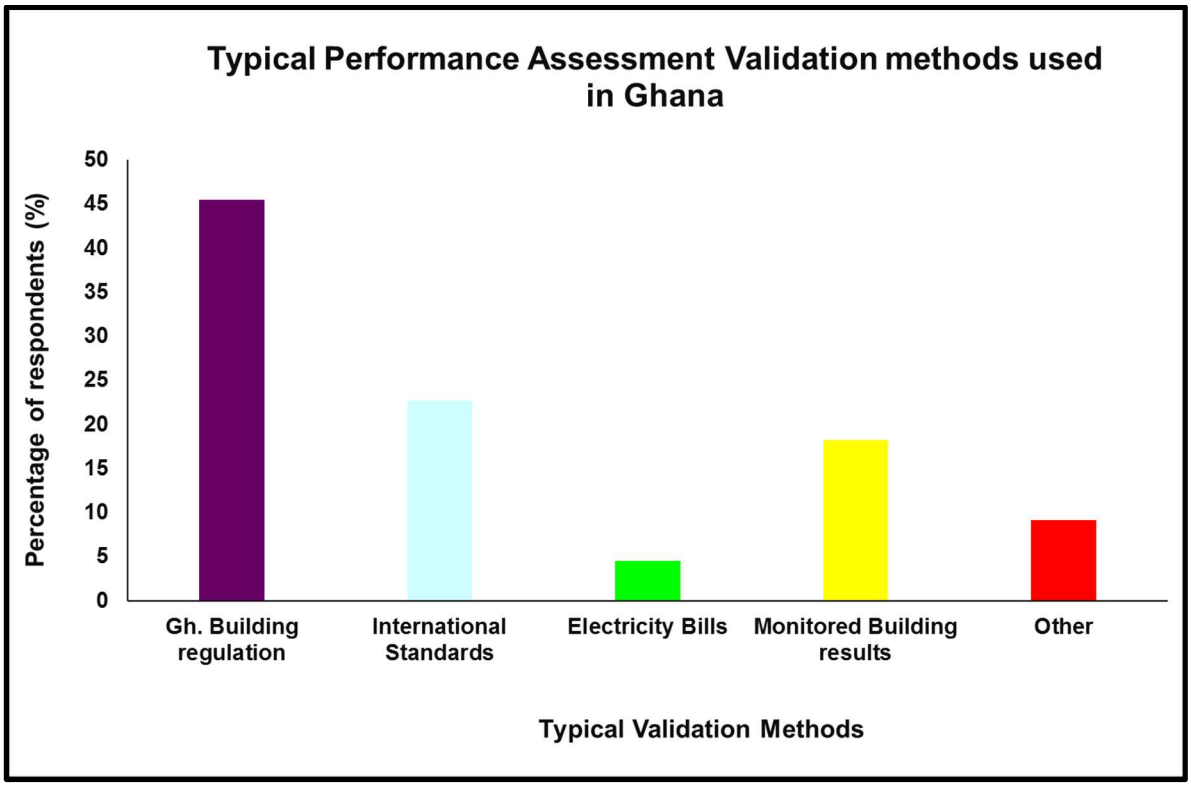

Figure 6.5: Typical performance assessment validation methods

Although, from Figure 6.2 the percentage of building professionals who conduct performance assessment is low, it is worth noting the typical validation methods used. From Figure 6.5, majority of the building professionals use Ghana building regulations for assessment followed by international standards, with the least being electricity bills representing 45.5%, 22.7% and 4.5% respectively. This result was expected since building service engineers depends significantly on international standards with just about 11.4% conducting building performance assessment as seen in Figure 6.2. From Figure 6.2, significant professionals use Ghana building regulations in practice, hence the highest percentage is as expected. The use of electricity bills for validation of performance assessment is mainly undertaken by building service engineers mostly during the post occupancy stage; hence the 4.5% percentage is as expected compared to Figure 6.2.

Monitored building results are predominantly carried out by both building service engineers and architects in Ghana, although, it is accurate and efficient method, its percentage of usage by professionals is low compared to the use of Ghana building regulations and international standards.

f. Factors Influencing Selection Decisions of Building Professionals

Within the critical reviewed literature, there are several factors influencing selection decisions of building professionals' practices. On the other hand, the selection of designs and equipment varies among other professionals based on its role within designing and finishing of building envelope. The representative factors common to all the building professionals' practices were used to assess the details behind the trend of selection pattern in Ghana. Figure 6.6 shows the typical Factors which influences selecting selection decision of building professionals in Ghana.

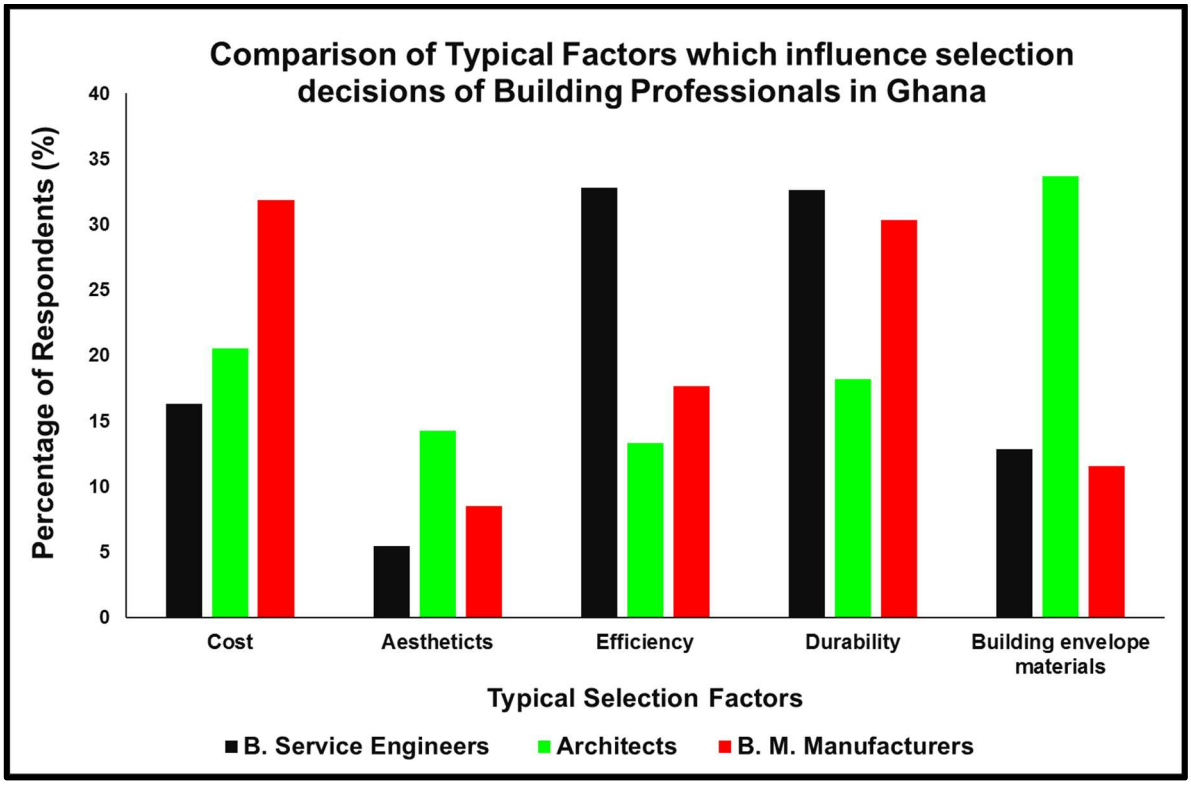

Figure 6.6: Typical Selection Factors used by Building Professionals

The typical factors for selecting designs and service equipment by building professionals are being shown in Figure 6.6. The highest characteristic selection factors varied among building service engineers, architects and building material manufacturers. It can be seen that, building envelope materials is the highest representative factor for architects, whiles efficiency and durability are the typical highest factors for building service engineers, and cost being the highest typical selection factor for building material manufacturers. Aesthetics was the least factor that influenced the selection decision of building material manufacturers and building service engineers whilst the least factor for architects was efficiency. These findings are contrary to a similar work undertaken in Ghana by Oppong and Badu, 2012. Within the findings of Oppong and Badu, 2012, the highest factor for selecting building material preferences and architectural practices were based on aesthetics with the least been investment into performance enhancement.

g. Typical factors used for sizing service equipment

From the field study, 66% of building service engineering participants indicated that building materials used currently in Ghana's climate is suitable. From Figure 6.2, though only 11.4% of building service engineers do conduct building performance assessment; typical factors use in sizing service equipment is essential. Figure 6.7 is typical factors use in sizing service equipment by building service engineers.

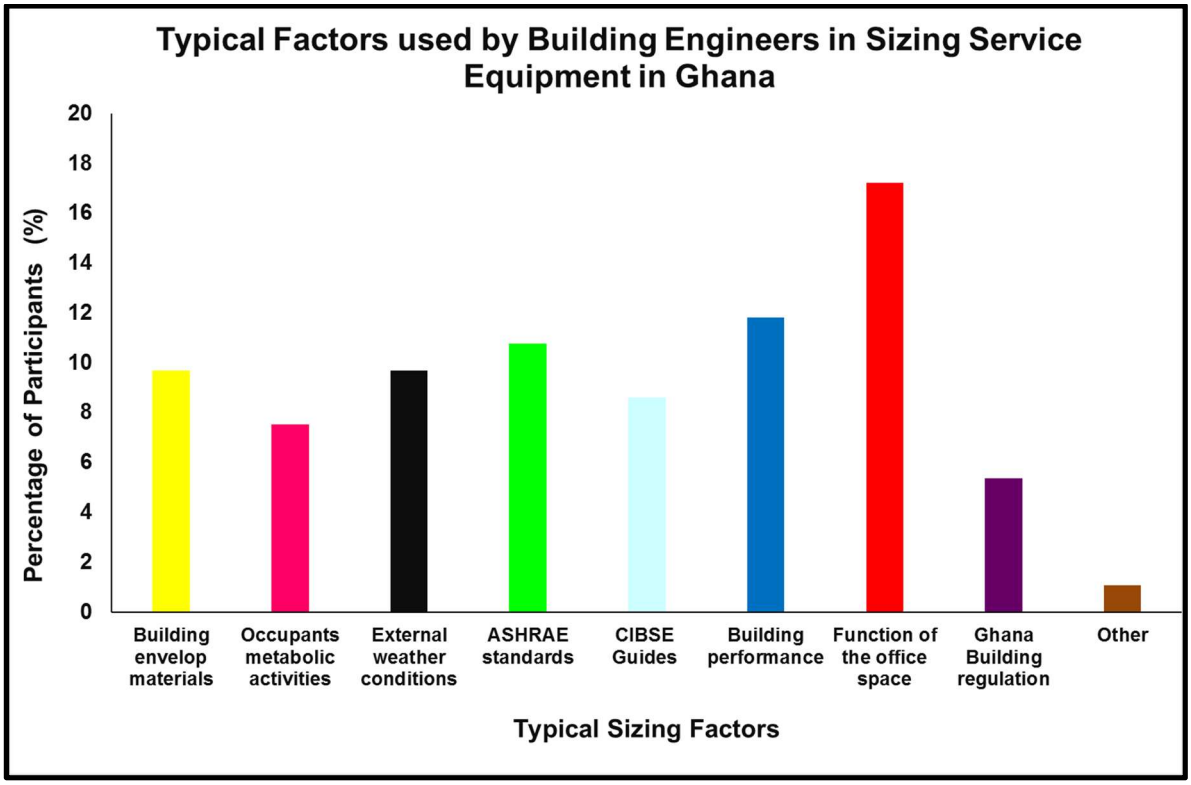

Figure 6.7: Representative factors used for sizing service equipment.

As shown in Figure 6.7, the results are fairly distributed among the factors. From the reviewed literature, in sizing service equipment, building envelope materials and external weather conditions are major factors considered. On the contrary, in Ghana, the function of the space and building performance (energy utilization and indoor environmental quality) were the most predominant factors. The percentages for the ASHRAE standards and CIBSE Guides as compared to Ghana building regulations

by building service engineering participants shows consistency in response of the regulations use in practice from the previous analysis. In conclusion, the factors use by building service engineers in Ghana within practice is in consistent with reviewed literature except for the order of priority.

ii. Building Material Manufacturers'

Building Material Manufacturers analysis was categorized into two:

1. Local Building Materials Survey Data

Local building materials survey data investigated the local materials being promoted and the factors affecting its implementation in office buildings as targeted by the policy.

2. Typical Building Materials Manufacture in Ghana.

Typical building materials manufacture in Ghana involves the survey data on dominant building fabric used for office building, enhancement approaches used and general fabric design practices.

Detailed description of the two subgroups on building material manufacturers are as follows.

1. Local Building Materials Policy

Ghana has enacted into law in 2010 local building materials policy. The policy recommends building professionals to use up 60% of local building materials in public buildings in order to enhance energy utilization, environmental friendliness and to reduce cost of building materials. Among the list of materials being promoted are mud bricks; bamboo, straw, clay pozzolana, clay roof tiles and clay block.

Though the policy has been legislated into law, building material manufacturers are yet to produce it in commercial quantities for office buildings. The dominant characteristic concerns by participants for the delay in commercial scale quantity manufacturing of building fabric outlined in the policy are, poor material properties, technology for refining, equipment for production, durability and cost.

The representative local building fabrics promoted by the policy is shown in Figure 6.8.

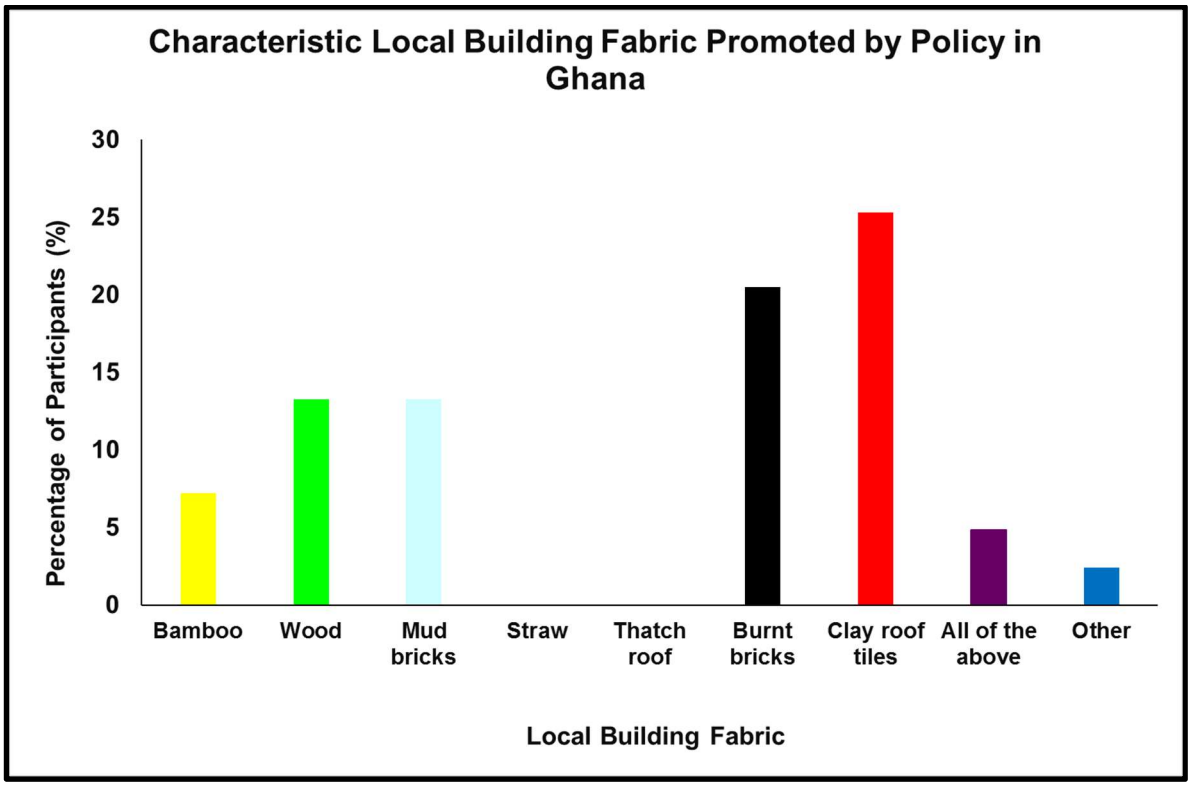

Figure 6.8: Dominant Local Building Materials promoted by the policy.

Clay roof tiles are the highest promoted building fabric by government agencies responsible for the policy implementation followed by burnt bricks. The conventional building fabric for public building walling and roofing are cement-based blocks and galvanised aluminium roofing sheets. On the contrary, the conventional fabric for public building are expensive but have improved properties. There is insignificant difference in the level of promotion of wood and mud bricks.

Straw and thatch roof has not received any promotion. Further investigation is required in studying the practicality and detail fabric properties for straw and thatch roof in public buildings.

2. Typical Building Materials Manufactured in Ghana

According 80% building material manufacturer respondents, customers are willing to pay for high quality materials which complies with low energy building regulation and 82% of participants indicated building construction materials used in Ghana is suitable for the climate. Figure 6.9 shows characteristic building materials currently manufactured for office building fabric in Ghana.

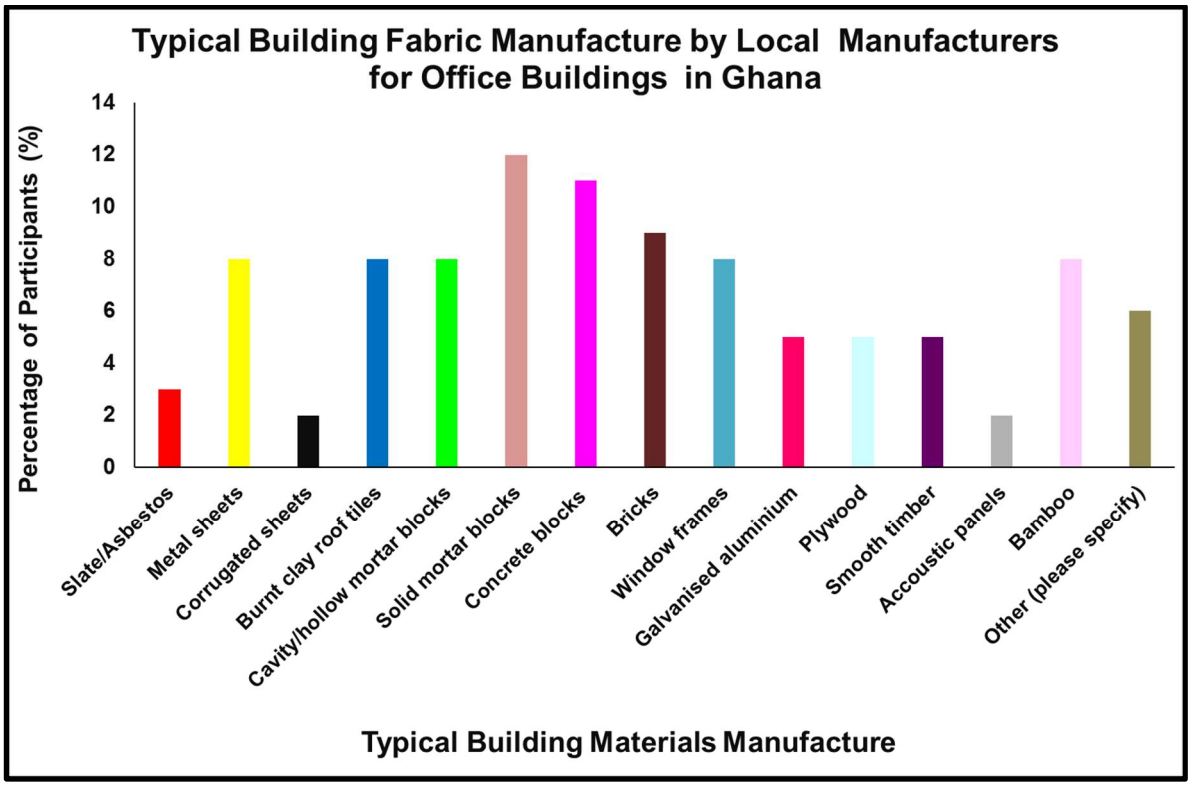

Figure 6.9: Typical Office building fabric.

From Figure 6.9, it can be seen that, the building materials are widely distributed the on contrary, the highest building fabrics manufactured by local manufacturers for office buildings are solid mortar and concrete blocks with the least being slate/ asbestos, corrugated sheets and acoustic panels.

iii. Government Agencies Practice

Government Agencies Practice were analysed along the following sub clusters:

- Robustness and Adequacy of Ghana building Permit Issuing
- Basis of Design Variables in Ghana Building Regulations
- Typical Non-compliance of the Ghana Building Regulations by building professionals

Detail description of the sub clusters for government Agencies Practices are as below.

- **Robustness and Adequacy of Ghana building Permit Issuing**

  The main purpose of the robust and adequacy assessment of Ghana building permit issuing was to critically evaluate the documentation and procedures involved for government Agencies practice. According to government agencies participants, during the certification of building permit, the main factors considered are structural strength analysis followed by site plan and certified architectural drawings. The key factors considered in the assessment are policy on low energy building, energy performance certificate and field inspection after building permit issuing. Figure 6.10 shows selected factors influencing robustness and adequacy of Ghana building permit issuing.

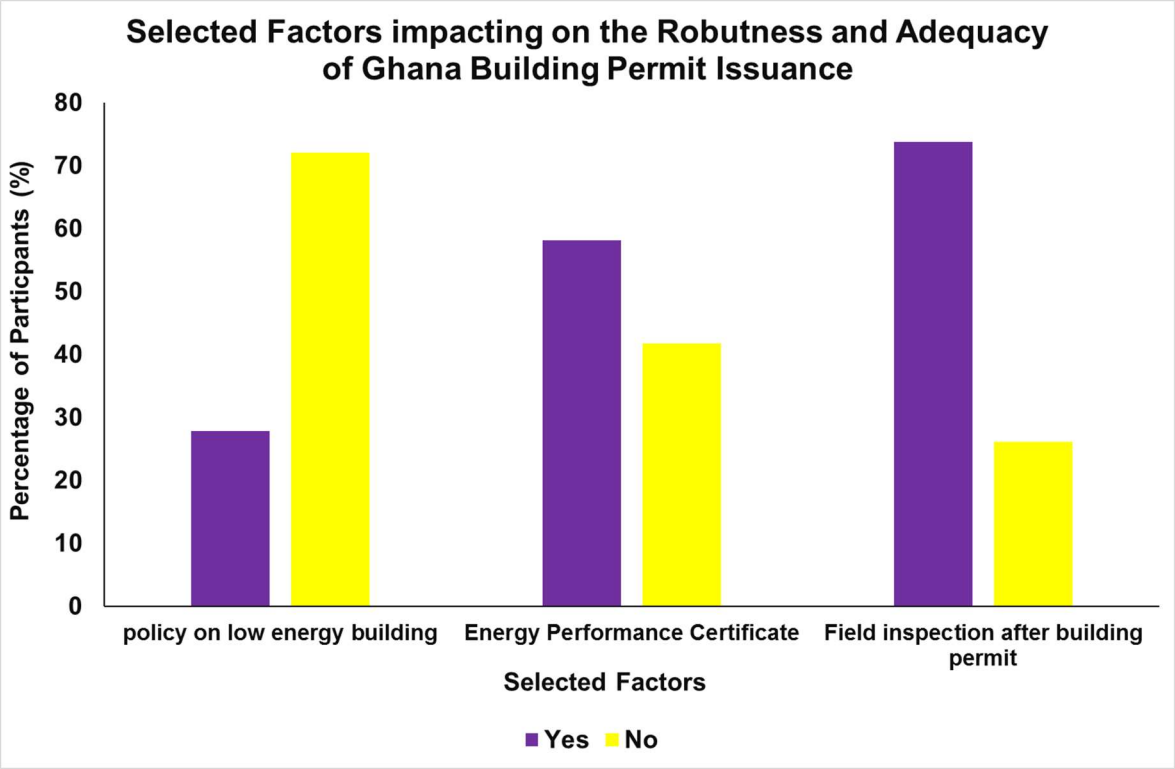

Figure 6.10: Robustness and Adequacy of Ghana Building Permit

On policy for low energy building, substantial of 72.1% of government agencies participants indicated that, there is no policy in Ghana on low energy building. There was low difference in percentage for participants who indicated 'yes' and 'no' that energy performance certificate is a requirement for building permit issuing. As a result of this close percentage difference, there is a need for further investigation at building permit issuing body to ascertain the existence of such certificate. Finally, 73.8% of participants indicated that field inspection is followed after building permit is issued to clients. In conclusion, from the percentages of participants' responses coupled with the factors considered during certification of building permit, the government agency practices are inadequate and not robust in solving energy utilization. It is important to undertake detail study of government agency practices in addressing rising energy utilization in buildings.

- **Basis of Design Variables in Ghana Building Regulations**

The present Ghana building regulations are prescriptive in nature without any technical guidelines on how the design variables were obtained or can be achieved. In view of this, the survey questionnaires were administered to verify the basis of the values whether it was obtained from simulation, application of adjustment factors to international standards, from experience, from experiments, among others.

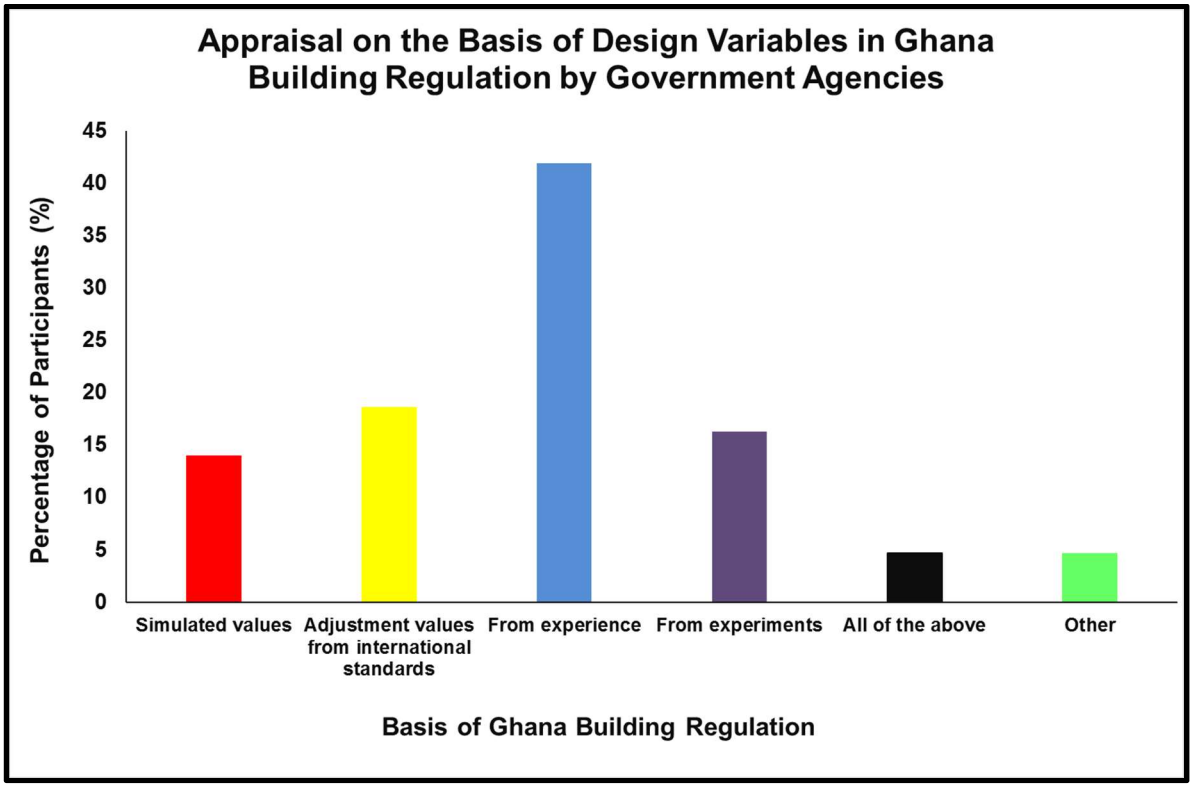

Figure 6.11: Basis of Design Variables in Ghana Building Regulations

Majority of government agency participants indicated that, the Ghana building regulations were obtained out of experience from long practice of using the design variables. The main scientific and technical approaches i.e. simulation and experiments for obtaining the design values in building regulations were very low.

In conclusion, scientific and technical basis i.e. simulated values as well as experiments for setting minimum design variables were found to be low.

On the other hand, long experience and application of adjustment factors to international existing values were high. In view of these findings, it is expedient to use experimental assessment and computer simulation to verify all the design variables outlined in the building regulations and to formulate technical guidelines in achieving them.

- **Typical Non-compliance of the Ghana Building Regulation by building professionals**

From the reviewed literature, the level of non-compliance of building regulations or codes remains a challenge in some countries. Compliance of building regulations or codes contributes in reducing energy utilization and indoor environmental discomfort.

As a result of this, it was essential to ascertain the level of compliance of building regulations or codes to understand the representative factors affecting building performance in Ghana. Figure 6.12 shows characteristic non-compliance of the building regulations during the issuance of building permit

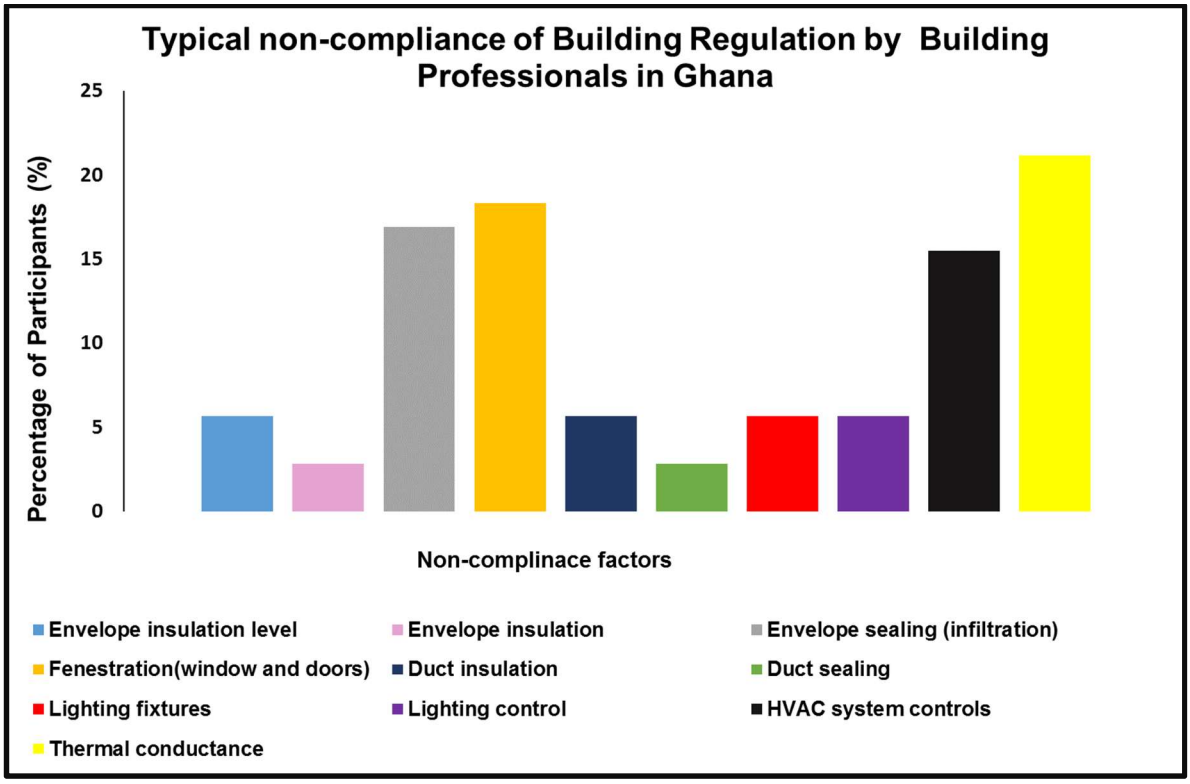

Figure 6.12: Typical Non-compliance of the Ghana Building Regulations.

The factors affecting non-compliance are fairly distributed, conversely, the higher factors are thermal conductance of materials, fenestration (window and doors), envelope sealing (infiltration), HVAC system controls and envelope insulation level. In summary, the level of compliance for duct insulation, duct sealing, lighting fixtures and lighting controls were high hence the research focused on the most significant factors of non-compliance listed above. In conclusion, the non-compliance factors thermal conductance of materials, fenestration types (window and doors), envelope sealing (infiltration), HVAC system controls and envelope insulation level have significant impact on building performance subsequently energy utilization in buildings.

iv. Representative Types of Technology integrated in Ghana Buildings

Characteristic types of technologies integrated into building envelope identified within the survey questionnaire data were analysed in the following sub headings:

a. Typical Passive Technologies used by Architects
b. Typical technologies recommended by building service engineers
c. Typical admixture incorporated into building materials

a. Typical Passive Technologies used by Architects

Several passive technologies are available and are used by architects in improving building performance as identified in the literature review. The objective for this investigation was to identify the specific representative passive technologies used by architects in Ghana to enhance building performance. Figure 6.13 is a representative passive technology incorporated into buildings in Ghana by architects for performance enhancement.

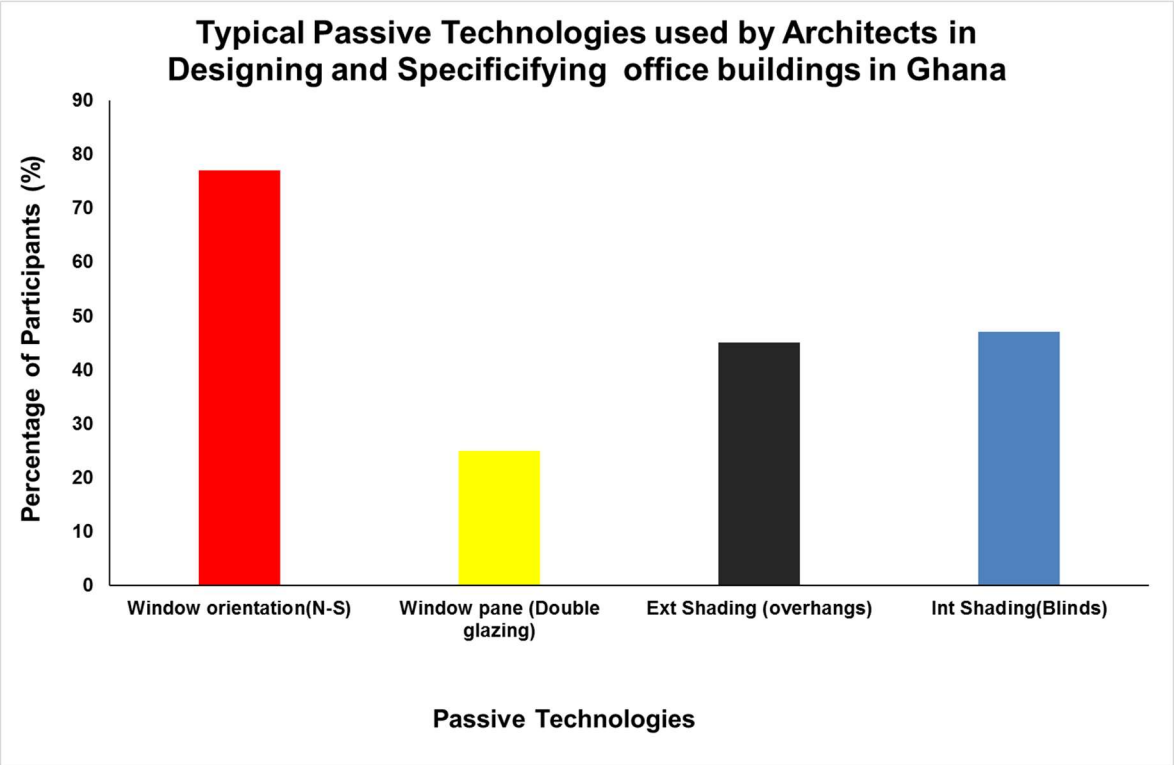

Figure 6.13: Typical Passive Technologies used by Architects

It can be deduced that the typical passive technology used in building design and specification are window orientation, use of blinds for internal shading use of overhangs for external shading and double glazing window pane representing 77% , 47%, 45% and 25% respectively. Although some passive technologies have been incorporated into building design specification, it is not significant. The use of North-South window orientation has significant impact on utilizing daylight to minimizing artificial lighting during the working period.

b. Typical technologies recommended by building service engineers

Building service engineer's participants indicated that cooling load in Ghana office buildings are dominantly contributed by 30%; 25% and 22% equipment, solar gain and dehumidifying load respectively.

The summary of all technologies typically recommended to clients by building service engineers are summarized in Figure 6.14.

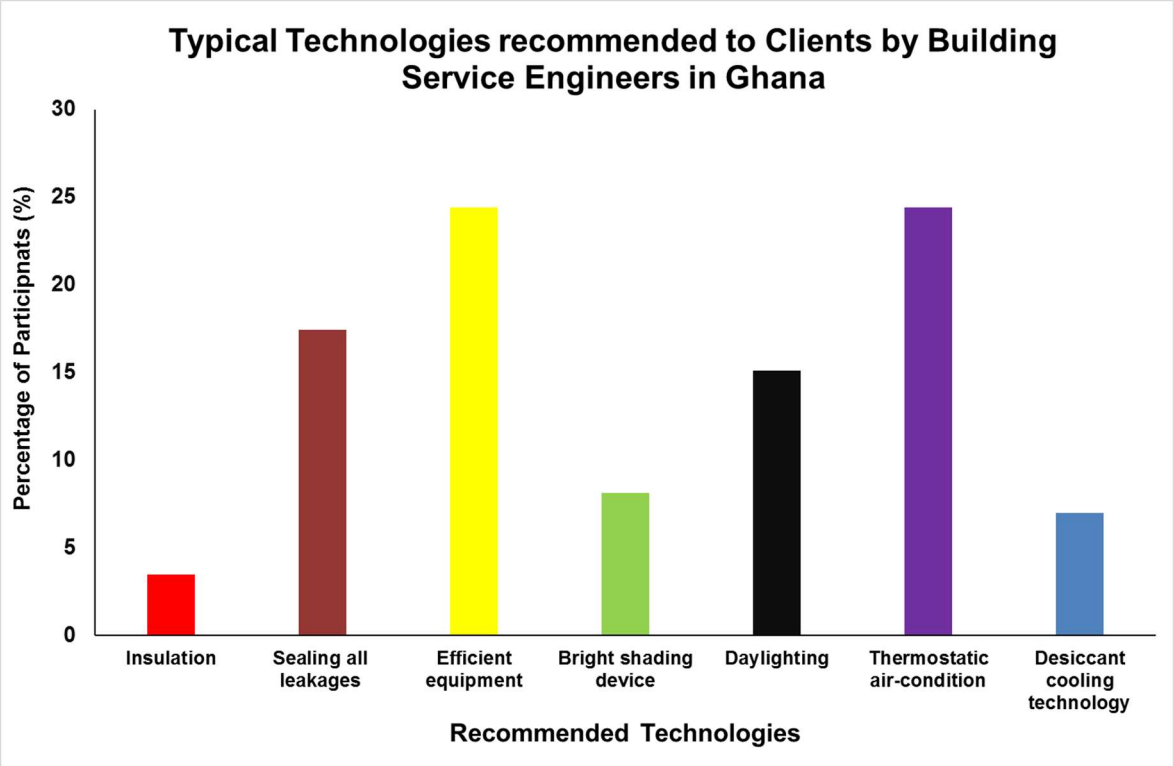

Figure 6.14: Typical recommended technologies to clients

From Figure 6.14, participants indicated that, if client intends to retrofit an office building to improve building performance they recommend the following: use of efficient building service equipment and thermostatic air-condition system were 24.4%, 17.4% for sealing all leakages to minimize infiltration, 15.1% for the use of daylighting and 8.1% for use of bright coloured indoor shading device. Conversely, only 7% and 3.4% recommended for use desiccant cooling system and insulating the whole building respectively.

c. Characteristic admixture incorporated into building materials

No significant technology was identified to be incorporated in building Materials. Admixtures are typically incorporated into building materials to achieve certain properties in concrete to enhance material properties. 79% building material manufacturer participants indicated no binding materials such as fly ash, blast furnace

slag and silica fumes as a replacement of ordinary Portland cement or as an admixture. Figure 6.15 shows a typical admixture incorporated into cement based building fabric.

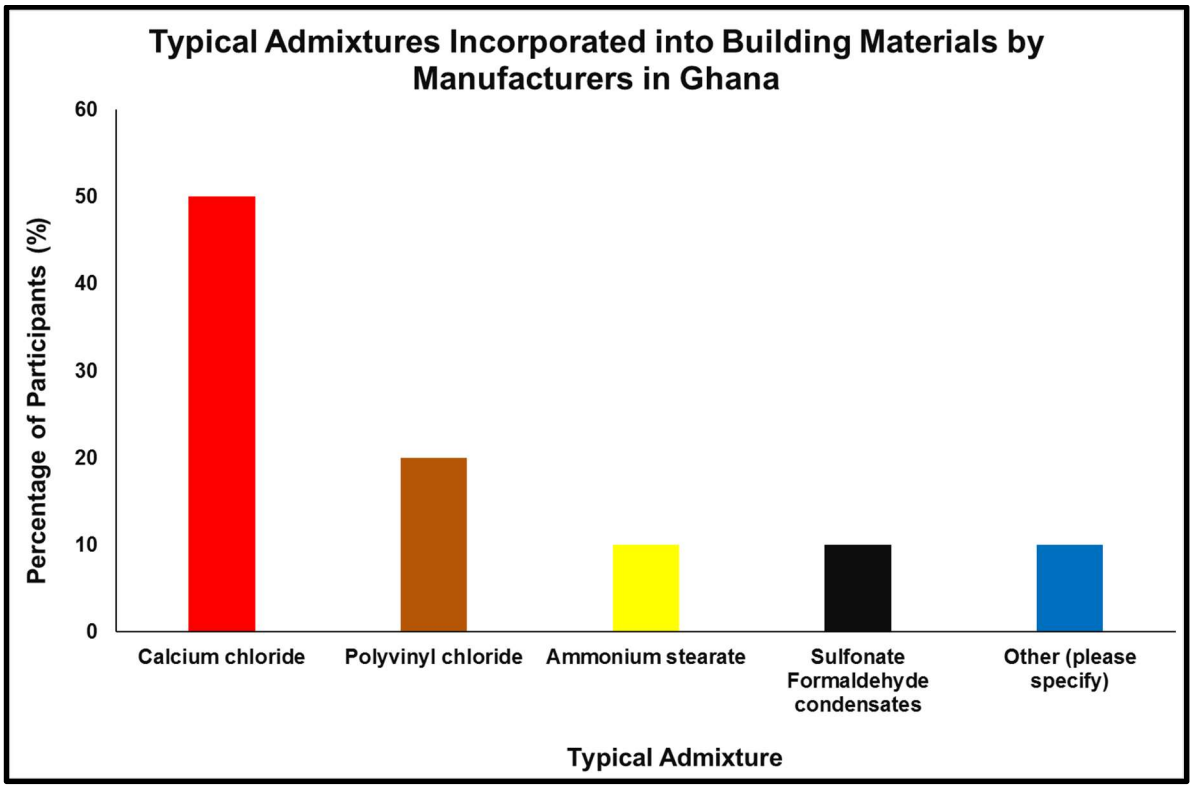

Figure 6.15: Typical Admixtures incorporated into Building Materials

From Figure 6.15, five typical admixtures incorporated into building materials are calcium chloride, polyvinyl chloride, ammonium stearate and sulfonate formaldehyde condensates with calcium chloride being the dominant admixture.

v. Building Regulation Appraisal

The appraisal of the Ghana building regulation was carried out using 9 key factors through survey questionnaire using 7 point Likert scale. The nine key factors used include, i. ease of implementation, ii. Proportionality, iii. Flexibility, iv. Cost effectiveness, v. consistency, vi. Empirical basis, vii. Adequacy, viii, modification and

ix. Government effectiveness in implementation. The 7 point Likert scale were: strongly satisfied, satisfied, turn to be satisfied, neither satisfied nor dissatisfied, turn to be dissatisfied, dissatisfied and strongly dissatisfied.

The nine key factors above were analyzed along the following sub clusters:

a. Cost effectiveness analysis (Cost Effectiveness)
b. Equality impact assessment (Proportionality, Consistency)
c. Outcome evaluation (Ease of Implementation, Flexibility, Government Effectiveness in Implementation)
d. Opportunity analysis (Empirical Basis, Adequacy and Modification)

Figure 6.16 to Figure 6.24 summarizes the 9 key factors used in the building regulation appraisal.

a. Cost effectiveness analysis (Cost Effectiveness)

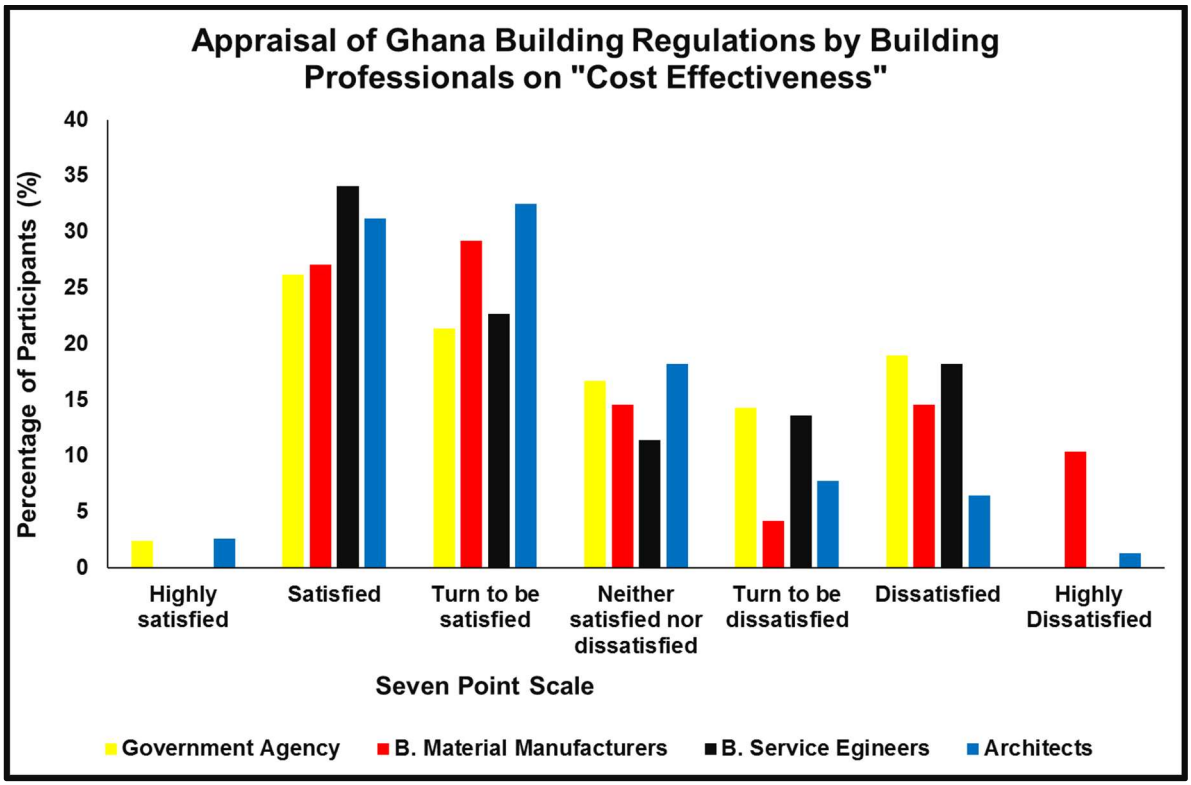

Figure 6.16: Cost Effectiveness of the regulation

From Figure 6.16, building professionals responses are fairly distributed over the seven point Likert scale except for highly satisfied and very dissatisfied. It should be noted that no participants of building material manufacturer and building service engineer indicated highly satisfied for cost effectiveness. No participants of government agency and building service engineer indicated highly dissatisfied for cost effectiveness. From the seven point Likert scale, there were no significant variation in building professionals' responses of neither satisfied nor dissatisfied compared to the other points. In terms of cost effectiveness of implementing building regulation, the highest point score for government agency, building material manufacturers, building service engineers and architects being 2, 1, 2 and 1 respectively. Government agency were satisfied, building material manufacturers turn to be satisfied, building service engineers were satisfied and architects turn to be satisfied respectively. In conclusion, there were variation in the various building professional responses of the building regulation; this is as a result of the level of usage.

b. Equality impact assessment (Proportionality, consistency)

Equality impact assessment was used to analyze proportionality and consistency factors and are shown in Figure 6.17 to Figure 6.18.

Proportionality of Building Regulation

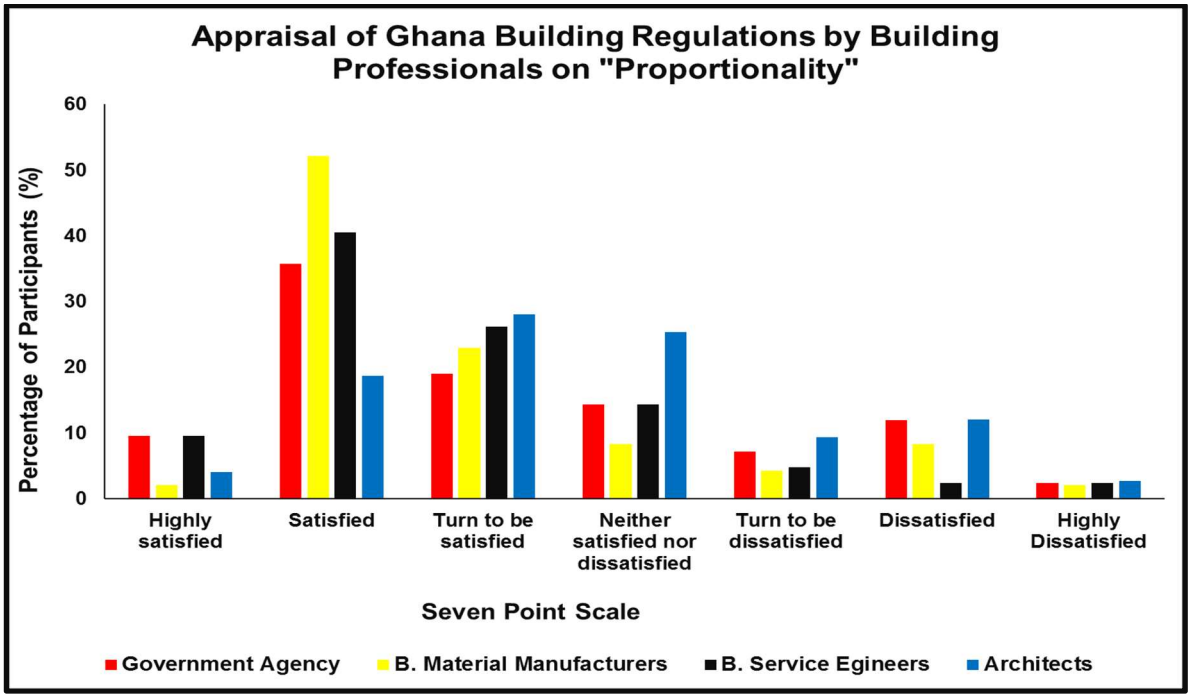

Figure 6.17: Proportionality of the regulation

From Figure 6.17, building professional's responses are fairly distributed over the seven point Likert scale with the exception of satisfied, turn to be satisfied, and neither satisfied nor dissatisfied. Significant percentage of building professionals were satisfied with proportionality in Ghana building regulation; however, building material manufacturers had the highest percentage of 52.1 with the least been Architects 18.7%. Individual building professional's participants who selected very dissatisfied were almost the same.

In terms of proportionality of building professionals' sections in the building regulation, the highest point score for government agency, building material manufacturers, building service engineers and architects being 2, 2, 2 and 1 respectively. government agency, building material manufacturers and building service engineers were satisfied and architects turn to be satisfied.

Consistency of Building Regulation

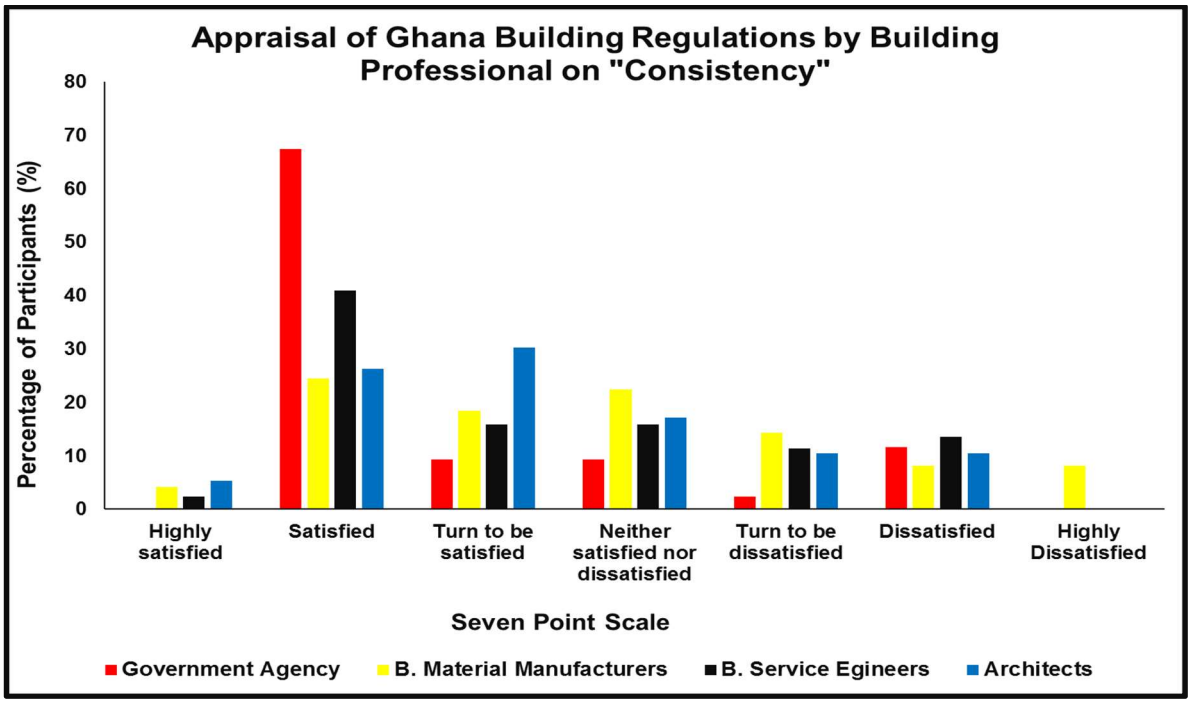

Figure 6.18: Consistency of the regulation

From Figure 6.18, significant government agency participants of 67.4% as well as 40.9% of building service engineers were satisfied with consistency of Ghana building regulation. The highest participants of government agency who selected satisfied point scale was not surprising, since the government agency is responsible for formulating the regulation and implementing it. However, 30.3% of architect's participants turn to be satisfied and the percentage is higher than those who were satisfied. No government agency respondent was neither highly satisfied nor highly dissatisfied.

In terms of consistency of the building regulation, the highest point score for government agency, building material manufacturers, building service engineers and architects being 2, 2, 2 and 1 respectively. Government agency, building material manufacturers and building service engineers were satisfied and architects turn to be satisfied. The equality impact assessment based on proportionality and consistency indicates that government agency, building material manufacturers, and building service engineers are satisfied; however, architects turn to be satisfied.

c. Outcome evaluation (ease of implementation, flexibility, government effectiveness in implementation)

Ease of implementation

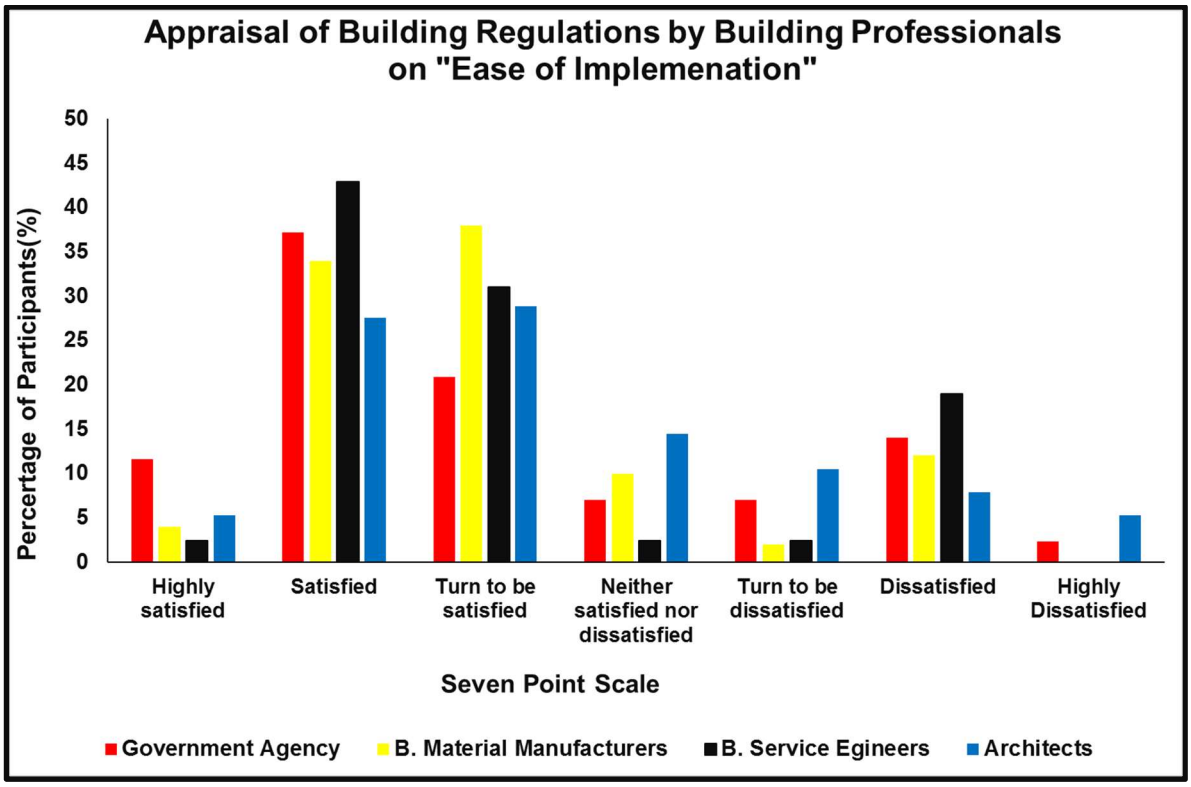

Figure 6.19: Ease of Implementation of the regulation

From Figure 6.19, substantial building service engineer's participants of 42.9% as well as 37.2% of government agency were satisfied with ease of implementing Ghana building regulation. Whiles 38% of building material manufacturers and 28.9% of Architects turn to be satisfied. 11.6% of government agency participants were highly satisfied with ease of Implementation of the regulation. No building material manufacturer and building service engineer were dissatisfied. In terms of ease of implementation of the building regulation, the highest point score for government agency, building material manufacturers, building service engineers and architects being 2, 1, 2 and 1 respectively.

Implying government agency was satisfied, building material manufacturers turn to be satisfied, building service engineers were satisfied and architects turn to be satisfied respectively. In conclusion, there were variation in the various building professional responses of the building regulation.

Flexibility of the building regulation

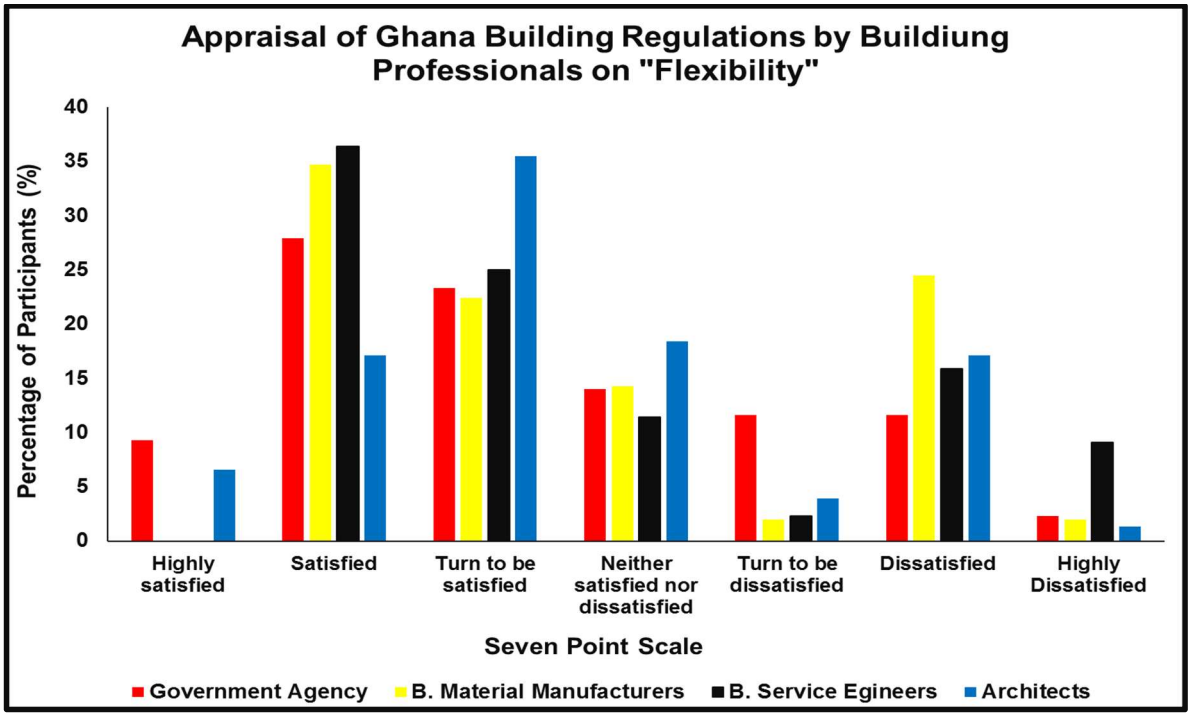

Figure 6.20: Flexibility of the regulation

From Figure 6.20, substantial building service engineer's participants of 42.9% as well as 37.2% of government agency were satisfied with ease of implementing Ghana building regulation. Whiles 38% of building material manufacturers and 28.9% of Architects turn to be satisfied. It can be seen that 11.6% of government agency participants were highly satisfied with ease of Implementation of the regulation. No building material manufacturer and building service engineer were dissatisfied. In terms of ease of implementation of the building regulation, the highest point score for Government Agency, building material manufacturers, Building Service Engineers and Architects being 2, 2, 2 and 1 respectively. Implying Government Agency, building material manufacturers and Building Service Engineers were satisfied and Architects

turn to be satisfied respectively. In conclusion, there were variation in the various building professional responses of the building regulation.

Government Effectiveness

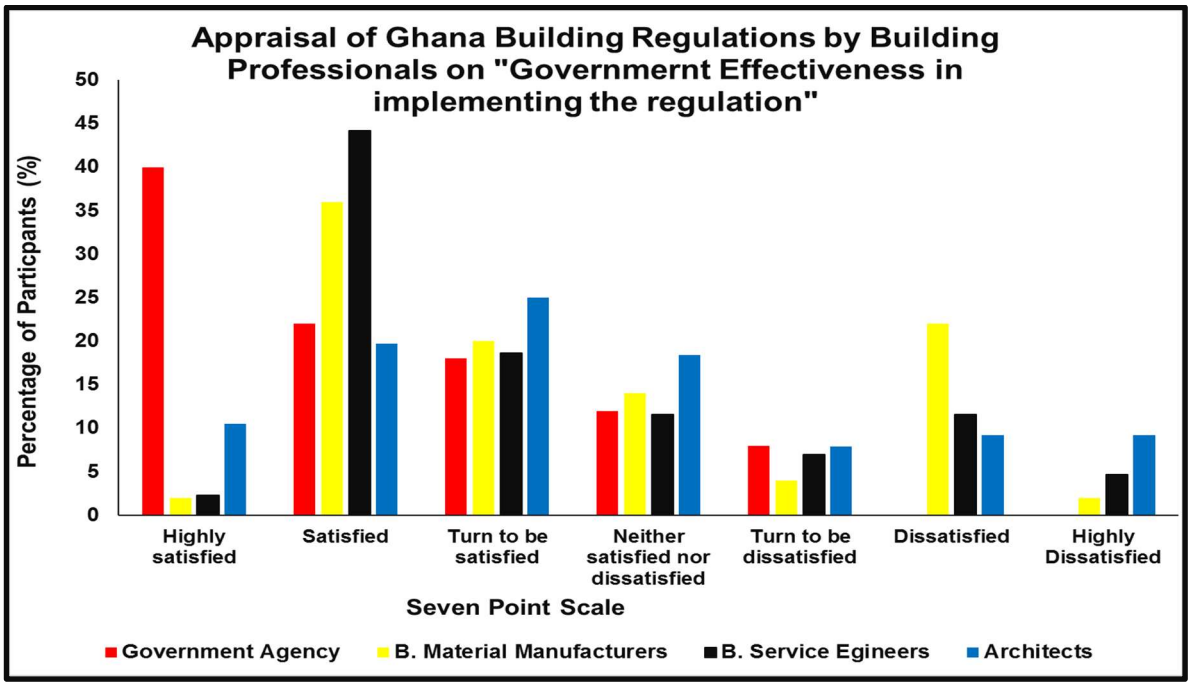

Figure 6.21: Government Effectiveness

From Figure 6.21, 40% of government agency were highly satisfied with no respondent highly dissatisfied about Government Effectiveness in implementing the building regulation. Conversely, 36% and 44.2% of building material manufacturers and building service engineer respectively were satisfied; however 25% of architects turn to be satisfied. There was no any major variations between the building professional's participants on the point scale on turn to be satisfied, neither satisfied nor dissatisfied and turn to be dissatisfied. In terms of Government Effectiveness in implementing the building regulation, the highest point score for Government Agency, Building material manufacturers, Building Service Engineers and Architects being 3, 2, 2 and 1 respectively. Implying Government Agency was highly satisfied, Building material manufacturers and Building Service Engineers were satisfied whiles Architects turn to be satisfied respectively.

In conclusion, on Outcome evaluation from Figure 6.19 to 6.21, it be seen that significant building professionals are satisfied with ease of implementation, flexibility, government effectiveness in implementation. However, Architects turn to be satisfied with the outcome evaluation for all the assessed factors.

d. Opportunity analysis (empirical basis, adequacy and modification)

Empirical basis

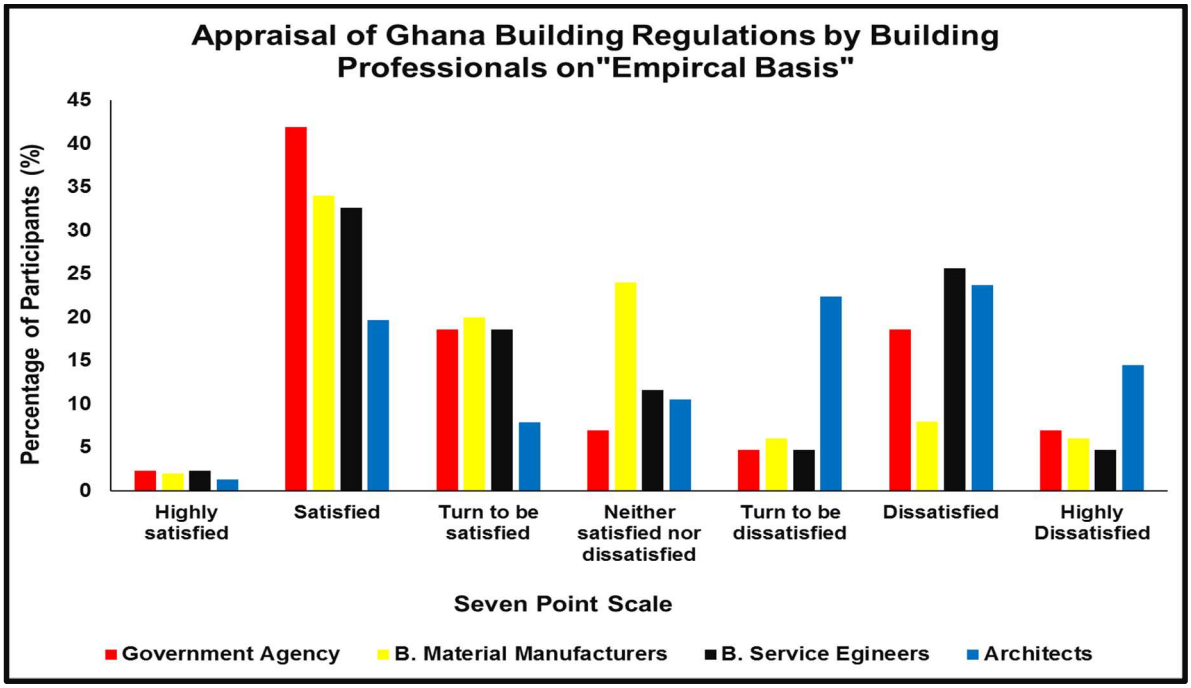

Figure 6.22: Empirical Basis

From Figure 6.22, it can be seen that all building professionals were satisfied with the empirical basis of the building regulation except architects who were dissatisfied. However, building professional participants who indicated highly dissatisfied were more than participants who were highly satisfied. In terms of empirical basis of the building regulation, the highest point score for Government Agency, Building material manufacturers, Building Service Engineers and Architects being 2, 2, 2 and -2 respectively.

Implying Government Agency, Building material manufacturers and Building Service Engineers were satisfied whiles Architects were dissatisfied respectively.

Adequacy

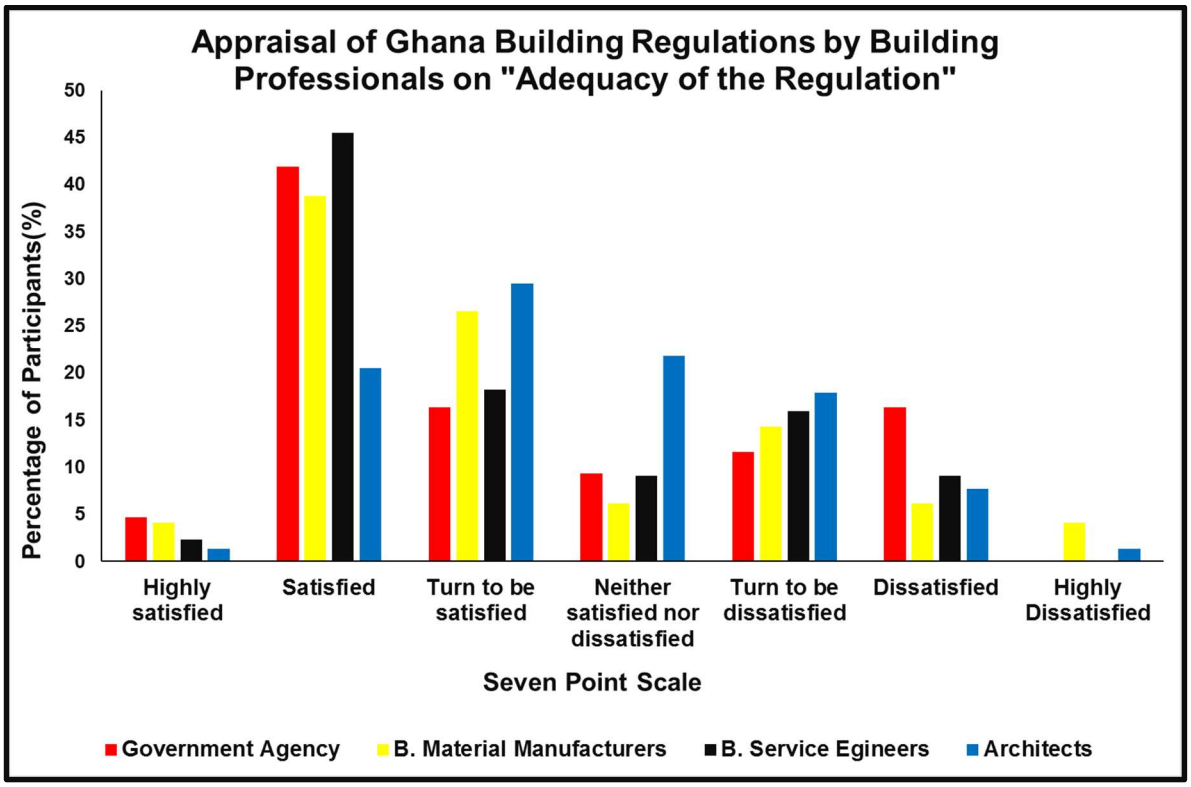

Figure 6.23: Adequacy of regulation

From Figure 6.23, it can be seen that all building professionals were satisfied with the adequacy of regulation of the building regulation except architects who turned to be satisfied. No government agency and building service engineer respondent was highly dissatisfied. There was no significant pattern variation seen along the point scale.

In terms of the adequacy of the building regulation, the highest point score for Government Agency, Building material manufacturers, Building Service Engineers and Architects being 2, 2, 2 and 1 respectively. Implying Government Agency, Building material manufacturers and Building Service Engineers were satisfied whiles Architects were turn to be satisfied respectively.

Modification

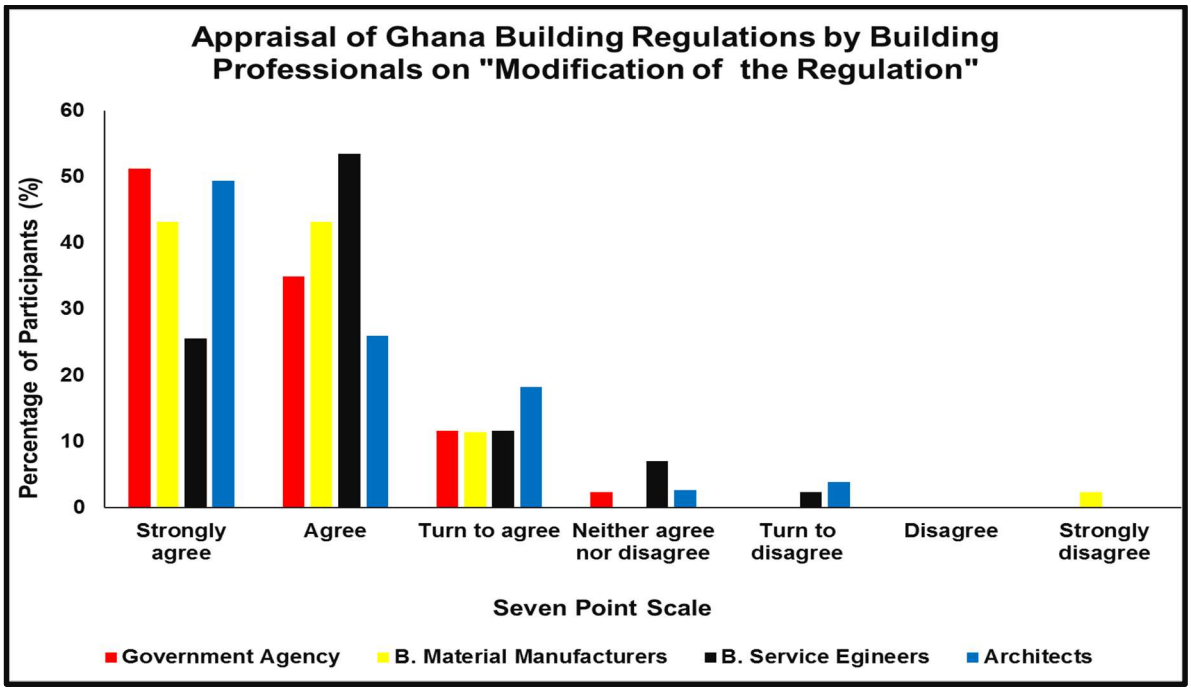

Figure 6.24: Modification of the Regulation

From Figure 6.24, significant percentage of building professionals indicated strongly agree and agree point scale with no participants disagreeing to modification of the building regulation. In terms of modification of the building regulation, the highest point score for Government Agency, Building Service Engineers and Architects being 3, 2 and 3 respectively. Government Agency being strongly agree, Building Service Engineers agreed and Architects strongly agree. Interestingly, the same percentage of building material manufacturers strongly agree and agree to modification of building regulation. Insignificant participants selected neither agree nor disagree, turn to disagree and strongly disagree. In conclusion, majority of building professional participants strongly agree that the building regulation should be modified. In conclusion, following the trend of architect's responses of turn to be satisfied to dissatisfied, it was not surprise for architects to strongly agree to the modification of the building regulation.

Overall conclusion of the building regulation appraisal of the nine key factors above using seven point Likert scale by building professionals in Ghana, were concluded as follows:

1. Building professionals highest score percentage was satisfaction of the appraisal of the nine key factors (Ease of implementation, Proportionality, Flexibility, Cost effectiveness, Consistency, Empirical basis, Adequacy, and Government effectiveness in implementation) excluding modification were 50%, 75%, 75%, 50%, 75%, 75%, 75% and 50% respectively.
2. 75% of all building professionals strongly agree with modification of the building regulation.
3. The level of application of building regulation in practice shows an important influence on the building professional's responses.
4. Further research is required on the lowest score percentage of satisfaction which are cost effectiveness and Government effectiveness in implementing the building regulation.

6.3.3 Typical Design Variables for whole building simulation

i. Occupants design variables
ii. Building envelope design variables
iii. Building Fabric design variables
iv. Service Equipment design variables

6.2.2 Typical Design Variables for whole building simulation

i. Occupants Input variables

According to typical occupant participants, 56.2% of their office building were constructed before 1996 and 50% indicated that there have been retrofitting of the whole building and equipment since the building was built.

From this premise, it implies the building performance assessment should be carried out on both office building before and after 1996 when the building regulation of Ghana was enacted. Figure 6.25 to 6.8 gives a description of design variables obtained from participants of building professionals and occupants. With Figure 6.25 being occupants design variables, Figure 6.26 being Building envelope design variables, Figure 6.27 being Building Fabric design variables and Figure 6.28 being Service equipment design variables.

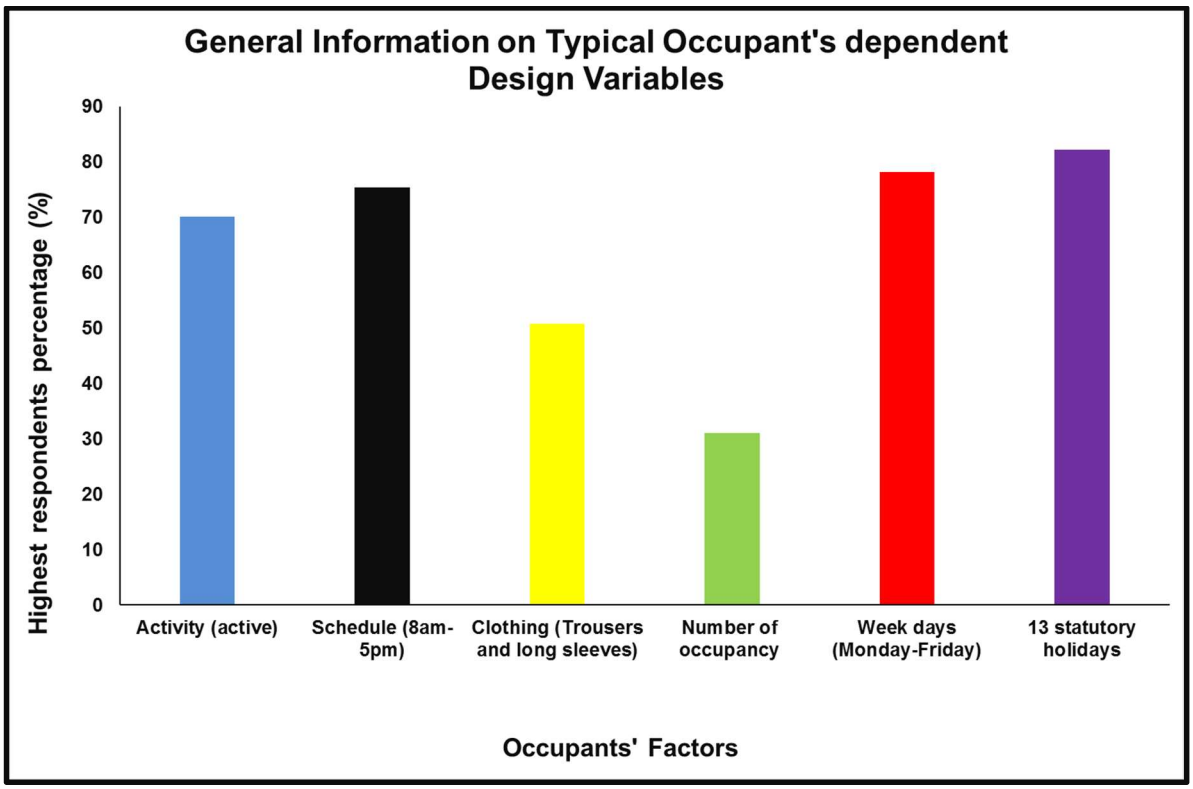

Figure 6.25: Occupants design variables

Figure 6.25 is description of the occupants' dependent variables; depicting highest percentage of participants versus design variables. 70.1% of the participants indicated that, their metabolic activity is active, with typical 31.1% occupancy of up to 6, of which 50.7% typically wear trousers and long sleeves. 78.1% of the participants works only weekdays i.e. Monday to Friday with 75.3% operating on 8am to 5pm schedule and 82.2% of participants closing on all average 13 statutory holidays in Ghana per annum.

From the work schedule of occupants and the calendar of the working days per annum, if the air-conditioning system is going to be used for ventilation and cooling of the indoor environmental climate; then significant electricity would be utilised. There is clear indication that, the recommended good practice for cooling load per annum may not be achieved using these occupant design variables, since the cooling calendar used by CIBSE Guide for the calculation is limited to only Summer period in a year whiles the climate for Ghana is constant temperature and relative humidity for the whole year.

ii. Building envelope design variables

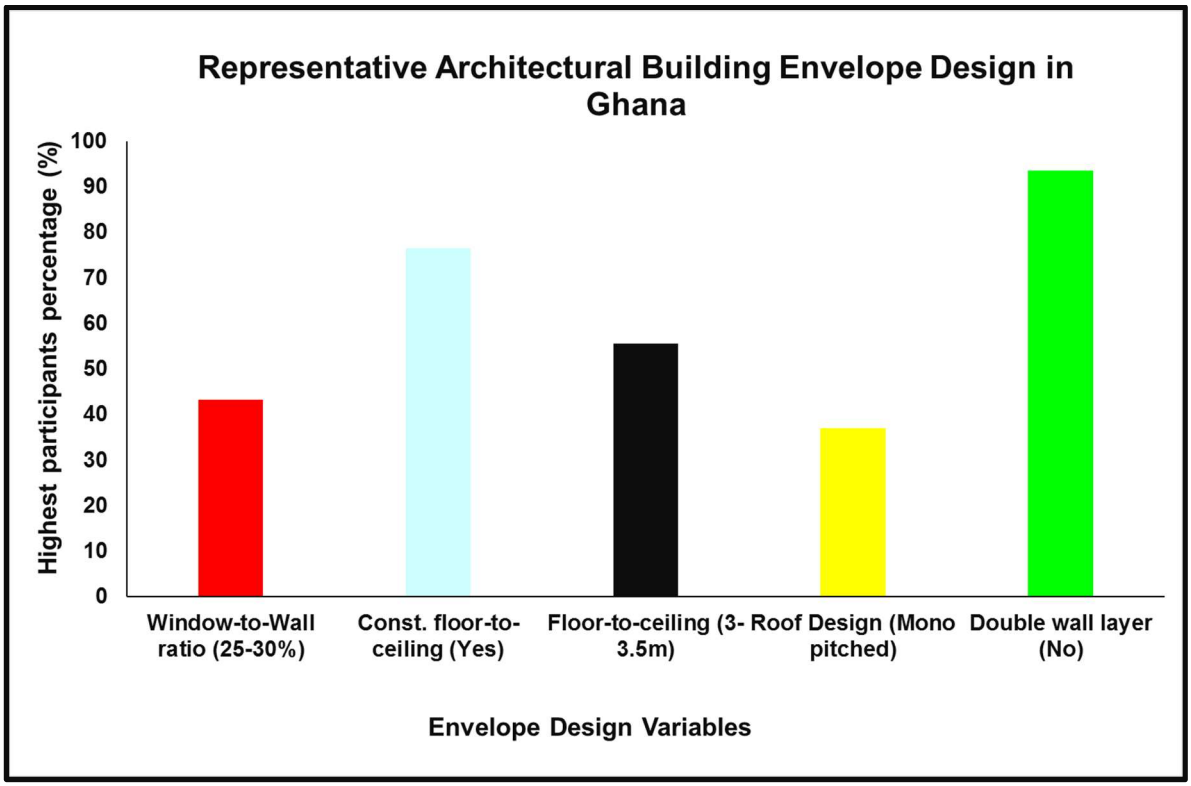

Figure 6.26: Building envelope design variables

Figure 6.26 signifies the highest respondent's percentage of typical building envelope design in Ghana. On building performance design variables, i.e. window-to-wall ratio (25-30%) and floor-to-ceiling height (3-3.5m) were 43.2% and 55.6% respectively. 76.6% of participants indicated that floor to ceiling height is constant for all floors within multi-storey building and these are building envelope designed purposely for

Mechanical cooling as well as design trend after the implementation of the building regulation of Ghana. Interestingly, 93.5% of participants indicated that they do not use double wall layer in their envelope design. From this enormous percentage of participants using single wall layer in building envelope design requires further investigation to ascertain the compliance with Ghana building regulation on u-values, dimensions and types of building fabric use in the design through numerical simulation.

iii. Building Fabric design variables

- 52.3% of building material manufacturers participants indicated that the typical mixing ratio of cement: sand: gravel for concrete roof, floor and concrete block in Ghana is 1:1:3. On typical thermal conductivity (W/mK) of concrete product, 40.5% of respondent indicated I do not know whiles 27.2% indicated that it is in a range of 0.3-0.7 W/mK.

- 34.1% of building material manufacturers participants indicated that the typical mixing ratio of cement: sand for mortar blocks in Ghana is 1:3. On typical thermal conductivity (W/mK) of concrete product, 31.2% indicated that it is in a range of 0.5-0.75 W/mk whiles 18.8% did not know the thermal conductivity.
- 67.5% of building material manufacturers participants indicated that typical block thickness/width produced is in the range of 5.0 - 6.0 inches.

- 21.1% building material manufacturers participants indicated that the typical range of thermal conductivity of 0.15 - 0.5 (W/mK) of the bricks products.

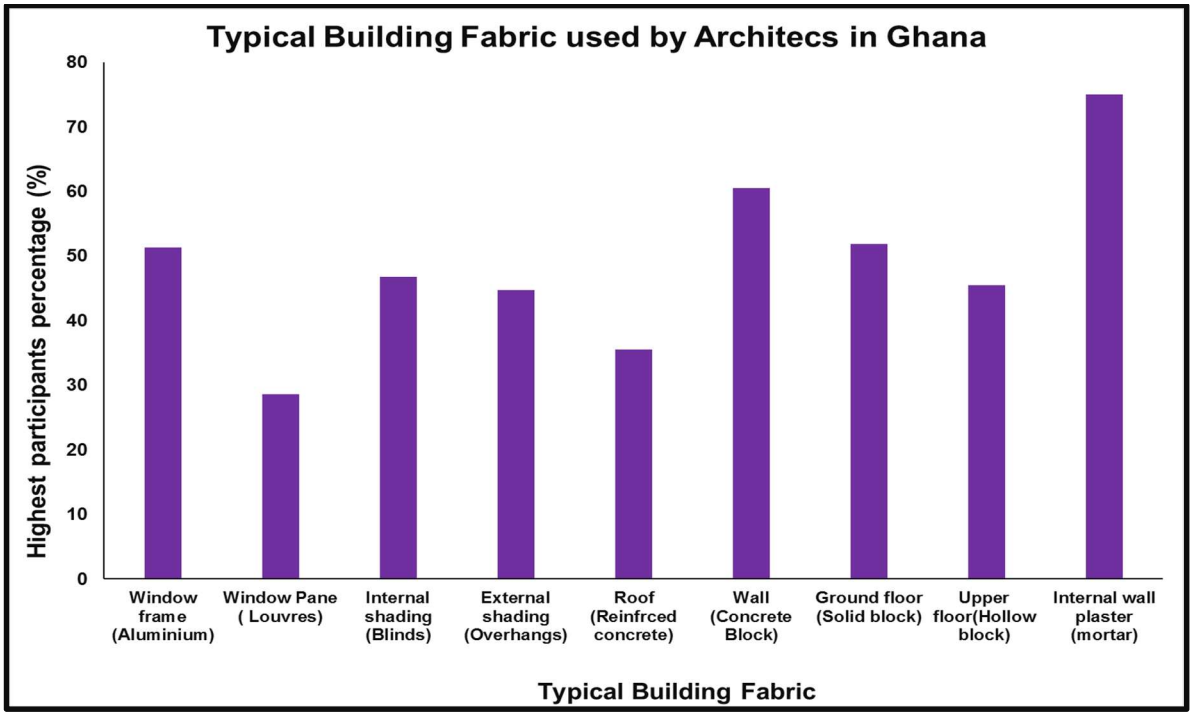

Figure 6.27: Building fabric design variables

Figure 6.27 shows, the highest percentage of typical building fabric used by architects in Ghana. From the Figure 6.27, 51.3% of participants typically use aluminium for window frame and 28.6% use louvers blades as window pane. For internal and external shading; typically, 46.8% use blinds and 44.7% use overhangs respectively.35.5% use reinforced concrete for roofing. 60.5% use concrete for Wall design, however for multi-storey buildings, 51.9% is constructed with solid block for ground floor and 45.5% hollow/ cavity blocks for upper floor whiles 75% use mortar for internal wall plastering. Building fabric has substantial impact on heat and moisture transfer, subsequently building performance. If the building fabric is selected without the consideration of the prevailing climate condition; hence, significant electricity would be required in for cooling to create comfortable indoor climate. From these characteristic building fabrics used by architects, coupled with typical building envelope design in Figure 6.26; it can be concluded that the u-values of all these cement-based fabrics can only be achieved unless the thickness of the material is wider than the typical market sizes with very low thermal conductivity.

iv. Service Equipment design variables

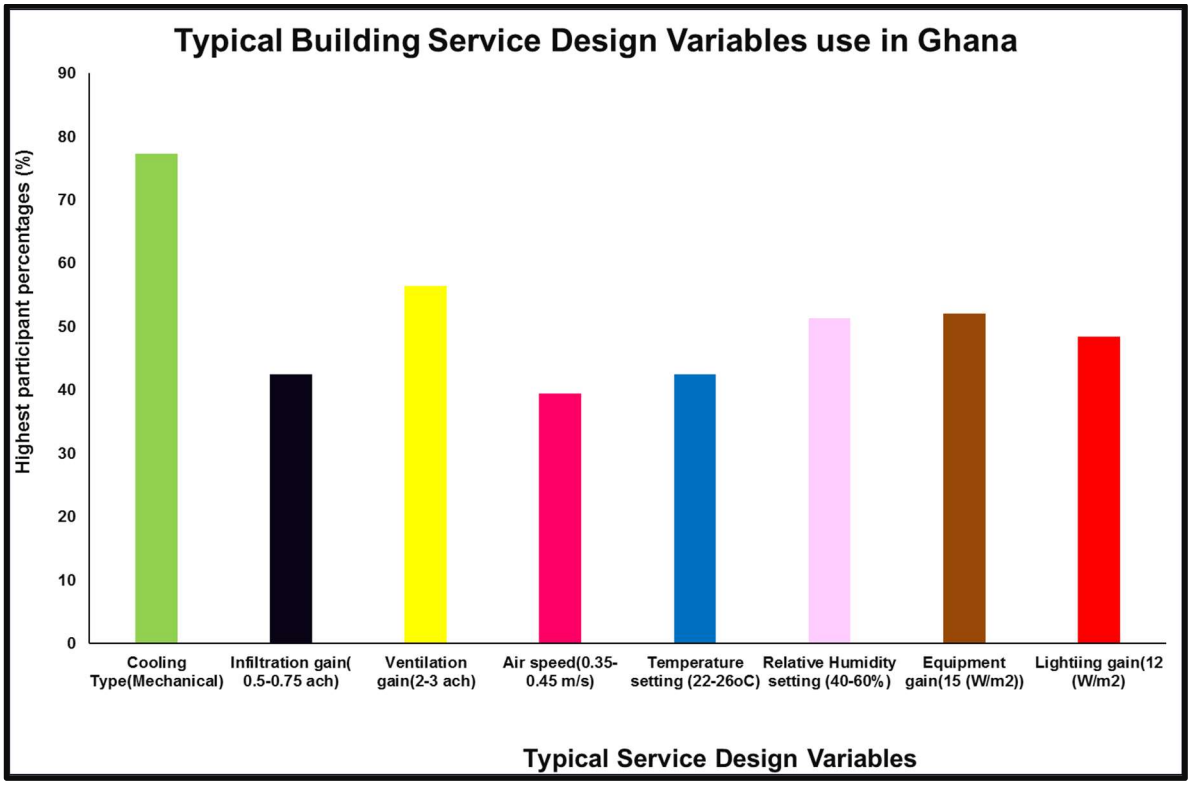

Figure 6.28: Service Equipment design variables

Figure 6.28 depicts highest respondent's percentage for typical design variables used by building service engineers in equipment selection and sizing in Ghana. According to building service engineering respondents, 77.3% of offices are mechanically cooled. Typical design variables used for selecting equipment are Infiltration gain (0.5-0.75 ach), ventilation gain (2-3 ach), equipment gain (15 W/m2) and lighting gain (12 W/m2) being 42.5%, 56.4%, 52.1% and 48.4% respectively. With typical thermometer setting of temperatures (22-26^{o}C) and relative humidity (40-60%) being 42.5% and 51.3% respectively as well as 39.5% using air speed in a range of 0.35-0.45m/s. The selection of accurate service design variables is crucial in selecting and sizing the right service equipment to meeting the occupants needs. The building envelope on its own does not utilize electricity but the service equipment and occupant's usage; hence it is imperative to select and size the service equipment appropriately to avoid under or over cooling.

These highest respondents' percentages of typical design variables from Figure 6.25 to 6.28 formed the basis for the dynamic simulation.

6.2.3 Occupants Comfort and Satisfaction Perception

Occupant's indoor environmental comfort and satisfaction perception were analysed along the following sub clusters:

a. Occupant's indoor environmental comfort
b. Occupant's satisfaction perception of building envelope and finishing.

Figures 6.29 and 6.30 describes the Occupant's indoor environmental comfort and Occupant's satisfaction perception of building envelope and finishing respectively using seven-point Likert scale.

a. Occupant's indoor environmental comfort

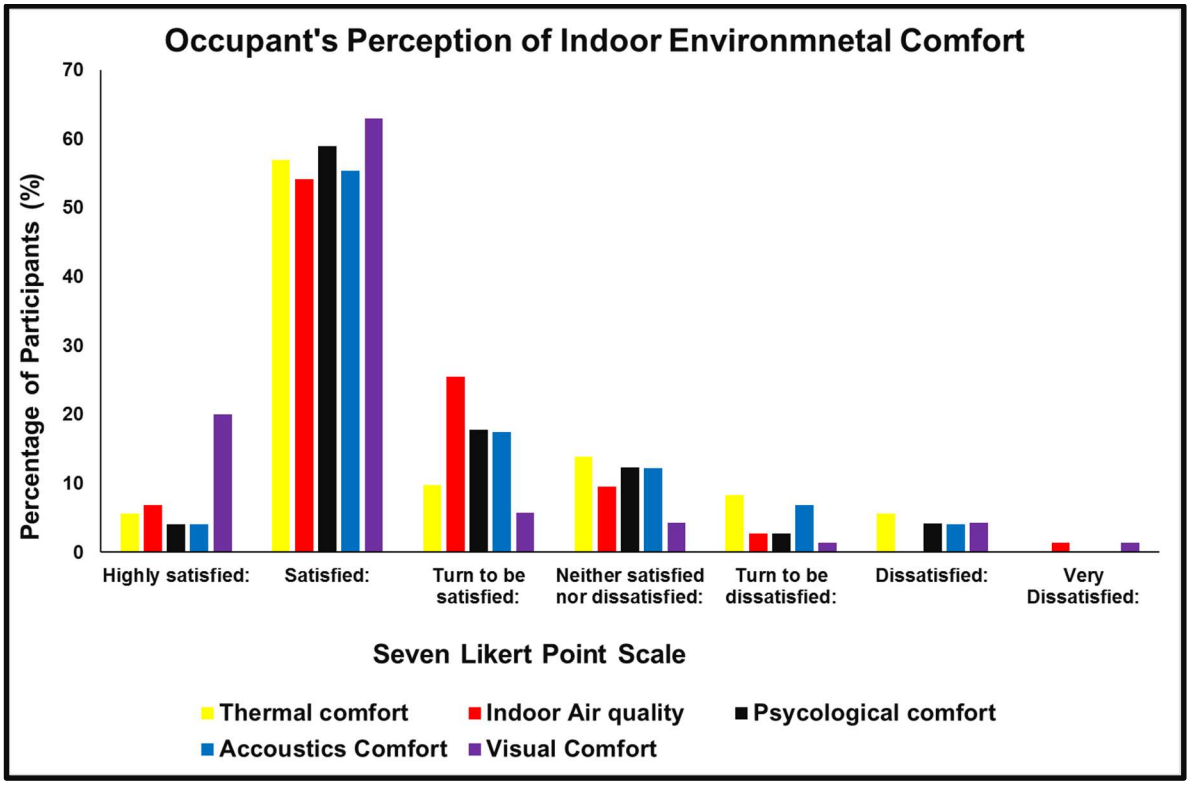

Figure 6.29: Occupant's indoor environmental comfort

From Figure 6.29, significant percentage of 54.1 to 62.9 of occupants are comfortable with the indoor environmental quality (thermal comfort, indoor air quality, psychological comfort, acoustics comfort and visual comfort). According to ASHRAE 55 standards, at least 80% of the occupants should be thermally comfortable with 20% dissatisfied. However, from Figure 6.29, 56.9% of the participants were satisfied with indoor thermal comfort. In comparison to ASHRAE 55 standard, it can be concluded that the indoor thermal comfort was comfortable by occupants; since the percentage sum of participants who turn to be dissatisfied, dissatisfied and very dissatisfied is 13.6% which falls within the standard predicted percentage of dissatisfied 20% to be comfortable. 54.1% of occupants are satisfied with indoor air quality; however, there is no existing guidelines to compare this performance indicated with. As a further investigation on the indoor air quality, 63% and 68.5% indicated that there is constant fresh air and good air circulation in the office respectively. Hence it can be concluded that the indoor air quality is comfortable. This assertion can be validated through simulation by assessing the concentration of carbon dioxide in the room. On psychological comfort, 58.9% of participants indicated are satisfied. In ESDL Tas, psychological comfort is not integrated in the tool box, hence this significant respondent's satisfaction would be used in supporting the psychological comfort. 55.4% of were satisfied with acoustic comfort, with insignificant 9.6 percentage sum of participants who turn to be dissatisfied, dissatisfied and very dissatisfied. From follow up questions, 82.2%, 22.5%, 19.5% and 56.9% of occupant respondents, representing comfortable with electric bub, noisy air-conditioning systems, office equipment and noise arising from the outdoor respectively. Hence it is important for building designers to control indoor environmental noise arising from outdoor environment. In conclusion, the overall indoor environmental climate was comfortable for occupants.

b. Occupant's satisfaction perception of building envelope and finishing.

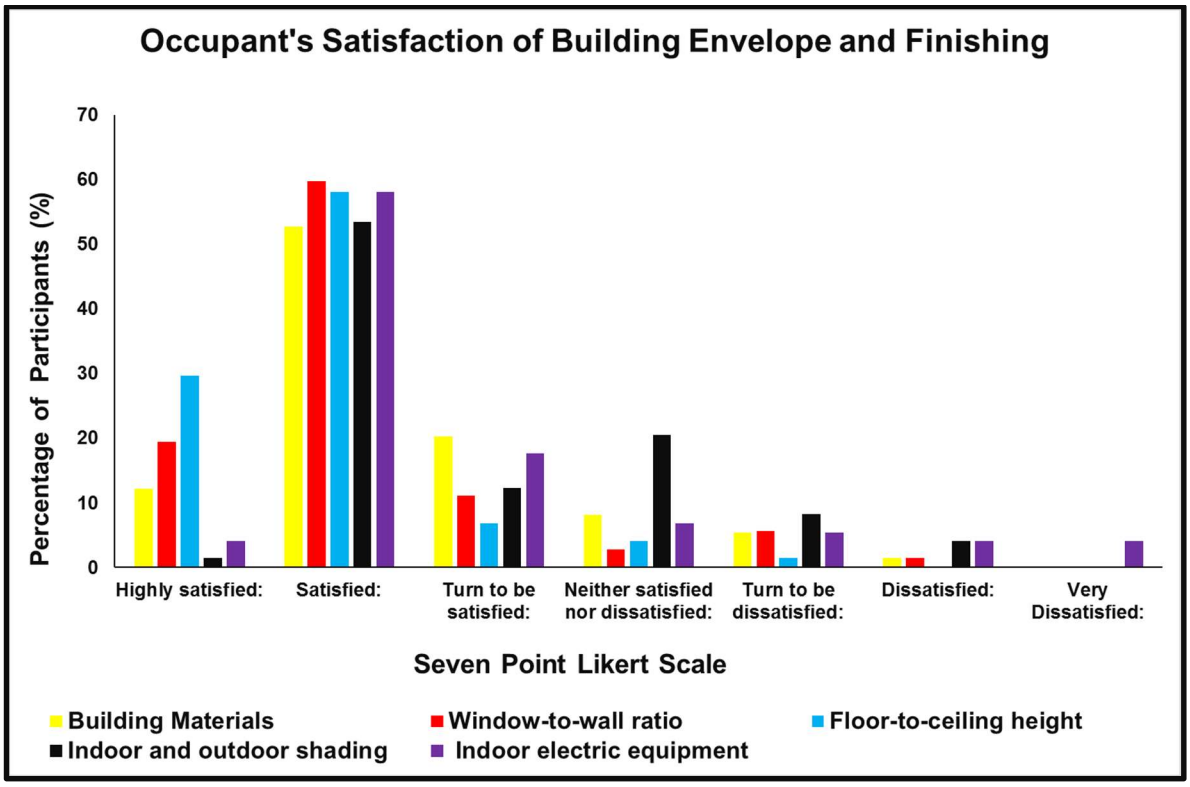

Figure 6.30: Occupants Satisfaction of Building Envelope and Finishing

From Figure 6.30, out of the seven-point Likert scale, used to assess building materials, window-to-wall ratio, floor-to-ceiling ratio, indoor and outdoor shading as well as indoor electric equipment, significant percentage above 50% of participants were satisfied with all the parameters assessed. The assessed parameters were fairly distributed along turn to be satisfied down to dissatisfied point scale. However, 29.7% of participants were highly satisfied with floor-to-ceiling height. In conclusion, occupants are generally satisfied with building envelope design and finishing.

6.3 Summary of Findings and Implications from Survey Questionnaires

The following are the findings identified from the research questions:

a. Low percentage of all building professionals do undertake building performance assessment with an average percentage of 18.8%.
b. Low percentage of technologies are presently incorporated into building design specification, selection and sizing
c. The overall appraisal of Ghana building regulation by building professionals shows satisfactory assessment, on the contrary, there was a strong recommendation for modification.
d. Improving building sealing to minimize infiltration is the main recommendation by building service engineers to clients for enhancing building performance.
e. All building professionals indicated that, the building fabric used for office building is suitable for Ghana's climate.
f. Building professionals' practices in Ghana have significant influence on the design variables used in selection and sizing, subsequently overall building performance.
g. Insignificant effort was identified within building professionals' practices in enhancing design variables to optimize building performance since the worse electricity crisis of the country's history in 2007 and after-effects to present.
h. Several design variables in Ghana building regulation are not based on scientific and technical approaches.
i. Over 50% of building service engineers do not achieve recommended minimum cooling load for good practice as stated in the CIBSE Guide at comfortable indoor quality.
j. Typical design variables used by Architects and Building Service Engineers in designing and sizing equipment include the following:
    - window-to-wall ratio:25-30%
    - floor-to-ceiling height: 3-3.5m
    - single wall layer, north-south window orientation
    - infiltration gain 0.5-0.75 ach

- ventilation gain 2-3 ach
- temperature setting 22-26^{o}C
- relative humidity setting 40-60%.

k. For typical deign variables used for building performance assessment to be outside typical variables in CIBSE Guide and ASHRAE standards, integration of new cost effective technology into building envelope and service finishing equipment is an option for minimizing electricity utilization for cooling.

l. Significant number of building professionals indicated that building fabric used in Ghana is suitable for the climate.

m. Government agencies are committed in enforcing any proposed building design guidelines.

n. Building professionals typical use Ghana building regulations for designing except building service engineers who mainly depend on international codes/regulations.

o. Issuing of building energy certificate to office buildings owners is one of the key approaches in educating professionals and clients on the need for optimizing electricity utilization in Ghana buildings.

p. The procedure for issuing building permit is not robust and adequate for enforcing design variables in the building regulation.

6.4 Outcome

In summary of the findings, the main cause of the problem of low building performance assessment among building professionals is due inadequate monitoring and evaluation of building permit issuing. In view of this problem, a creative on site final compliance feedback chart for building permit issuing has been design to enhance the government agencies practices as shown in Figure 6.31.

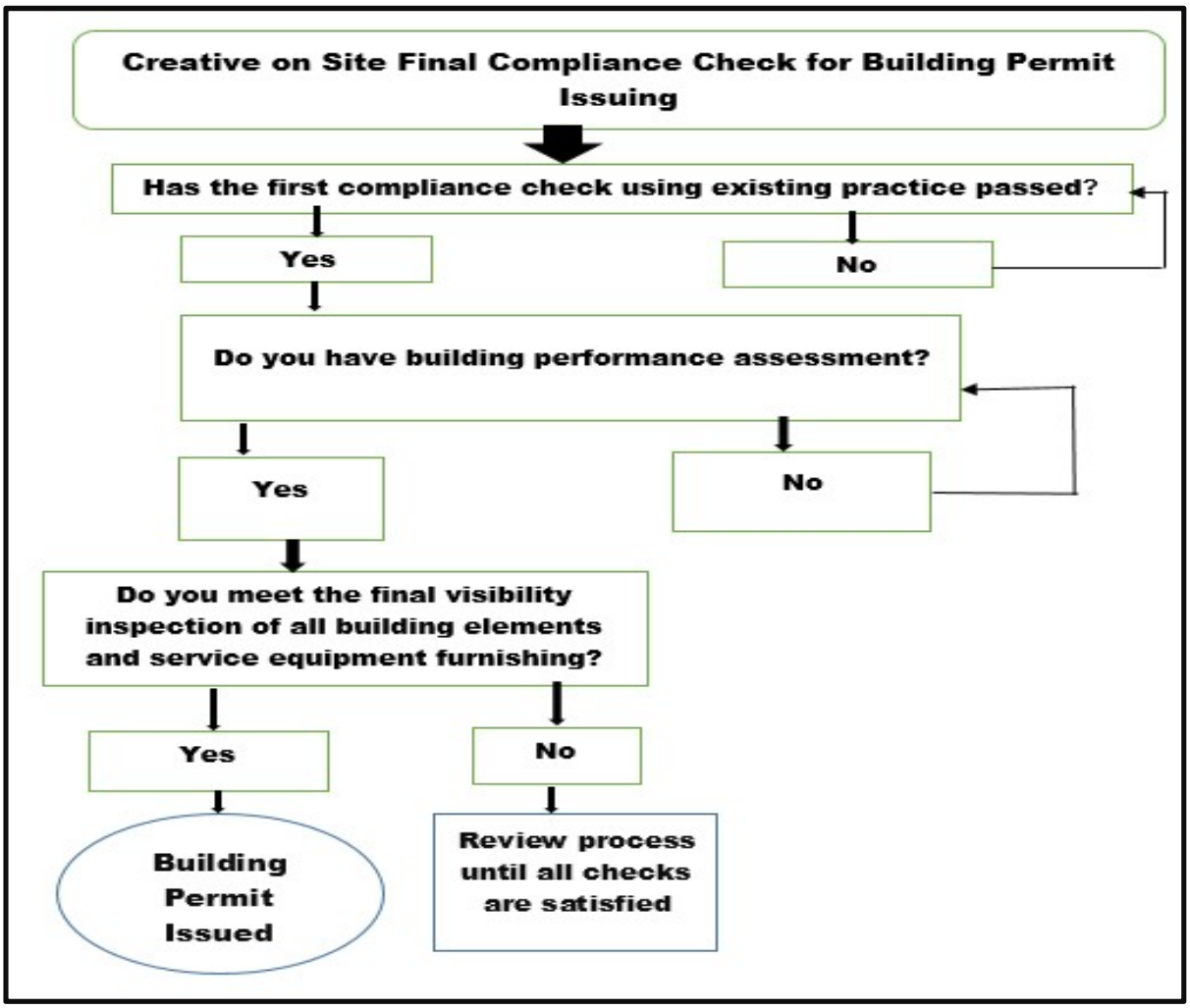

Figure 6.31: Creative on Site Final Compliance Check for Building Permit Issuing

6.5 Conclusion and Recommendation

The following significant outcomes have been concluded from the research:

1. Dominant high non-compliance factors with adverse impact on building performance identified among building professionals are thermal conductance of materials, fenestration (window and doors), envelope sealing (infiltration), HVAC system controls and envelope insulation level.
2. Majority of the typical building design variables used in Ghana among building professionals are relatively higher compared to international standards and some variables in Ghana building regulation.

3. Occupants are comfortable and satisfied with indoor environmental climates as well as building design and finishing.
4. Building permit issuing process is not robust and adequate on building fabric design variables within the application.
5. Insignificant building performance assessment by building professionals, is one of the major contributing factor to increasing electricity in buildings.
6. Inconsequential performance improvement was identified within building professional practices to enhancing design variables.

Finally, local building professional practices should be quantified in percentage and listed among typical factors which influences building performance

Recommendation

1. The building regulation of Ghana should be modified into performance based regulation. This would encourage building professionals in undertaking performance assessment of design, selection and sizing equipment; integrate sustainable building technology and minimize high electricity utilization caused by high cooling load arising in commercial and institutional buildings.
2. Government should introduce the use of building energy certificate to office buildings to optimize electricity utilization in Ghana.
3. Building permit issuance body should be trained and equipped with equipment for thermo-physical properties of building fabric to increase
4. Building service engineers and building material manufacturers should be encouraged to form associations with common aim of sharing knowledge and updating members on new techniques in improving their practices.
5. Government Agencies and building professional associations should have a comprehensive robust up to date accessible research on building performance.

7. CHAPTER SEVEN: EXPERIMENT ASSESSMENT

7.1 Introduction

Tropical climates are classified either into hot-humid or hot-dry climate. Depending on the classification of the climate, temperature and moisture dependent factors become critical in the building materials selection. Ghana is generally hot humid climate, hence no matter the architectural design of the building. Materials selections have vital role in minimizing heat and moisture transfer into the indoor environment and maximizing extraction of heat and moisture out of the indoor environment of the building. Building materials are basically grouped into transparent and opaque. From Ghana Building regulations, at least 30% of building envelope should constitute transparent materials with 70% been opaque. In Ghana, all the 30% transparent materials are imported into country and certified by Ghana Standards Boards. The remaining 70% opaque materials are produced and manufactured locally to the standard and certification of Ghana Building regulation.

According to description of the climate of Ghana given Chapter 8, then the thermal and moisture behaviour of the materials remains crucial to building professionals in designing and constructing efficient buildings. On the contrary, from the literature review and field study conducted as part of this research, it was evident that thermal properties of building materials testing are low and there is lack of knowledge on the impact of thermal properties of building materials on building performance, although this is stated in the building regulation. This is due to lack of equipment and the priority of the agencies to test the properties of the materials. These two findings confirmed the need of an experiment to be conducted on samples of building materials from Ghana. The experimental assessments on building fabric from Ghana, were used to ascertain if the fabrics manufacture in Ghana are meeting the regulations in consideration.

Hypothesis

The main hypothesis of this experimental assessment are as follows:

1. Is there a relationship between mixing ratio and sand type with thermo-physical properties?
2. What is the actual representative thermo-physical properties of materials in Ghana?
3. Are there any variations of thermo-physical from one company to other using the same building regulations and raw materials to produce the same products?
4. How can the thermo-physical of the products be enhanced if it is inadequately compared to the specifications of Ghana building regulations?

The details of the overall purpose , specific objectives and the building fabric sampling from Ghana for this experimental assessment have been presented in Chapter 5.

7.2 Experimental Results and Discussion

The details of the experimental results analysis procedure are represented in Chapter 5. The experimental results are categorized into preliminary results for set-up validation, selected building fabric from Ghana and the creative parametric blocks. The results in each category was summarised into Foam test method and Polymer test method.

7.2.1 Preliminary Test to Validate Equipment Set-up

Preliminary test was carried out to establish the validity and reliability of the instruments used in the experimental set up in Figure 5.4. The preliminary validity tests accessed Content Validity (to access weather C-Therm Tci system functions as stated by the manufacturer); Concurrent Validity (correlation with other established results); Reliability (measure of consistency within readings) and Construct Validity (appropriateness of the instruments to measure the objectives set out for the experiment).

The above validity and reliability preliminary test were summarised in these three categories:

1. Test Method ((Foam, Polymer, Ceramics) to test Reliability and Content Validity)
2. Contact agent (to test Construct Validity and Reliability of readings carried out with and without contacting agent).
3. Material (Pyrex glass test to ascertain Construct Validity)

Summary of preliminary experiment

The Manufacturer obtained its recommended values of both the thermal conductivity and thermal effusivity from an experiment using Pyrex glass, polymer test method and the use of wake field 120 thermal contacting agents. The comparison of the preliminary experimental scenarios for the set-up validation is shown in Figure 7.1 and 7.2.

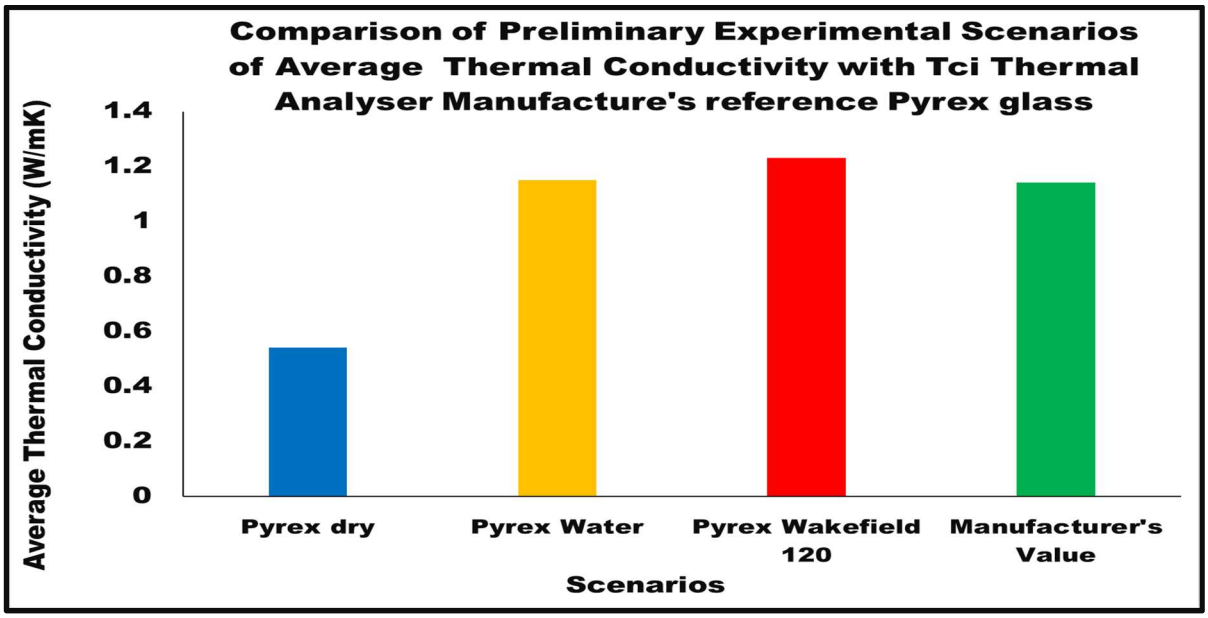

Figure 7.1: Comparison of Preliminary Experimental Scenarios of Average Thermal Conductivity with Tci Thermal Analyser Manufacturer's reference Pyrex glass

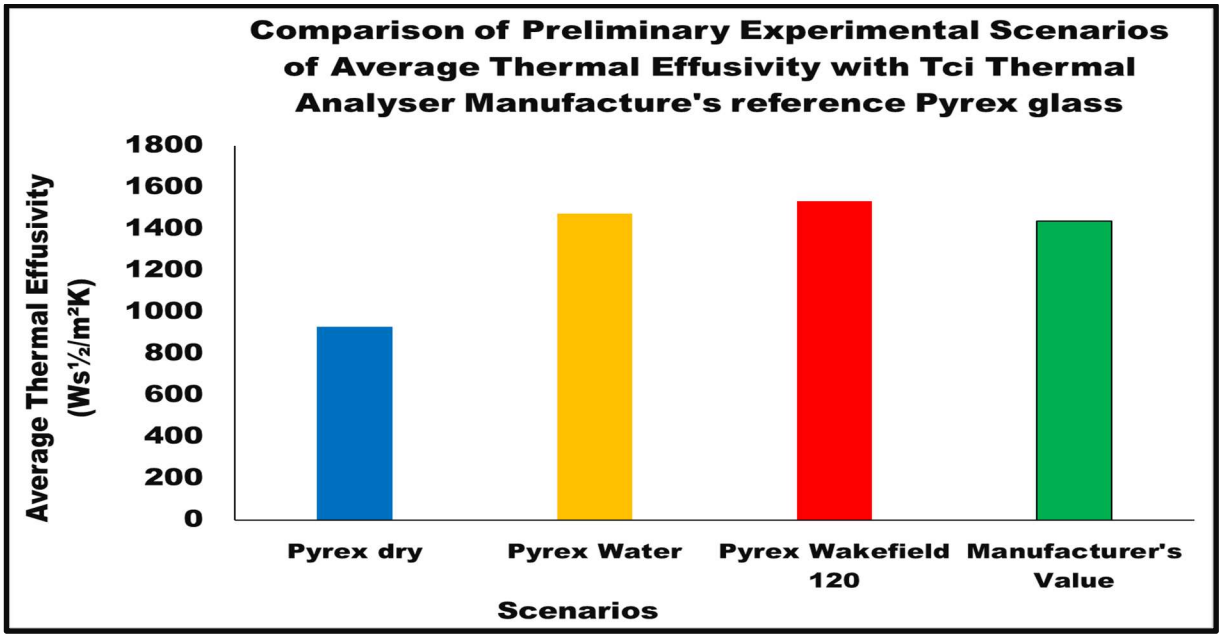

Figure 7.2: Comparison of Preliminary Experimental Scenarios of Average Thermal Effusivity with Tci Thermal Analyser Manufacturer's reference Pyrex glass

The compared results of the manufacturers' value with the preliminary experiment of Pyrex glass using wake field 120 and other thermal contacting agent showed high correlation. Conversely, the test of Pyrex glass conducted without thermal contacting agent (dry) deviated about 40% from the manufacturers' value for both the thermal conductivity and thermal effusivity.

In summary, from this preliminary assessment of the experimental set-up carried out, the use of C-Therm Tci system is valid and reliable in measuring thermal properties. On the other hand, due to the permeability and porosity of the cement-based fabrics, the use of Pyrex water and dry (without thermal contacting agent) are not appropriate contacting agent and scenario to consider respectively for the subsequent measurements. Hence, Wakefield 120 contacting agent (gel) was selected for the subsequent test measurements.

7.2.2 Building Fabric from Ghana

The experimental data for building fabrics from Ghana is categorized into two, that is, foam test method and polymer test method. The building fabrics tested included mortar, concrete, brick and concrete roofing tile.

7.2.21Foam test method for blocks from Ghana

Foam test method is conducted with no thermal contacting agent with low heat penetration depth into the specimen. Its acceptable range of thermal conductivity and thermal effusivity specified by the manufacturer are 0.04 to 0.09W/mK and 6-180 Ws½/m²K respectively. From the manufacturers' manual, any thermal conductivity and thermal effusivity of any measured material with properties outside these range should be discarded.

- Foam test method for mortar block

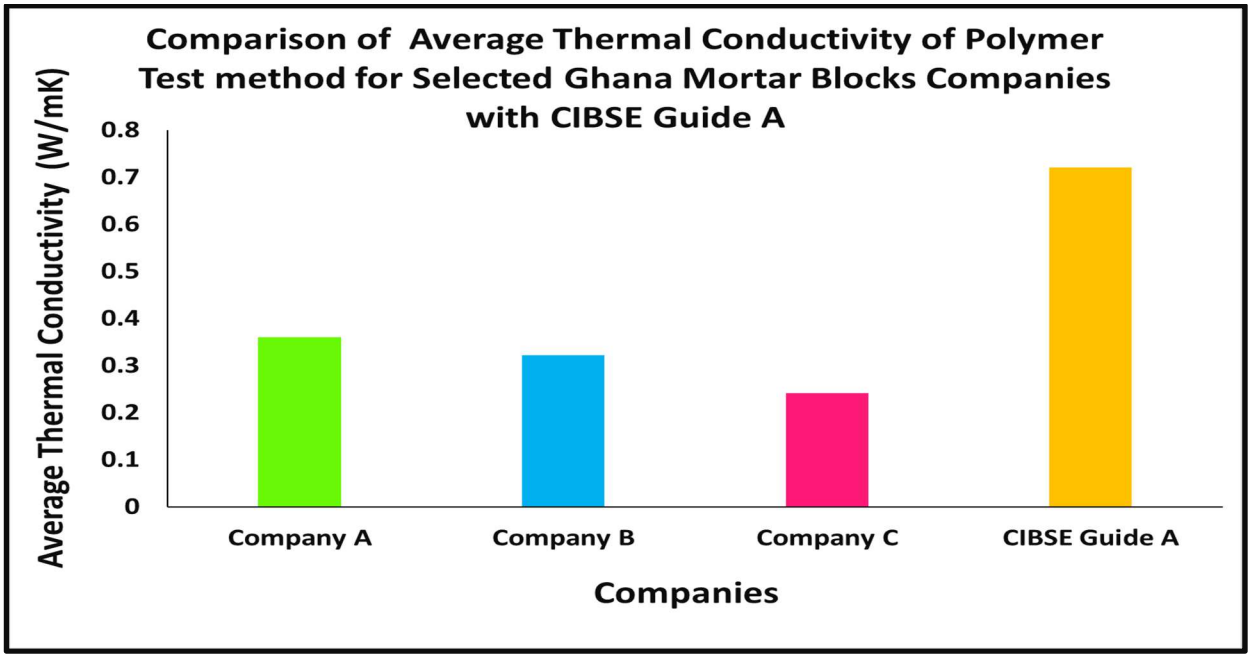

Figure 7.3: Comparison of Average Thermal Conductivity of Foam Test method for Selected Ghana Mortar Blocks Companies with CIBSE Guide A

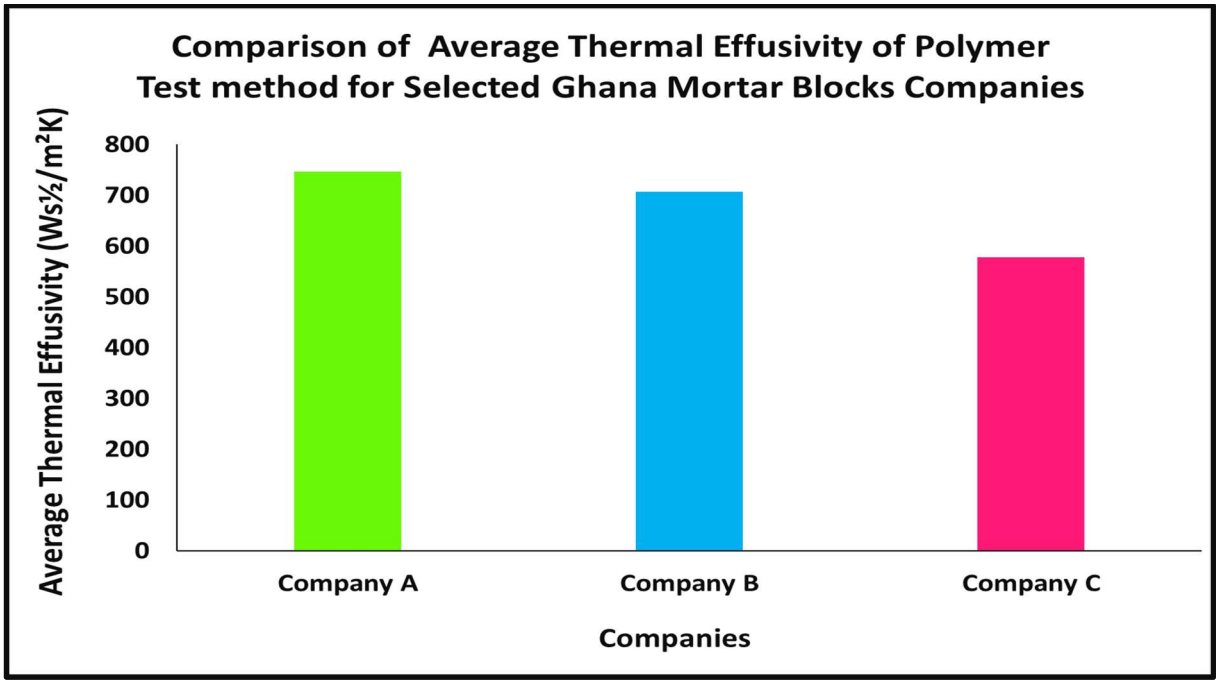

Figure 7.4: Comparison of Average Thermal Effusivity of Foam Test method for Selected Ghana Mortar Blocks Companies

Figure 7.3 and 7.4 are the thermal conductivity and thermal effusivity measurements for the anonymous companies' mortar blocks from Ghana. Using the manufactures specification for foam test method, all the companies' mortar blocks results meet the CIBSE Guide specification for mortar block.

- Foam test method for concrete block

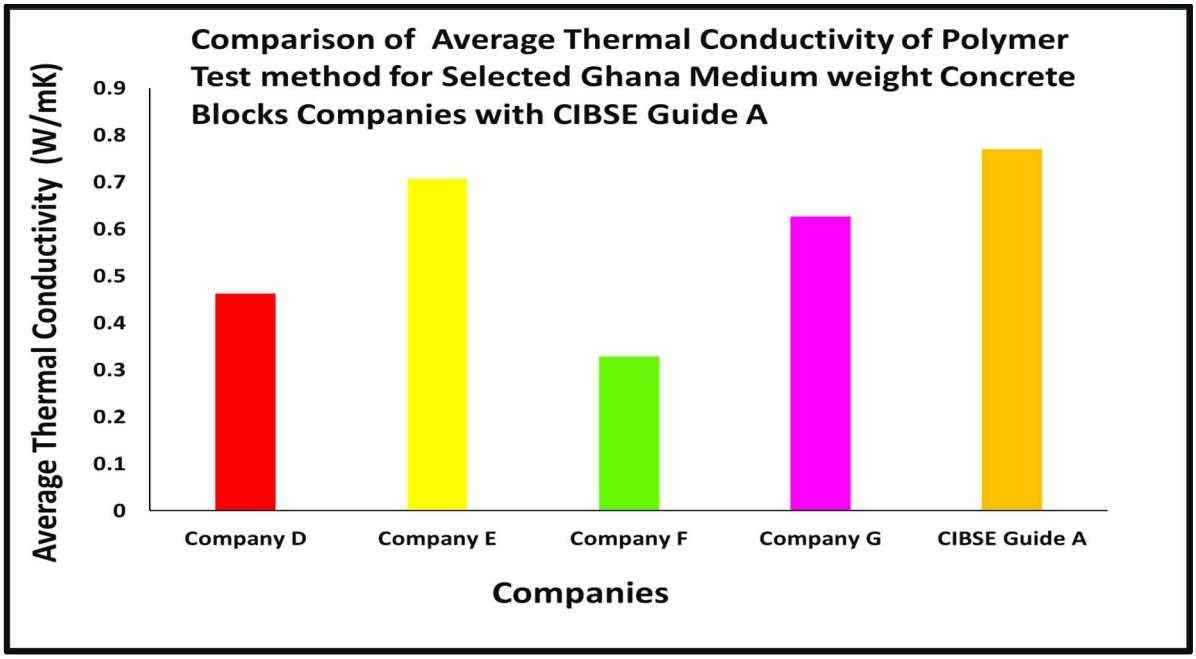

Figure 7.5: Comparison of Average Thermal Conductivity of Foam Test method for Selected Ghana Medium Weight Concrete Blocks Companies with CIBSE Guide A

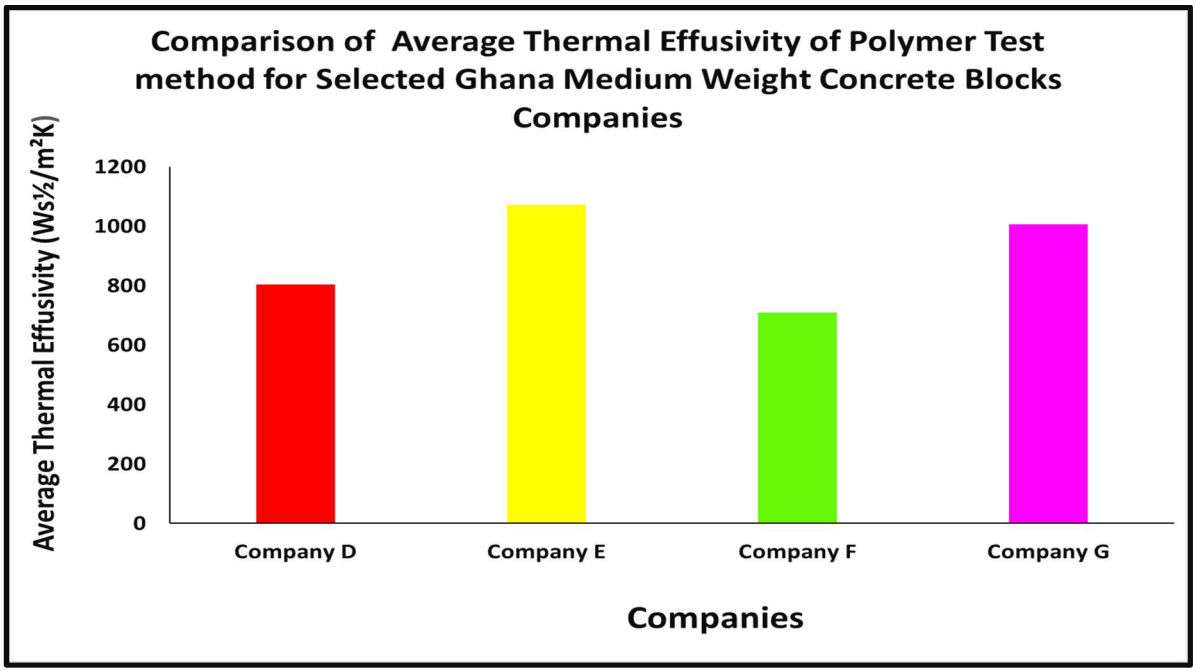

Figure 7.6: Comparison of Average Thermal Effusivity of Foam Test method for Selected Ghana Medium Weight Concrete Blocks Companies

In Figure 7.5 and 7.6, none of the companies' concrete block thermal properties met the manufactures specification for foam test method, hence the entire results were discarded and retested using polymer test method.

- ✓ Foam test method for brick

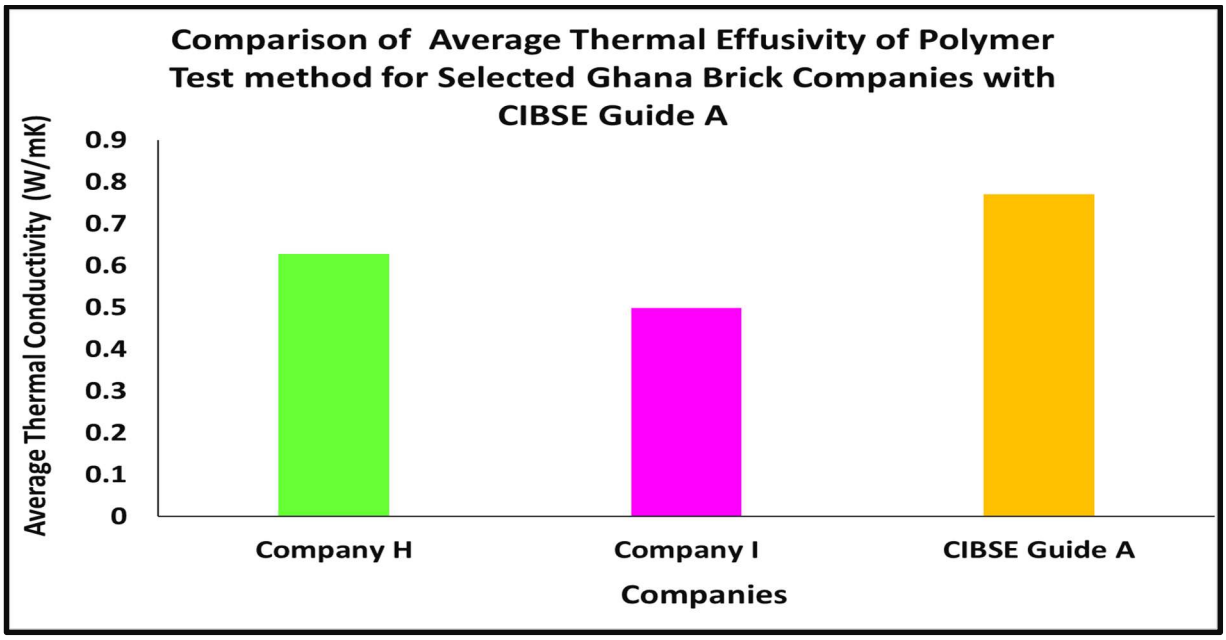

Figure 7.7: Comparison of Average Thermal Effusivity of Foam Test method for Selected Ghana Brick Companies with CIBSE Guide A

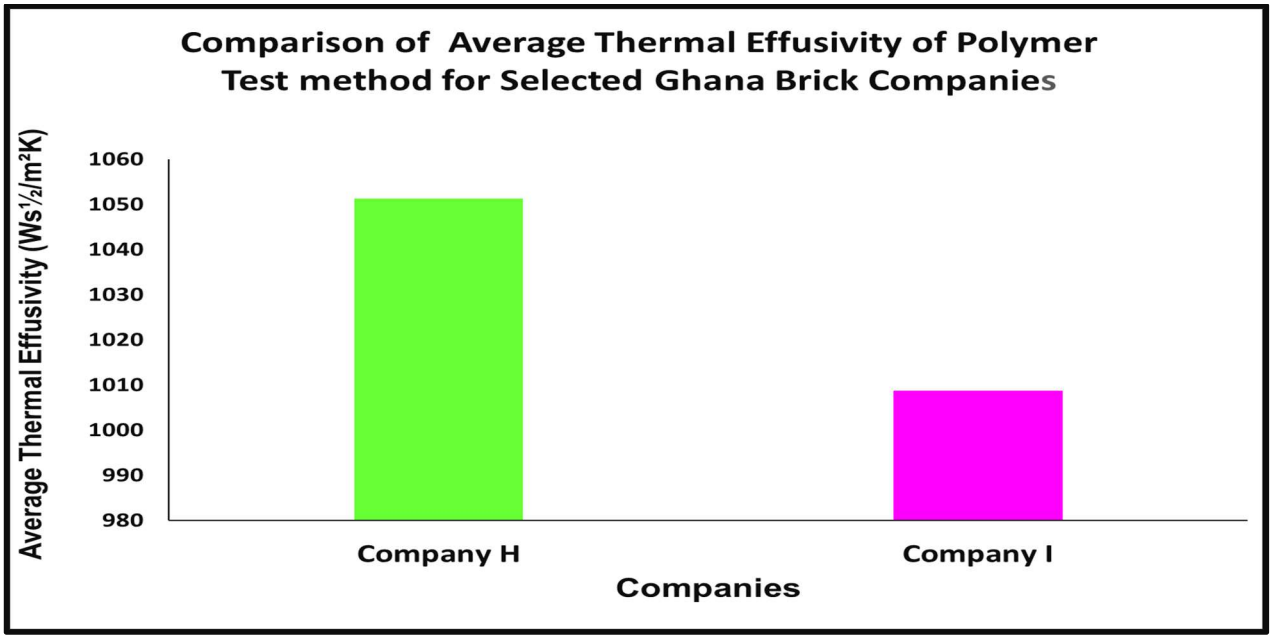

Figure 7.8: Comparison of Average Thermal Effusivity of Foam Test method for Selected Ghana Brick Companies

From Figure 7.7 and 7.8, none of the companies' brick thermal properties met the manufactures specification for foam test method, hence the entire results were discarded and retested using polymer test method.

- Foam test method for concrete roof tiles block

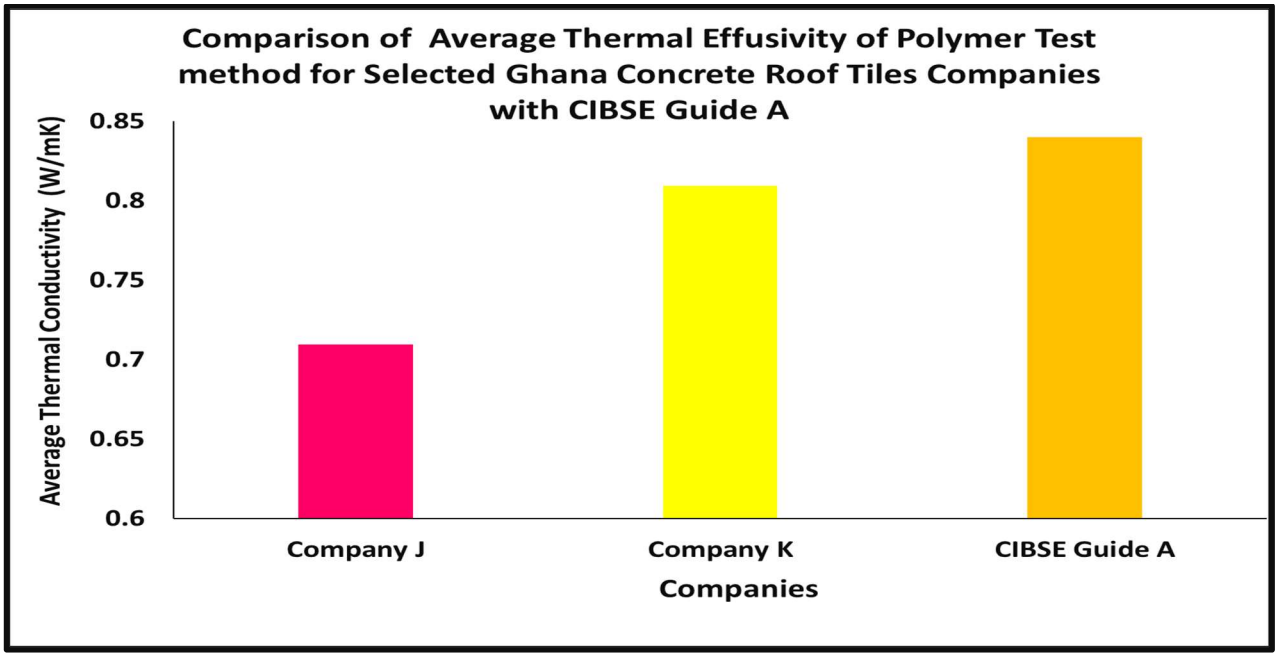

Figure 7.9: Comparison of Average Thermal Effusivity of Foam Test method for Selected Ghana Concrete Roof Tiles Companies with CIBSE Guide A

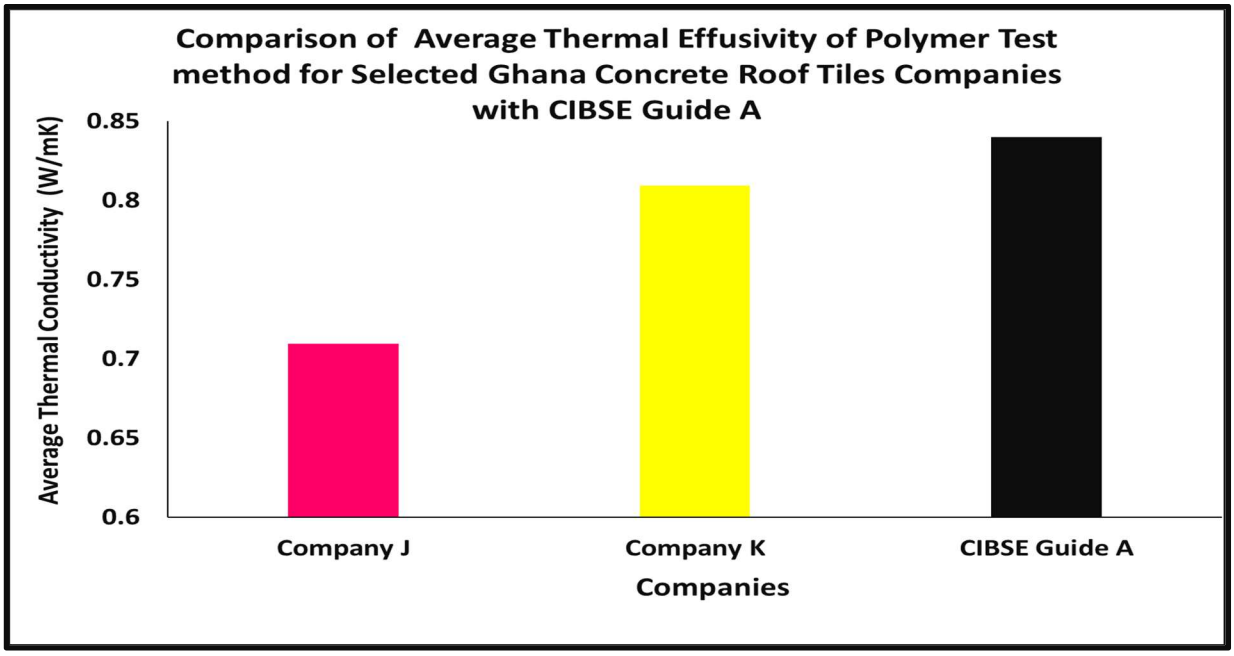

Figure 7.10: Comparison of Average Thermal Effusivity of Foam Test method for Selected Ghana Concrete Roof Tiles Companies

In Figure 7.9 and 7.10, none of the companies' concrete roof tiles thermal properties met the manufactures specification for foam test method, hence the entire results were discarded and retested using polymer test method.

In conclusion, the foam test method was not suitable for concrete block, brick and concrete roof tiles measurements. Since the representative standard blocks have thermal conductivity outside the range of foam test method. In view of this, polymer test method was used for further test measurements.

7.2.22 Polymer Test for Ghana block

Polymer test method employs the use of thermal contacting agent to enhance the heat penetration into the specimen. It has high depth of penetration compared to foam test method with thermal conductivity and thermal effusivity in the range of 0.2 to 1.2 W/mK and 500 to 1450 Ws½/m²K respectively. The polymer test method measurements for the mortar, concrete, brick and concrete roofing tiles are presented below.

- ✓ Polymer test method for mortar block

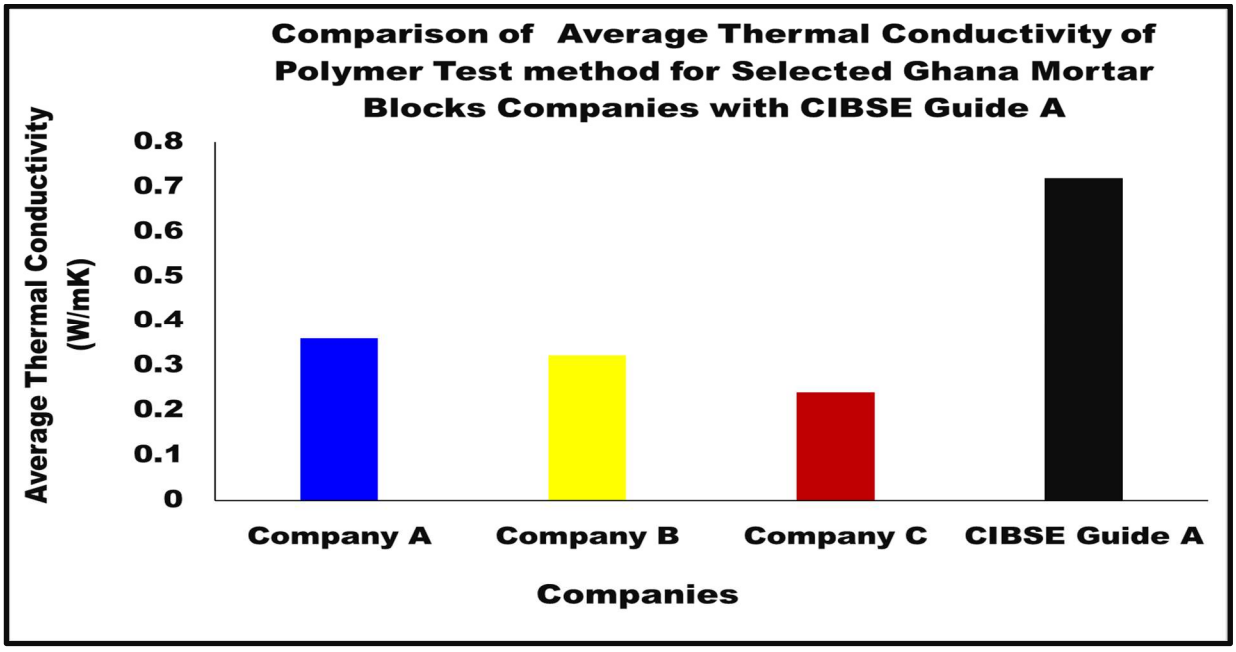

Figure 7.11: Comparison of Average Thermal Conductivity of Polymer Test method for Selected Ghana Mortar Blocks Companies with CIBSE Guide A

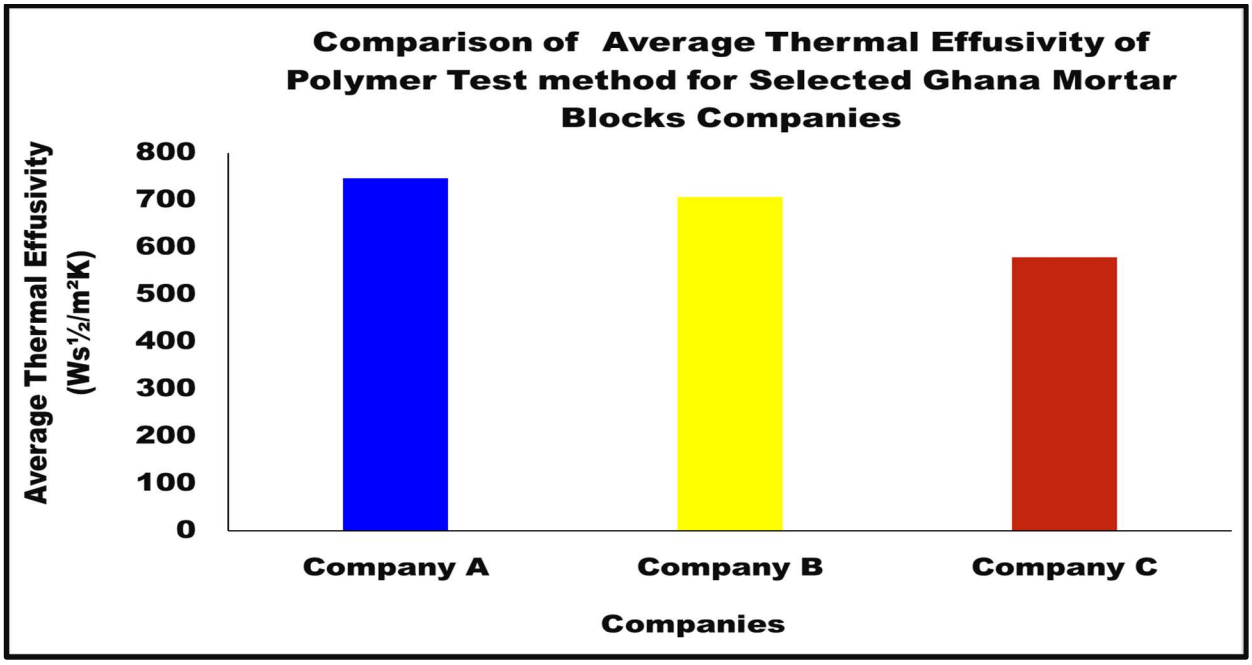

Figure 7.12: Comparison of Average Thermal Effusivity of Polymer Test method for Selected Ghana Mortar Blocks Companies

From Figure 7.11 and 7.12, all the mortar blocks are within the range of polymer test method. The thermal conductivity for the representative companies were in the range of 0.25 to 0.38 W/mK with coresponding thermal effusivity in the range of 630 to 750 Ws½/m²K and it meet the CIBSE Guide specification for mortar block. A trend of increasing thermal conductivity with increasing thermal effusivity was observed. There is no high deviation of thermal properties among the representative mortar block manufacturing companies was found.

✓ Polymer test method for concrete block

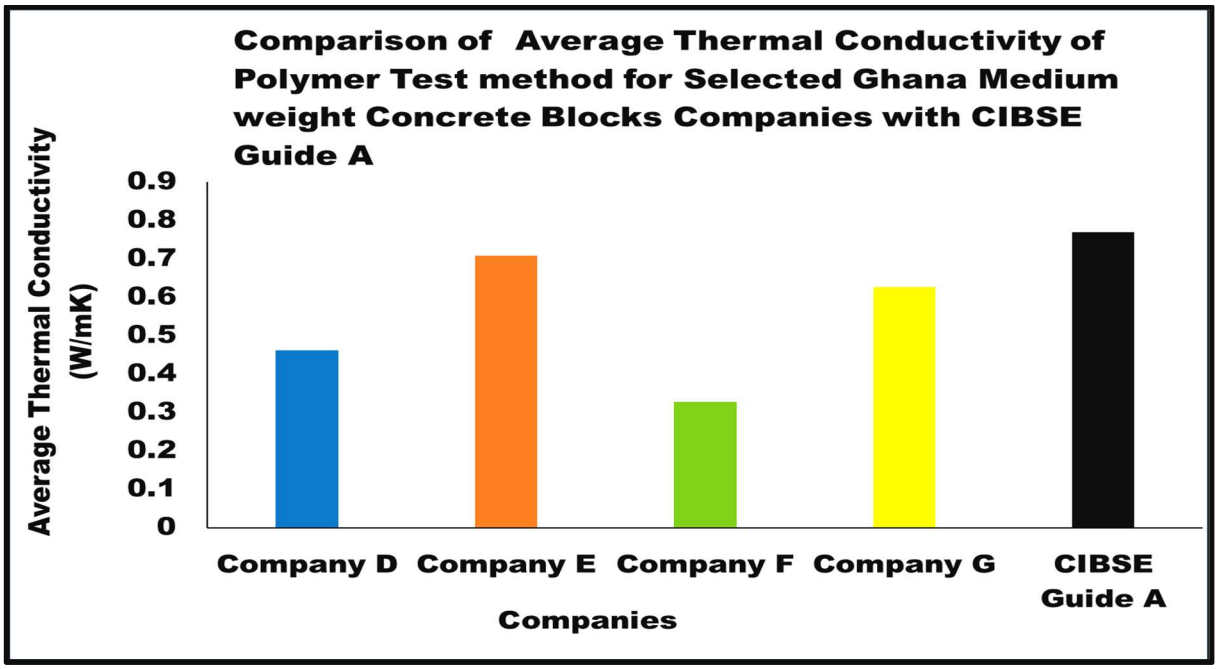

Figure 7.13: Comparison of Average Thermal Conductivity of Polymer Test method for Selected Ghana Medium Weight Concrete Blocks Companies with CIBSE Guide A

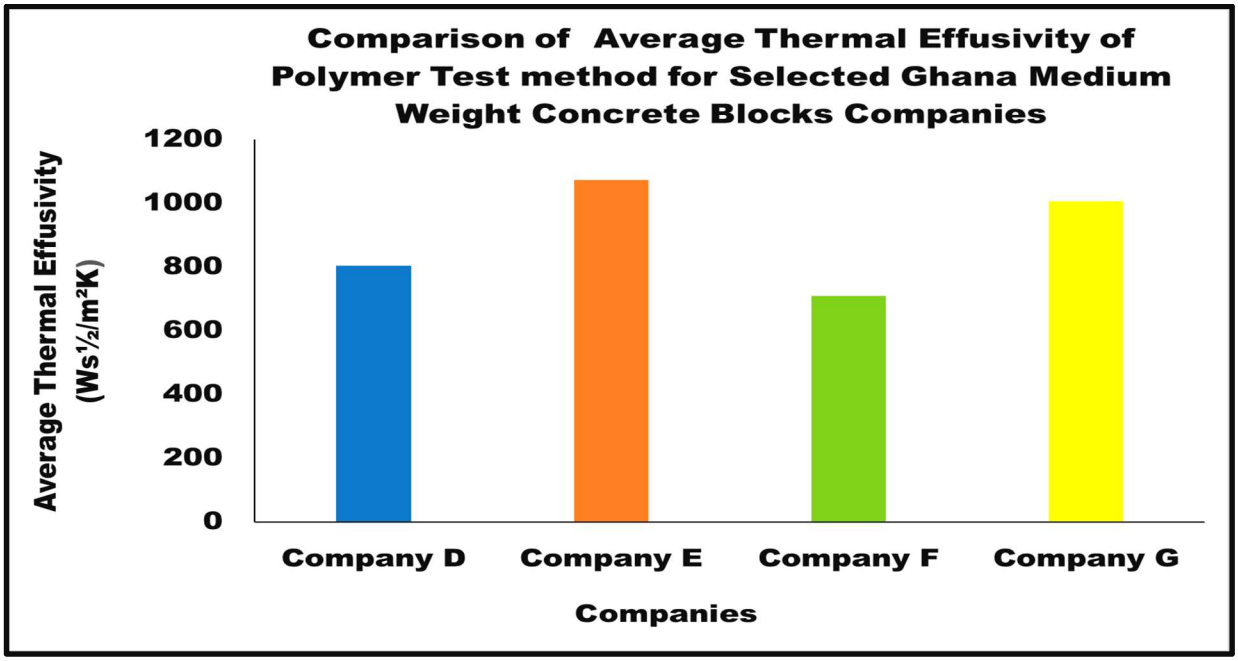

Figure 7.14: Comparison of Average Thermal Effusivity of Polymer Test method for Selected Ghana Medium Weight Concrete Blocks Companies

In Figure 7.13 and 7.14 all the concrete blocks are within the range of polymer test method. The thermal conductivity for the representative companies were in the range of 0.34 to 0.68 W/mK with corresponding thermal effusivity in the range of 650 to 1100 Ws½/m²K and it meet the CIBSE Guide specification for concrete block. A trend of increasing thermal conductivity with increasing thermal effusivity was observed. On the contrary, there is a high deviation of thermal properties among the representative concrete block manufacturing companies was found.

- ✓ Polymer test method for brick block

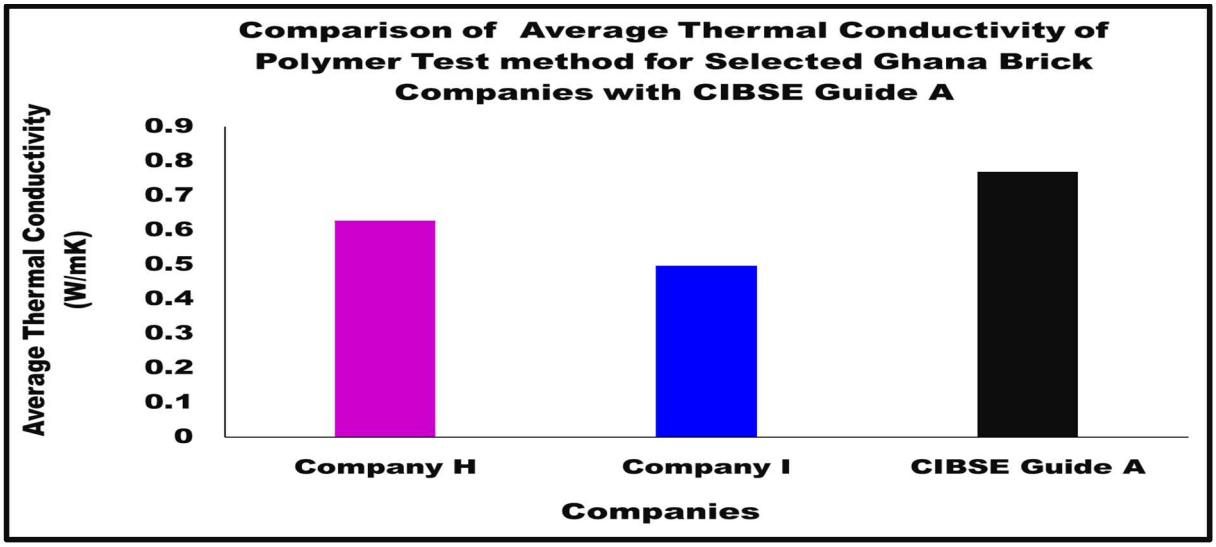

Figure 7.15: Comparison of Average Thermal Conductivity of Polymer Test method for Selected Ghana Bricks Companies with CIBSE Guide A

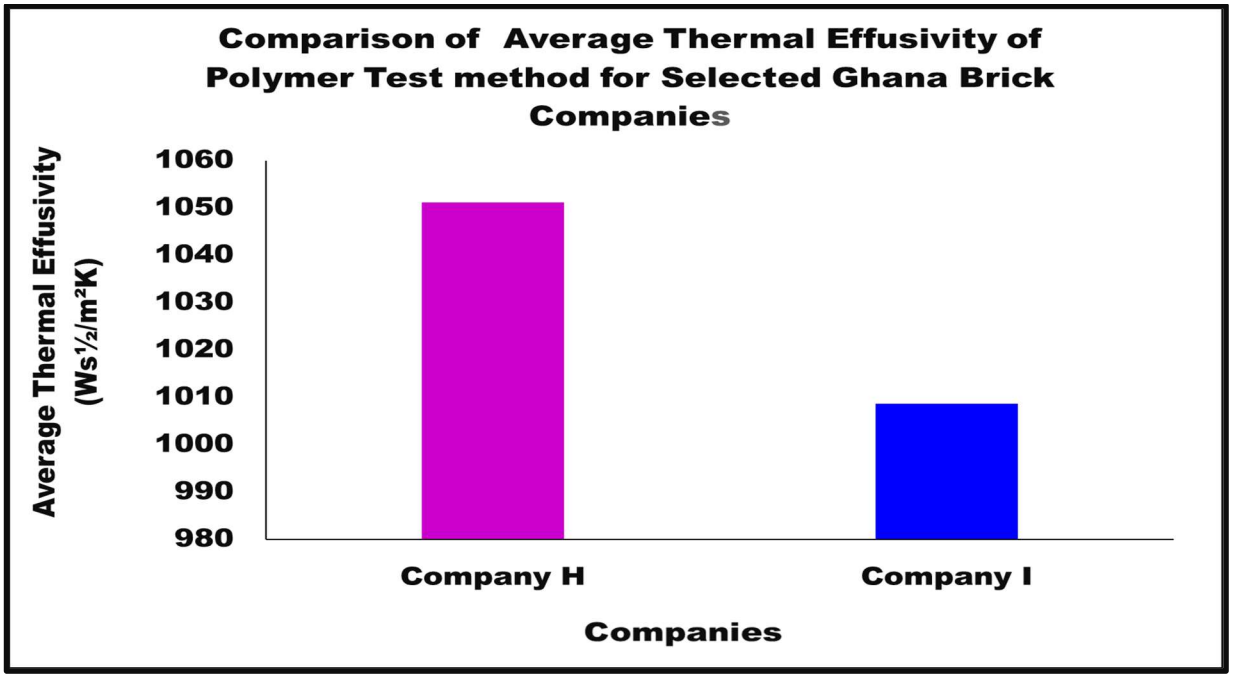

Figure 7.16: Comparison of Average Thermal Effusivity of Polymer Test method for Selected Ghana Bricks Companies with CIBSE Guide A

From Figure 7.15 and 7.16 all the bricks are within the range of polymer test method. The thermal conductivity for the representative companies were in the range of 0.52 to 0.62 W/mK with corresponding thermal effusivity in the range of 1010 to 1050 Ws½/m²K and it meet the CIBSE Guide specification for brick. A trend of increasing thermal conductivity with increasing thermal effusivity was observed. No significant deviation of thermal properties among the representative brick manufacturing companies was found.

✓ Polymer test for concrete roof tiles

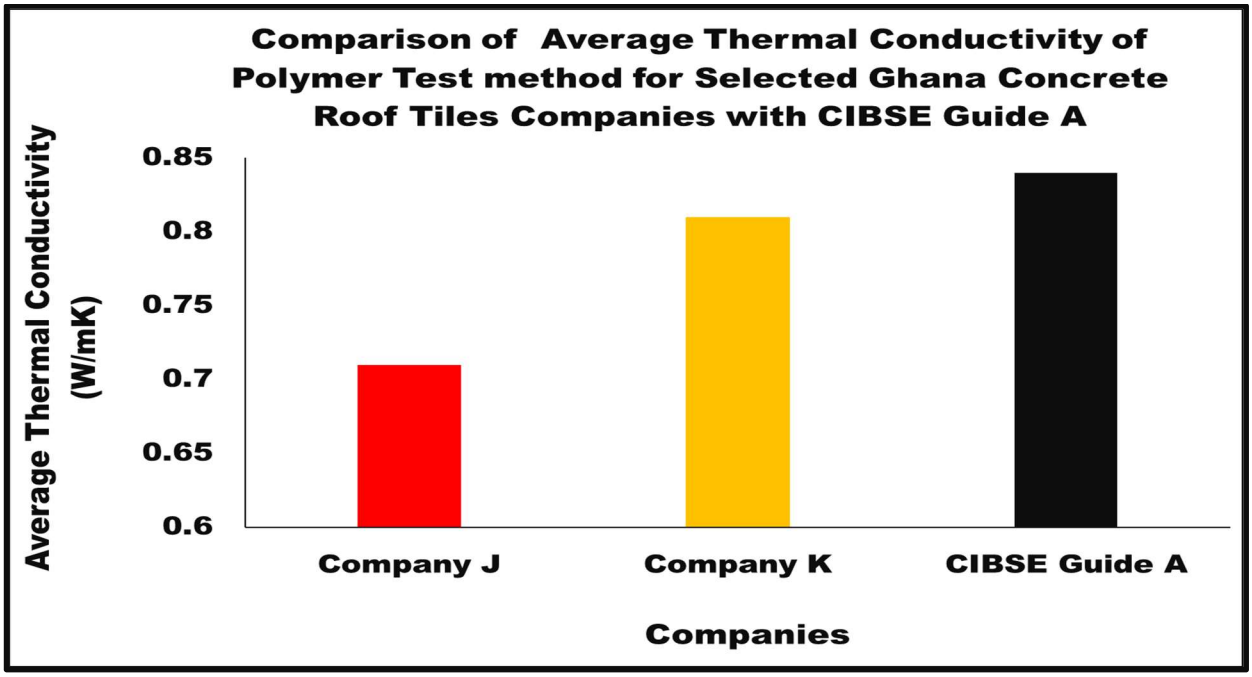

Figure 7.17: Comparison of Average Thermal Effusivity of Polymer Test method for Selected Ghana Concrete Roof Tiles Companies with CIBSE Guide A

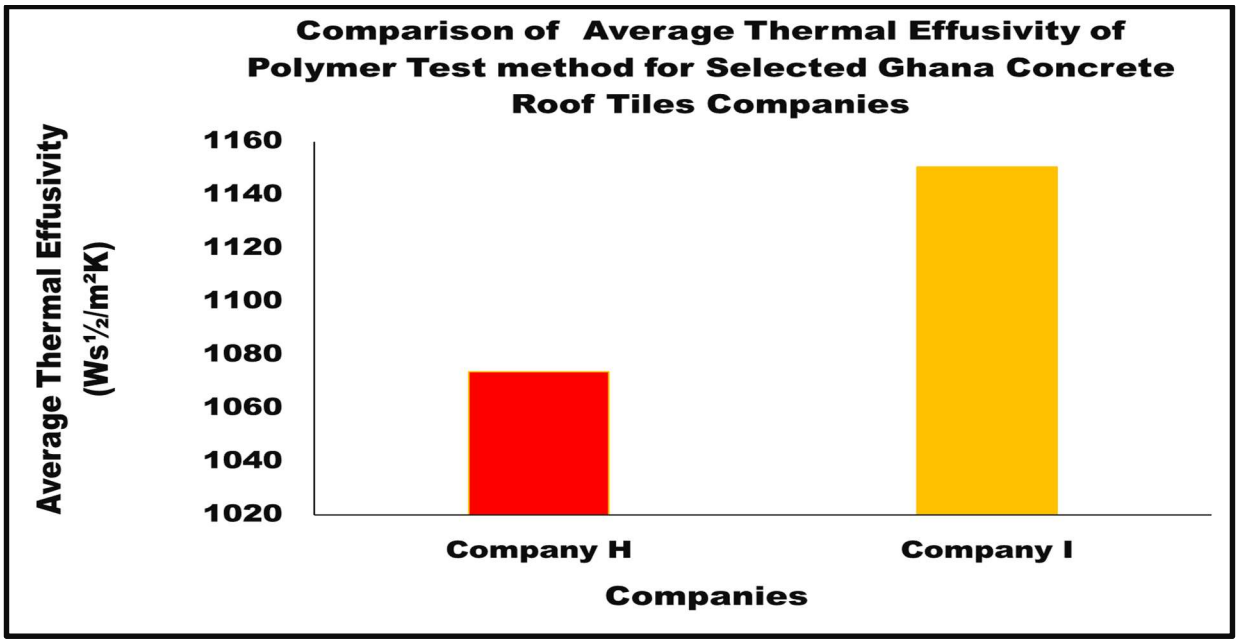

Figure 7.18: Comparison of Average Thermal Effusivity of Polymer Test method for Selected Ghana Concrete Roof Tiles Companies

In Figure 7.17 and 7.18, all the concrete roof tiles are within the range of polymer test method. The thermal conductivity for the representative companies were in the range of 0.72 to 0.81 W/mK with corresponding thermal effusivity in the range of 1070 to 1155 Ws½/m²K and it meet the CIBSE Guide specification for brick. A trend of increasing thermal conductivity with increasing thermal effusivity was observed. High deviation of thermal properties among the representative brick manufacturing companies was found.

7.3 Parametric Building Fabric

The creative parametric blocks results consist of mortar and concrete using the two test methods as represented in Ghana building fabrics. There are 15 parametric mortar blocks and 15 parametric concrete blocks consisting of different sand types and mixing ratio designs.

The symbols used to represent the fifteen blocks are the following: Mixing Design ratio for mortar block that is, Cement: Sand type ratio

T1 = 1:6

T2=1:5

T3= 1:4

T4= 1:3

T5= 1:2

Mixing Design ratio for concrete block that is, Cement : Gravels sizes (10mm and 20mm) : Sand type

T1 = 1:5:1

T2=1:4:1

T3= 1:3:1

T4= 1:1:4

T5= 1:1:3

The parametric study for mortar blocks using builders sand (MbsTn), washed sand (MwsTn), and mixed sand (MbwsTn) with different mixing ratio.
Where
M represents mortar block,
bs represents builders sand type
Tn represents the test series of mixing ratio from n=1, 2,3, 4 and 5.
ws represents washing sand type
bws represents mixed builders and washing sand type

The parametric study for concrete blocks using builders sand (CbsTn), washed sand (CwsTn), and mixed sand (cbwsTn)with different mixing ratio.
Where
C represents concrete block,
bs represents builders sand type
Tn represents the test series of mixing ratio from n=1, 2,3, 4 and 5.
ws represents washing sand type
bws represents mixed builders and washing sand type

The creative parametric blocks measurement results are categorised into foam and polymer test for both mortar and concrete.

7.3.1 Foam Test Method for parametric blocks

Foam test method is conducted with no thermal contacting agent with low heat penetration depth into the specimen. Its acceptable range of thermal conductivity and thermal effusivity specified by the manufacturer are 0.04 to 0.09W/mK and 6-180 Ws½/m²K respectively. From the manufacturers' manual, any thermal conductivity and thermal effusivity of any measured material with properties outside these range should be discarded.

- Foam test method for creative parametric mortar blocks

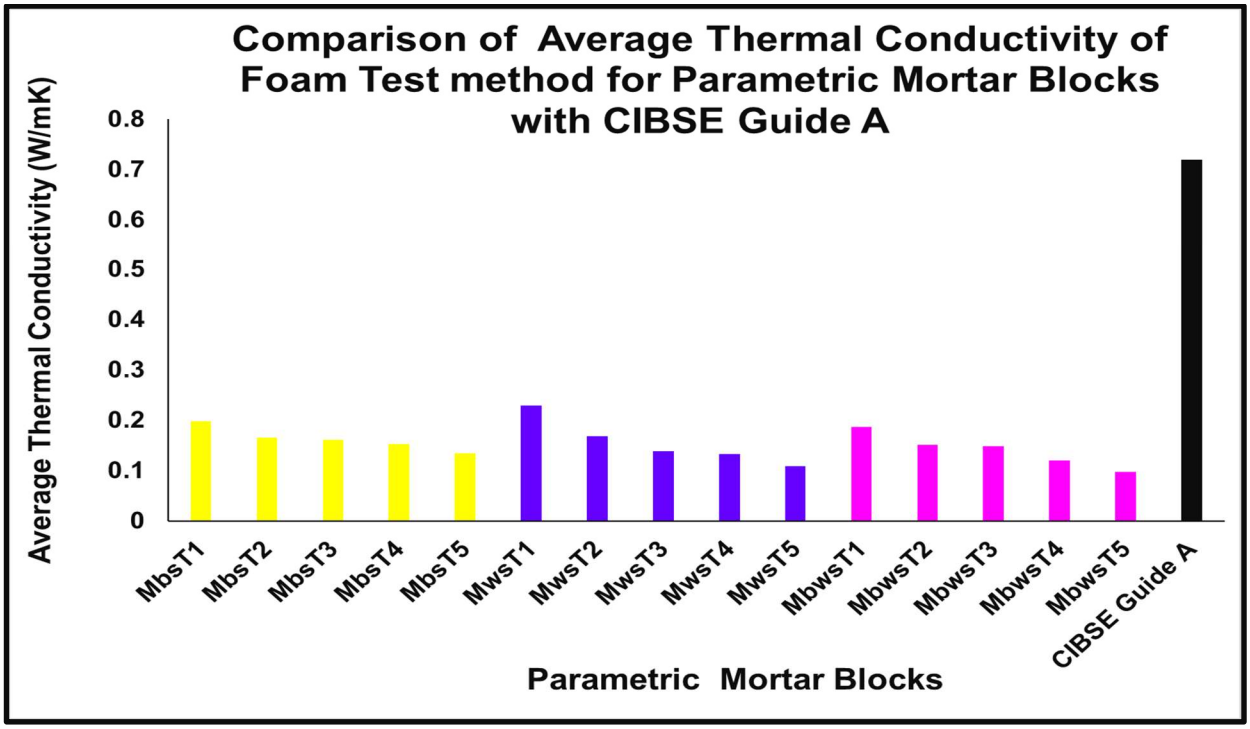

Figure 7.19: Comparison of Average Thermal Conductivity of Foam Test method for Parametric Mortar Blocks with CIBSE Guide A

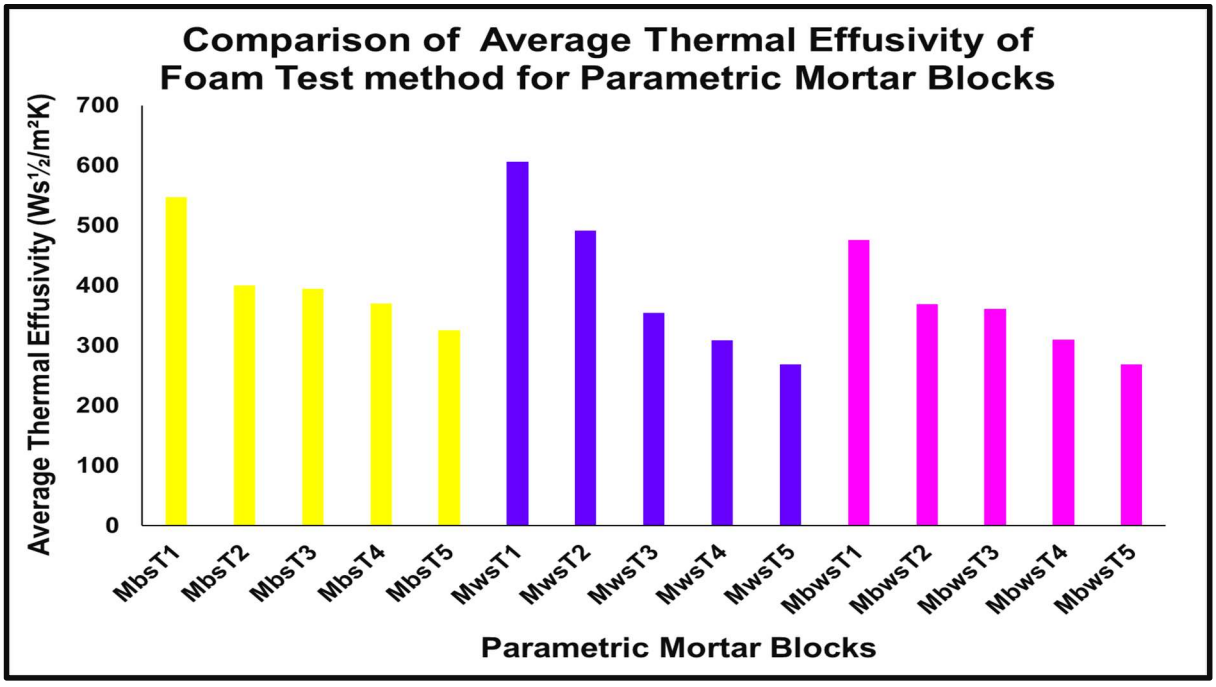

Figure 7.20: Comparison of Average Thermal Effusivity of Foam Test method for Parametric Mortar Blocks

- Foam test method for creative parametric concrete block

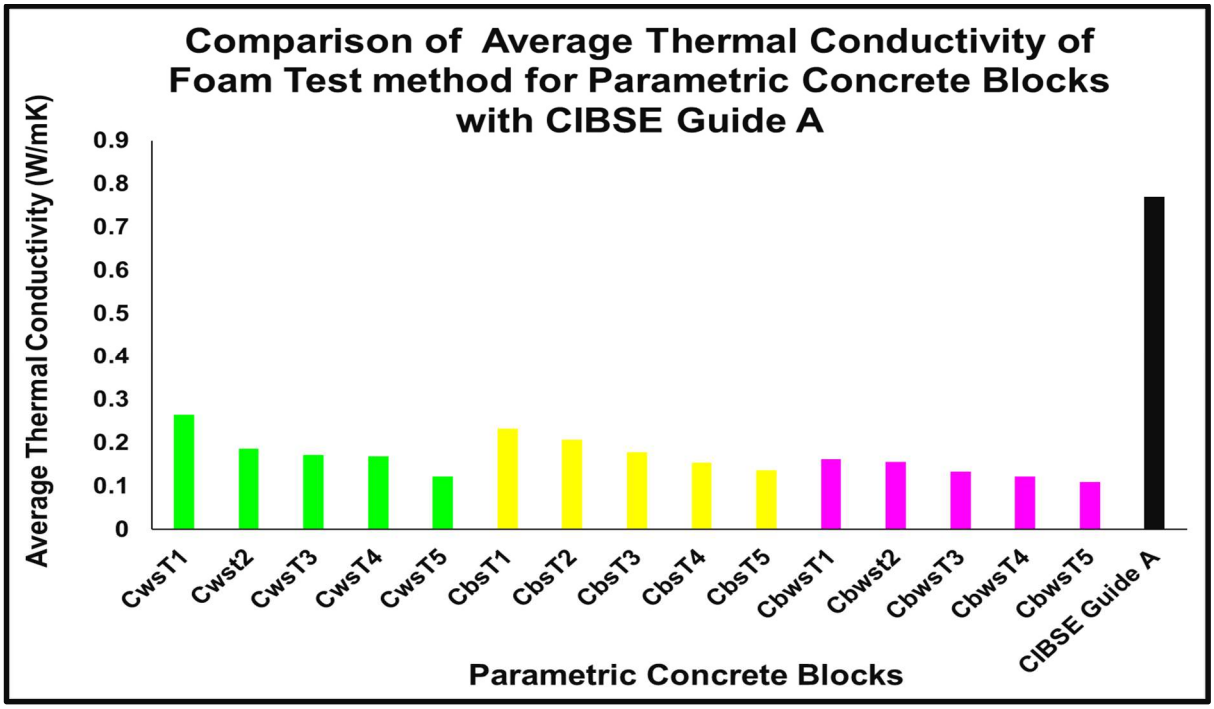

Figure 7.21: Comparison of Average Thermal Conductivity of Foam Test method for Parametric Concrete Blocks with CIBSE Guide A

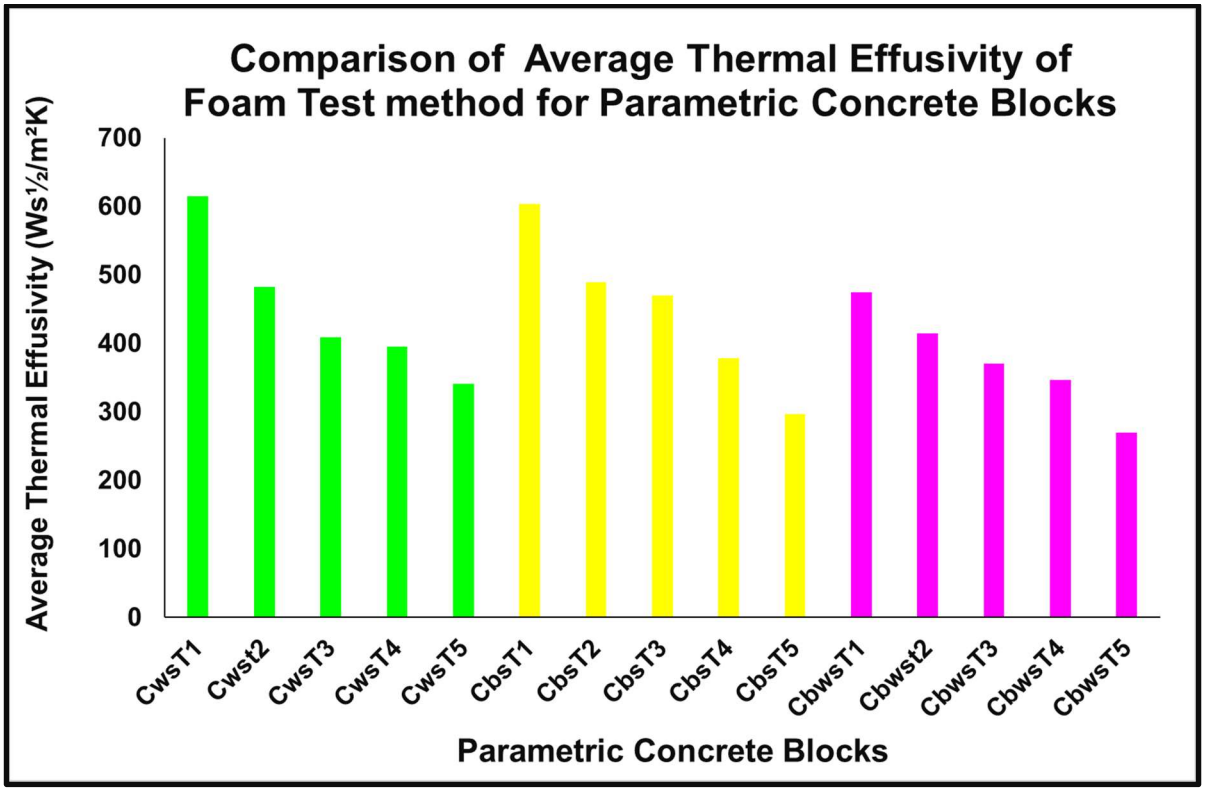

Figure 7.22 Comparison of Average Thermal Effusivity of Foam Test method for Parametric Concrete Block

From Figure 7.18 to 7.22, both the creative parametric mortar and concrete blocks are outside range for thermal conductivity and thermal effusivity as specified by the manufacturer. In view of this, all the results were discarded and retested using polymer test method.

7.3.2 Polymer Test Method for Parametric Blocks

Polymer test method employs the use of thermal contacting agent to enhance the heat penetration into the specimen. It has high depth of penetration compared to foam test method with thermal conductivity and thermal effusivity in the range of 0.2 to 1.2 W/mK and 500 to 1450 Ws½/m²K respectively.

❖ Creative parametric mortar blocks

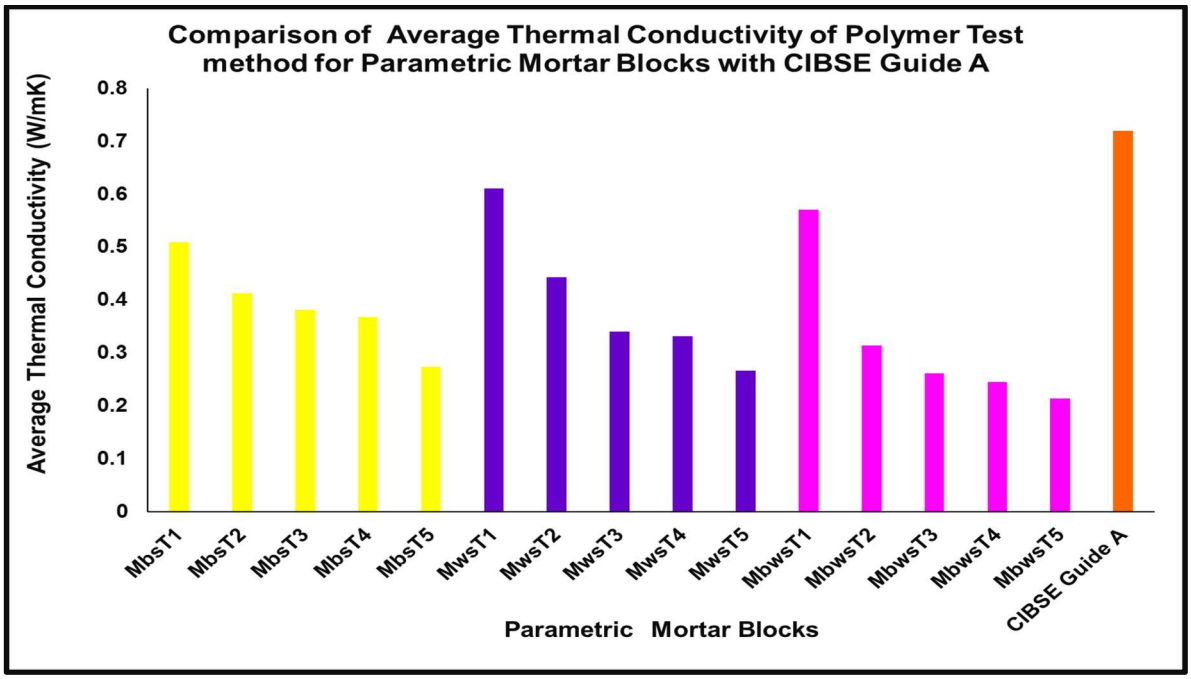

Figure 7.23: Comparison of Average Thermal Conductivity of Polymer Test method for Parametric Mortar Blocks with CIBSE Guide A

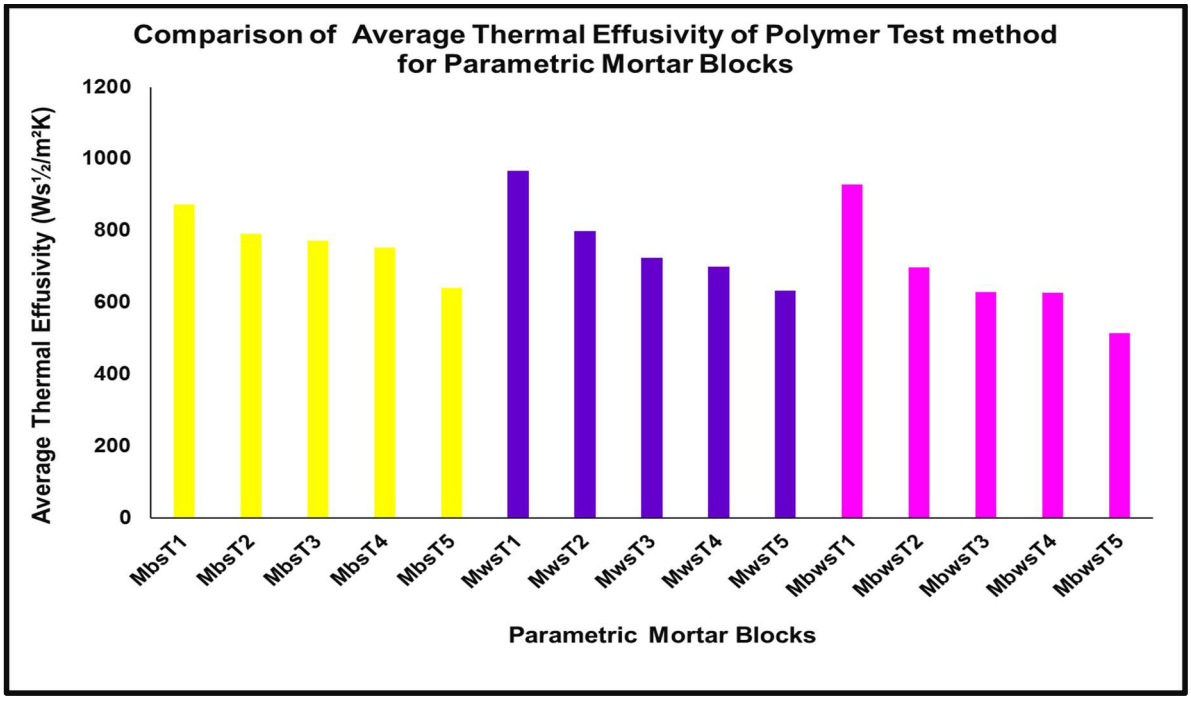

Figure 7.24: Comparison of Average Thermal Effusivity of Polymer Test method for Parametric Mortar Blocks

In Figure 7.23 and 7.24 all the parametric mortar blocks thermal conductivity and thermal effusivity were in the range of the polymer test method as specified by the manufacturer and it meet the CIBSE Guide specifications.

A trend of decreasing thermal conductivity and thermal effusivity with corresponding decreasing sand content within the mixing ratio was observed with all the different sand types. For example, MbsT1 had thermal conductivity of 0.51 W/mK and MbsT5 had thermal conductivity of 0.28 W/mK. From the mixing ratio design, T1 has 1 part of cement to 6 parts of sand, whiles T5 has 1 part of cement to 2 parts of sand. This implies that, assuming all the conditions which can affect the experimental results (mixture uniformity, compactness of blocks, minimal porosity, right contacting agent, standard level of dryness of sample, among others) been equal, increasing cement content of the block can reduce the thermal conductivity. No substantial deviation of both thermal conductivity and thermal effusivity was observed among the sand types, on the contrary the mixed sand type had lower thermal properties across all the mixing ratio designs.

The thermal properties of T1 (1 cement: 6 sand) had high thermal properties. This implies that, mixing ratio of T1 is not suitable for building fabric manufacturing in Ghana.

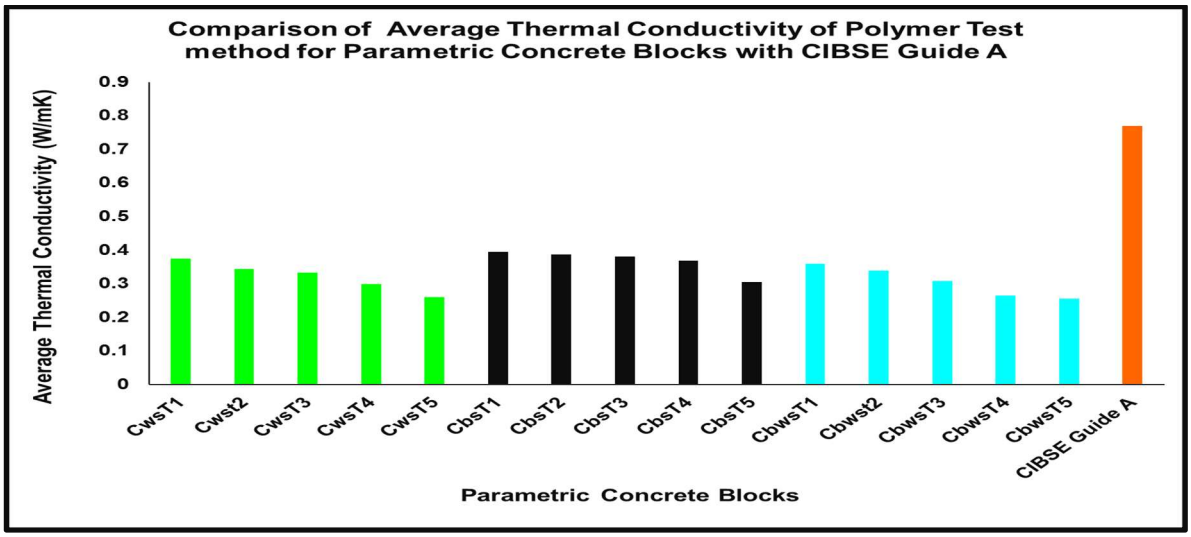

Figure 7.25: Comparison of Average Thermal Conductivity of Polymer Test method for Parametric Concrete Blocks with CIBSE Guide A

❖ Polymer test method for creative parametric concrete block

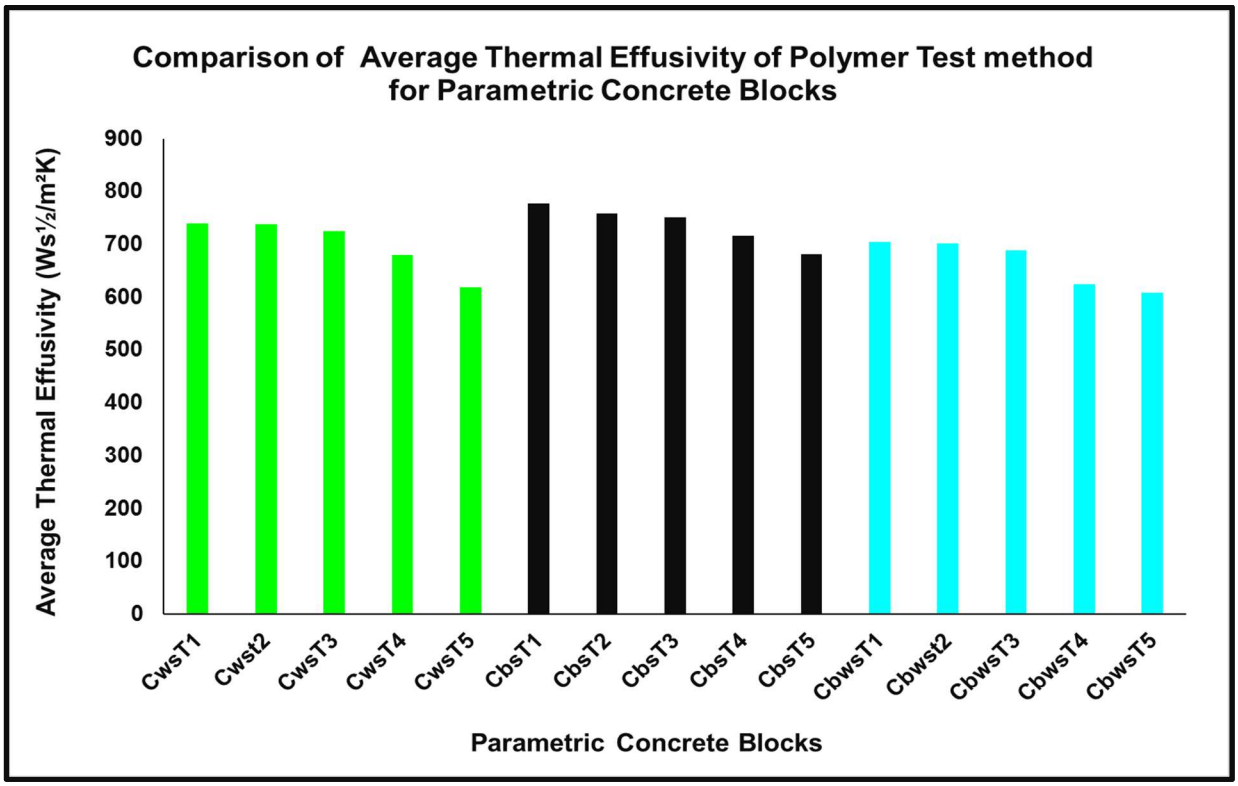

Figure 7.26: Comparison of Average Thermal Effusivity of Polymer Test method for Parametric Concrete Blocks

From Figure 7.25 and 7.26, all the parametric concrete blocks thermal conductivity and thermal effusivity were in the range of the polymer test method as specified by the manufacturer and it meet the CIBSE Guide specifications. A trend of decreasing thermal conductivity and thermal effusivity with corresponding decreasing gravel content within the mixing ratio was observed with all the different sand types from concrete mixing ratio T1 to T3. A similar trend of decreasing thermal conductivity and thermal effusivity with corresponding decreasing sand content within the mixing ratio was observed with all the different sand types from concrete mixing ratio T4 to T5. This implies that, assuming all the conditions which can affect the experimental results (mixture uniformity, compactness of blocks, minimal porosity, right contacting agent, standard level of dryness of sample, size of gravels, among others) been equal, increasing cement content of the block can reduce the thermal conductivity.

No substantial deviation of both thermal conductivity and thermal effusivity was observed among the sand types, on the contrary the mixed sand type had lower thermal properties across all the mixing ratio designs. The identified design mixing ratios' for concrete block from the survey questionnaires, shows that the mixing ratios' are suitable for manufacturing concrete blocks in Ghana. Conversely, if the major aim is to use concrete design mixing ratio for enhancing thermal conductivity, then appropriate technology needs to be applied.

7.3 Comparison of Experimental with Theoretical Density

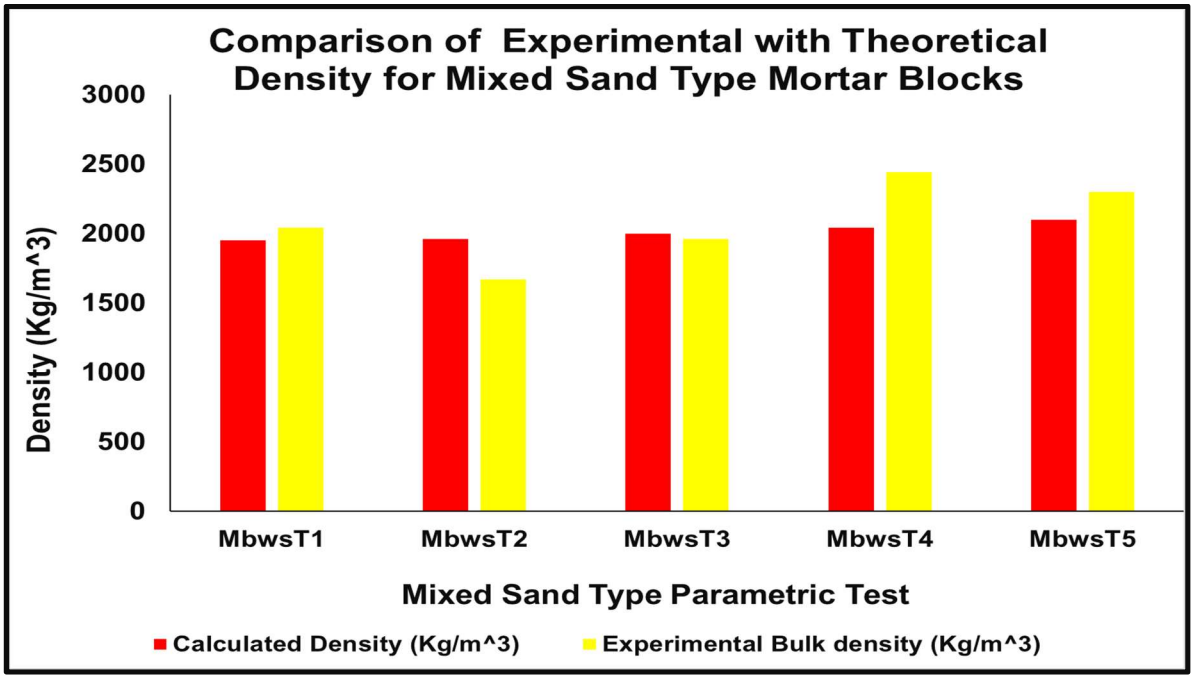

Figure 7.27: Comparison of Experimental with Theoretical Density for Mixed Sand Type Mortar Block

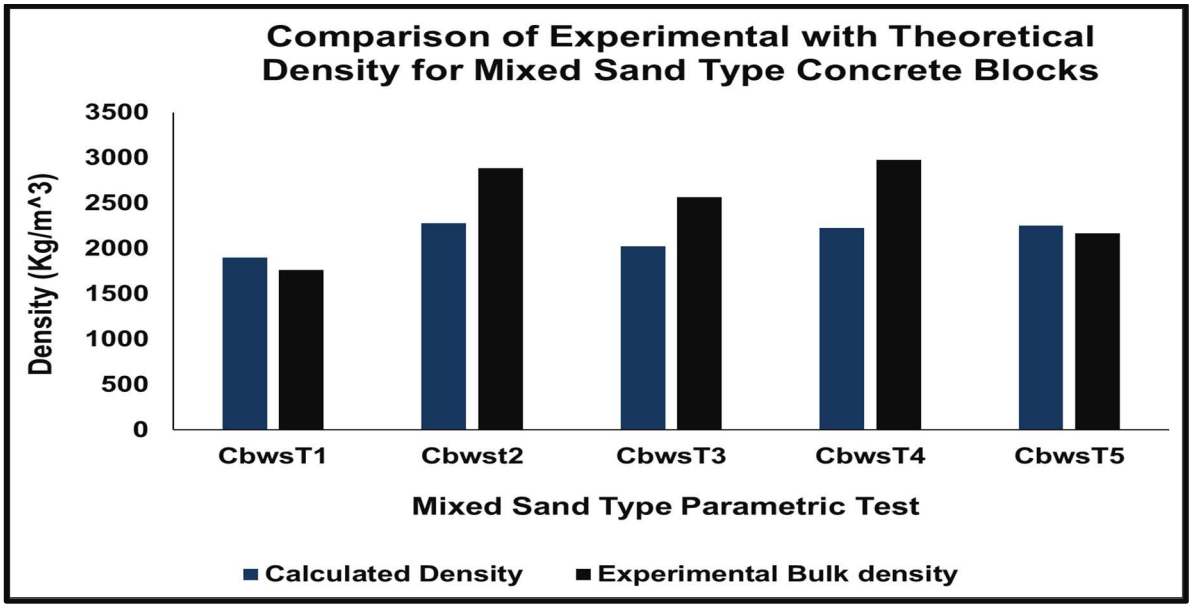

Figure 7.28: Comparison of Experimental with Theoretical Density for Mixed Sand Type Concrete Block

In Figure 7.27 and 7.28, the theoretical density obtained from the average weight of all the dried mortar and concrete blocks are highly correlated with the obtained experimental block densities using AutoPore IV. Hence, the selection of AutoPore IV equipment was appropriate in characterising the properties of the blocks. The porosity parameters obtained from alongside of the density was not analysed, since it was outside the scope of the research.

7.5 Comparison of Experimental results with CIBSE Guide A and Survey Questionnaires

The comparison of the experimental results with CIBSE Guides and survey questionnaires data was undertaking to answer the main hypothesis listed within the introduction in section 7.1 as presented below.

- **Hypothesis 1**

Is there a relationship between mixing ratio and sand type with thermo-physical properties?

From the creative parametric mortar and concrete blocks discussion, there is a relationship between mixing ratio and sand type with thermo-physical properties based on the following deductions:

a. The mortar block with T1 (1 cement: 6 sand) mixing design ratio had high thermal properties. This implies that, mixing ratio of T1 (1 cement: 6 sand) is not suitable for building fabric manufacturing in Ghana.

b. The of use concrete design mixing ratio for enhancing thermal conductivity is not appropriate approach for achieving lower transmittance value in Ghana, technology needs to be applied to building fabric manufacturing.

c. The cost-effective approach adopted using the novel parametric design (sand type and mixing ratio) enhanced the thermal conductivities of the mortar blocks and concrete blocks. For example, from the selected concrete blocks from Ghana, the minimum thermal conductivity was 0.32 W/m K, conversely, the novel parametric designed concrete block was 0.26W/m K.

d. A trend of decreasing thermal conductivity and thermal effusivity with corresponding decreasing sand content within the mixing ratio was observed with all the different sand types. For example, MbsT1 had thermal conductivity of 0.51 W/mK and MbsT5 had thermal conductivity of 0.28 W/mK. From the mixing ratio design, T1 has 1 part of cement to 6 parts of sand, whiles T5 has 1 part of cement to 2 parts of sand

- Hypothesis 2

What is the actual representative thermo-physical properties of materials in Ghana?
The actual representative thermo-physical properties of materials in Ghana was obtained using the survey questionnaires and the experimental assessment of selected fabrics from Ghana and creative parametric blocks designed using typical mixing ratios used in Ghana. The following results were achieved:

a. From the survey questionnaires responses, majority of participants selected the thermal conductivity of concrete blocks and mortar blocks to be in the range of 0.3-0.7 W/mK and 0.5-0.75 W/mK respectively.

b. The experimental thermal conductivity of the selected fabrics from Ghana are in the ranges of 0.33-0.63 W/mK , 0.24-0.36 W/mK, 0.49-0.63 W/mK and 0.71-0.81 W/mK for concrete blocks, mortar blocks, bricks and concrete roofing tiles respectively.

c. The experimental thermal conductivity of parametric fabrics is in the ranges of 0.25 -0.39 W/mK and 0.26-0.61 W/mK for parametric concrete and mortar blocks respectively.

- Hypothesis 3

Are there any variations of thermo-physical from one company to other using the same building regulations and raw materials to produce the same products?
Deviations were observed among all the companies using the same building regulations and raw materials, but it was at different levels of variations. For example,

1. High deviation of thermal properties among the representative concrete block manufacturing companies was found

2. No significant deviation of thermal properties among the representative brick manufacturing companies was found.
3.High deviation of thermal properties among the representative brick manufacturing companies was found.

- Hypothesis 4

How can the thermo-physical of the products be enhanced if it is inadequately compared to the specifications of Ghana building regulations?

All the selected building fabrics from Ghana and the creative parametric concrete and mortar blocks meets the thermo-physical properties specified in CIBSE Guide A.

7.6 Overall Findings and Implications on Experimental Assessments

1. The obtained experimental thermal conductivity and effusivity of the building fabrics indicates that, the use of thermal contacting agent has significant influence on thermo-physical property measurements as seen the literature.
2. The thermal conductivity of all the selected building fabrics from Ghana meets the range of expected standard values outlined in CIBSE Guide A.
3. The typical dimensions of building materials of cement-based building elements manufactured in Ghana are about one third lower than the stipulated minimum dimensions in Ghana building regulation.
4. Burnt brick is the second highest indigenous building fabric within the policy; its experimental thermal conductivity is within the range of representative experimental thermal conductivity of concrete blocks
5. The typical thermal conductivity values of local building fabric obtained from experiment and the indicated response by the survey participants are highly correlated.
6. The identified design mixing ratios for concrete block from the survey questionnaires, shows that the mixing ratios are suitable for manufacturing concrete blocks in Ghana.

7.7 Conclusion on Experimental Study

In conclusion, the selected representative building fabrics from Ghana and the parametric blocks meets the CIBSE Guide A and are highly correlated with the participants' responses from the survey questionnaires. On the contrary, the use of the parametric sand types and mixing design ratios did not yield any substantial reduction of the thermo-physical properties from Ghana as intended.

As a recommendation, there is the need for education to enhance the understanding of building fabric manufacturers as well as other building professionals on significance of thermo-physical properties on electricity utilization in Ghana.

Also, technologies and additives are to be incorporated to designing and manufacturing of building fabrics in Ghana, to achieve the thermal transmittance of 0.2 and 0.3kW/m^2 for roof and wall systems respectively, as outlined in Ghana building regulations.

Finally, the indigenous burnt brick is within the range of thermo-physical properties of concrete block, hence there should be considerable effort to promote its usage in public buildings.

8 CHAPTER EIGHT: NOVEL COMPUTER SIMULATIONS

8.1 Introduction

Computer simulation has been proven as an effective approach to assess the performance of building envelops, (Clarke, 2001; Chowdhury et al, 2008; Koranteng et al, 2010 and Rysanek and Choudhary, 2012) Their assessment focused on dynamic simulation of energy and indoor environmental performance of a whole-building, considering the integration and interaction of building components and systems. The methodologies of (Chowdhury et al. 2008; Koranteng et al, 2010 and Rysanek and Choudhary, 2012) were adopted and modified for this simulation.

As identified in the critical literature review; building performance are dependent on the technology, climate, building service equipment, policy/regulation / code used and architectural factors. However, from the reviewed scientific and technical journals, significant number of building performance assessment carried out turn to neglect the impact of the local building practices impact on the design variables. Detailed write up on the purpose, objectives and methodology have been presented in Chapter 5.

In conclusion, the accomplishment of the purpose and specific objectives outlined above would yield a robust cost effective solution in optimizing typical building performance in hot-humid climate in developing countries.

8.2 Building Purposes

Ghana's building designs and materials have been changing since the slave trade was abolished in July 1833; it has evolved from straw, clay, brick, and cement block houses to glass (De-Souza, 2012).

According to Ghana building regulations Schedule I Part II, buildings can be categorized into the following types based on purposes of usage:

1. Military buildings: Buildings structures typically designed for military functions only. Within the building permit issuing processes; it is exempted from submitting building plans. For example, barracks, ammunition deports, wireless rooms, training units, offices and any other buildings for military purposes
2. Ports, airports, sea ports and inland water ports buildings: Building structure which is purposely special commercial based for transit of people or goods. Within the building permit issuing processes; it is exempted from submitting building plans. For example, Kotoka international airport, Tema harbour, offices, among others.
3. Security buildings: Typically, specialized controlled buildings structures. Within the building permit issuing processes; it is exempted from submitting building plans. For example, prisons, police stations, barracks, fire service stations and other building for security purposes.
4. Civil Service buildings: Building structures constructed purposely for public services by a government department or an agency. Within the building permit issuing processes; it is not exempted from submitting building plans. For example, residential, offices, commercial hospitals, clinics, research building. However, from the categorization in Ghana building regulation, residential building was named as an example of civil service building. This makes the categorization of civil service buildings ambiguous.
5. University buildings: typical building structures designed for higher education purposes. Within the building permit issuing processes; it is exempted from submitting building plans. For example, administration buildings, halls of residence, lecture rooms, laboratories, libraries, swimming pools, offices, farm buildings, maintenance facilities and other building for university use
6. Mining buildings: The building regulation differentiated building structures used for purely mining operations from auxiliary structures for non-mining purposes. Within the building permit issuing processes; it is not exempted from submitting building plans. For example, offices, residential hospital, schools, recreational buildings and other building for non-mining purposes

7. Buildings for foreign missions and embassies: Typical building structures or buildings for diplomatic purposes. Within the building permit issuing processes; it is not exempted from submitting building plans. For example, diplomatic offices, ambassadorial residential buildings among others.
8. Quasi-government buildings: Typical building structures for higher institutions of learning, organizations related to government activities except universities and Corporation. Within the building permit issuing processes; it is not exempted from submitting building plans. For example, research building, organization, agencies among others.
9. Agricultural building: design and install a variety of multi-purpose general agricultural buildings to suit all of your needs. Within the building permit issuing processes; it is not exempted from submitting building plans. For example, general storage, garages, machinery housing, livestock or any plant and machinery building.
10. Kiosk, corn mills, carpenters, shops, small garages and workshops, any other buildings or structures which are in areas intended for use other than buildings or structure specified within the regulation. Within the building permit issuing processes; it is not exempted from submitting building plans.

In conclusion, within the building regulation, there is insignificant distinction between the building design specifications for each category. Conversely, office buildings are dominant building example among all the categories above.

8.2.1 Building type for case study

Commercial building is basically a building used purposefully for commercial activities. Among the examples of commercial buildings are offices, retails, warehouses, food shops, storage buildings among others. Though there are several commercial building examples are listed above, but this research focuses on office buildings. Office buildings have high predictable certainty of specifications and design specifications. Among them are type of occupants, schedule of usage, electricity usage, occupant

density, metabolic rate, activity level specific building performance variables for electricity conservation and indoor environmental quality among others.

According to Commercial Buildings Energy Consumption Survey (CBECS), office buildings are classified according to principal activity, which is the primary business, commerce, or function carried within each building. Six different categories of office buildings with its sub groupings are as follows and examples are shown in Figure 8.1.

- **Administrative or professional office**
  - Educational office buildings (non-formal education, tertiary and non-tertiary,)
  - Insurance company headquarters building
  - Local insurance agency
  - Social services office
  - Attorney's office
  - Real estate sales office
- **Government office**
  - State agency headquarters office (Police, Fire Service, Immigration)
  - Ministries Offices (e.g. agriculture, works and housing, high ways, Interior, Trade and Industry)
  - Metropolitan Assemblies office (Accra, Kumasi, Tema, Takoradi)
- **Bank or other financial office**
  - Bank
  - Savings and loan
  - Credit union
- **Mixed-use office**
  - Bank offices and insurance office
  - Training centre and administrative office
- **Medical office without medical diagnostic equipment**
  - Health services administrative centre
  - Mental health services
- **Other type of office**
  - Contractor's office
  - Call centre

- religious office

Figure 8.1 is an example of office building representing the six categories outlined above.

Figure 8.1: Examples of six different categories of Office building

As shown in Figure 8.1, typical office buildings in Ghana are mostly rectangular and multi-storey.

8.2.2 Rationale for building type for the case study

- From (E. Azar and C.C. Menassa, 2011), the commercial building sector has become the focus of many governmental energy reduction initiatives to achieve more sustainable development.
- Electricity remains the second highest form of energy utilized in the world, but it is the highest form of total primary energy end-use in commercial building sector in the world as shown in Figure 2.8 (Outlook, 2013)
- Most frequently considered building types are office, residential and engineering buildings, varying from small rooms to big estate (Hai-xiang Zhao and Federic Magoules, 2012).
- There is a lot of existing literature on residential housing types and type of building ownership, however there is a limited coverage of the literature on commercial building in Ghana (Nyame-Tawiah et.al.,2011; Damptey,2006 and Amos-Abanyie et al. 2009)
- Commercial buildings are complex collection of architectural, structural, mechanical, electrical and other elements that form distinct systems within integrated building designs and consumes large amount of energy (Stegou-Sagia et al., 2007 and Andrews and Krogmann,2009)
- Among the World Bank (Crookes, 2013) recommendations to Ghana are:
  i. Ghana Energy Commission should draw up an aggressive energy efficiency and demand-side management plans for all end-use sectors within 3 months.
  ii. Weak management and regulations of the electricity sector by the government remains key issue.
  iii. Enhancing efficiency in all aspects of the electricity sector is the key challenge before Ghana policy makers.

8.3 Representative Sources of Weather Data

Typical sources of climate data include:

1. Meteonorm
2. WeatherBank
3. White Box Technologies (WBT)
4. EnergyPlus

Brief description of weather sources:

1. Meteonorm

Meteonorm encompasses worldwide weather data which can be obtained in over 35 data formats. Among the data formats are an Excel file for manual analysis, an import to photovoltaic, solar thermal or building simulation software, among others. Meteonorm has over 30 metrological parameters for example, Wind direction, Global illuminance [lux], Days with precipitation (> 0.1 mm), Dewpoint temperature, Global radiation under clear sky among others. Meteonorm contains 8,325 weather stations, five geostationary satellites with 30 years of experience and up to date interpolation models deliver global data with highest accuracy (Meteonorm, 2016).

2. WeatherBank

WeatherBank Inc. offers complete sources for both weather and environmental solutions. The sources of both weather and environmental solutions include meteorological monitoring, ambient air quality monitoring, instrumentation and calibration, environmental system audits, data reductions, and forensic weather studies for claims verification. WeatherBank, Inc. offers in-depth database of weather products that can benefit professionals in every industry. The weather datasets of hourly and daily metrics can simply be incorporated into client-specific modelling routines. The datasets can be formatted in Excel, or as comma or tab delimited, and sent to you via FTP, XML, or HTTP. WeatherBank's weather graphics includes temperature, precipitation, watch and warning, visibility, high wind warnings, and extreme weather condition, Isographic (DIFAX) charts and many more.

WeatherBank's hourly forecasting products include short, medium and long-term forecasts of 20 different weather parameters, for example, temperature, humidity, wind speed and direction, precipitation among others (WeatherBank, 2016).

3. White Box Technologies (WBT)

White Box Technologies offers suitable tools to determine typical and historical year files created from weather reports of over 10,000 official weather stations around the world. WBT has relied upon official weather station data archived by the National Center for Environmental Information (NCEI). The IWEC2 weather files were generated from ISD data as far back as 1986 to 2009. White Box Technologies uses software to change the raw ISD data to local time and conditions, fill or reduce them to hourly time steps, and most significantly to calculate the solar radiation. The software has been proven to be robust over long years of usage and test. The resultant weather files are provided in BINM format for DOE-2-based programs, EPW format for EnergyPlus-based programs, TMY2 and TMY3 CSV formats can also be provided (WBT, 2016).

4. EnergyPlus

EnergyPlus has weather data for more than 2100 locations with 1042 locations in the USA, 71 locations in Canada, and more than 1000 locations in 100 other countries all over the world. The weather data are arranged by World Meteorological Organization region and Country. The weather data provided in EnergyPlus weather format are derived from 20 sources, among them are CTZ2 California Climate Zones 2, CWEC Canadian Weather for Energy Calculations, CIBSE Chartered Institution of Building Services Engineers, CityUHK City University of Hong Kong, CSWD Chinese Standard Weather Data and Typical Meteorological Year (TMY). EnergyPlus weather data are widely used as climate data for building performance assessment due its accuracy and easy accessibility.

8.4 Climatic Zones in Ghana

Representative climatic zones of Ghana are shown in Figure 8.2. According to Global Buildings Performance Network, Ghana is classified as dominant cooling and dehumidification (very high cooling demand).

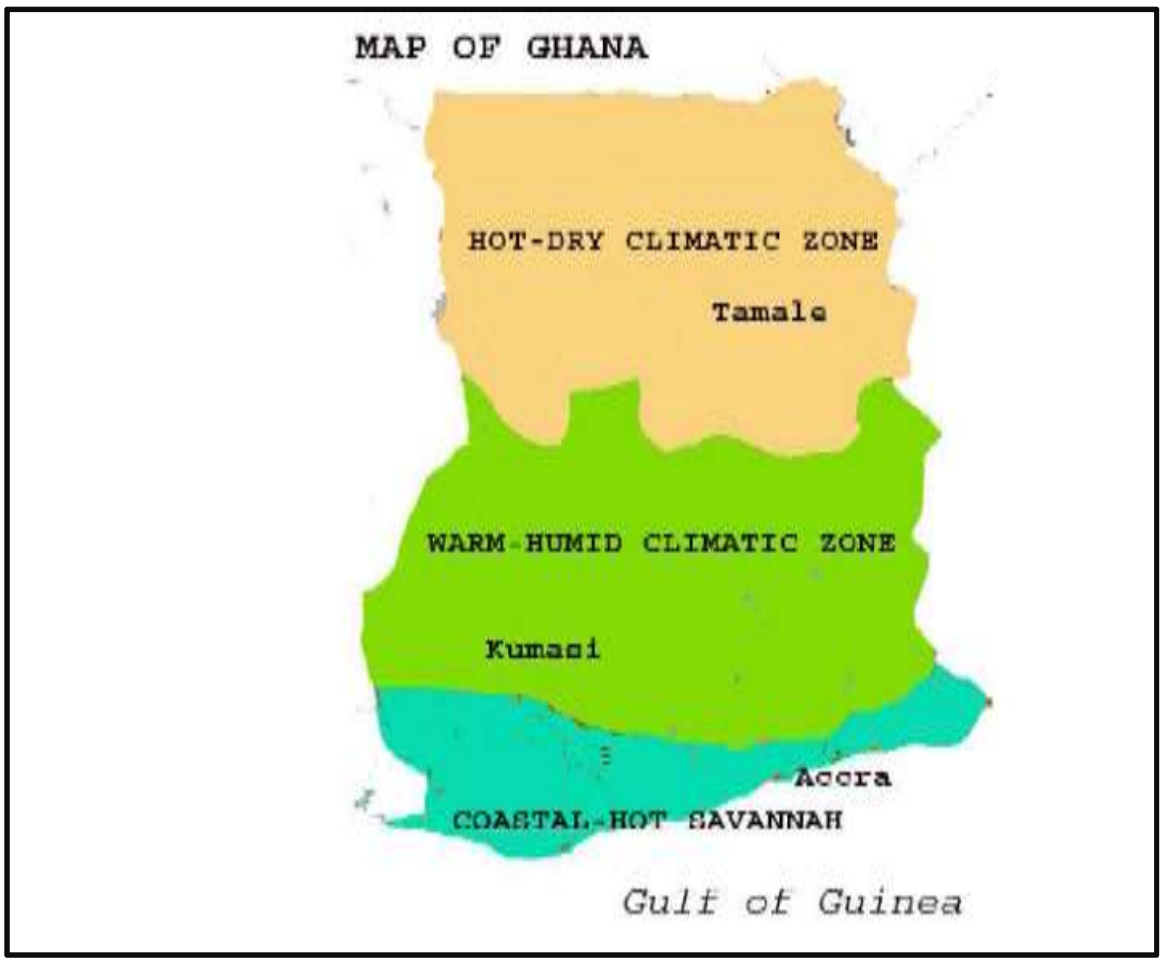

Figure 8.2: Map of Ghana showing three main climatic zones
Source: (R. A. Oppong and E. Badu, 2012)

Ghana is characterised as a tropical climate according to Köppen classification. According to (R. A. Oppong and E. Badu, 2012), climate of Ghana is divided into hot-dry, warm-humid and coastal- hot savannah as shown in Figure 8.2.

Hot-dry climate

As seen in Figure 8.2, the northern part of the country is a hot-dry climate. It is usually seen as having low rainfall, low humidity, and high temperature difference between night and day, with typical high solar radiation.
Recommended building envelope design in this climate is often made of mud walls, which acts as good insulating materials with smaller window-to-wall ratio to limit solar radiation and normally oriented in North-South. Often shading devices are also employed for solar radiation control. Generally, compact building envelope form is preferred to limit expose surface to high solar radiation. Roofs are commonly made of thicker insulation materials to reduce the effect of solar radiation. Mostly, bright colours are used for painting the external building envelope.

Warm-humid climate

From Figure 8.2, the middle belt of the country, Kumasi is regarded as warm-humid climate There is no noticeable difference between air temperature between day and night with high solar radiation accompanied by constant high relative humidiy across the year leading to thermal discomfort. Also there is high precipation across most months of the year with mainly low wind velocity.
Recommended building design is normally characterise by pitched roof to reduce the transfer of heat in the building enevelope. Walls are mostly plastered single layered to mitigate high solar radiation. Generally shading device are employed to reduce direct solar radiation and use of compact buiding form to reduce exposed surface. Building envelopes are air tight to minimize indoor moisture transfer, but proper ventiltion remains priority at all times. Buildings are mostly oriented in North-South orientation with the aim of enhancing heat dissipation.

Hot-humid climate

As shown in Figure 8.2, Accra is tropical savanna or tropical wet and dry climate climate. From Köppen classification, tropical savanna or tropical wet and dry climate is the third type of tropical climate that corresponds to the categories "Aw" and "As".

Tropical savanna climates have monthly mean temperatures above 18 °C (64 °F) in every month of the year. This climate is characterised by a representative distinct dry and wet season, with the driest month commencing in November to March and having precipitation normally less than 60 mm with the rest of the year been dry. With relative humidity remaining above 70% for the whole year. From these ranges of temperature and relative humidity there is eminent thermal discomfort as described in ASHRAE 55, therefore high dependence on mechanical cooling leading to high electricity consumption.

Building design is normally like warm-humid climate, except relatively more emphases are placed on shading to minimize solar radiation transfer.

8.5 Selected Building Computer Simulation Software

Typical building energy simulation models have several physical inputs (construction materials, internal heat gain, building envelop, weather data, operational times etc). TAS building simulation was selected (Please refer to first year report for the comparison of TAS with other building simulation software's). TAS building simulation software is a dynamic building simulation package with 3D modeller, building simulator and result viewer. It accurately predicts key features of building performance.

The A-TAS module of TAS Building Designer software by Environmental Design Solutions Limited has been used, in this study, for calculating the thermal loads and analysing the effects of varying parameters. A-TAS provides hourly data for air temperature, mean radiant temperature, and humidity for the simulated building. It uses the effects of the HVAC control variables and climatic data to perform its calculations. These results are then used in equations that solve variables used in the PMV equation. This software tool dynamically simulates the thermal performance of buildings and their systems. The application creates the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces.

These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is calculated simultaneously to generate air temperatures, surface temperatures and room loads. Conduction in the fabric of the building is treated dynamically, using two methods for the analysis of wall heat flows. For state-representation, finite difference methods are applied whereas conductive heat flows at the surfaces of walls and other building elements are calculated with a response factor method. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation ex-change is modelled using the Stefan-Boltzmann law. Long-wave radiation from the sky and the ground is treated using empirical relationships (EDSL 2007).

Conduction in the fabric of the building is treated dynamically, using two methods for the analysis of wall heat flows. State-representation and finite difference methods are applied whereas conductive heat flows at the surfaces of walls and other building elements are calculated with a response factor method.
Equation used for calculating heat transfer through surfaces:

$$q_{i,\theta} = \left[h_{ci}\left(t_{a,\theta} - t_{i,\theta}\right) + \sum_{j=1,j\neq i}^{m} g_{ij}\left(t_{j,\theta} - t_{i,\theta}\right)\right]A_i + RS_{i,\theta} + RL_{i,\theta} + RE_{i,\theta} \quad \text{eqn 8.1}$$

For i=1,2,3,4,5,
Where
m = number of surfaces in room
qi,□□= rate of heat conducted into surface *i* at inside surface at time □
Ai = area of surface *i*
hci = convective heat transfer coefficient at interior surface *i*
gij = radiation heat transfer factor between interior surface *i* and interior surface *j*
ta,□□= inside air temperature at time □
ti,□□= average temperature of interior surface *i* at time □
tj,□□= average temperature of interior surface *j* at time □
RSi,□□= rate of solar energy coming through windows and absorbed by surface *i* at time □
RLi,□□= rate of heat radiated from lights and absorbed by surface *i* at time □
REi,□□= rate of heat radiated from equipment, occupants and absorbed by surface *i* at time □

The admittance procedure for cooling load calculation recognises that a person's feeling of thermal comfort depends on the heat exchanges between the body of a person to the indoor environment by convective heat loss to the indoor air and by radiant heat loss to the indoor environment.

The application creates the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is calculated simultaneously to generate air temperatures, surface temperatures and room loads. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation exchange is modelled using the Stefan-Boltzmann law. Long-wave radiation from the sky and the ground is treated using empirical relationships (EDSL 2007).

8.6 Computer Modelling of Base Building

The base building is a standard medium-sized single use rectangular four story office building commissioned in 1951 before the building regulation of Ghana was enacted into law in 1996. Rectangular building form is the shape of typical office buildings in Ghana; as seen in Figure 2aThe base building has a total floor area of about 1848m^2, each floor has north-south window facing position representing 30% window to wall ratio and increasing floor-to-ceiling height because of the conversion from natural room ventilation to air conditioned building. The building was constructed with single layer concrete blocks wall as well as internal mortar wall plaster with aluminium window frame, clear louvers blades, reinforced concrete inter floor ceiling and reinforced mono-pitched roof. There are about 200 sedentary occupants with occasional movements of people in-out of the offices; operating on 8 hours schedule on weekdays through the year and closed on Ghana public holiday calendar as well as weekends. The occupant's electricity dependent equipment are computer, printer, artificial lighting and photocopier with air-condition system been the dominant.

Summary of the base building is represented in Figure 8a to 8d been selected office building, internal layout of the air-conditioned floors, display of building elements from TAS model, detailed dimensions of floor plan in millimetres of the office building respectively. TAS model focused on 12 rooms out of the 44; the assumption made was that same level of occupant's activities happens across the entire building. Hence the building performance assessment in the 12 rooms will be representative of the entire building.

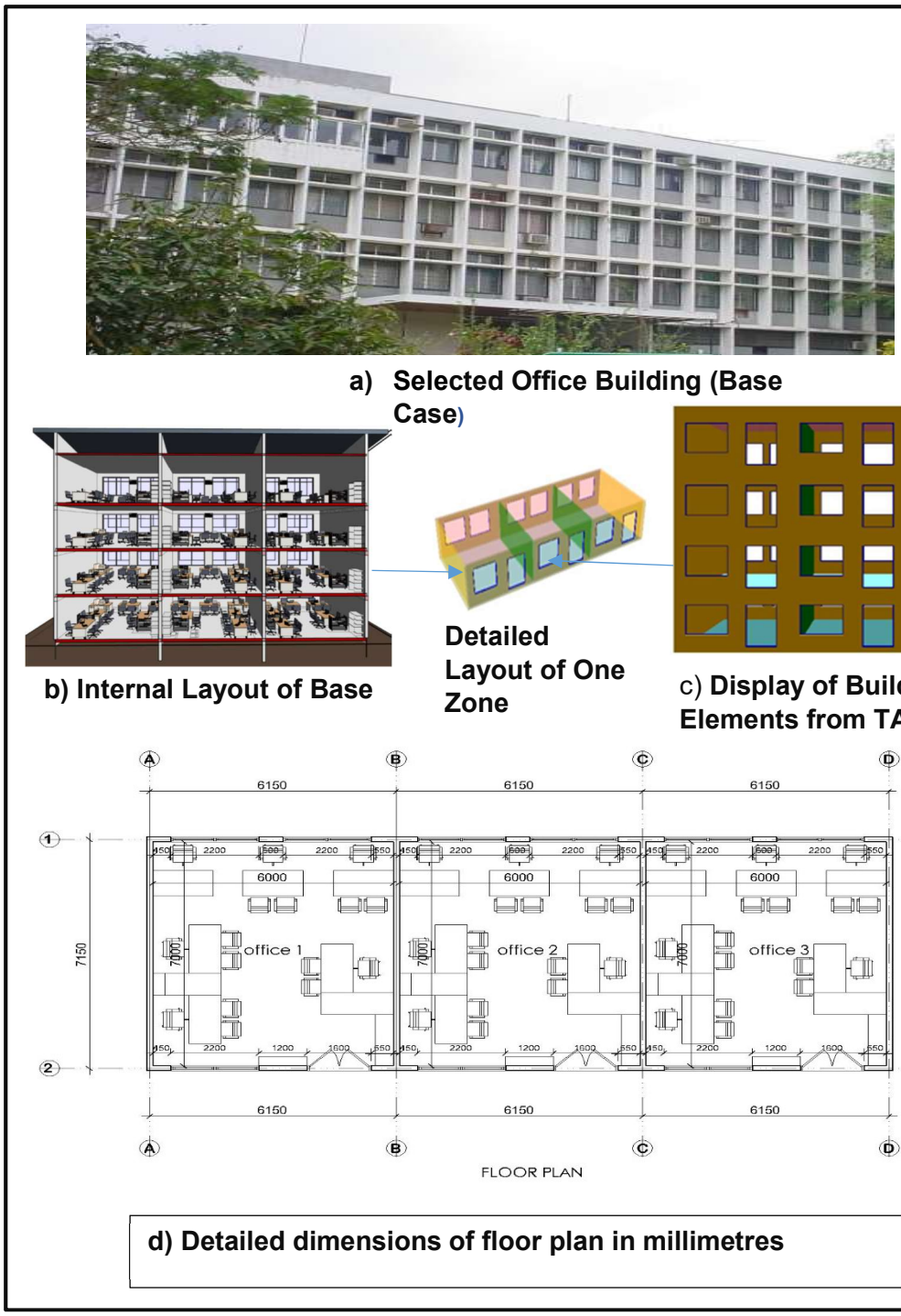

Figure 8.3: Base Case building description

Detail dimensions

The building consists of four floors namely ground floor, first floor, second floor and third floor. Each floor has three air-conditioned rooms with the same length and width of 7mx6m respectively but a varying floor-to-ceiling height of 3.2m from ground floor to 3.5m at the third floor. There are two north facing windows and one south facing window with width 2m x 2m height and a level of 0.7m from the floor to the window base. The door is located at the south with dimensions of width 1.6m x 2.5m height into a walking corridor. A detail description of the floor plan and dimensions of the model can found in Figure 8.3d.

8.7 Justification of selected office building for case study

Representative office building, which is an example of commercial building sector was selected for the case study. The rationales for the selection of the case study are as follows:

1. According to Zhao and Magoulès (2012), the most frequently considered building types are office, residential and engineering buildings, varying from small rooms to big estates.
2. There are a lot of existing literature on residential housing types, however there is a limited coverage of the literature on commercial building in Ghana, (Damptey, 2006; Amos-Abanyie et al, 2009 and Nyame-Tawiah et al, 2011).
3. Most of the residential buildings are affordable compound buildings for low income earners owned by individual landlords; with few semi-detached and apartment houses for high income earners by real estate's developers as well as individuals hence their priority remains on reducing cost for the buildings to meet their target groups need and not on energy efficiency of the buildings, GLSS, 2008.

4. From GPSIA, 2004 and GLSS,2008 the electrical equipment used for cooling in residential buildings are mostly mechanical fan which represents about 31.6% with about 0.4% of air conditions and the rest been natural ventilation in households.
5. Commercial buildings are complex collection of architectural, structural, mechanical, electrical and other elements that form distinct systems within integrated building designs and consumes large amount of energy (Stegou-Sagia, 2007 and Andrews and Krogmann, 2009).

8.8 Design Variables

Design variables are used in estimating building performance through manual calculation or simulation. Among the design variables are: Location of site; Internal conditions; Infiltration and ventilation requirements; Internal gains and patterns of use; Building Fabric properties; Building geometry and External design conditions. Figure 8.4 shows the design variables use in ESDL Tas.

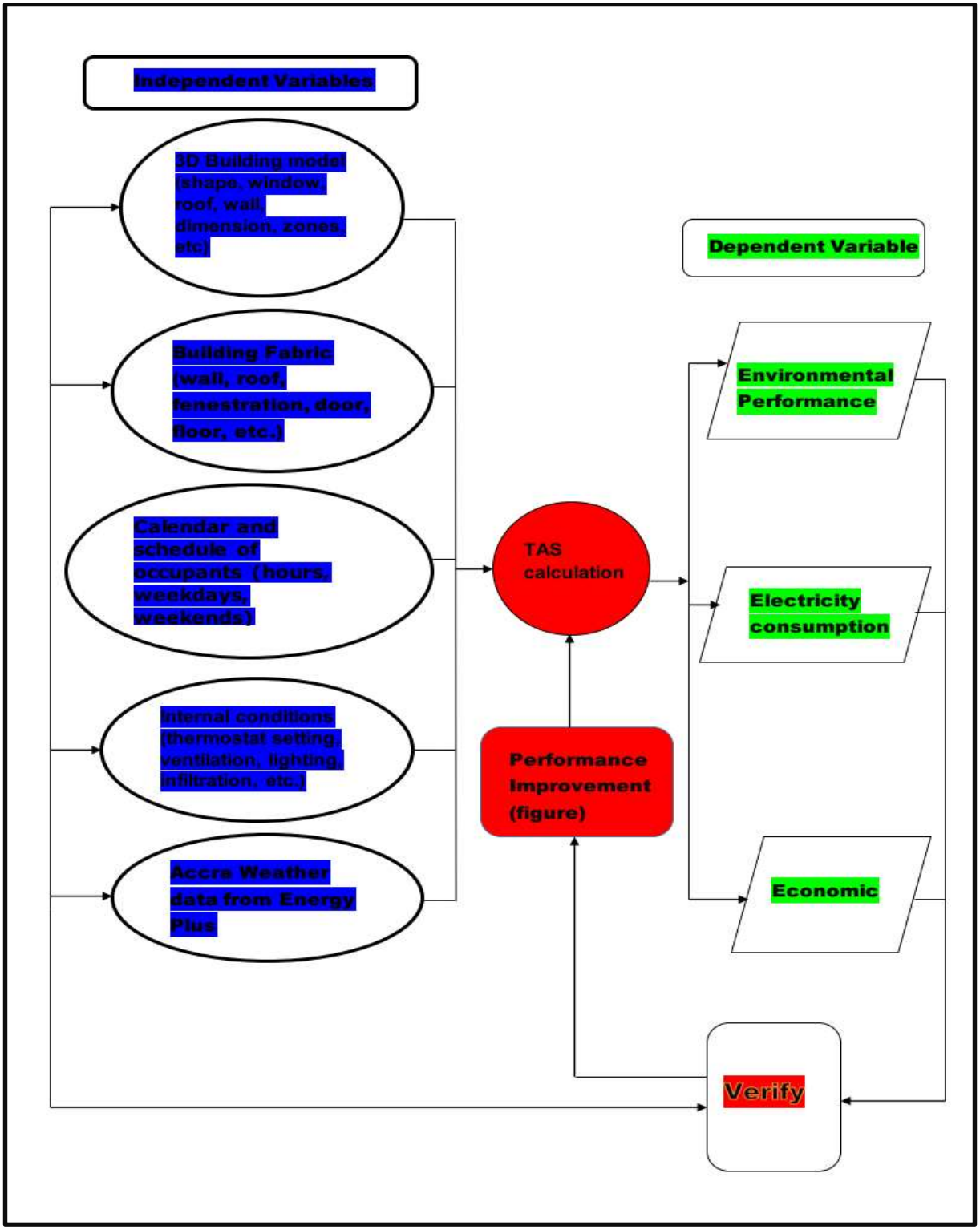

Figure 8.4: Design variables for ESDL Tas

Reviewed literature on design variables indicates the representative sources are as follows:

a. building codes/regulations/ standards/policy
b. survey questionnaire
c. from literature
d. from monitored building
e. experiment

There are several literatures on design variables; among the selected relevant design variables to this research are:

- The use of various design parameters in buildings in a hot and humid climate is commended to regulate the indoor thermal comfort and lower the cooling energy demand (Baruti, 2009).

- According to Koranteng et al. (2009), selected the following design variables for simulation in Kumasi-Ghana are summarised in Table 8.1. On the contrary, the bases of these design variables are unknown. In contrast, the detail of the modification to yield all the modified design variables are not sufficiently explained hence the practically of design variables are unclear hence adopting their design variables for this research is not appropriate.

  Table: 8.1: Design variables

Design Variables	Base Values	Improved Values
Wall	3.4 W/m^2 K	0.4 W/m^2 K
Artic floor	3.4 W/m^2 K	0.4 W/m^2 K
Window	5.8 W/m^2 K	1.8 W/m^2 K
Lighting load	6 W/m	2 W/m
Equipment load	1 to 7 W/m	-

- The building parameters included the thermo-physical properties of the basic building materials used for the model. Building parameters were obtained from the specifications and architectural drawings of the conventional mode of building design as specified in the Ghana Building Regulations.

- Building parameters helped to correctly dimension the model and specify zone data Amos-Abanyie et al.,2013.
- According to Amos-Abanyie et al. (2013), the pilot survey of selected buildings in the Ashanti region, established the average window-to-wall ratio to be 54%.

8.8.1 Internal condition input variables

Typical building design variables for building performance assessment are selected in accordance of BS EN ISO 9000. Most of CIBSE Guides A on environmental design variables were based on temperate weather conditions example, infiltration gain. To compound the challenges of acquiring reliable design variables; there is also insignificant scientific and technical journals on typical building performance assessment in Ghana. The design variables form the core of this research; therefore, acquisition of accurate and robust typical design variables on Ghana is paramount. From the building professional's respondents of the administered survey questionnaire in Ghana the internal condition variables were obtained.

Among the design variables are: Internal gains (lighting, equipment, infiltration and ventilation), office schedules, annual cooling calendar and typical thermostat setting

(temperature and relative humidity). The values of the design variables are summarized as in Table 8.2.

Table 8.2: Internal Condition Variables

Variables	Value
Lighting sensible heat gain(W/m2)	12
Equipment sensible heat gain(W/m2)	15
Infiltration (ACH)	0.7
Ventilation(ACH)	3
Upper dry bulb temperature for comfort cooling	26C
Lower dry bulb temperature for heating	-50 ^{o}C
Upper relative humidity	60%
Lower relative humidity	40%
Target illuminance (lux)	500
Annual cooling Load	5 days a week except Ghana public holidays
Occupants Schedule	8 am to 5pm

Source: Field study

The occupant gains were obtained from CIBSE Guide A due to the difficulty to estimate them by the participants. For office building with general use for occupancy density of 12/person/m^2 at an internal temperature of 24^0C and 50% relative humidity; occupant sensible heat gain was 6-7 W/m2 and Latent heat gain was 5W/m2

8.8.2 Description of materials types and properties input variables from survey and experimental findings

From the identified gaps in literature; thermo-physical properties of building fabric remain one of the vital information gaps. From the survey questionnaires conducted; unfortunately, the expected results on thermo-physical properties of building fabric was not achieved. This is because of low participants of building materials manufacturers on conduction of the thermo-physical properties of building fabric question. In view of this, experiment was conducted on selected building materials from Ghana. The summary of the experimental data was integrated into building envelope element for building fabric design variables are shown in Table 8.3.

Table 8.3: Building Fabric Design Variables

Actual Case envelope properties	**Description**	**U-values ($W/m^2.^oC$)**
Wall system	Single mortar wall with lightweight plaster both internal and external wall as well as paint finish.	**2.2**
Roof and inter floor system	Reinforced medium weight Concrete	
Window pane	Single clear 6mm louver blades	**5.682**
Window frame	Smoothed Planed Timber	**5.8**
Underground floor	Sand, laterite soil, concrete and carpet	**0.566**
Door	Smoothed Planed Timber	**4.5**
Door frame	Smoothed Planed Timber	**5.8**

Source: Field Study

8.8.3 Climate Data from EnergyPlus

The weather data for Accra was obtained from EnergyPlus.This is due to lack of weather data from ESDL Tas on Accra. The geographical coordinates of Accra, Ghana are at latitude 5.56^{o} N, longitude -0.2^{o} E and an altitude of 298ft above sea level. It is a tropical climate mainly hot and humid with temperature range from 22 to 34 ^{o}C. The average wind speed is 3.5 ms^{-1} with maximum irradiation of 1402 Wm^{-2}. The relative humidity goes up to 71% the dry season.

8.9 Creative Computer Simulation Results

The computer simulation results for the base case was grouped into building design before enactment of building regulation and after enactment of building regulation. Figure 8.5 to Figure 8.10 gives represents the annual total demand, annual peak load, predicted mean votes, predicted percentage of dissatisfaction as well as the comparison of annual total demand for both groups.

8.9.1 Simulation Results for Base Case

Due to the difference in building design for before and after the enactment of Ghana building regulations, this research investigated its impact on performance.

(Before Enactment of Building Regulation)

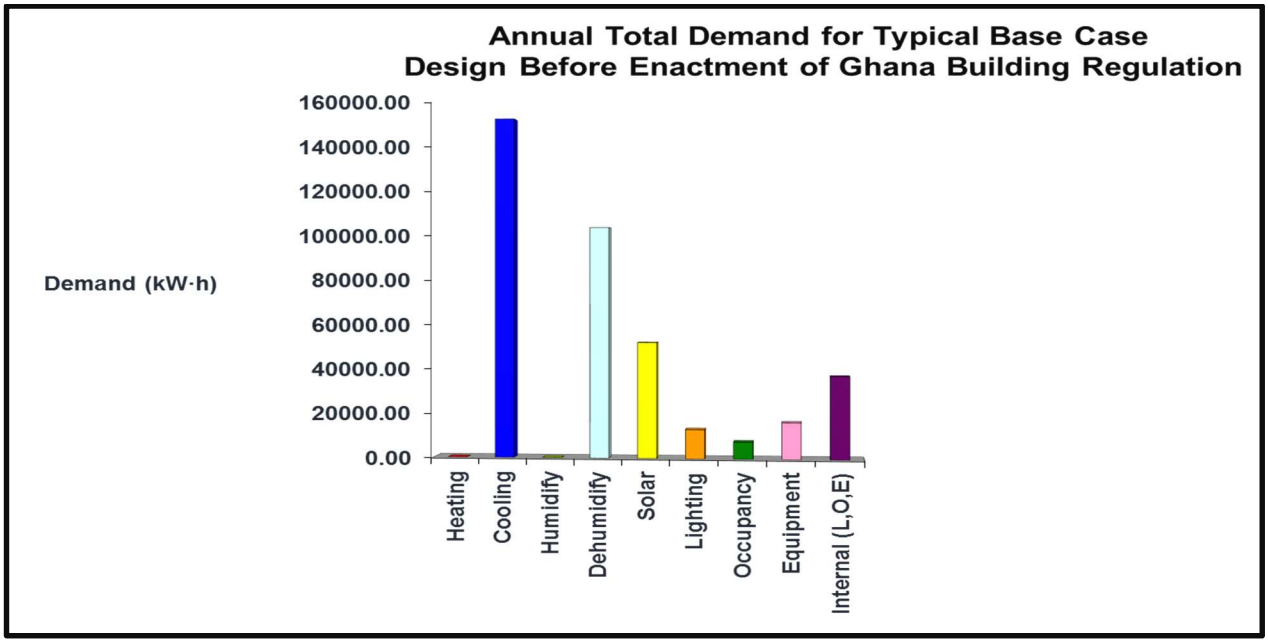

Figure 8.5: Annual Total Demand for design before the enactment of Ghana Building Regulations

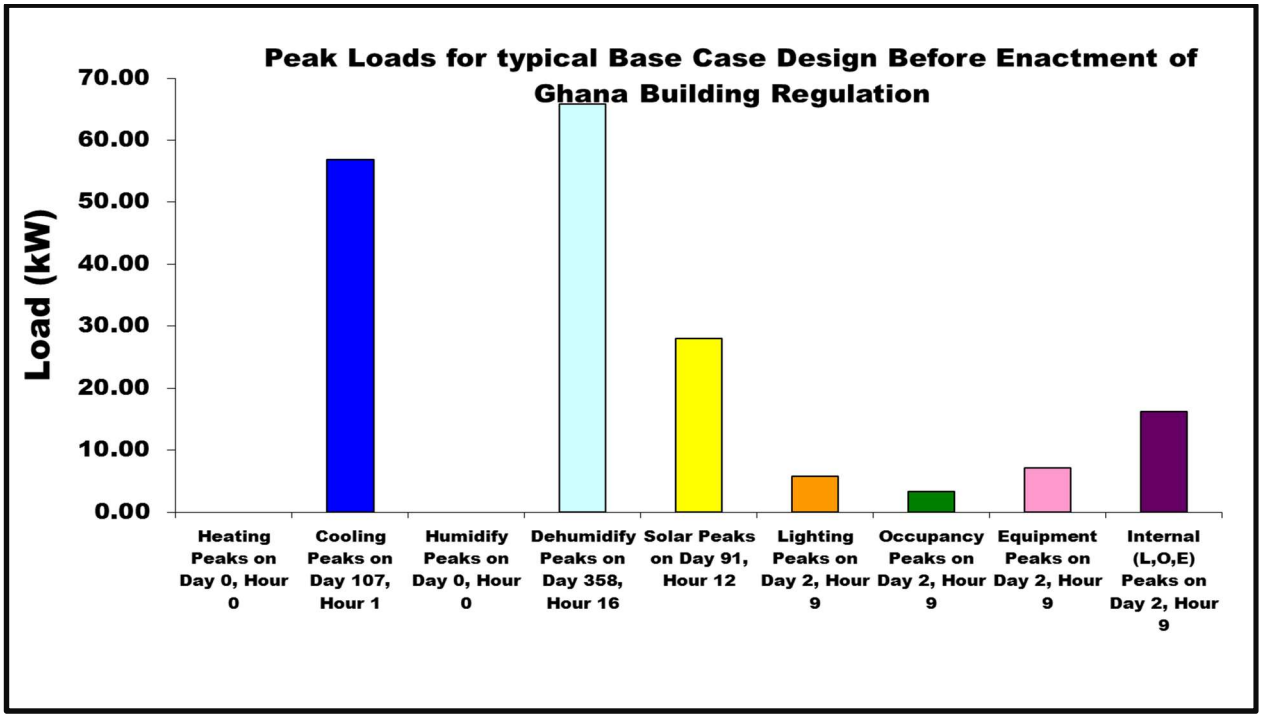

Figure 8.6: Annual Peak Base Case for design before the enactment of Ghana Building Regulations

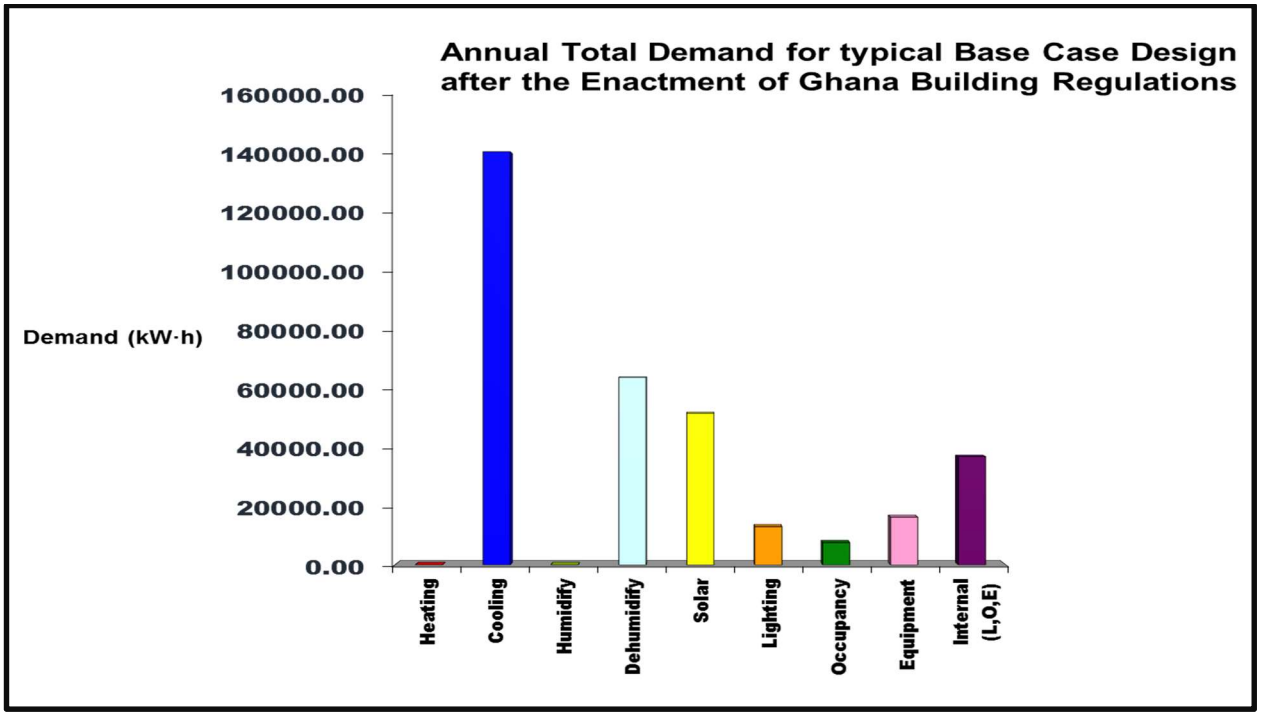

Figure 8.7: Annual Total Demand Base Case Design after Enactment of Building Regulations

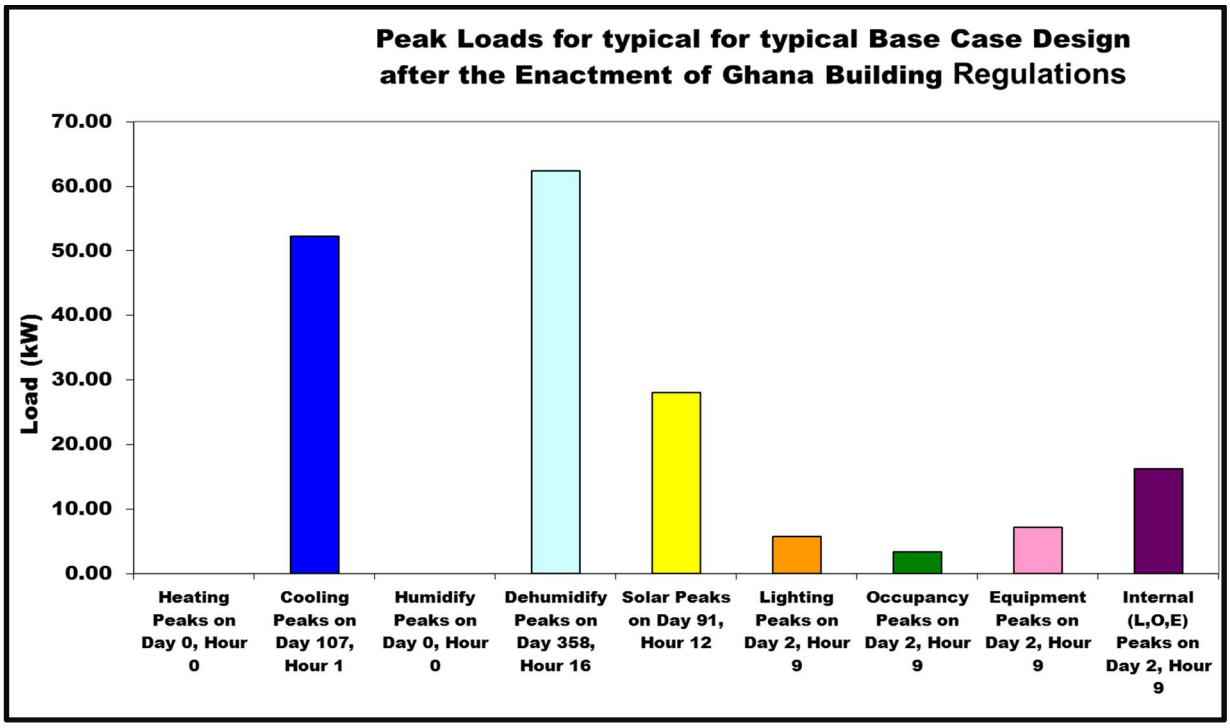

Figure 8.8: Annual Peak (Base Case) for design after the enactment of Ghana Building Regulations

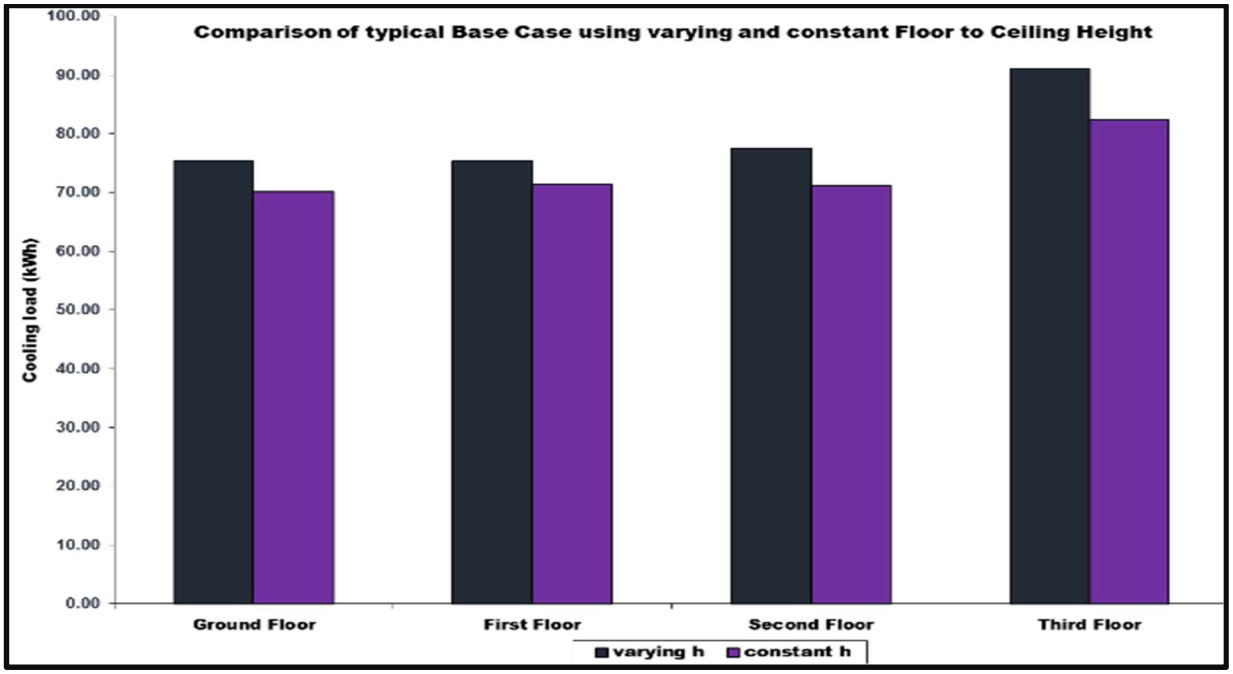

Figure 8.9: Comparison of Annual Total Load (Before and After Enactment of Building Regulations

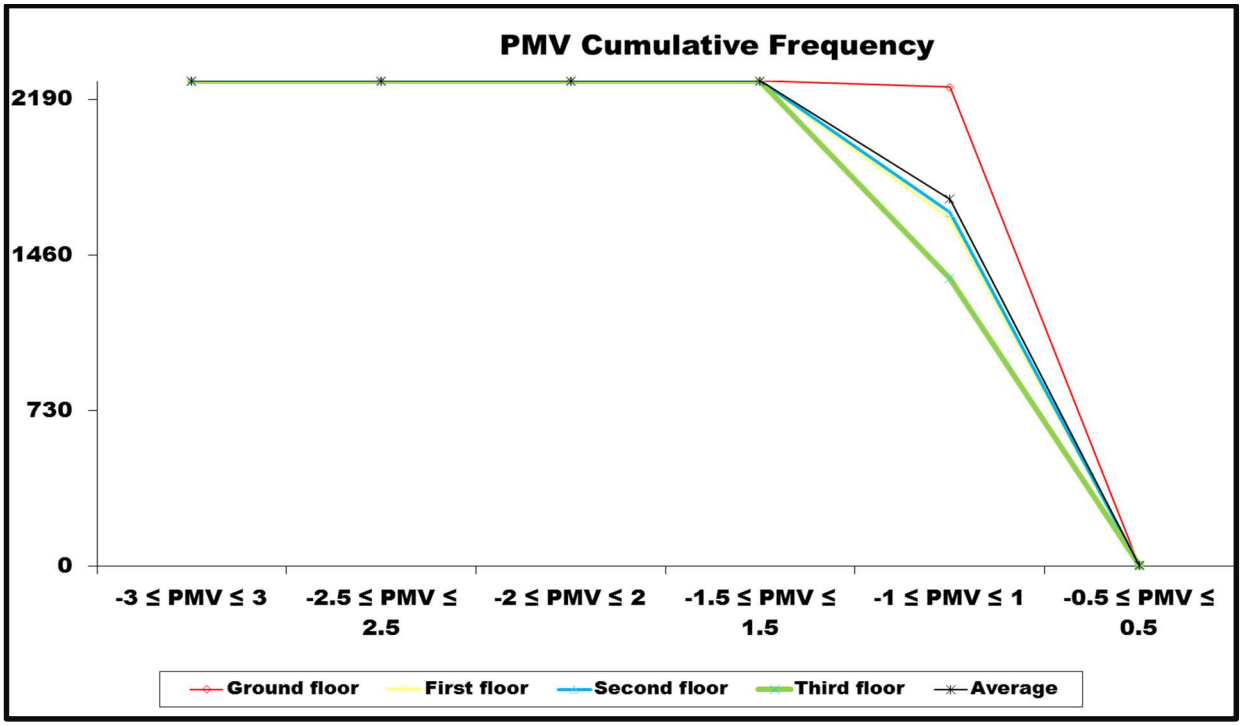

Figure 8.10: Predicted Mean Votes for Base Case

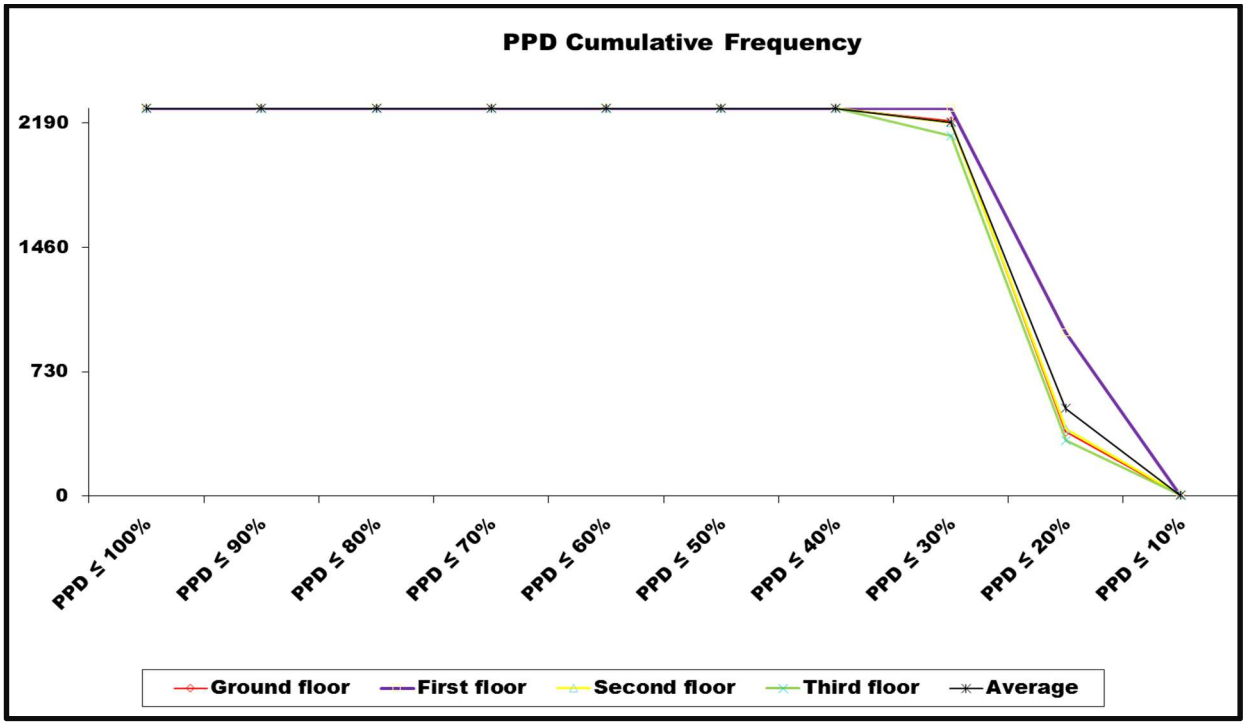

Figure 8.11: Predicted Percentage of Dissatisfaction

8.9.2 Initial Findings

From the base case simulation for building design before and after the building regulation enactment from Figure 8.5 to Figure 8.10; the following findings were observed:

1. From Figure 8.5, the annual total demand load was 152806 kWh and represents 319 kWh/m2 for typical office floor area with varying floor to ceiling height. That is, building design before the enactment of building regulation
2. In Figure 8.5, the dominant contributors to the total annual cooling load were dehumidifying load, solar gain load and equipment load representing 54%, 27% and 8.5% respectively.
3. From the peak load in Figure 8.6, the dehumidifying load exceeded the cooling load. Signifying that in sizing and selecting air-conditioning system, building service engineers needs to focus on dehumidification control technology.

4. From Figure 8.9, the annual total demand load was 141273 kWh and represents 295 kWh/m2 for characteristic office floor area with constant floor to ceiling height. That is, building design after the enactment of building regulation
5. From Figure 8.7, dominant contributor to the total annual cooling load was dehumidifying load with solar gain load been the second highest followed by Equipment load representing 42%, 34% and 8.5% respectively.
6. Figure 10, is the comparisons of annual total cooling loads for individual floors in Figure 8.5 and Figure 8.7. The building design before the enactment of building regulations are higher than the building design after the enactment of the regulations as expected. This is due to the variation in floor to ceiling height across the storey.
7. From Figure 8.9, the Predicted Mean Votes for base case for all floors shows thermally comfortable indoor environment as defined by ASHRAE 55 thermal comfort standard
8. From Figure 8.10, the Predicted Percentage of Dissatisfaction shows that $\leq$10% of occupants on all the floors were dissatisfied. Hence from Figure 8.9 and 8.10 shows that the all the floors have acceptable indoor thermal comfort environment.
9. The obtained cooling load of the base results of Ghana is inconsistent with a similar hot-humid weather climate assessment by Qin et al.,2009.
10. Local building professional practices in selecting design variables have significant impact on the building performance.
11. From the survey questionnaires, the main difference identified between building designs before and after the enactment of Ghana building regulations was the floor to ceiling height, which have impact on the overall dehumidifying load, subsequently the cooling load as seen in Figure 8.7 and 8.9.

- Implications of the findings

The cooling load for both building design for before and after the enactment of the Ghana building regulations do not meet the recommended cooling for good practice as specified by CIBSE Guides. On the contrary, the indoor environmental thermal comfort is acceptable by ASHRAE 55 standards.

Hence the proceeding research was focused on minimizing the dominant contributing load and optimizing the design variables used by building professionals in Ghana.

In conclusion, the base case building for before and after the enactment of building regulation of Ghana, do not meet the minimum design variables of the building fabric specification in the regulation. Furthermore, the typical respondents internal condition input variables used in the simulations deviates from the standard input internal conditions in CIBSE Guide and ASHARAE standards. Again, the cooling loads obtained from both cases are about 10 times that of recommended cooling load for good typical practices in CIBSE Guide. On the other hand, the lighting load meet the recommended CIBSE Guide but the equipment load was just about 3kWh/m2 more than the recommended, but it can be controlled.

Last but not the least, the indoor environmental quality on thermal and visual comfort was acceptable, conversely, psychological and acoustic comfort do not have supporting toolbox in ESDL Tas. Finally, the outstanding simulations focused on the remaining flow chart outlined in Figure 5.8 in optimizing the design variables to enhancing building performance of the base cases.

8.10 Sensitivity Parametric Simulation Results

Sensitivity parametric simulations were carried out to ascertain the dominant influent design variables for the optimization. The results were categorized into the following two building performance factors:

i. Internal condition Variables
ii. Building fabric Variables

The details of both the internal condition variables and building fabric are discussed in 8.10.1 and 8.10.2 respectively.

8.10.1 Internal Condition Variables

The internal conditions variables used were in accordance with the ASHRAE 55 and CIBSE Guide A & B for air conditioned building. The internal condition variables consisted of the following:

i. equipment gain
ii. Temperature setting
iii. Relative humidity
iv. Infiltration gain
v. Ventilation gain

The parametric lighting gain assessment was not carried out due to the long day lighting availability and the North-South building orientation for daylight usage in Ghana throughout the year reducing the use of artificial lighting. The details of the parametric simulation results of the assessed internal condition variables are presented below. Parametric assessment of occupancy gain was not considered since fixed mixed occupants activity level was selected based on the characteristic survey questionnaires. Final the annual calendar was selected based on statutory Ghana holidays.

i. Equipment Gain

Equipment gain consist of the sum of representative electrical equipment use in standard office building. For example, computers, laptops, printers/copiers, mail processing devices, paper shredders, water coolers, among others.

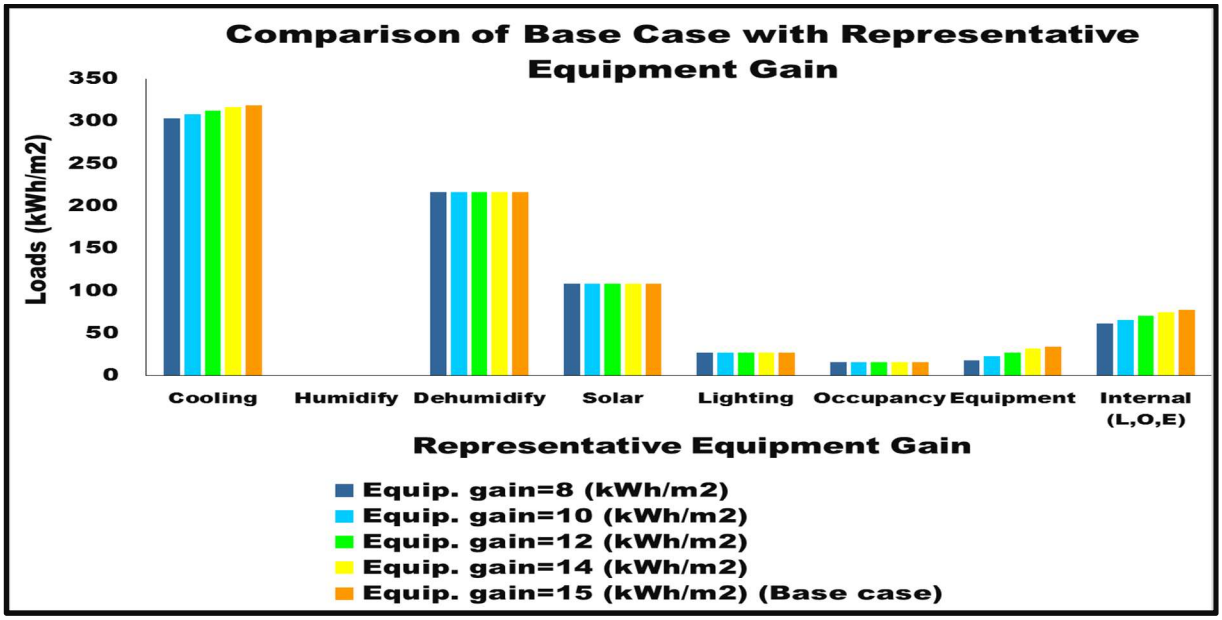

Figure 8.12: Equipment Gain

The trend of increasing cooling load with increasing equipment gain was observed. On the contrary, equipment gain has insignificant influence on dehumidifying load as well as solar and lighting. On the dehumidifying load, although the equipment gain has two components that is, latent and sensible, the latent gain component was very small hence it was neglected and no impact on, minimizing the dehumidifying load. Equipment gain can be controlled by selecting more energy efficient appliances in the office.

ii. **Ventilation Gain**

Ventilation gain is a controlled movement of air in and out of a building because of pressure difference. Generally, ventilation gain selection is directly related to the indoor air quality, the occupant activity level and introduction of moisture into the indoor space depending on the equipment as well as the climate understudy.

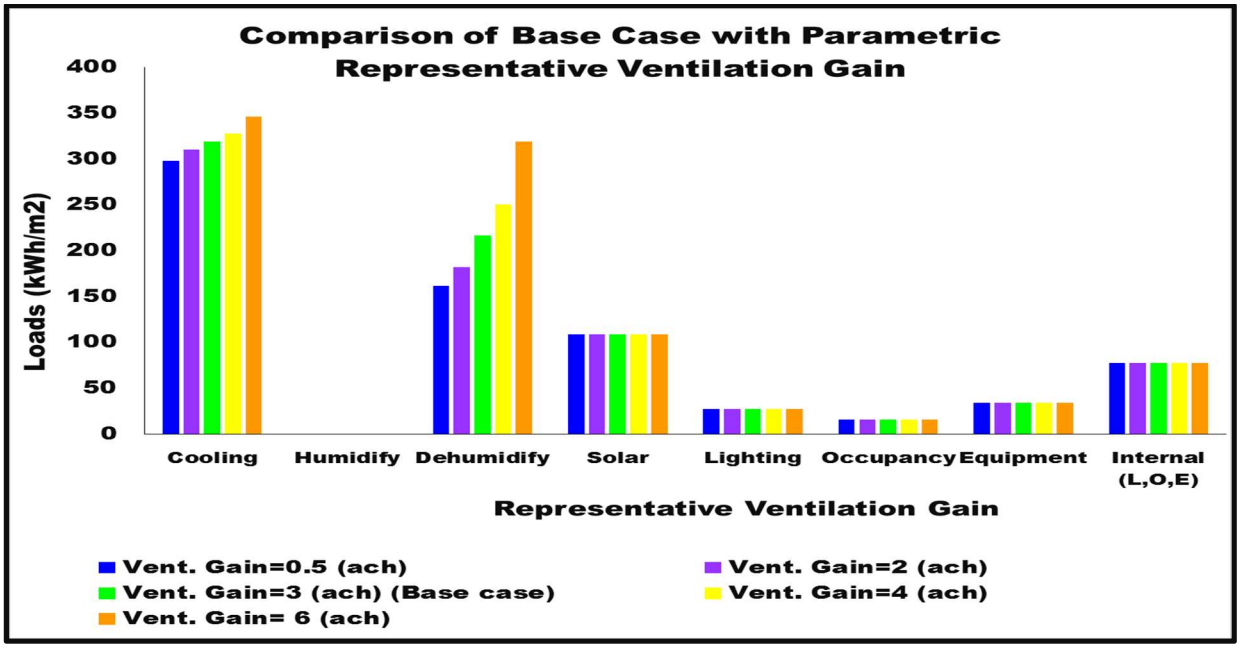

Figure 8.13: Ventilation Gain

Trend of increasing ventilation gain with increasing cooling load and dehumidifying load was observed. Conversely, no change was observed among the other loads. Reducing the ventilation gain have impact on minimizing the dehumidifying load and subsequently the resulting cooling load.

The decreasing of the ventilation gain from 6 to 0.5 ACH reduced the dehumidifying load and the cooling load by 49% and 14% respectively. On the other hand, there is a constraint on the rate of ventilation gain reduction that is permitted for occupants with certain activity level due to indoor air quality issues.

In summary, the ventilation gain has the potential in minimizing the dehumidification load and consequently the cooling load in hot-humid climate, but, requires caution on indoor air quality issues and appropriate dehumidifying technology.

iii. Infiltration Gain

Infiltration gain arises because of uncontrolled air movement arising from the building fabrics, leakages, among others due to pressure difference between indoor and outdoor environment. Figure 8.18 is the graph for variation of infiltration

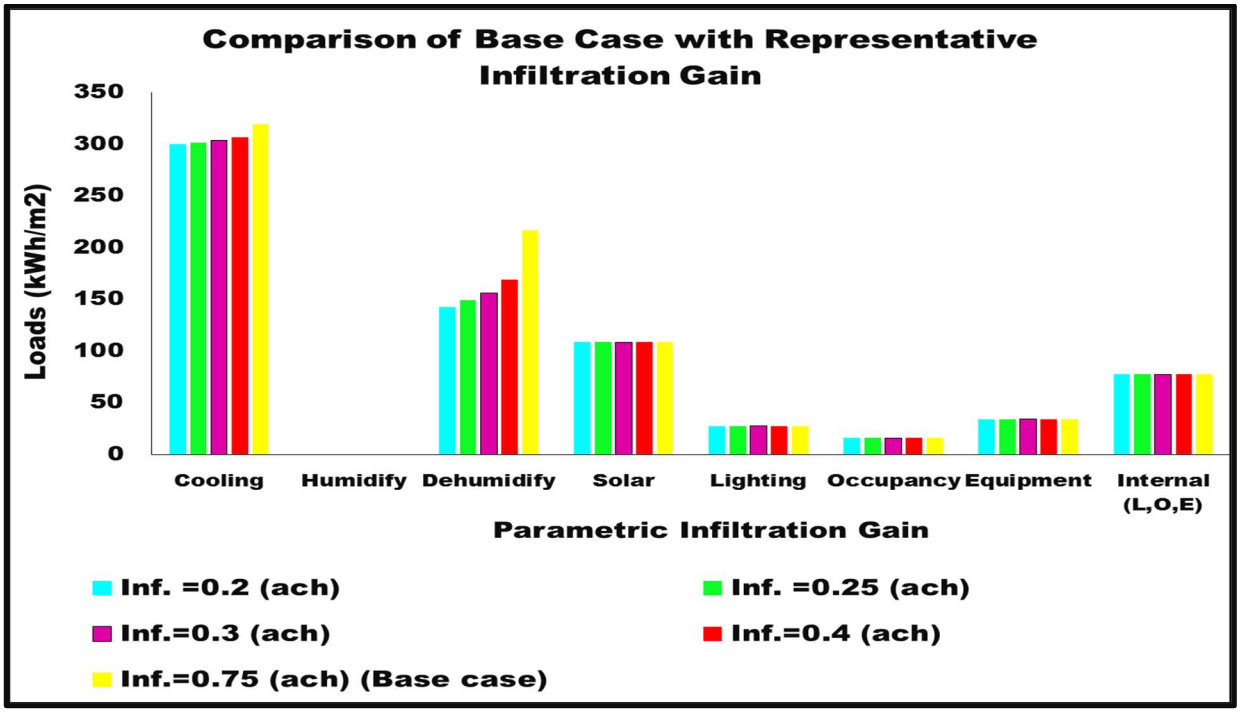

Figure 8.14: Infiltration Gain

Dehumidifying loads and cooling loads increases with increasing infiltration gain. On the other hand, the variation of dehumidifying loads with increasing infiltration gain is substantial as compared to cooling load.

The cooling load gradually increases with increasing infiltration gain. No change is observed on solar, occupant, and internal load as expected. In conclusion, there is a strong correlation between infiltration gain and dehumidifying load. Designing a tighter building in hot-humid climate remains vital in minimizing the infiltration gain leading to a lower dehumidifying load.

iv. Temperature setting

Temperature setting is one of the simplest approach in controlling energy utilization of occupants at offices.

Though, recommended temperature setting for comfortable indoor environmental climate has been specified by ASHRAE standards 55, the thermometer setting can be altered slightly whiles checking its effect on thermal comfort. Figure 8.19 represents the comparison of representative temperature setting at offices in Ghana with the base temperature setting.

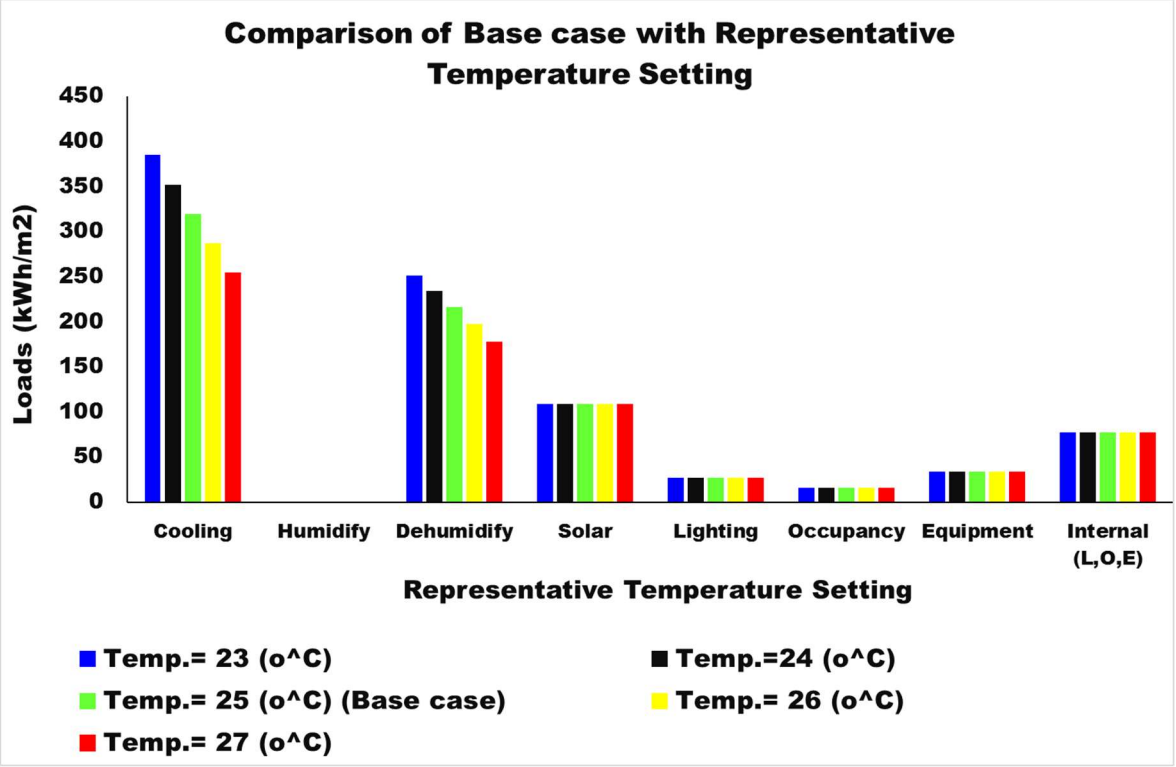

Figure 8.15: Temperature setting

From Figure 8.19, temperature setting has impact on both dehumidifying load and cooling load with no change on the other loads as anticipated. A trend of increasing temperature with decreasing dehumidifying load and cooling load was observed. As indicated above, though temperature setting can be increased from the acceptable recommended point, care must be taken not to compromise on occupants' thermal comfort.

v. Relative humidity

Relative humidity is one of the key elements in determining the thermal comfort of occupants. The set point of relative humidity was altered from the standard value to verify its repercussive effect on minimizing cooling load and maintaining indoor thermal comfort.

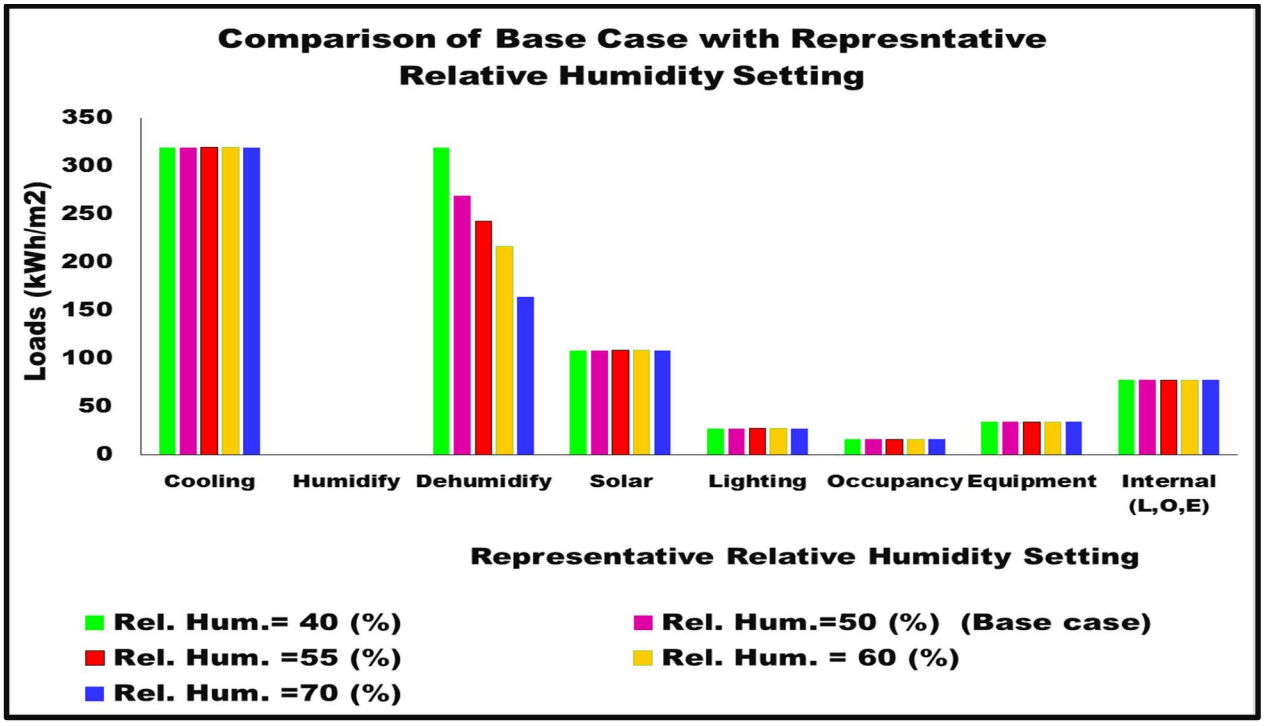

Figure 8.16: Relative humidity

Variation of relative humidity set points affected the dehumidifying loads only, on the other hand, there was no change on the overall cooling load.

- **Findings on Internal condition design variables**

The following findings have been deduced from the parametric simulation on the internal design variables:

1. Reducing the equipment gain to 8Wm-2, improved the cooling and made the equipment load acceptable according to CIBSE Guide recommendation. On the other hand, this minimum gain is subject to availability of highly efficient equipment systems.

2. Ventilation gain have the potential for minimizing dehumidification load and subsequently cooling load; conversely, caution must be taken not to compromise the indoor air quality of occupants.
3. Increasing the thermostat temperature setting beyond 27^{o}C reduces the cooling load; conversely, this leads to thermal discomfort for occupants.
   The sensitivity test showed that, the variation of the relative humidity setting on the thermostat has no influence on the cooling load.
4. The most sensitive internal condition design variables in reducing cooling load were thermostat temperature setting and infiltration gain (0.2 ACH) with percentage reduction of 20% and 6% respectively.
5. The total dehumidifying load of the base case was reduced by 67.2% with a corresponding reduction of 39.8 % of the total cooling load by the following significant approaches: i. Changing the thermostat temperature and relative humidity setting to 27^{o}C and 70% respectively. ii. Reducing infiltration arising from all leakages to a practically feasible minimum of 0 2ACH as well as ventilation gain of 2 ACH.

- **Implications of findings on Internal condition design variables**

From the findings, dehumidifying load contributes 53.8% to the overall base cooling load and is contributed dominantly by ventilation gain, infiltration gain and thermostat setting (temperature and relative humidity). Hence, controlling ventilation gain, infiltration gain and thermostat setting would have significant effect in minimizing the overall cooling load. The equipment load contributes 8.5% to the base cooling load and the equipment gain can be reduced by selecting more energy efficient equipment.

In summary, the optimal practical internal design variables have been obtained, on the other hand, it requires the service engineer to design as well as select systems to achieving the optimal practical values.

8.10.2 Building Fabric Design Variables

a. Thermal Mass of wall and roof systems

b. Thickness of fabrics wall and roof systems

c. Low transmittance building fabrics of all envelope elements

d. Vapour Diffusion Factor

The details of each building fabric design variables are as below.

a. Thermal mass of wall and roof systems

The thermal mass approach for minimizing cooling load was categorized into wall system and roof system. Figure 8.21 and 8.22 are the thermal mass variation for the wall and roof systems respectively.

- **Thermal mass of Wall system**

From the reviewed literature, thermal mass is of the approaches for minimizing cooling load.

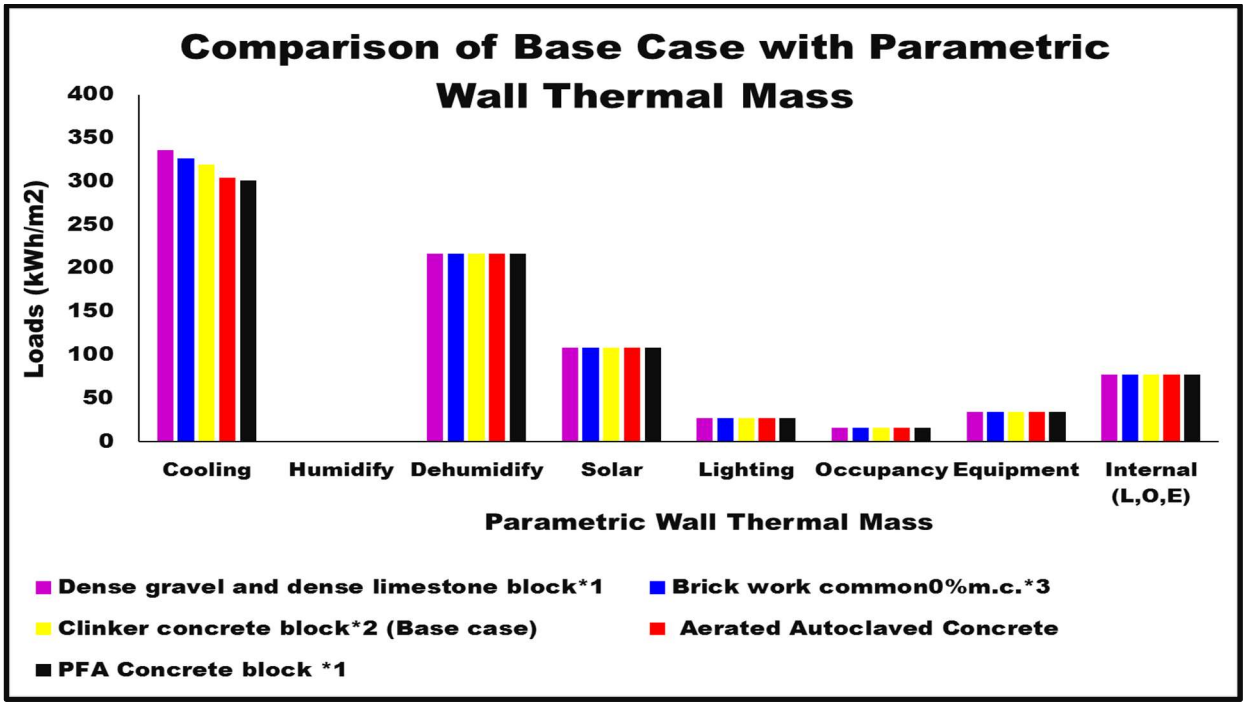

Figure 8.17: Thermal mass of wall system

From the fabrics with different thermal masses simulated and compared with base case, it can see that there is minimal reduction of cooling load with no effect on the other loads. In conclusion, use of thermal mass is inappropriate approach in reducing cooling load contribution from the wall system under Ghana climate.

➢ **Thermal mass of Roof system**

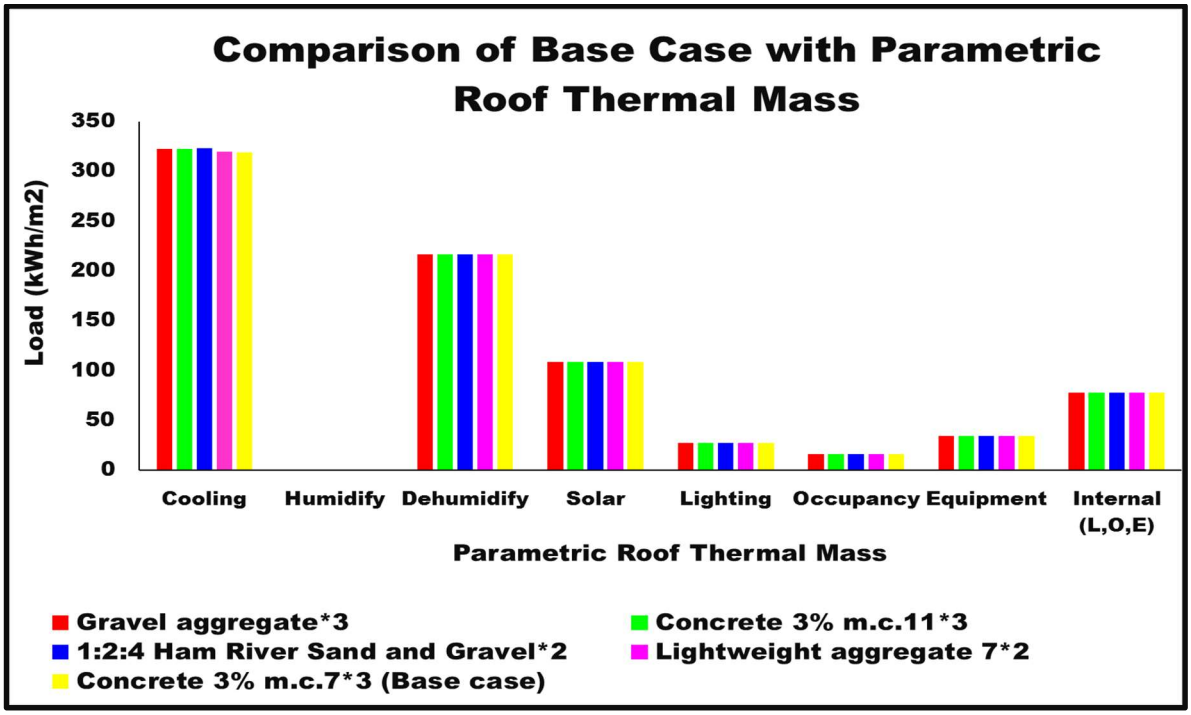

Figure 8.18: Thermal mass of roof system

Thermal mass of the various fabrics for the roofing system had insignificant variations across all the contributing loads. In conclusion, the use of thermal mass in reducing cooling loads contributions from the roof and wall system, had no substantial impact in Ghana climate.

b. Thickness of fabrics wall and roof systems

Thickness of building envelope elements have impact in minimizing thermal conductance, conversely, how wide can elements be increase to and how cost effective is this approach? The parametric thickness of wall and roof systems were simulated to identify its effectiveness in reducing cooling loads.

- **Wall system thickness**

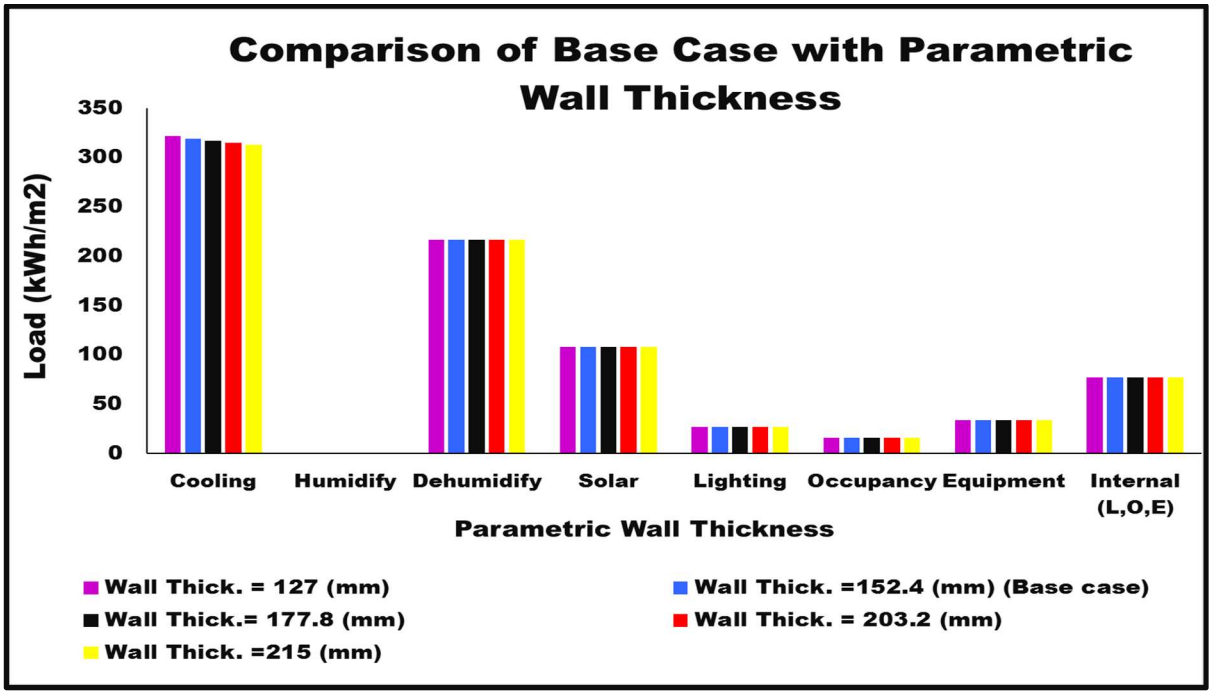

Figure 8.19: Wall thickness variation

From the various parametric thickness considered, a trend of increasing thickness of wall system with reducing cooling was observed. Conversely, the increasing wall system thickness have no effect on the other contributing loads. The resulting cooling reduction with increasing wall system thickness is very low. In conclusion, wall thickness with the aim of reducing cooling load is an inappropriate approach and expensive.

- Roof system thickness

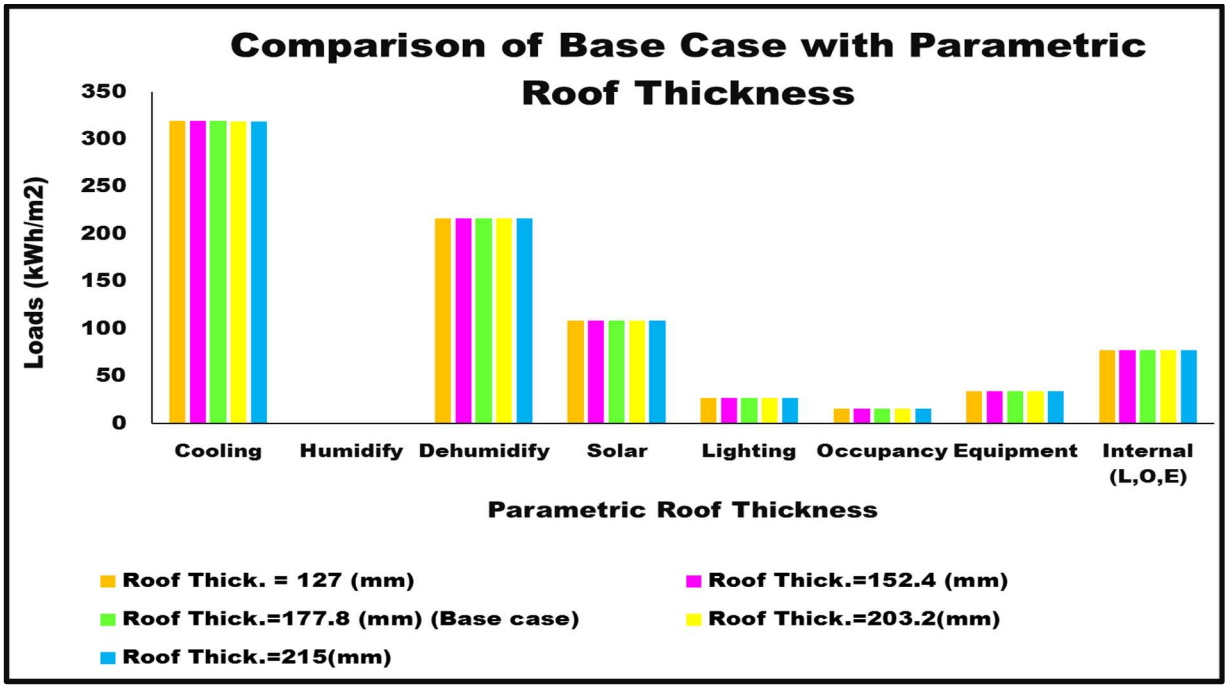

Figure 8.20: Roof thickness variation

Variation of roof thickness had no impact on the cooling load and the other contributing loads. This is because of the roof ceiling system incorporated into the mono-pithed reinforced concrete, hence the sun radiation through the roof system is controlled.

In conclusion, the use of thickness variation of wall and roof system in minimizing cooling load is not an efficient and cost-effective approach.

c. Low transmittance building fabrics of all envelope elements

There are several properties of building fabrics as outlined in the literature.

Building fabric of low thermal transmittance value (u-value) and glazing value have the potential in reducing the heat gain contribution to the overall cooling load. Parametric simulation of the various window panes and opaque fabrics were assessed for the window systems, wall systems and roof systems with increased fabric thickness. Details of the low transmittance fabrics for both transparent and opaque are presented in Figures 8.21 to 8.25.

- Window pane

Parametric simulation of four different low glazing windows were undertaken and compared with the base case.

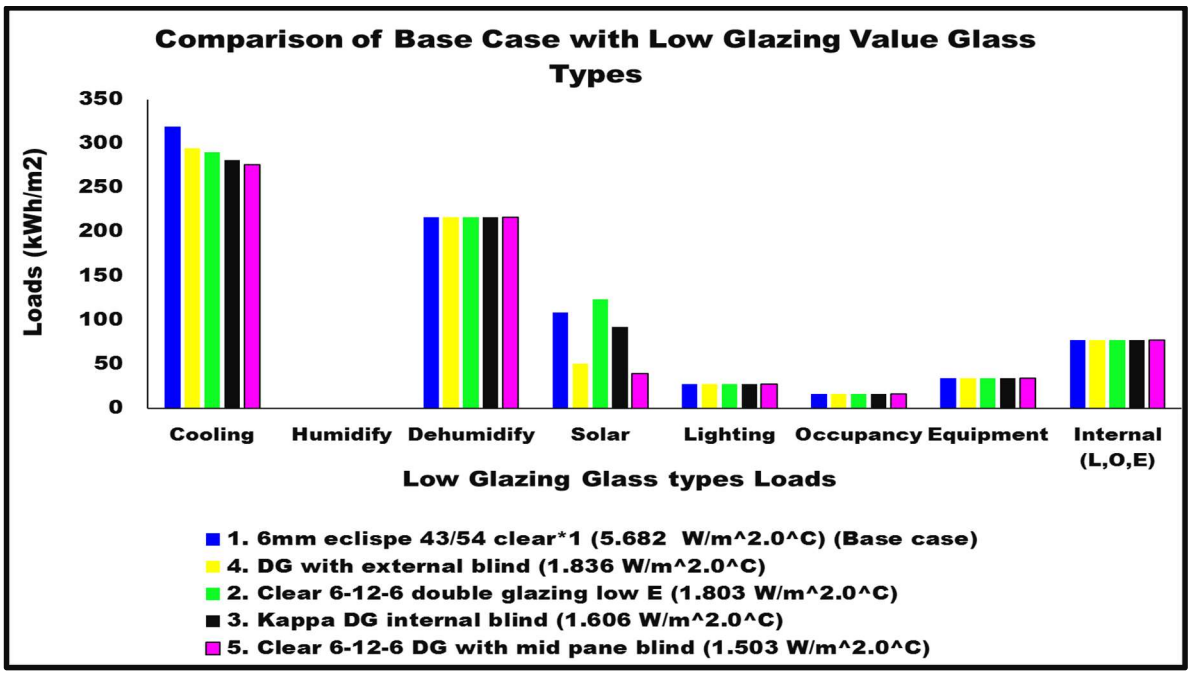

Figure 8.21: Types of window pane

The window pane variations had effect on the solar gain load and overall cooling load. The variation of the window pane had no impact on the dehumidifying and the overall internal load. A strong correlation trend of decreasing u-value with decreasing overall cooling loads were observed. The most suitable window pane for this case study was clear 6-12-6 DG with mid pane blind.

Low transmittance value (u-value) for wall system

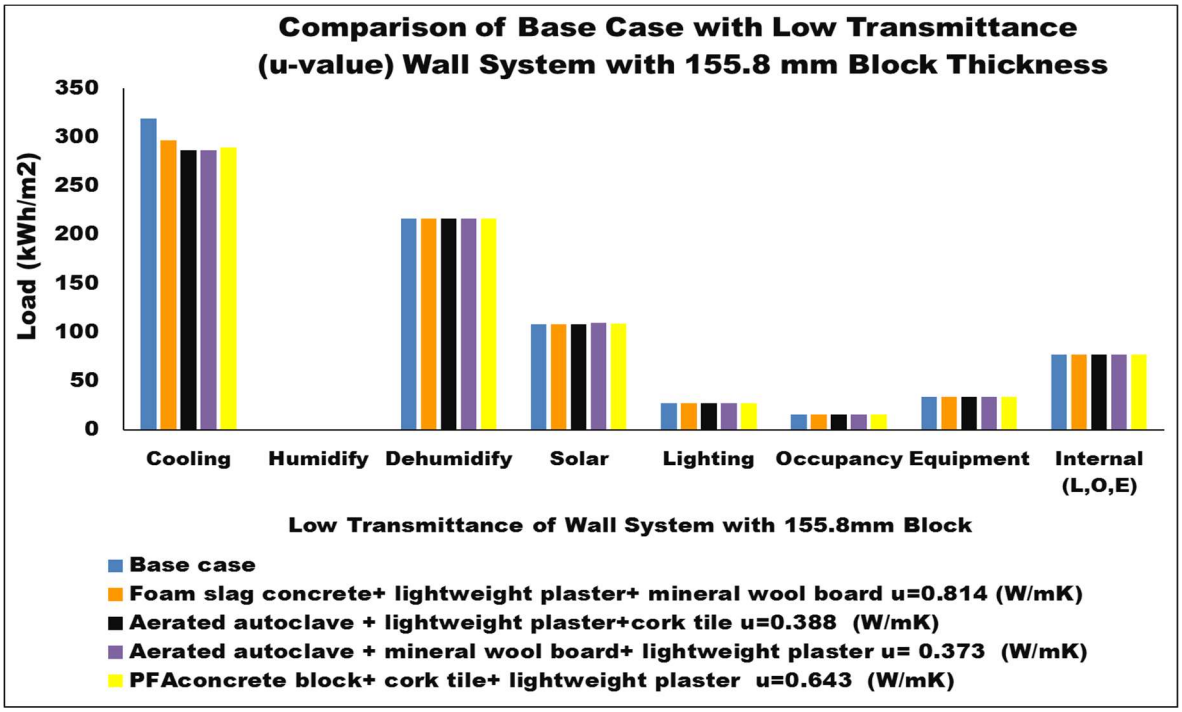

Figure 8.22: Low transmittance value (u-value) for wall system

A correlation trend of decreasing u-value with decreasing overall cooling loads were observed with insignificant change in the other loads for 6 inches' block thickness.

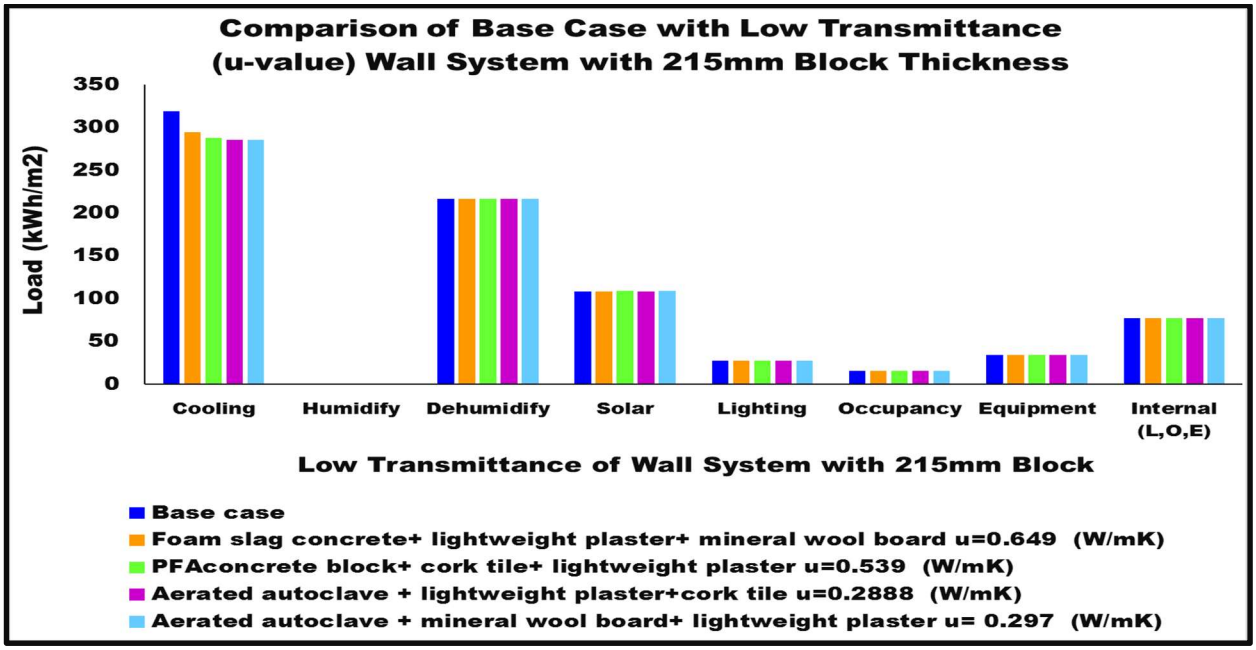

Figure 8.23: Low u-value for wall system with 215mm thickness

A correlation trend of decreasing u-value with decreasing overall cooling loads were observed with insignificant change in the other loads for 8 inches' mortar/concrete block thickness. On the contrary, although increasing the thickness of the mortar/concrete block resulted in reduction of the u-values, its overall impact on the cooling load reduction was not substantial. In conclusion, using increasing mortar/concrete block thickness for reducing cooling load is not a recommended approach.

Low transmittance value (u-value) for Roof System

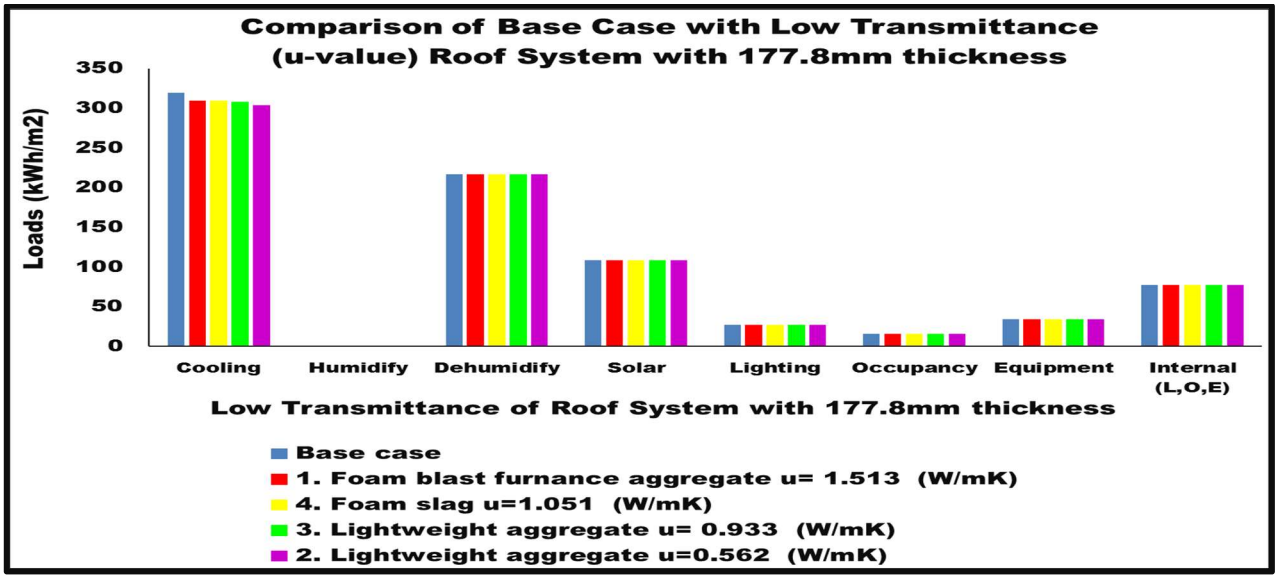

Figure 8.24: Low transmittance value (u-value) for Roof System

A correlation trend of decreasing u-value with decreasing overall cooling loads were observed with insignificant change in the other loads for 7 inches' concrete block thickness.

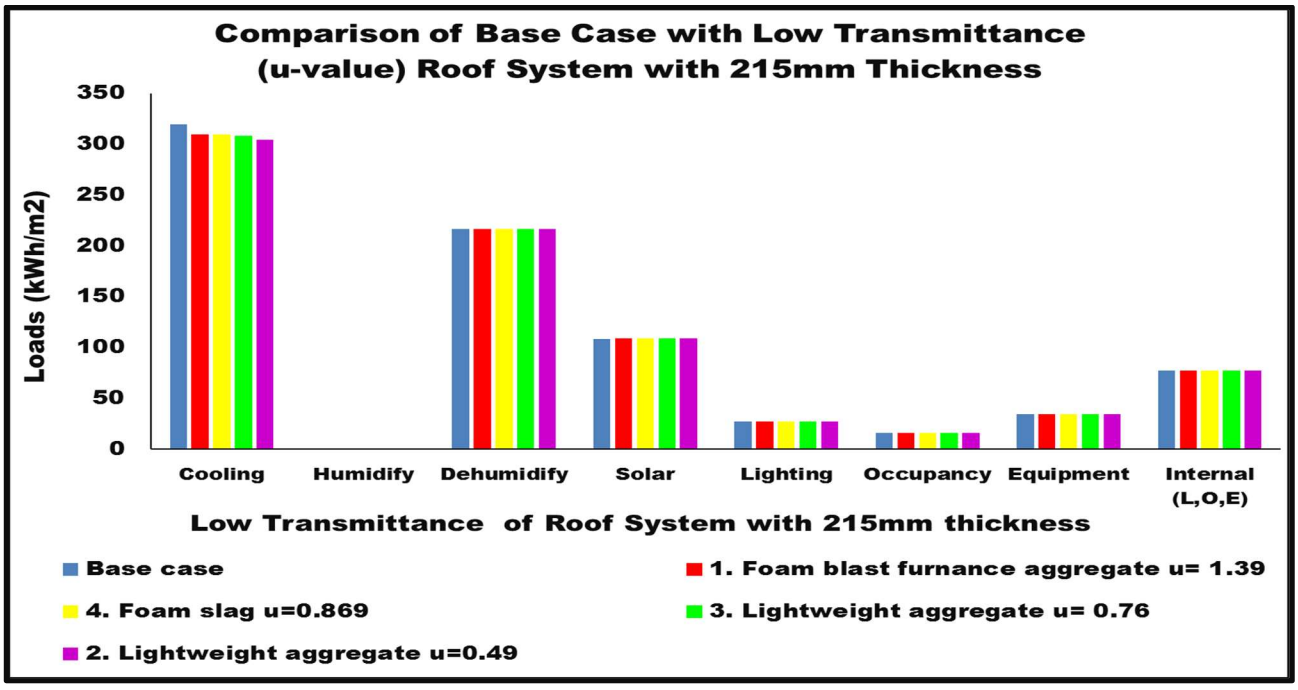

Figure 8.25: Low u-value for roof system with 215mm thickness

A correlation trend of decreasing u-value with decreasing overall cooling loads were observed with insignificant change in the other loads for 8 inches' mortar/concrete roof thickness. On the contrary, although increasing the thickness of the mortar/concrete roof resulted in reduction of the u-values, its overall impact on the cooling load reduction was not substantial. In conclusion, using increasing mortar/concrete roof thickness for reducing cooling load is not a recommended approach.

d. Vapour diffusion factor of cement based fabric

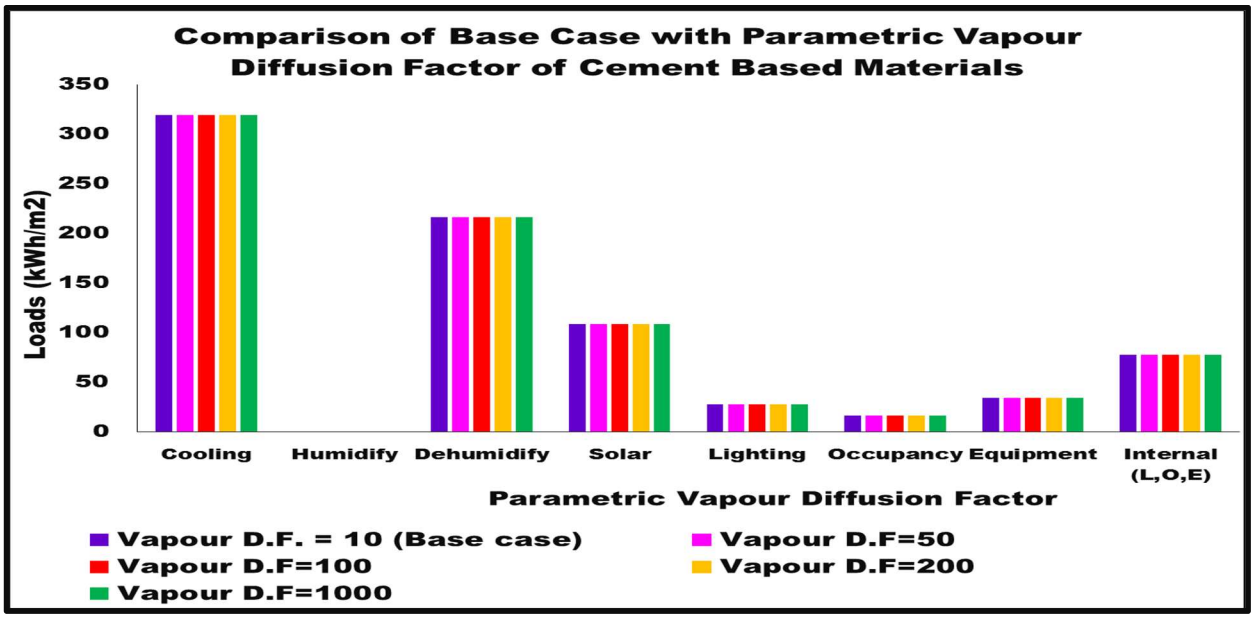

Figure 8.26: Vapour diffusion factor

Variation of vapour diffusion factor had no influence on the overall cooling loads. This is due to inadequacy of ESDL Tas to incorporate vapour diffusion factor into the cooling load calculation.

- **Findings on Building Fabric**

1. The wall thickness affects the calculation of the u-value, conversely, the wall thickness cannot be increased beyond the standard to achieving the u-value of 0.3 W/m^{2}K as stated in the building code.

Detail study is required to improve the thermal conductivity property of cement-based fabrics to achieving u-value of 0.3 and 0.25 W/m^{2}K for wall and roof systems respectively.

2. Then variation of the window pane has a significant reduction on the cooling load; on the other hand, clear 6-12-6 DG with mid pane blind was the best window pane type.
3. TAS do not accurately predict the moisture transfer through the building envelop materials; this is because no change observed in parametric simulation of vapour diffusion factor. The Flicks law is generally used for the moisture transfer. The Flicks law depend on diffusion coefficient and the concentration gradient.

   On the other hand, the only material property provided by TAS in its data base is water vapour diffusion. In conclusion, for further investigation into moisture transfer from both internal and external of the building envelop; there is the need for different building simulation software to investigate moisture transfer.
4. From the sensitivity test, there is no way where the current wall system and roof design can attain the u-values of 0.3 and 0.25 W/m^{2}K respectively as stated in the building regulations. This is because of standard values of thermal conductivity and dimensions of blocks differ from that of Ghana.
5. Using thickness of building element materials to achieve you u-values stipulated in the building code, the simulation results did not yield significant practical optimized economic, energy and environmental simulation.
6. From the parametric simulation (low thermal conductivity values, and low glazing value) results, the cooling load was reduced by about 16% and 14% respectively with no change on dehumidifying load.

   Hence there is the need to select technology to control moisture transfer into the building envelop.
7. Achieving the u-values stipulated for building fabric alone does not guarantee the recommended energy performance by CIBSE Guide.
8. There is no single approach for enhancing building performance.

- **Implications of Building Fabric Findings**

From the research knowledge gaps identified, achieving the u-values of 0.25 and 0.3 W/m^2 K for roof and wall systems respectively using current single wall layer designs as well as fabrics remains a challenge in Ghana. In view of this, parametric simulation of redesigning wall and roof systems of different fabric compositions as well as designs were undertaken.

8.10.3 Achieving the u-values in Ghana Building Regulations

From the research knowledge gaps identified, achieving the u-values of 0.25 and 0.3 W/m^2 K for roof and wall systems respectively using current single wall layer designs as well as fabrics remains a challenge in Ghana.

In view of this, parametric simulation of redesigning wall and roof systems of different material compositions as well as designs were considered. Figures 8.27 and 8.28 are the parametric simulations for the proposed redesigned wall and roof systems to achieving Ghana building regulation.

a. Proposed Redesign of Wall System

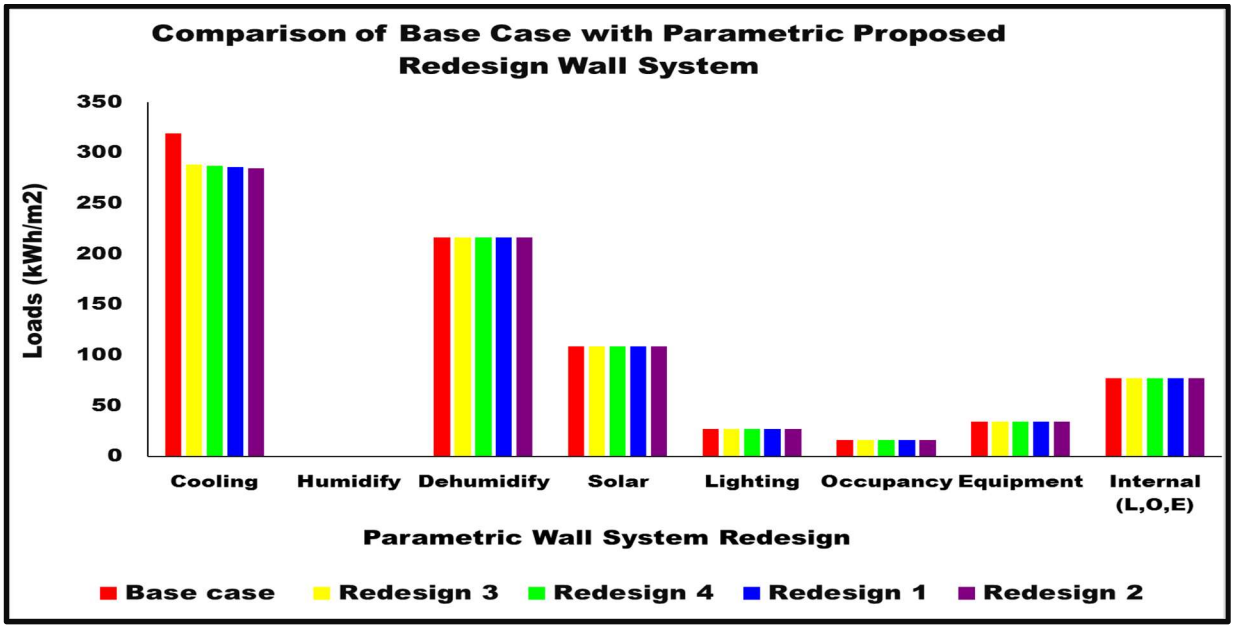

Figure 8.27: Proposed Redesign of Wall System

Proposed redesigned 1 and 2 wall systems using different fabrics and double wall layer designs achieved the 0.3 W/m^{2}K u-value in the Ghana building regulations with about 10% reduction of the cooling load. Though, the recommended u-value in the Ghana building regulation has been achieved using the proposed redesigned double layer wall system, its economic benefit needs to be assessed to ascertain the cost effectiveness of this approach.

c. **Proposed Redesign Roof System**

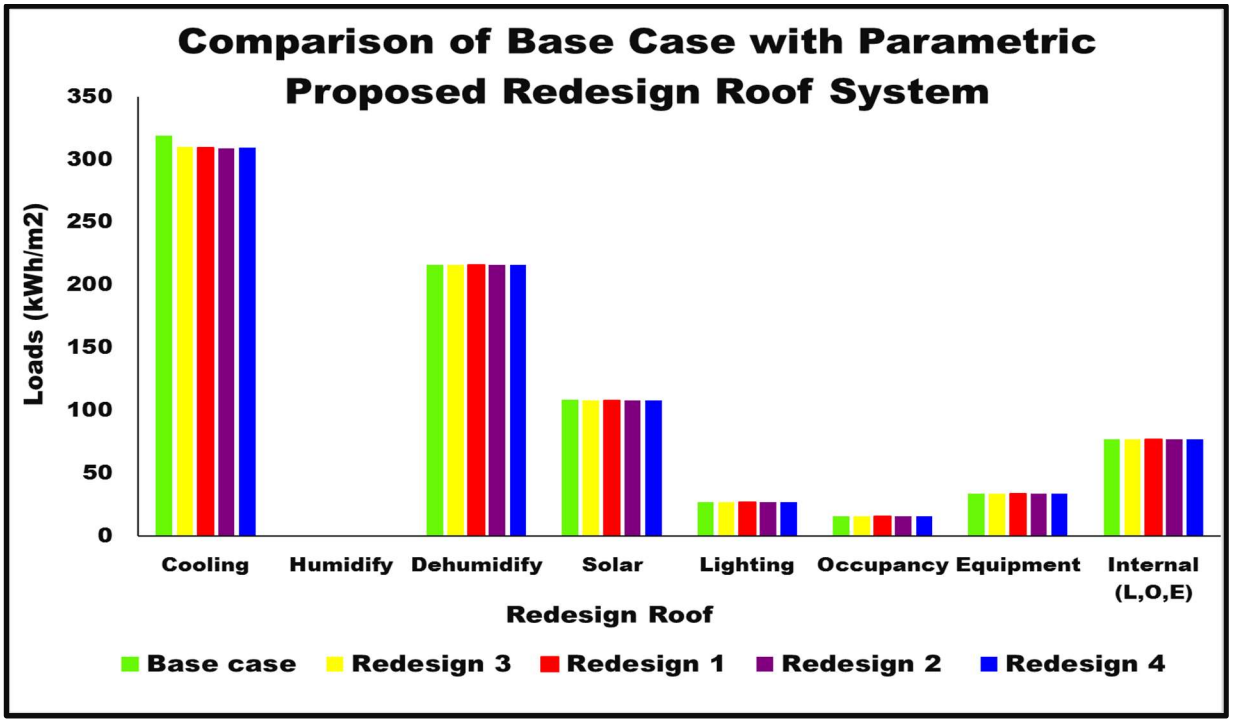

Figure 8.28: Proposed Redesign of Roof System

Redesigned roof system using different fabrics and designs had very low impact on all the loads contributing to overall cooling loads although 0.25 W/m^{2}K u-value in the Ghana building regulations was attained. This is because of the high floor-to- ceiling height and the ceiling fabric used.

8.10.4 Combination of optimum design variables and Verification Simulation for both before and after Building Regulation.

The optimum design variables for all the parametric simulations of both low transmittance building fabric and indoor internal conditions were combined and plotted for two major scenarios that is, enhanced design scenarios before and after the enactment of the 1996 Ghana Building Regulation. Figures 2.29 and 2.30 are comparison of enhanced design scenarios before and after the enactment of the 1996 Ghana Building Regulation.

a. Comparison of enhanced design scenarios before the enactment of the 1996 Ghana Building Regulation

In enhanced design scenarios before the enactment of the 1996 Ghana Building Regulation, the base building was designed using building design specification with varying floor-to ceiling height across the floors. As explained in the survey questionnaires data, this scenario is for the verification of the findings that, the converted natural cooling buildings with varying floor-to-ceiling height to mechanical air-cooled space, consume more energy than a space originally designed for mechanical cooling.

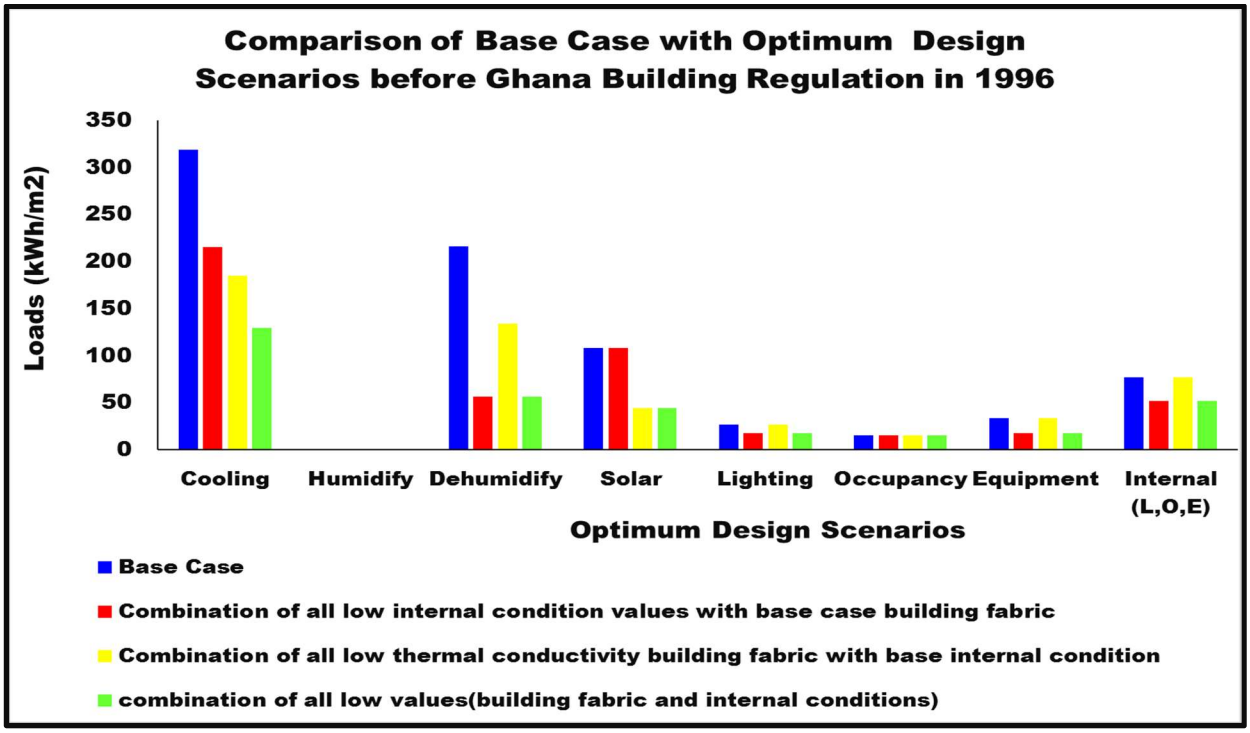

Figure 8.29: Combination of enhanced optimum design scenarios before enactment of Ghana building regulation

Integration of combination of all optimum design variables into building design before the enactment of building regulation yielded different varying percentages of reduction of all loads depending on the scenario. The major variations occurred within the dehumidifying and solar loads as well as the overall cooling load.

The most enhanced optimum design combination scenario was combination of all low optimum values (building fabric and internal conditions) with percentage reduction of cooling and dehumidifying load been 60% and 73% respectively. Conversely, the least enhanced optimum design combination scenario for cooling load was combination of all low internal condition values with base case building fabric; whiles the least enhanced dehumidification been combination of all low thermal conductivity building fabric with base internal condition. In conclusion, in optimising both cooling load and dehumidifying load concurrently, it is appropriate to use both internal condition variables and low thermal conductivity building fabric; specifically internal condition variables are more appropriate for reducing dehumidifying load.

Comparison of enhanced design scenarios after the enactment of the 1996 Ghana Building Regulation

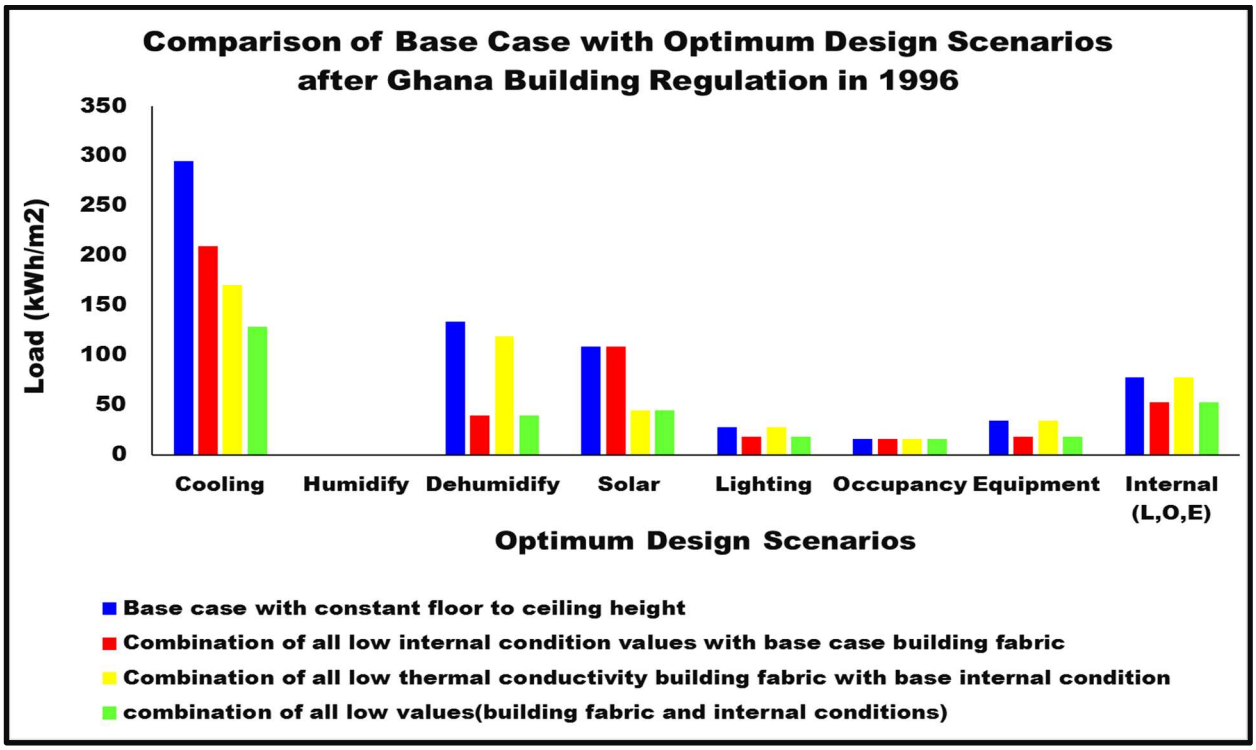

Figure 8.30: Combination of enhanced design scenarios after Ghana building regulation

Integration of combination of all optimum design variables into building design after the enactment of building regulation yielded different varying percentages of reduction of all loads depending on the scenario. The most enhanced optimum design combination scenario was combination of all low optimum values (building fabric and internal conditions) with percentage reduction of cooling and dehumidifying load been 57% and 70% respectively. Conversely, the least enhanced optimum design combination scenario for cooling load was combination of all low internal condition values with base case building fabric; whiles the least enhanced dehumidification been combination of all low thermal conductivity building fabric with base internal condition. The dominant difference between building design before and after the enactment of Ghana building regulations is the volume of the cooling space across the floors of the base case. In conclusion, in optimising both cooling load and dehumidifying load concurrently, it is appropriate to use both internal condition variables and low thermal conductivity building fabric; specifically, internal condition variables are more appropriate for reducing dehumidifying load.

- **Findings**

1. The difference between the cooling load of building design before and after the enactment of Ghana building regulations was 24kWh/m^2 per annum.
2. The most enhanced optimum design combination scenario for both building design before and after the enactment of Ghana building regulations was combination of all low optimum values (building fabric and internal conditions).
3. The best enhanced optimum design scenario for all the creative computer simulations was, combination of all low optimum values (building fabric and internal conditions) for building design after the enactment of Ghana building regulations with 128.8 kWh/m^2 per annum.

In conclusion, from the best creative combination approach, the recommended CIBSE Guide for typical good practice for cooling load was not achieved, however the new cooing load is just about 4 times that of CIBSE Guide. In view of this, the best enhanced optimum computer simulation was select for the integration of the low energy technology to further minimise the dehumidification load.

8.8.5 Proposed Optimized design variables and Integration of Technology

From the conclusion of technologies in Chapter 4, chilled beam technology was selected to further minimize the dehumidification load. Integration of the selected chilled beam technology into the best enhanced optimum computer simulation was carried out in ESDL Tas and presented in Figure 8.31.

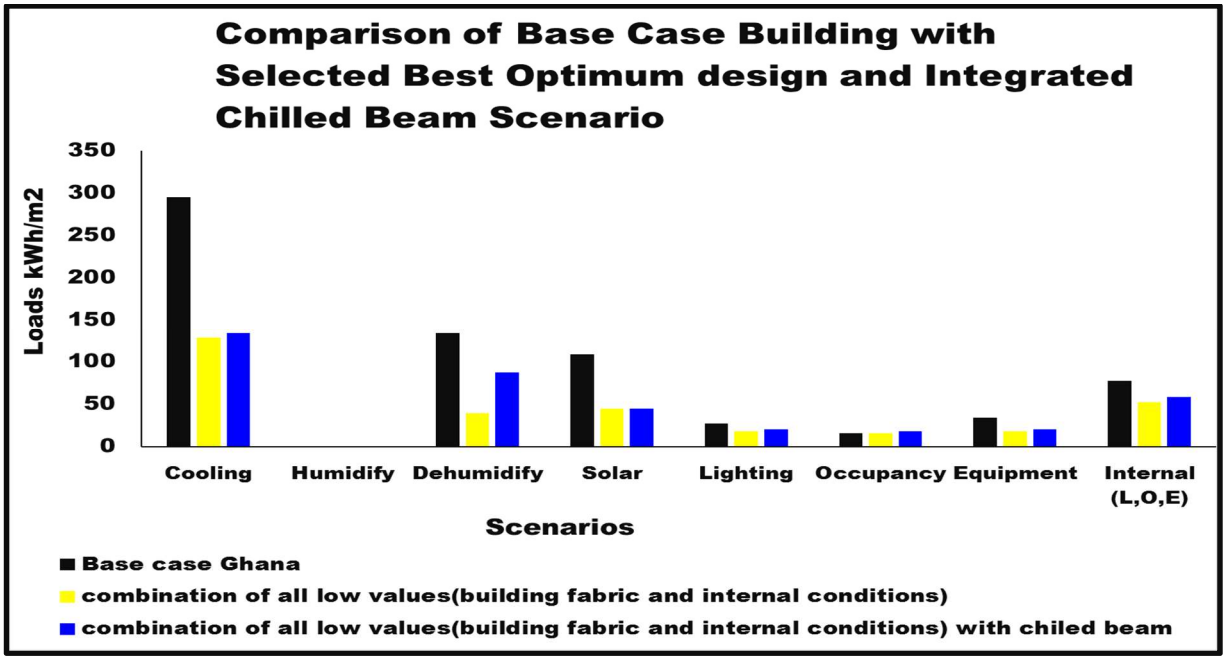

Figure 8.31: Proposed optimised design variables

From the comparisons, the base case building loads were reduced on an average of about 52% per annum in both scenarios with the significant change arising from solar and dehumidification loads leading to over 50% of overall cooling load. On the other hand, the integrated chilled beam technology introduced about 54% of additional dehumidification load to the best optimum design scenario.

In conclusion, the selected low cost energy technology integrated into the best optimum computer simulation design was not appropriate to reducing the dehumidifying load in hot-humid climate.

8.11 Overall Findings and Implication of Computer Simulation

Several findings have been concluded on the novel computer simulations on the optimization of the design variables to enhancing the building performance using low energy technologies approaches.

The summary of the dominant findings and the respective implications are as follows:

1. Dehumidifying load has been reduced significantly for about 73% per annum from the base case leading to considerable reduction of cooling load and subsequently energy utilization. On the contrary, the chilled beam technology is not appropriate for Ghana climate hence, desiccant cooling technology should be considered although it has high initial cost.

2. Several approaches are required for minimizing heat and moisture transfers since there is currently no existing single technology available for solving both concurrently. In hot-humid climate, both heat arising from building fabrics and moisture from outdoor as well as indoor environment transfers needs to be minimized when considering optimization of building performance qualities.

3. Building performance design factors in Ghana have changed considerably since the enactment of the building regulations with the major changes been window-to-wall ratio and constant floor to ceiling heights across multi-storey buildings. The increasing window-to-wall ratio leads to enhanced visible daylighting with increased heat gain leading to high cooling load for thermal comfort. The use of constant floor-to-ceiling height also contributed to reduction of 24kWh/m^2 cooling load per annum. Though it seems to be insignificant but is extra savings arising from building fabrics

3. Building fabric selection is one of the most important factors to be considered from design stage or retrofitting. From the data acquired through survey questionnaires, experiments and computer simulations, there a strong contrast. Considerable percentage of the participants of the survey questionnaires indicated that the building fabrics used in Ghana are suitable for the climate.

On the other hand, the experimental assessments have shown that, the thermal conductivity of the cement-based fabrics are too high. Whiles the simulations have shown that, thermal conductivity of less than 0.1 W/mK is required to achieving the thermal transmittance of 0.3 and 0.25 W/m^{2}K for wall and roof systems respectively as in Ghana building regulations.

4. Thermal mass of building fabrics are used for improving building performance especially in climates where there is a major difference in day and night temperatures. From the percentage of reduction in cooling load from the computer simulations, the use of thermal mass for enhancing building performance, is not a viable approach

5. From the computer simulations, building fabric thickness improves the thermal transmittance, but the resulting improvement to the overall cooling load reduction is inconsequential.

6. The thermal comfort was acceptable based on the computer simulations. On the contrary, other indoor environmental properties were not assessed due to the limitation of ESDL Tas library.

8.12 Conclusions and Recommendations

The optimum design variables for building performance assessments in Ghana have been obtained through the creative computer simulations. In conclusion, the recommended good practice in CIBSE Guides for cooling load was not achieved using the optimum practical design variables with the integration of chilled beam technology.

It is therefore recommended that; future research should investigate into using these optimum practical design variables under hot-dry weather data to investigate whether the recommended good practice for cooling load in CIBSE Guide is achievable.

9. CHAPTER NINE: CREATIVE ECONOMIC BENEFIT ASSESSMENT

9.1 Introduction

Several modifications have been considered in this research to enhance building performance in Ghana. As identified in the survey questionnaire, cost is a major constraint impeding the advancement of technology and modification integration in buildings in Ghana. This is in consistent with Perez-Lombard et al.,2011 review which concluded that policy makers and consumers were interested in the economic impact of energy saving requirements with cost effective and payback period below 2 years.

In view of this, any modification proposed should be cost effective with corresponding significant benefit to the clients and energy savings to Ghana as well as acceptable indoor environmental climate.

Kneifel (2011), results show that the use of conventional energy efficiency technologies in an integrated design framework can reduce energy use by 15–20% on average in new commercial buildings and over 35% base on building types and locations. According to Galvin (2010), it is challenging to compare renovation costs and outcomes accurately due to several variations in thermal standards, shapes as well as building sizes

As said by Kneifel (2011), the financial benefits from energy efficiency improvements are impacted by the building type, local climate, location-specific costs, and study period. Also, increasing energy efficiency frequently increases the initial costs of a building, but the energy savings over the service life of the building often offsets these initial higher costs.

The final and most complex approach for the development of future energy standards seeks for the ‘optimal target’.

Basically, the idea is to identify the 'savings level' which leads to the lowest life cycle cost (LCC) during the estimated economic lifecycle Perez-Lombard et al., 2011.
Representative cost components of building performance optimization include initial capital cost, maintenance cost, operational cost (Fernández-Membrive et al.,2015 and Gupta et al., 2016)

Several researchers assume characteristic life span of building envelope in the range of 25 to 50 years and up to 100 years (Utama and Gheewala,2009; Castleton et.al.,2010; Williams et al., 2012; Peuportier et al.,2013 and Bonakdar et al.,2014).
Life Cycle Cost analysis is a dominant best approach used in technical and scientific journals for systematically determining suitable alternatives of choices in terms of total cost, benefits and cost savings over life span (Galvin 2010; Kneifel, 2011; Koranteng and Mahdavi, 2011; Grignon-Masse et al.,2011 and Han et al., 2014).
Buildings come in all shapes and sizes and are renovated to various thermal standards, so it is not easy to compare costs and outcomes accurately (Galvin, 2010)

Kneifel (2011), results show that the use of conventional energy efficiency technologies in an integrated design framework can decrease energy use by 15–20% on average in new commercial buildings, and over 35% for some building types and locations. These energy reductions can often be accomplished at negative incremental life-cycle costs and reduce a building's energy-related carbon footprint by 9–33%. On the other hand, generalizing these results on energy use, life-cycle costs, and carbon emissions eliminates the exceptions in the results that, show the importance of location-specific characteristics.
In conclusion, the details of purpose, objectives, input and output variables, flow chart, in addition to the details of the creative parametric scenarios for testing the comparator decision tool has been outlined in Chapter 5.

9.2 Representative Cost Benefit Data from Survey questionnaire

The following data on cost and life cycles of building envelopes as well as service equipment finishing were obtained from the survey questionnaires data:

1. 34.9% of participants indicated that the life cycle of air-conditioning systems in the offices are within a range of 20-25 years. Whiles 27.9% participants indicated the life cycle is within a range of 25-30 years.
2. Half of the participants (50%) indicated that the typical life cycle of electrical bulbs in the offices are within 1-3 years with 33.3% indicating 5-11months.
3. 47.6% of participants indicated that other office electrical equipment has life cycle within the range of 5-7years whiles 33.3% indicated 3-5years.
4. Majority of participants representing 55.8% indicated that office building permit are typically issued for 30-40 years.
5. Substantial number of participants representing 64.7% specified that, classically there is 30-50% of upfront cost of added to conventional building cost if passive design is incorporated within the building.
6. 45.45% participants specified that, building fabric contributes to range of 40-50% of the overall cost of office building with 29.5% indicating a range of 50-60%.
7. Several participants representing 80% pointed out that, customers will pay for pay for cost of modification to attain low energy building.
8. Significant participants of 63.1% are of the opinion that, full passive multi-story office building designed and constructed with acceptable building performance at effective cost cannot be built in Ghana.

- **Implications of economic benefit and life cycle cost from the survey questionnaires**

Majority of participants indicated that, building fabric cost a range of 40-50% for overall building cost and have longer life span over the service equipment. This implies that, the selection of suitable fabric would have long time impact on the building performance. With substantial percentage of participants indicating that, clients will pay for additional modification cost to achieve low energy building performance, it implies that clients have knowledge of the benefits hence this study is practicable.

9.3 Design of Comparator Cooling Load Decision-Making Tool

The economic equations for designing the comparator cooling load decision-making tool are as follows:

a. **Difference in cost of modification (Z_d) is expressed mathematically as,**

$$Z_d = z_m - z_b \quad \text{Eqn 9.1}$$

b.**Savings in electricity cost per annum after modification (Z_{se}) is expressed mathematically as,**

$$Z_{se} = z_{bo} - z_{mo} \quad \text{Eqn 9.2}$$

c. **Simple Payback period (Zp) is expressed mathematically as,**

$$Zp = Zd / Zmo \quad \text{Eqn 9.3}$$

d. Simple net electricity benefit after modification for life cycle (Zn) is expressed mathematically as,

$$\mathbf{Zn = Z_{se} * Zp} \quad \text{Eqn 9.4}$$

e. Total operating cost for base building (Z_{tbb}) is expressed mathematically as,

$$Z_{tbb} = z_b + B*T \quad \text{Eqn 9.5}$$

f. Total operating cost for modified building (Z_{tmb}) is expressed mathematically as,

$$Z_{tmb} = z_m + M*T \quad \text{Eqn 9.6}$$

g. Electricity operating cost for modified building (z_{mo}) is expressed mathematically as,

$$z_{mo} = M*T \quad \text{Eqn 9.7}$$

h. Electricity operating cost for base case (z_{bo}) is expressed mathematically as,

$$z_{bo} = B* T \quad \text{Eqn 9.8}$$

Where

z_b= cost of base building envelope

B= base cooling load per meter square floor area

z_m= cost of modified building envelope

M= modified building cooling load for floor area

T= electricity tariff

Zp = payback

Note

Cost of modified building (Z_m) was obtained from the cost of both the improved building service equipment and fabrics using the parametric increments from 5-25% of the base building.

Cost of base building (Z_b) was obtained from cost estimate engineer from Ghana using the base building for the simulation see Appendix B

Electricity tariffs for Ghana was obtained from PURC price list, see Appendix B

If there is significant variation in inflation rate of your economy, it is recommended to undertake time value of money on your final decision, i.e. largest net benefit.

Figure 9.1 shows the data acquisition processes from the economic comparator decision tool.

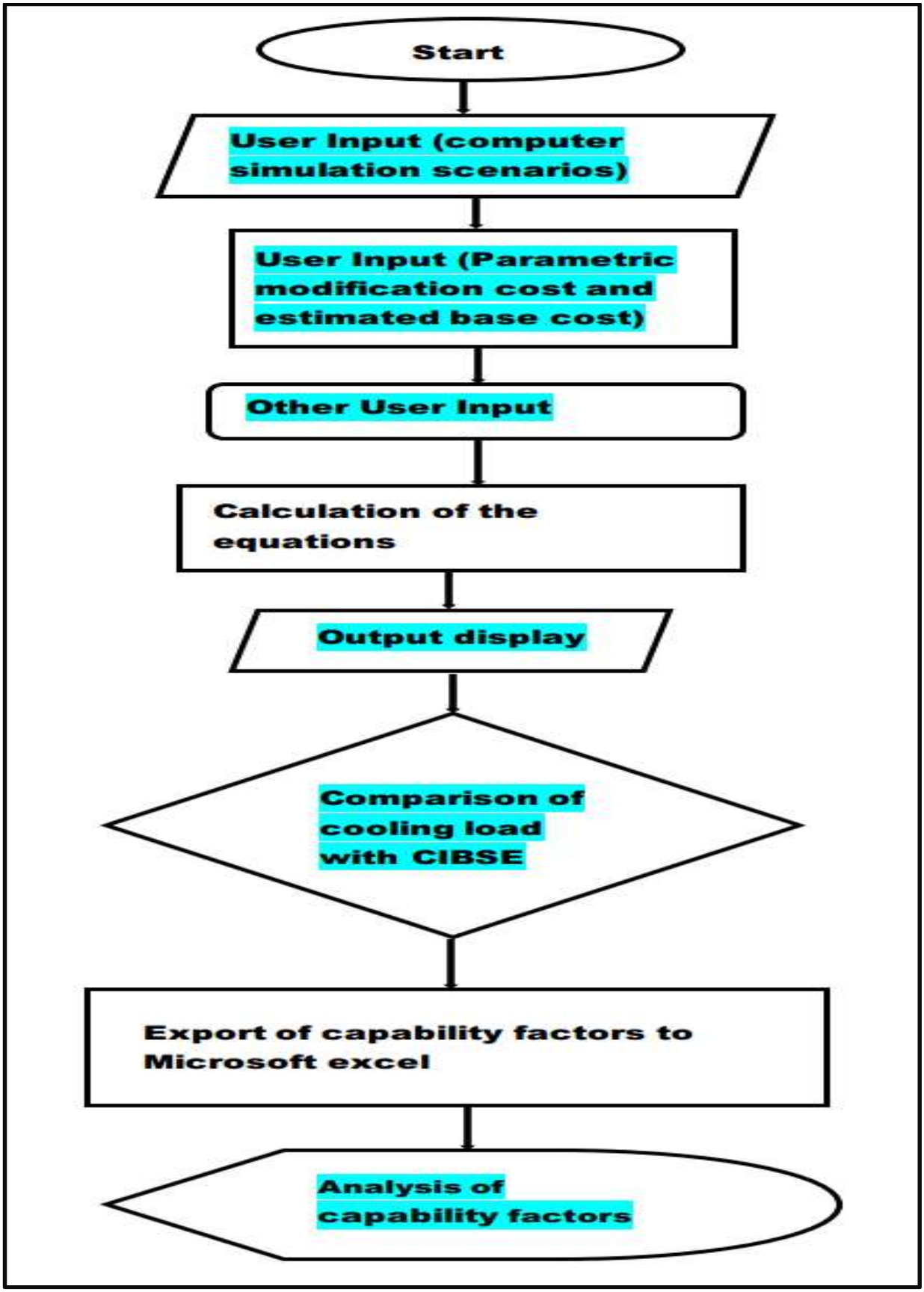

Figure 9.1: Flow chart for the processing of the economic assessment data

9.3.1 Input data

The user is required to enter the input variables displayed in Figure 9.2. The details of input variables are as follows:

1. Total Base building cooling load per annum (kWh)
2. Modified building cooling load per meter square floor area per annum (kWh/m^2)
3. Electricity tariff (kWh) per annum
4. Cost of base building envelope
5. Cost of modified building envelope

Friendly user interface of the economic comparator decision tool with the input variables and output parameters are shown in Figure 9.2.

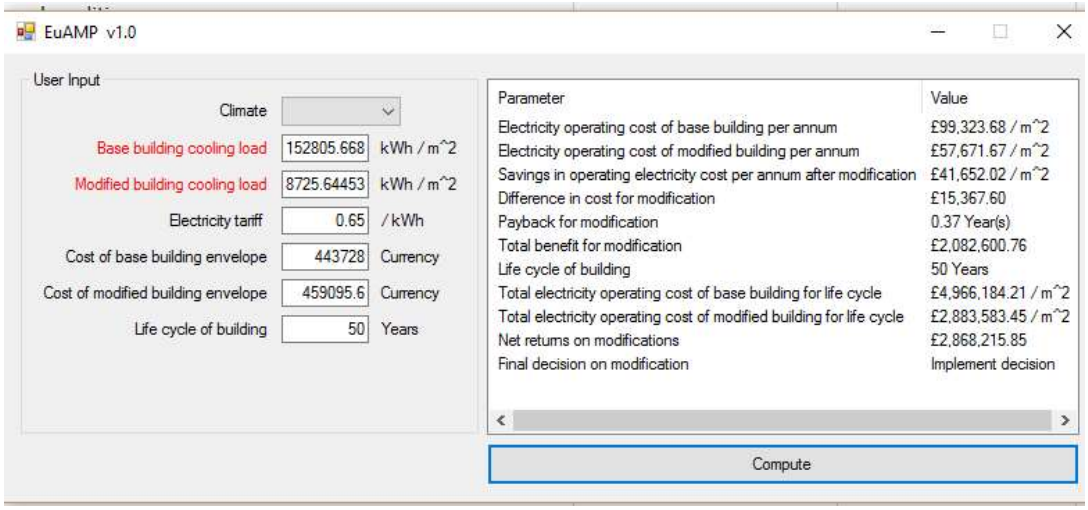

Figure 9.2: Friendly user interface of the economic comparator decision tool

Table 9.1: Selected sample of input data for economic assessment

Input	Values
Base building cooling load per meter square floor area per annum (kWh) for building design after the enactment of Ghana building regulations	319.1963
Modified building cooling load per meter square floor area per annum (kWh)	128.843
Electricity tariff (kWh) per annum for commercial buildings with consumption of 301-600(kWh) ($)	0.26
Cost of base building envelope (Ghana cedis)	443728
Cost of modified building envelope (Ghana cedis)	459095.6
Representative life cycle of building (years)	50

Source: Field Study

9.3.2 Comparison with CIBSE Guide

From the click of start button, the user needs to select the climate understudy, i.e. hot humid or hot-dry. Then the user enters both the base and modified cooling loads.

The comparator then compares the input cooling load with the recommended good practice cooling load by CIBSE Guide; if it does not meet the standard, then the following recommendations for further modification would be offered based on the initial climate selected:

Representative recommended appropriate modifications for enhancing cooling load in hot-humid climate:

1. Ventilation Gain
2. Infiltration Gain
3. Indoor Environmental Temperature setting
4. Low thermal conductance Wall systems
5. Mid pane blind window
6. Wall thermal mass
7. Desiccant Cooling Technology

Typical recommended appropriate modifications for enhancing cooling load in hot-dry climate:

1. Infiltration Gain
2. Indoor Environmental Temperature setting
3. Low thermal conductance Wall systems
4. Chilled beams and chilled ceilings low energy cooling
5. Mid pane blind window

9.3.3 Output Display of comparator cooling load decision-making tool

From Figure 9.2, the following selected important outputs were exported for plotting in Microsoft Excel for further analysis:

- Difference in the cost of modification
- Payback for modification
- Savings in electricity cost per annum after modification
- Simple net return in cost for life cycle.
- Final decision, ‘largest net benefits’

9.4 Analysis and Discussions of Parametric Scenarios

To assess the sensitivity of electricity tariff on all the scenarios, low and high tariffs from the PURC report were considered. The low tariff is 0.65 ‘pesewa’ for commercial consumption in the range of 301-600(Ghp/kWh) whiles high tariff is 1.02 ‘Ghana pesewa’ above 601 (Ghp/kWh). Section 9.4.1 and 9.4.2 are the analysis as well as the discussion of high and low electricity tariffs respectively.

9.4.1 Discussion and Analysis of Parametric Scenarios using Low electricity tariff

The discussion and analysis for parametric scenario assessment using higher electricity tariff consist of building design before and after the enactment of the Ghana building regulations and a hypothetical scenario.

Legend

Case 1: Combination of all low internal condition values with base case building fabric

Case 2: Combination of all low thermal conductivity building fabric with base internal condition

Case 3: Combination of all low values (building fabric and internal conditions)

LTC= low thermal conductivity building fabric (opaque and transparent)

AIC= All internal condition variables (infiltration gain, ventilation gain, equipment gain, lighting gain and thermostat setting for temperature and relative humidity)

SNROLC =Simple net return over life cycle
(SPA)=Savings per annum
(DC) = Difference in cost

- **Building design before enactment of Ghana regulations scenario**

  - Difference in cost of modification vs cooling load

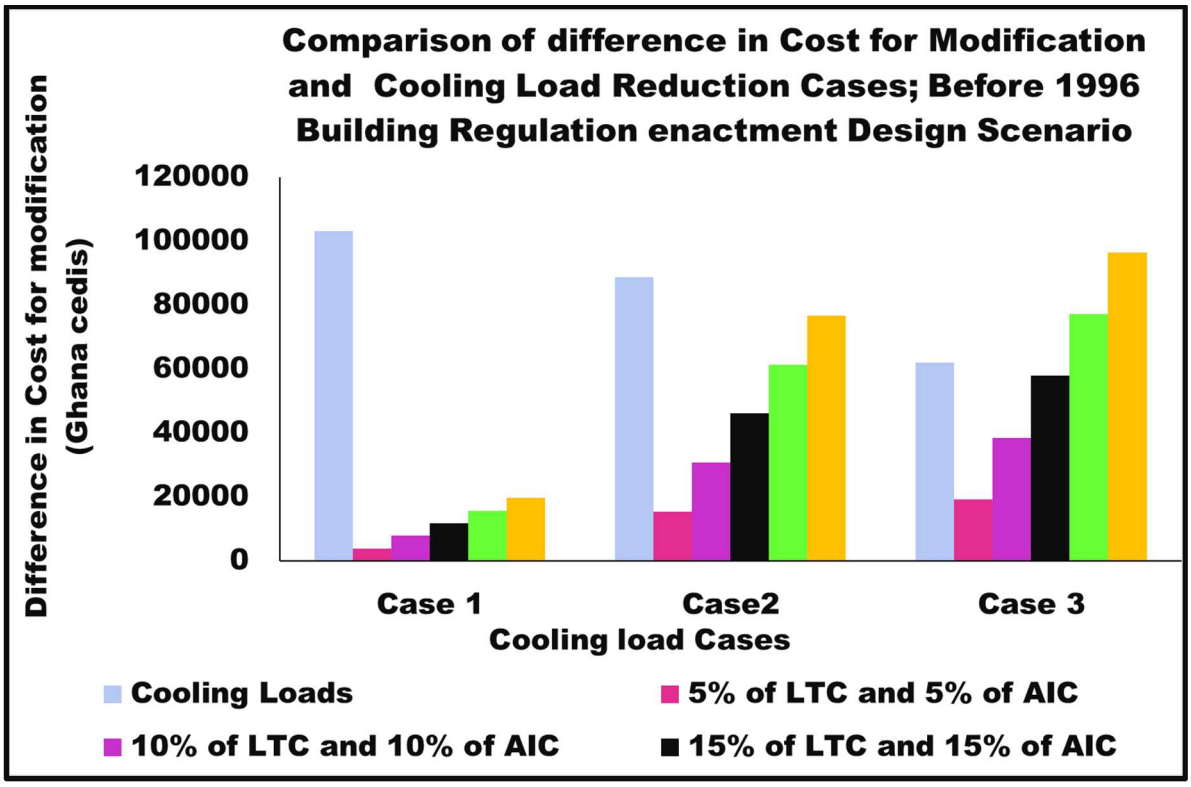

Figure 9.3: Comparison of Difference in Cost for Modification and Cooling Load Reduction Cases

Increasing trend of inverse correlation between difference in modification cost (arising from both increasing all internal condition and low thermal conductivity fabric) with reduction of cooling load was observed. That is, for reduction in cooling load, there is an increasing cost in modification respectively. For example, reduction of cooling load of 40% from Case 1 to Case 3, resulted in a corresponding increase in modification cost of 79%.

In Case1, low benefit in terms of cooling load reduction was achieved for increasing the modification cost arising from both increasing internal condition and low thermal conductivity fabric cost compared to Case 2 and Case 3 for the same percentages.

This implies that, for optimum economic benefit, the appropriate combination of solutions (integration of all internal condition and low thermal conductivity fabric) for the climate understudy is important.

- **Difference in cost vs savings per annum**

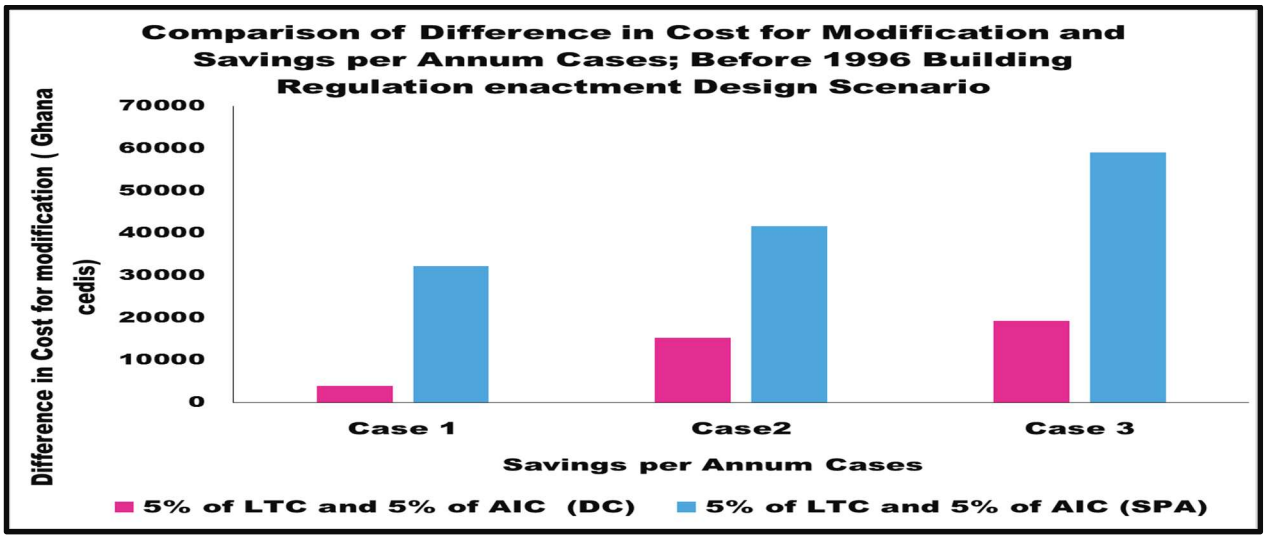

Figure 9.4: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario.

For 5% investment in both low thermal conductivity fabrics and all internal condition variables from case 1 to case 3, there is benefit in savings per annum. More savings per annum was achieved in case 1 than the other cases for the same 5% investment made in both low thermal conductivity fabrics and all internal condition variables. The percentage savings for case 1, case 2 and case 3 are 87%, 63% and 67% respectively. On the other hand, the cooling load reduction was the lowest compared to case 2 and case 3.

Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. On the contrary, from 15% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.5.

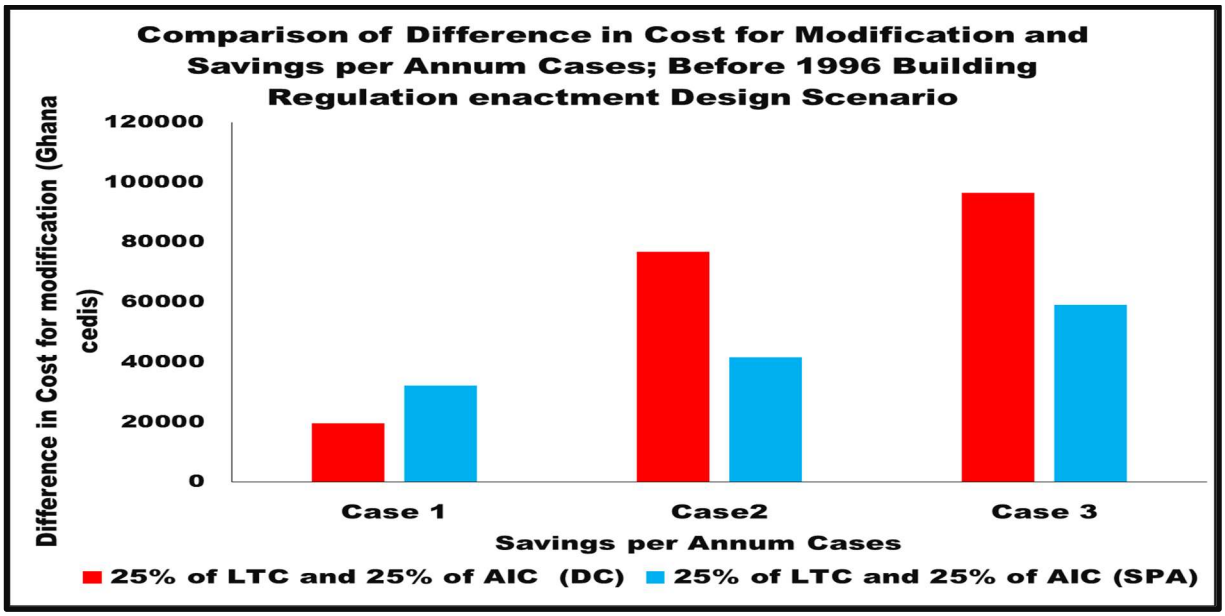

Figure 9.5: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario.

At 25% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases with increasing modification cost. In case 1, the savings per annum was higher than the difference in modification cost compared to case 2 and case 3 where it was the reverse.

In conclusion, as the percentage of modification cost (both low thermal conductivity fabrics and all internal condition variables) increases from 5% to 25% of both, low thermal conductivity fabrics and all internal condition variables the savings per annum would decrease. In this research, due to the assumption of constant electricity tariff, the savings per annum remained constant.

- **Difference in cost vs simple net return over life cycle**

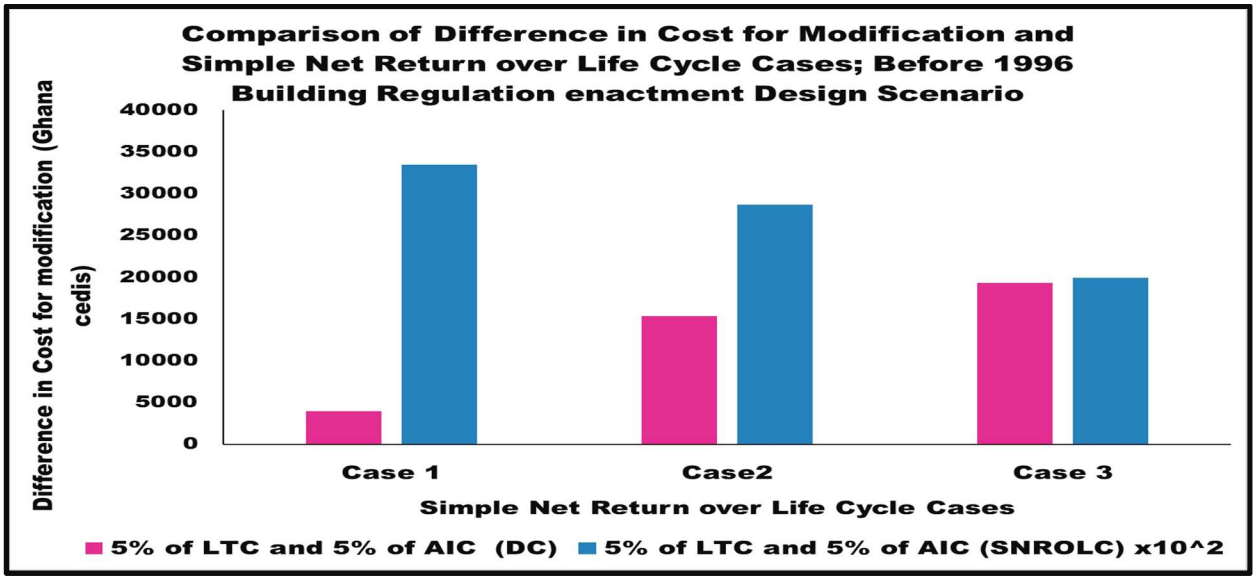

Figure 9.6: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario.

At 5% investment in both low thermal conductivity fabrics and all internal condition variables, the simple net return over life cycle for all the three cases decreases with increasing modification cost. Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.7.

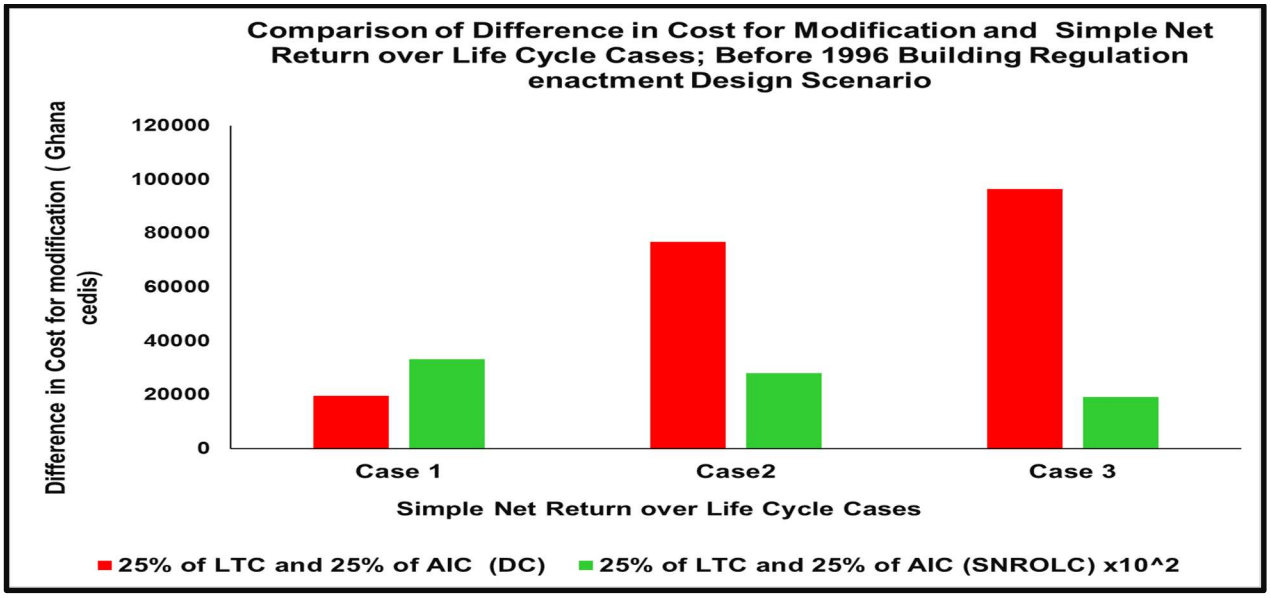

Figure 9.7: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario.

Case 3 at 25% of increment of both low thermal conductivity fabrics and all internal condition variables, had the highest difference in modification cost and lowest simple net return over life cycle. Although, in case 3, more money was used in the investment of both low thermal conductivity fabrics and all internal condition variables to produce the optimum combination computer simulation with the best cooling load reduction, yet benefit can be achieved over the life cycle.

Finally, the case 3 has the highest difference in cost of modification for all the parametric percentages considered. On the other hand, it has the highest cooling load reduction and good return per annum as well as simple rate of return over life cycle.

In conclusion, building envelope design before the enactment of Ghana building regulations is economical for all the combinations in case 1, case 2 and case 3.

➢ **Building design after enactment of Ghana Building regulations scenario**

- Difference in cost of modification vs cooling load

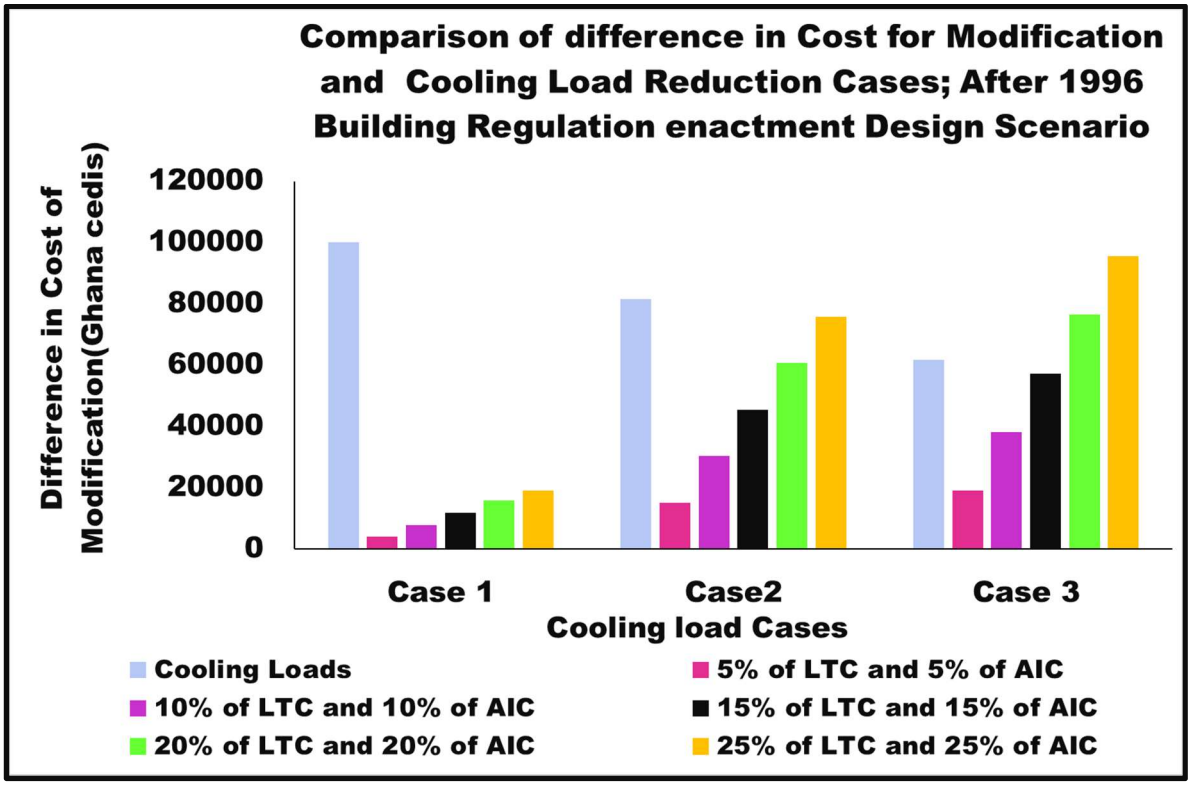

Figure 9.8: Comparison of Difference in Cost for Modification and Cooling Load Reduction Cases; After 1996 Building Regulation enactment Design Scenario.

Increasing trend of inverse correlation between difference in modification cost (arising from both increasing all internal condition and low thermal conductivity fabric) with reduction of cooling load was observed. That is, for reduction in cooling load, there is an increasing cost in modification respectively. For example, reduction of cooling load of 40% from Case 1 to Case 3, resulted in a corresponding increase in modification cost of 79%.

In Case1, low benefit in terms of cooling load reduction was achieved for increasing the modification cost arising from both increasing internal condition and low thermal conductivity fabric cost compared to Case 2 and Case 3 for the same percentages.

This implies that, for optimum economic benefit, the appropriate combination of solutions (integration of all internal condition and low thermal conductivity fabric) for the climate understudy is important

- Difference in cost vs savings per annum

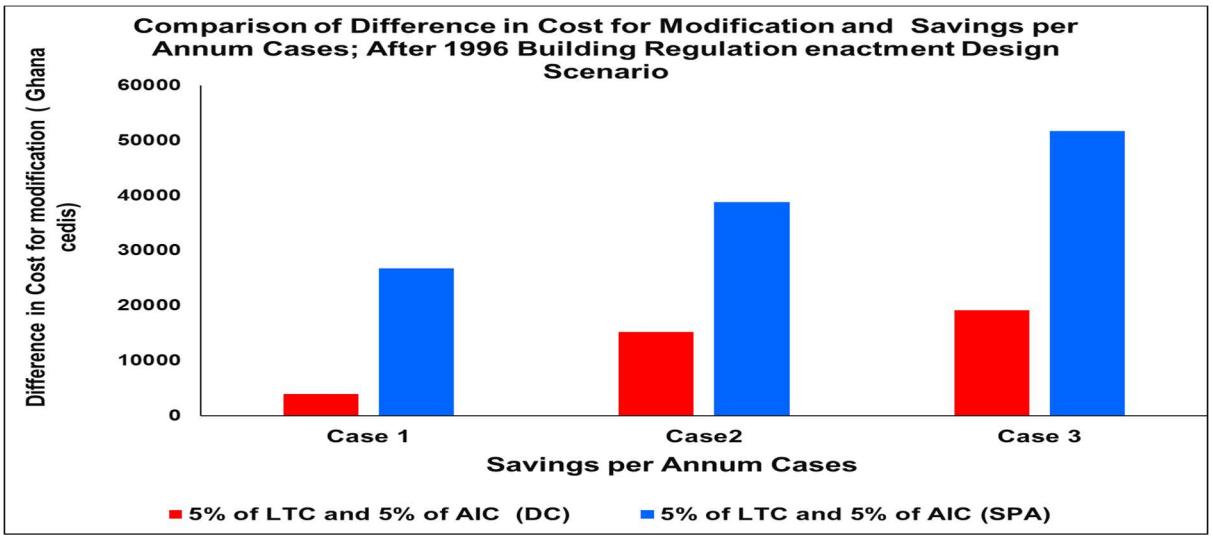

Figure 9.9: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation enactment Design Scenario.

For 5% investment in both low thermal conductivity fabrics and all internal condition variables from case 1 to case 3, there is benefit in savings per annum. More savings per annum was achieved in case 1 than the other cases for the same 5% investment made in both low thermal conductivity fabrics and all internal condition variables. The percentage savings for case 1, case 2 and case 3 are 87%, 63% and 67% respectively. On the other hand, the cooling load reduction was the lowest compared to case 2 and case3.

Similar trend was observed for and investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. On the contrary, from 15% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.10.

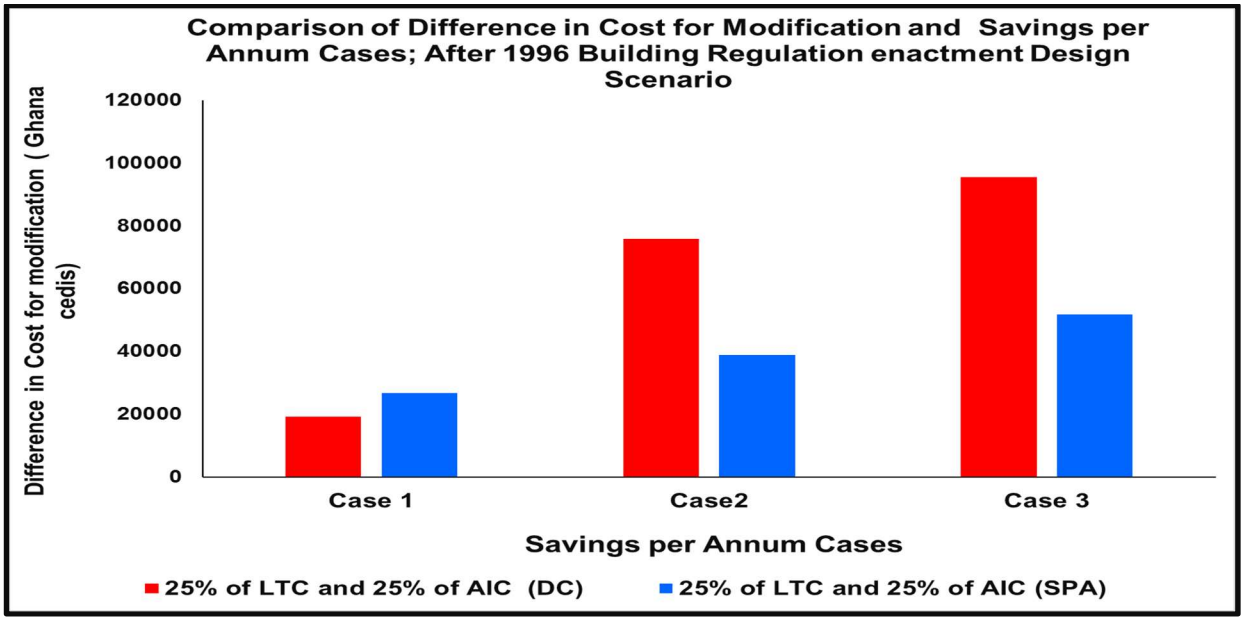

Figure 9.10: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation enactment Design Scenario.

At 25% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases with increasing modification cost. In case 1, the savings per annum was higher than the difference in modification cost compared to case 2 and case 3 where it was the reverse.

In conclusion, as the percentage of modification cost (both low thermal conductivity fabrics and all internal condition variables) increases from 5% to 25% of both, low thermal conductivity fabrics and all internal condition variables the savings per annum would decrease. In this research, due to the assumption of constant electricity tariff, the savings per annum remained constant.

- **Difference in cost vs simple net return over life cycle**

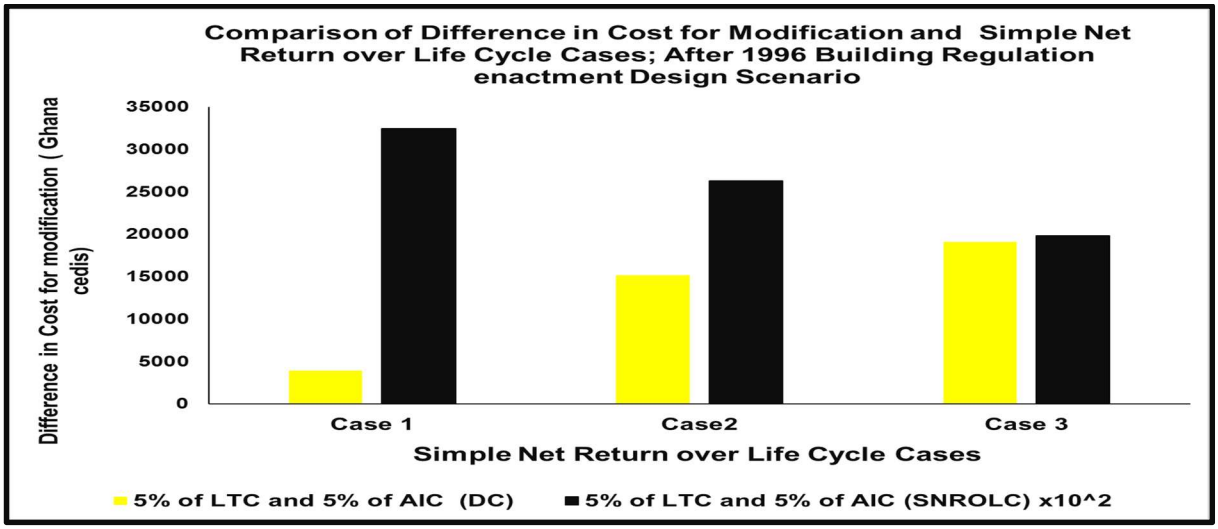

Figure 9.11: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario

At 5% investment in both low thermal conductivity fabrics and all internal condition variables, the simple net return over life cycle for all the three cases decreases with increasing modification cost. Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.12.

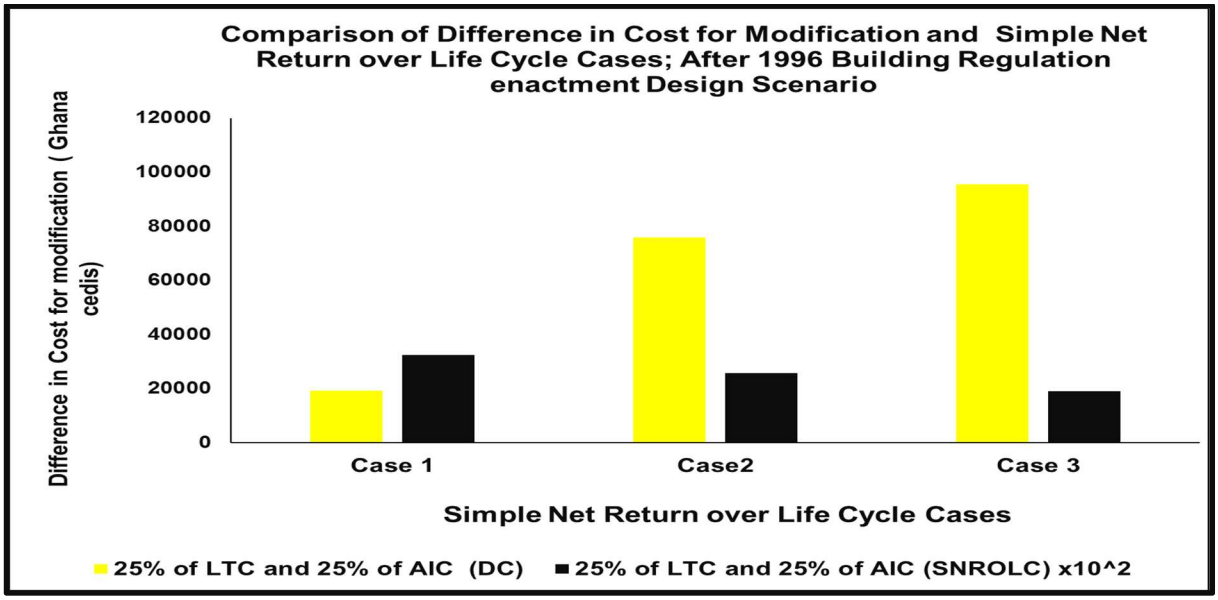

Figure 9.12: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario.

Case 3 at 25% of increment of both low thermal conductivity fabrics and all internal condition variables, had the highest difference in modification cost and lowest simple net return over life cycle. Although, in case 3, more money was used in the investment of both low thermal conductivity fabrics and all internal condition variables to produce the optimum combination computer simulation with the best cooling load reduction, yet benefit can be achieved over the life cycle.

Finally, the case 3, has the highest difference in cost of modification for all the parametric percentages considered. On the other hand, it has the highest cooling load reduction and good return per annum as well as simple rate of return over life cycle.

In conclusion, building envelope design before the enactment of Ghana building regulations is economical for all the combinations in case 1, case 2 and case 3.

➢ **Hypothetical Scenario**

- Difference in cost of modification vs cooling load

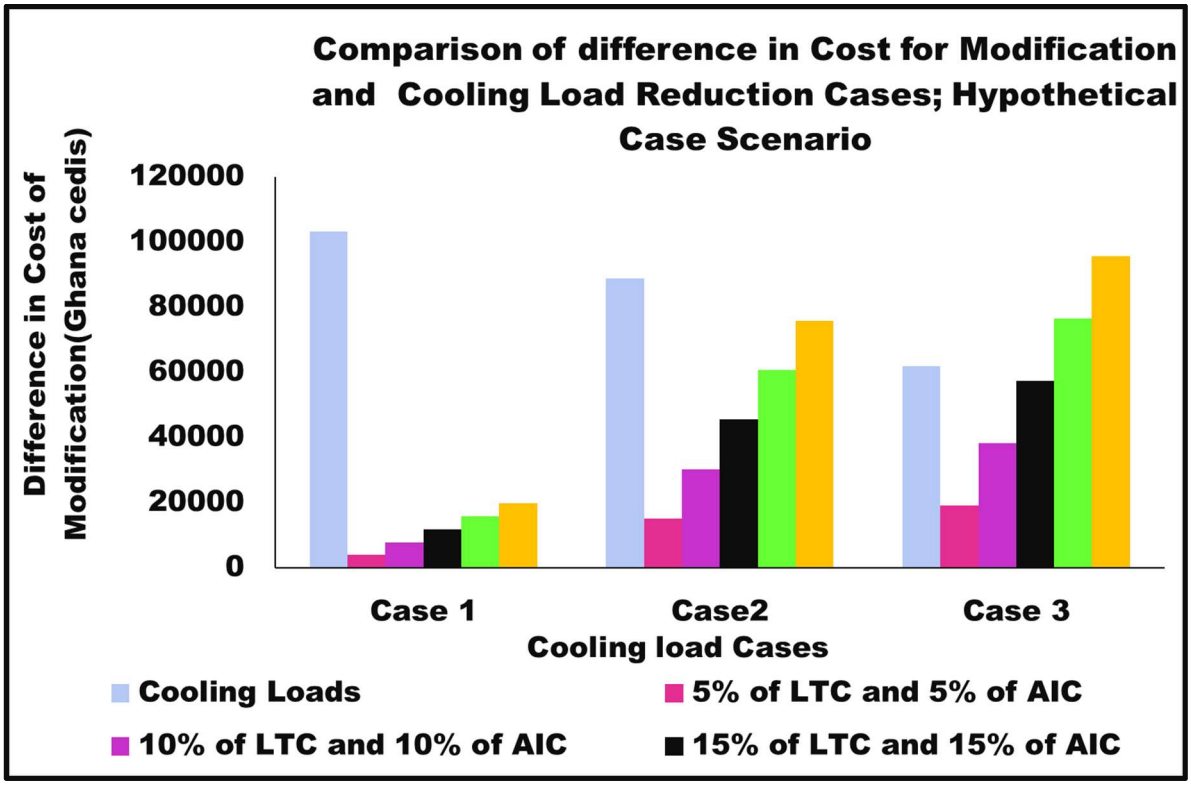

Figure 9.13: Comparison of Difference in Cost for Modification and Cooling Load Reduction Cases; Hypothetical Case Scenario.

Increasing trend of inverse correlation between difference in modification cost (arising from both increasing all internal condition and low thermal conductivity fabric) with reduction of cooling load was observed. That is, for reduction in cooling load, there is an increasing cost in modification respectively. For example, reduction of cooling load of 40% from Case 1 to Case 3, resulted in a corresponding increase in modification cost of 79%.

In Case 1, low benefit in terms of cooling load reduction was achieved for increasing the modification cost arising from both increasing internal condition and low thermal conductivity fabric cost compared to Case 2 and Case 3 for the same percentages. This implies that, for optimum economic benefit, the appropriate combination of solutions (integration of all internal condition and low thermal conductivity fabric) for the climate understudy is important

- Difference vs savings per annum

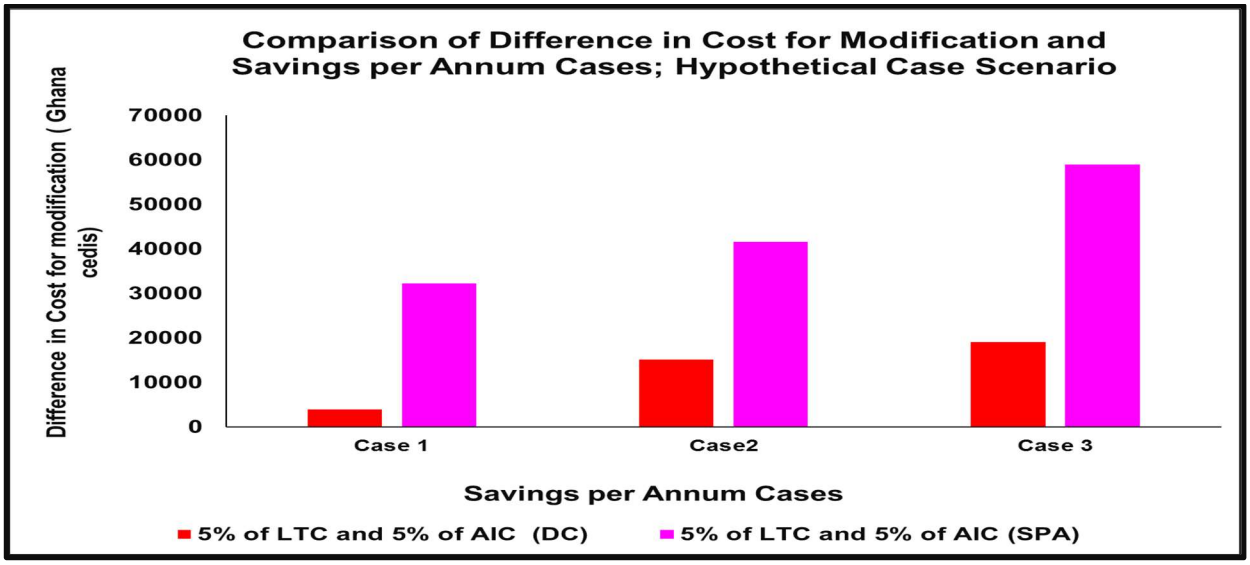

Figure 9.14: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario

For 5% investment in both low thermal conductivity fabrics and all internal condition variables from case 1 to case 3, there is benefit in savings per annum. More savings per annum was achieved in case 1 than the other cases for the same 5% investment made in both low thermal conductivity fabrics and all internal condition variables. The percentage savings for case 1, case 2 and case 3 are 87%, 63% and 67% respectively. On the other hand, the cooling load reduction was the lowest compared to case 2 and case3.

Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. On the contrary, from 15% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.15.

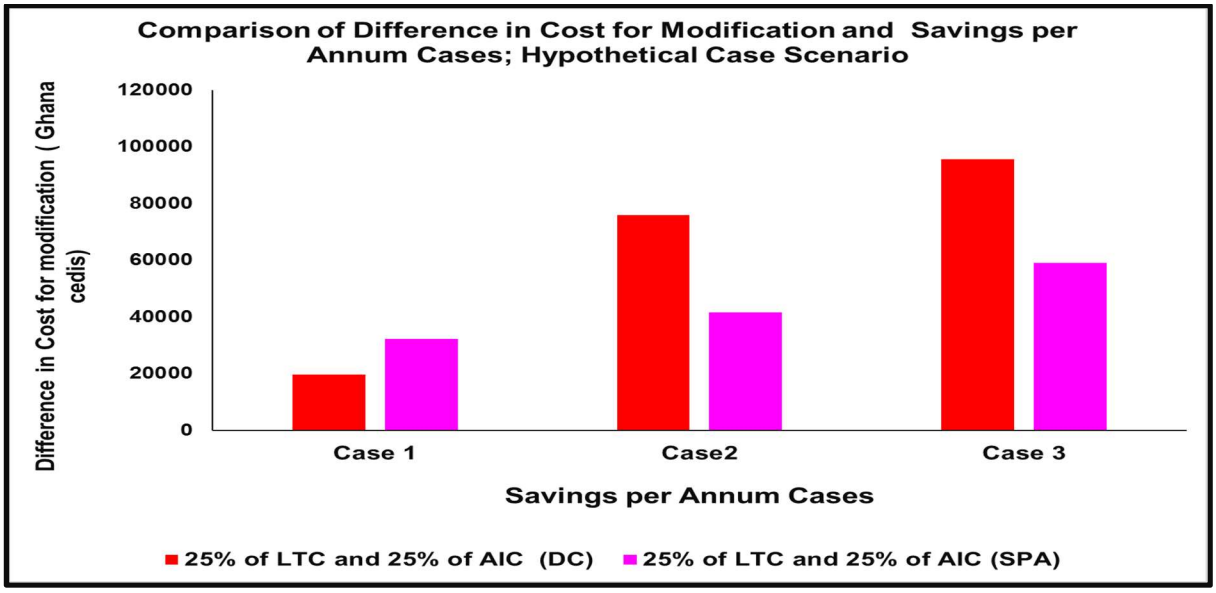

Figure 9.15: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario.

At 25% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases with increasing modification cost. In case 1, the savings per annum was higher than the difference in modification cost compared to case 2 and case 3 where it was the reverse.

In conclusion, as the percentage of modification cost (both low thermal conductivity fabrics and all internal condition variables) increases from 5% to 25% of both low thermal conductivity fabrics and all internal condition variables, the savings per annum would decrease. In this research, due to the assumption of constant electricity tariff, the savings per annum remained constant.

- **Difference in cost vs simple net return over life cycle**

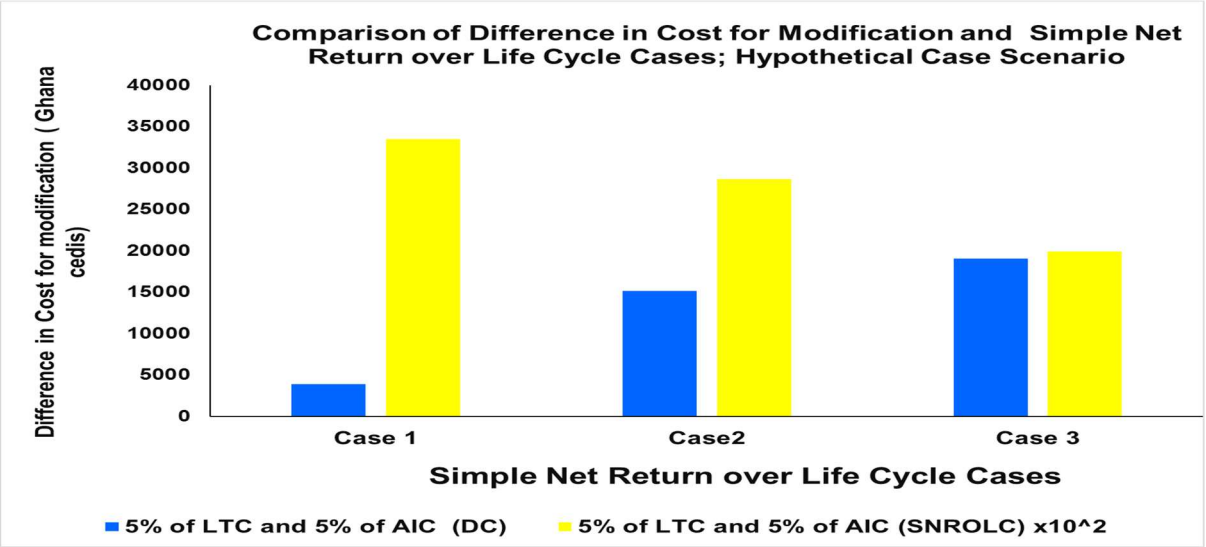

Figure 9.16: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cases; Hypothetical Case Scenario.

At 5% investment in both low thermal conductivity fabrics and all internal condition variables, the simple net return over life cycle for all the three cases decreases with increasing modification cost. Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.17.

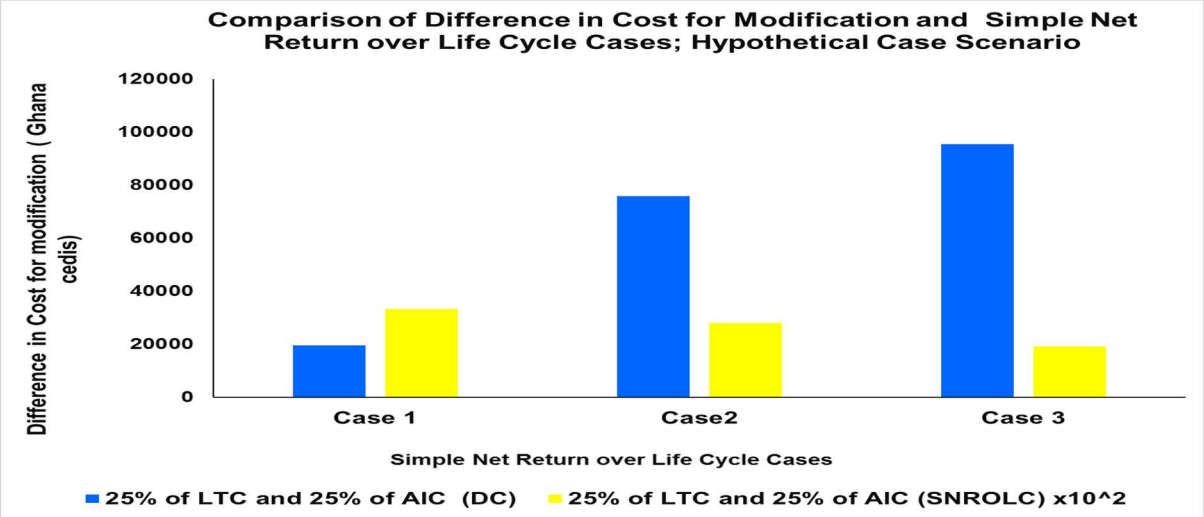

Figure 9.17: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cases; Hypothetical Case Scenario.

Case 3 at 25% of increment of both low thermal conductivity fabrics and all internal condition variables, had the highest difference in modification cost and lowest simple net return over life cycle. Although, in case 3, more money was used in the investment of both low thermal conductivity fabrics and all internal condition variables to produce the optimum combination computer simulation with the best cooling load reduction, yet benefit can be achieved over the life cycle.

Finally, the case 3, has the highest difference in cost of modification for all the parametric percentages considered. On the other hand, it has the highest cooling load reduction and good return per annum as well as simple rate of return over life cycle.

In conclusion, building envelope design before the enactment of Ghana building regulations is economical for all the combinations in case 1, case 2 and case 3.

9.4.2 Discussion and Analysis of Parametric Scenarios using High electricity tariff

The discussion and analysis for parametric scenarios using lower electricity tariff consist of building design before and after the enactment of the Ghana building regulations and a hypothetical scenario.

a. Building design before enactment of Ghana building regulations scenario

i. Difference in cost of modification vs cooling load

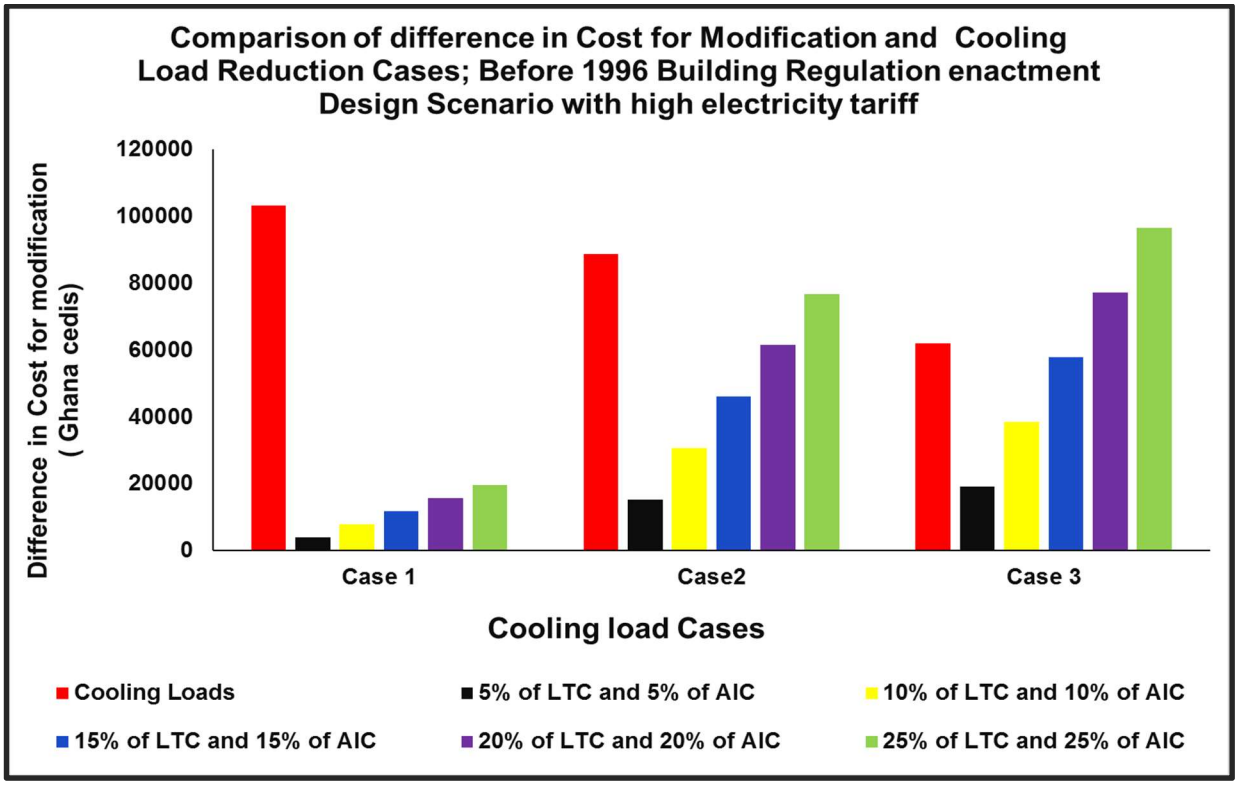

Figure 9.18: Comparison of Difference in Cost for Modification and Cooling Reduction Cases; Before 1996 Building Regulation enactment Design Scenario with high electricity tariff.

Increasing trend of inverse correlation between difference in modification cost (arising from both increasing all internal condition and low thermal conductivity fabric) with reduction of cooling load was observed. That is, for reduction in cooling load, there is an increasing cost in modification respectively. For example, reduction of cooling load of 40% from Case 1 to Case 3, resulted in a corresponding increase in modification cost of 79%.

In Case1, low benefit in terms of cooling load reduction was achieved for increasing the modification cost arising from both increasing internal condition and low thermal conductivity fabric cost compared to Case 2 and Case 3 for the same percentages. This implies that, for optimum economic benefit, the appropriate combination of solutions (integration of all internal condition and low thermal conductivity fabric) for the climate under study is important

Difference vs savings per annum

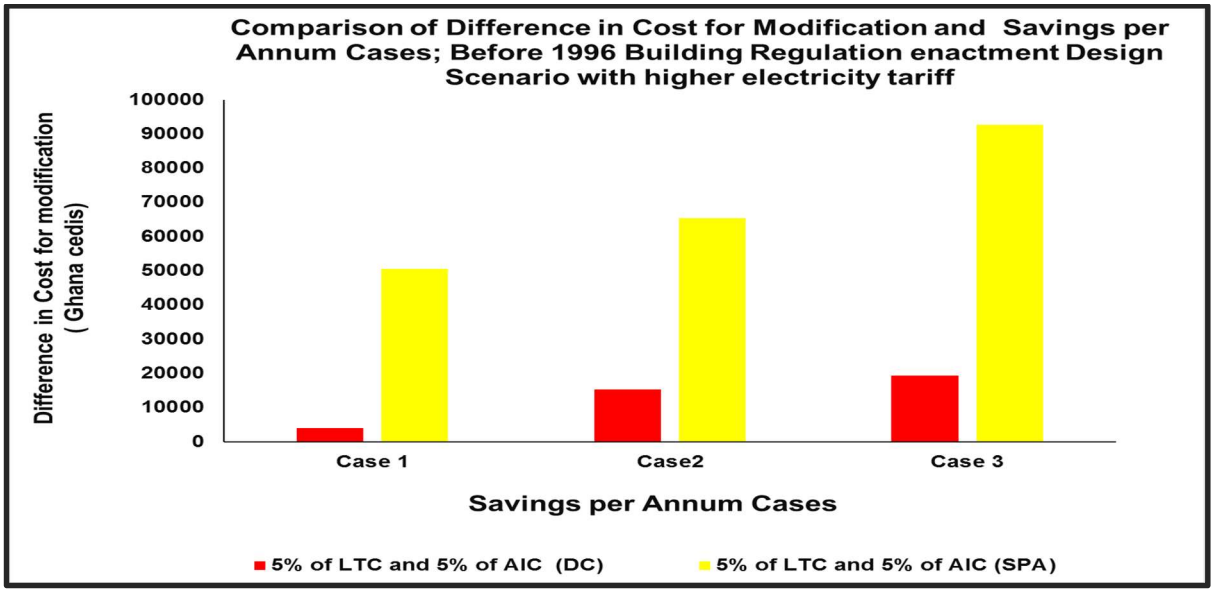

Figure 9.19: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

For 5% investment in both low thermal conductivity fabrics and all internal condition variables from case 1 to case 3, there is benefit in savings per annum.

More savings per annum was achieved in case 1 than the other cases for the same 5% investment made in both low thermal conductivity fabrics and all internal condition variables. The percentage savings for case 1, case 2 and case 3 are 87%, 63% and 67% respectively. On the other hand, the cooling load reduction was the lowest compared to case 2 and case 3.

Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. On the contrary, from 15% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.20.

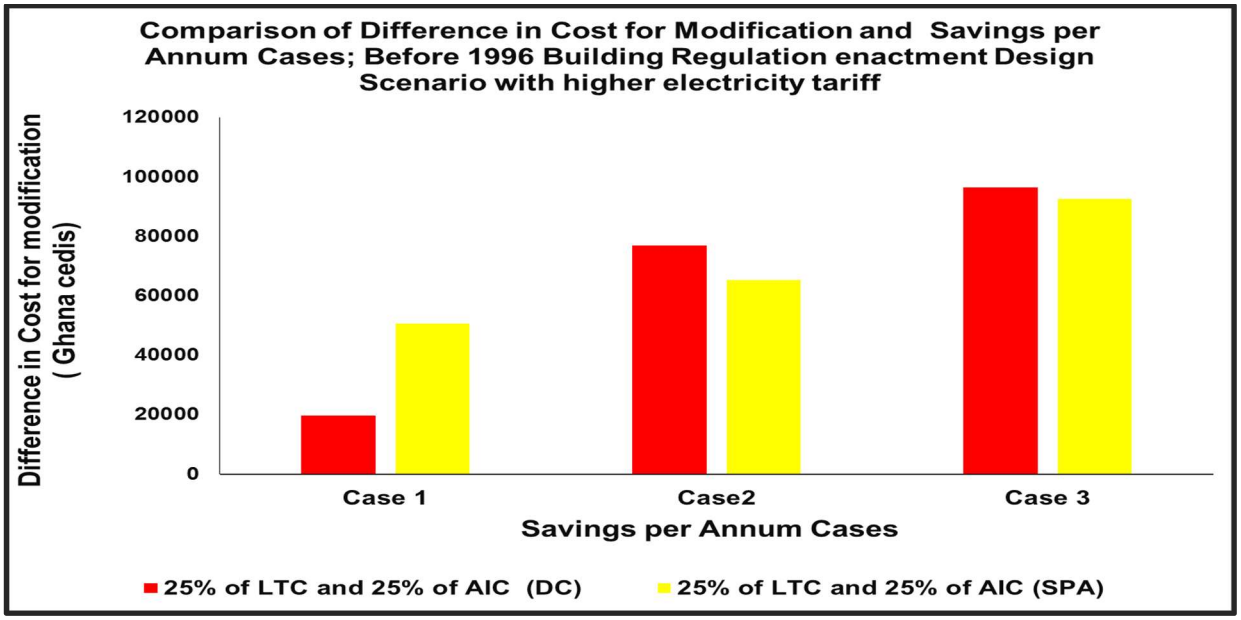

Figure 9.20: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

At 25% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases with increasing modification cost. In case 1, the savings per annum was higher than the difference in modification cost compared to case 2 and case 3 where it was the reverse.

In conclusion, as the percentage of modification cost (both low thermal conductivity fabrics and all internal condition variables) increases from 5% to 25% of both low thermal conductivity fabrics and all internal condition variables, the savings per annum would decrease. In this research, due to the assumption of constant electricity tariff, the savings per annum remained constant.

- **Difference in cost vs simple net return over life cycle**

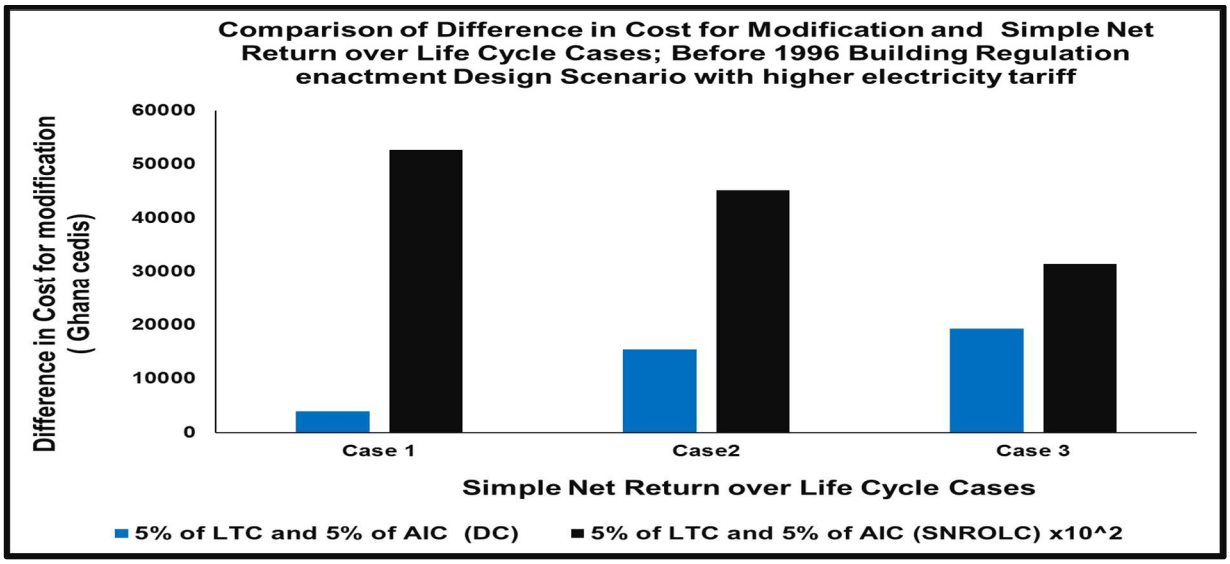

Figure 9.21: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

At 5% investment in both low thermal conductivity fabrics and all internal condition variables, the simple net return over life cycle for all the three cases decreases with increasing modification cost. Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.22.

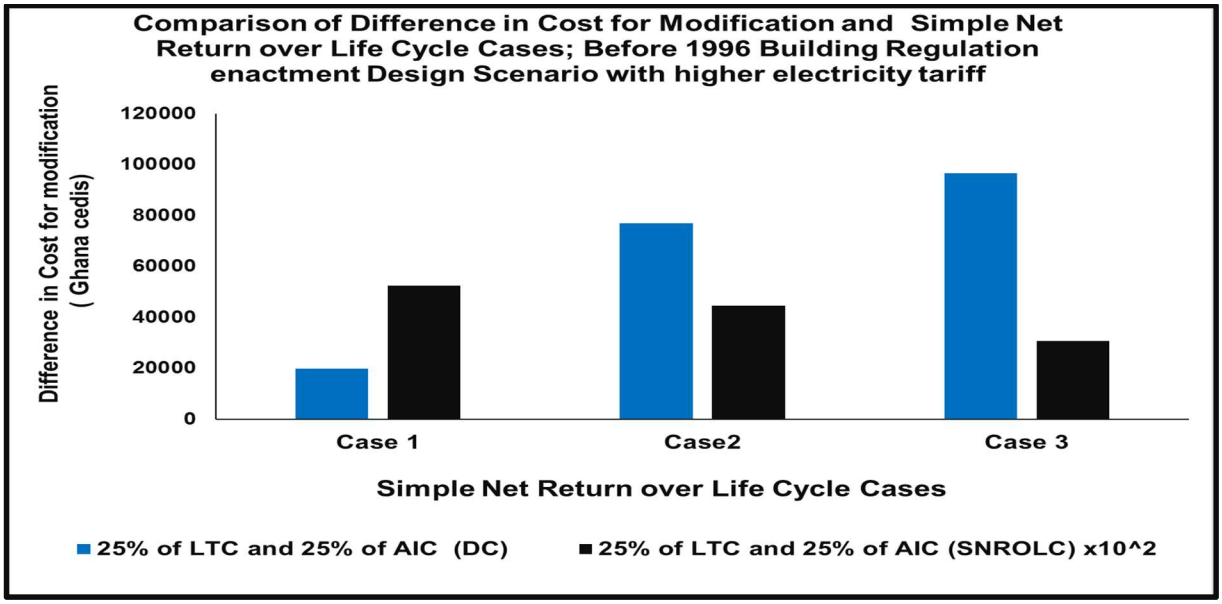

Figure 9.22: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

Case 3 at 25% of increment of both low thermal conductivity fabrics and all internal condition variables, had the highest difference in modification cost and lowest simple net return over life cycle. Although, in case 3, more money was used in the investment of both low thermal conductivity fabrics and all internal condition variables to produce the optimum combination computer simulation with the best cooling load reduction, yet benefit can be achieved over the life cycle.

Finally, the case 3 has the highest difference in cost of modification for all the parametric percentages considered. On the other hand, it has the highest cooling load reduction and good return per annum as well as simple rate of return over life cycle.

In conclusion, building envelope design before the enactment of Ghana building regulations is economical for all the combinations in case 1, case 2 and case 3.

b. Building design after the enactment of Ghana building regulations scenario

Difference in cost of modification vs cooling load

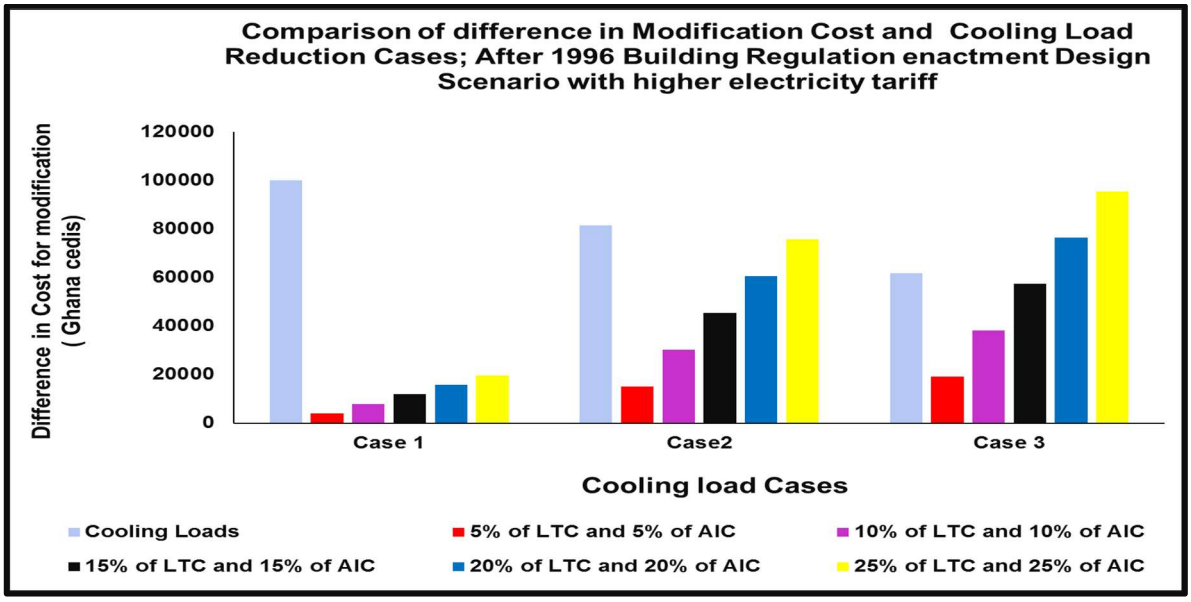

Figure 9.23: Comparison of Difference in Cost for Modification and Cooling Load Reduction Cases; After 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

Increasing trend of inverse correlation between difference in modification cost (arising from both increasing all internal condition and low thermal conductivity fabric) with reduction of cooling load was observed. That is, for reduction in cooling load, there is an increasing cost in modification respectively. For example, reduction of cooling load of 40% from Case 1 to Case 3, resulted in a corresponding increase in modification cost of 79%.

In Case1, low benefit in terms of cooling load reduction was achieved for increasing the modification cost arising from both increasing internal condition and low thermal conductivity fabric cost compared to Case 2 and Case 3 for the same percentages. This implies that, for optimum economic benefit, the appropriate combination of solutions (integration of all internal condition and low thermal conductivity fabric) for the climate understudy is important.

Difference vs savings per annum

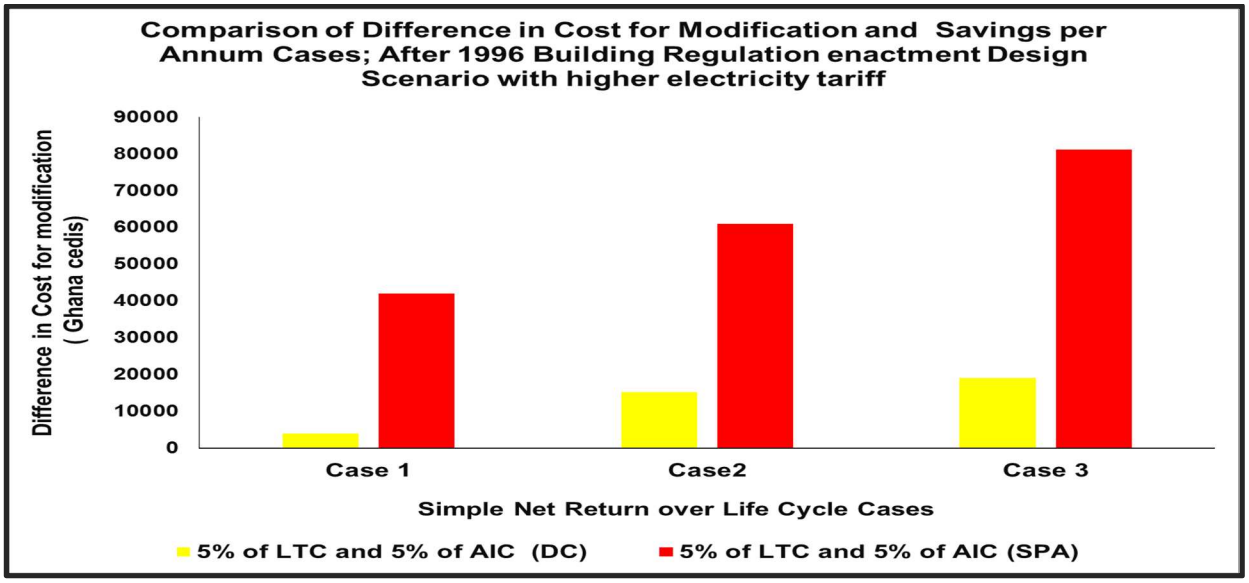

Figure 9.24: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation Enactment Design Scenario with higher electricity tariff

For 5% investment in both low thermal conductivity fabrics and all internal condition variables from case 1 to case 3, there is benefit in savings per annum. More savings per annum was achieved in case 1 than the other cases for the same 5% investment made in both low thermal conductivity fabrics and all internal condition variables. The percentage savings for case 1, case 2 and case 3 are 87%, 63% and 67% respectively. On the other hand, the cooling load reduction was the lowest compared to case 2 and case 3.

Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. On the contrary, from 15% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.25.

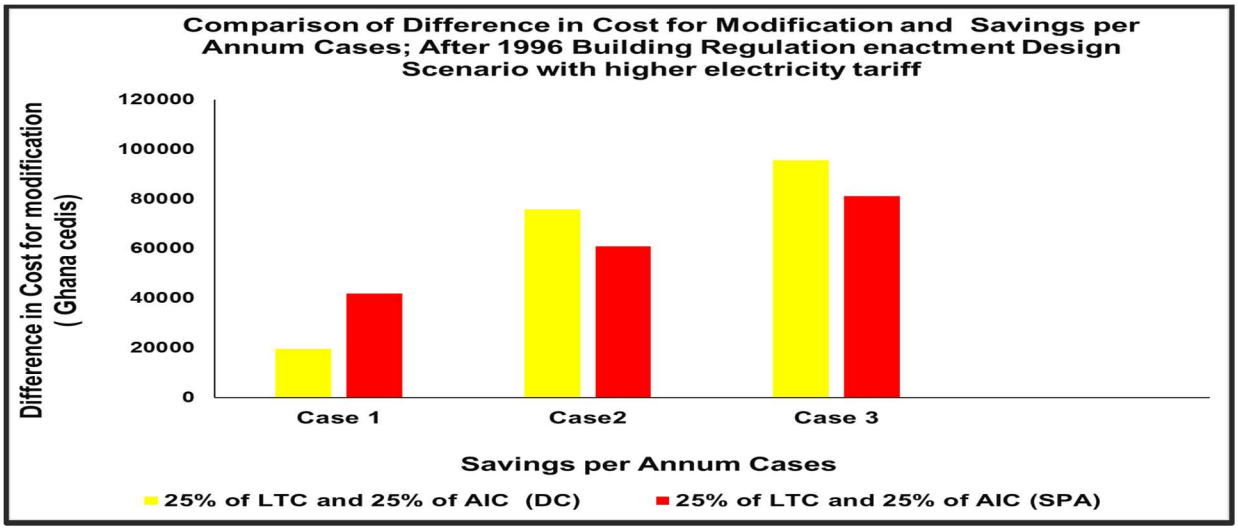

Figure 9.25: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation Enactment Design Scenario with higher electricity tariff.

At 25% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases with increasing modification cost. In case 1, the savings per annum was higher than the difference in modification cost compared to case 2 and case 3, where it was the reverse.

In conclusion, as the percentage of modification cost (both low thermal conductivity fabrics and all internal condition variables) increases from 5% to 25% of both low thermal conductivity fabrics and all internal condition variables, the savings per annum would decrease. In this research, due to the assumption of constant electricity tariff, the savings per annum remained constant.

Difference vs savings over life time

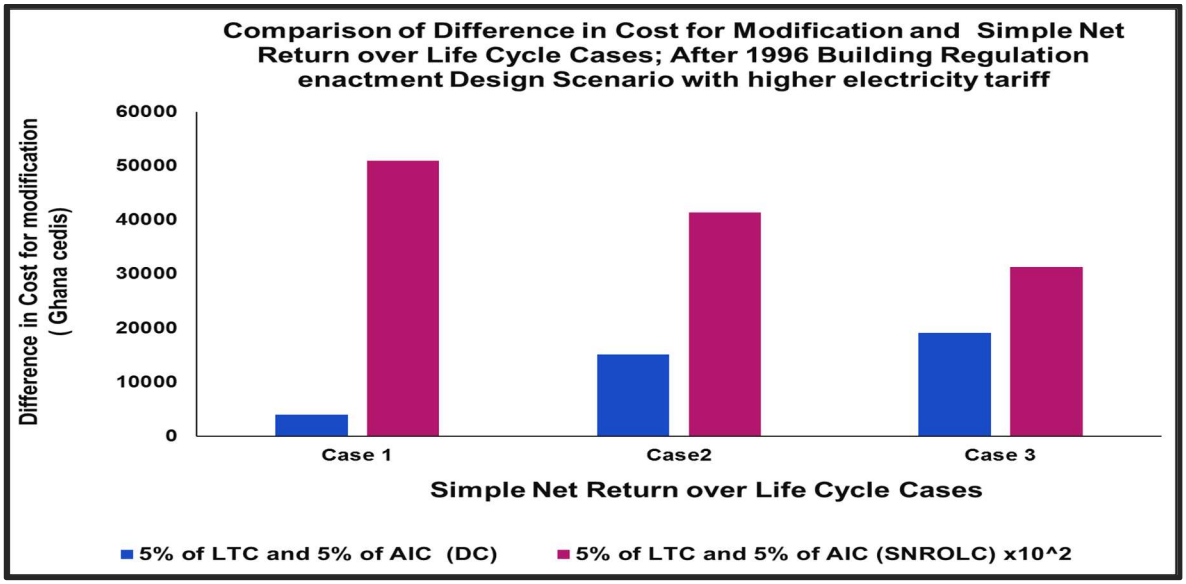

Figure 9.26: Comparison of Difference in Cost for Modification and Simple Net Returns over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario with higher electricity tariff

At 5% investment in both low thermal conductivity fabrics and all internal condition variables, the simple net return over life cycle for all the three cases decreases with increasing modification cost. Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.27.

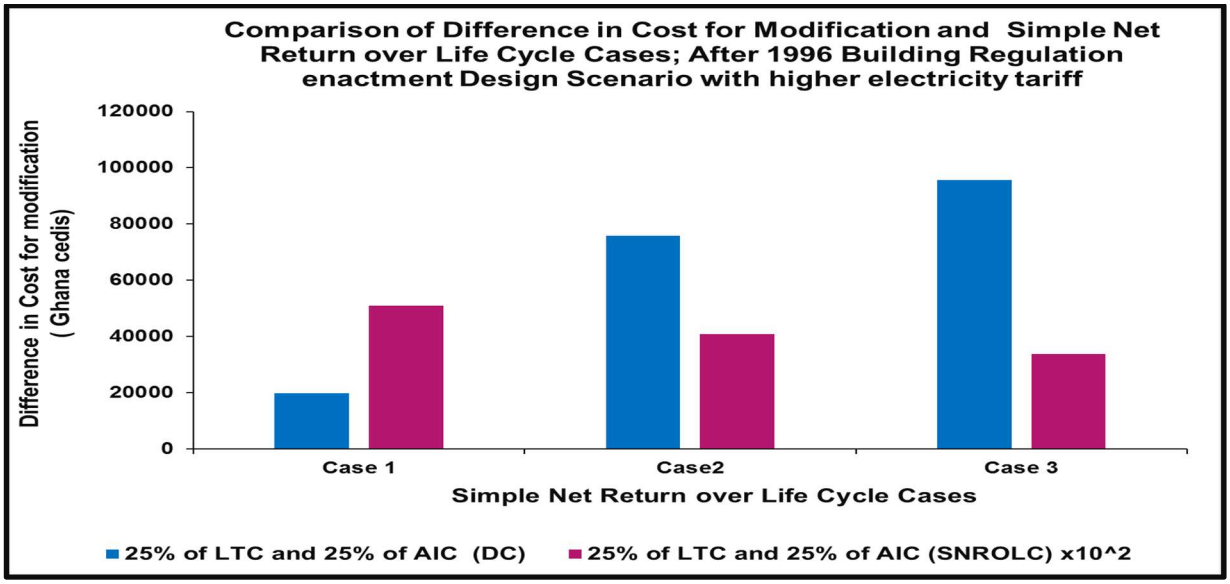

Figure 9.27: Comparison of Difference in Cost for Modification and Simple Net Returns over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

Case 3 at 25% of increment of both low thermal conductivity fabrics and all internal condition variables, had the highest difference in modification cost and lowest simple net return over life cycle. Although, in case 3, more money was used in the investment of both low thermal conductivity fabrics and all internal condition variables to produce the optimum combination computer simulation with the best cooling load reduction, yet benefit can be achieved over the life cycle.

Finally, the case 3 has the highest difference in cost of modification for all the parametric percentages considered. On the other hand, it has the highest cooling load reduction and good return per annum as well as simple rate of return over life cycle.

In conclusion, building envelope design before the enactment of Ghana building regulations is economical for all the combinations in case 1, case 2 and case 3.

c. Hypothetical Scenario

- ❖ Difference in cost of modification vs cooling load

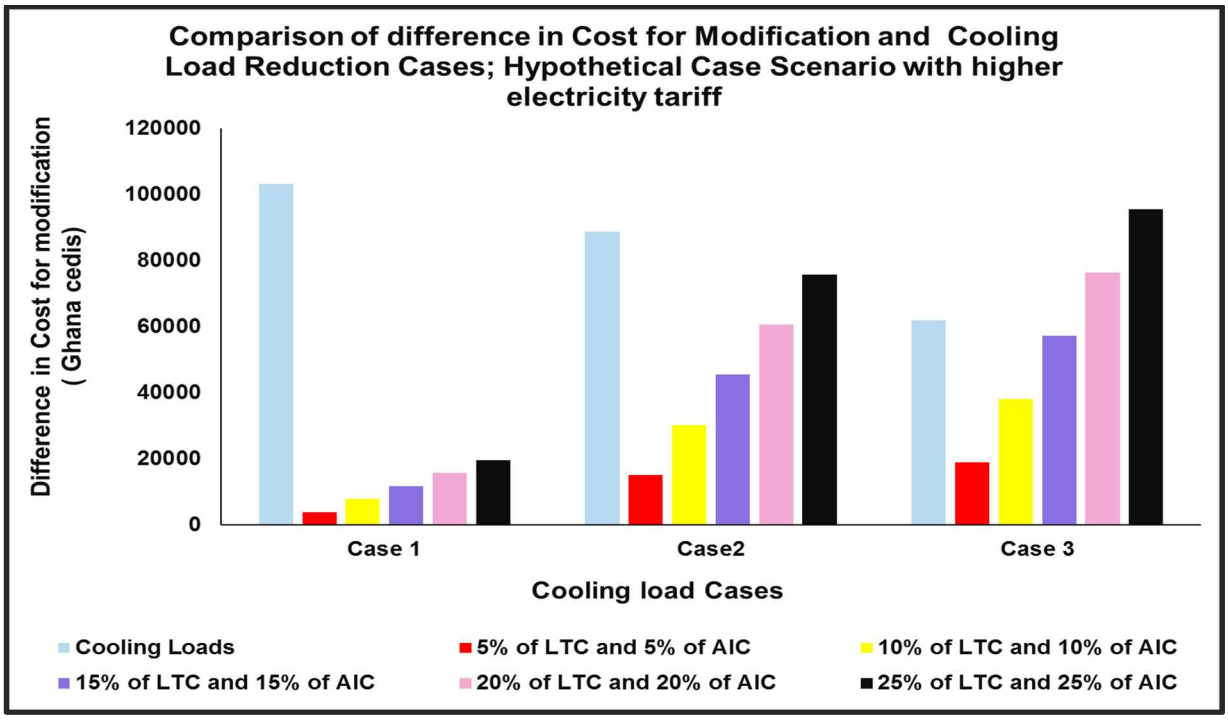

Figure 9.28: Comparison of Difference in Cost for Modification and Cooling Load Reduction Cases; Hypothetical Case Scenario with higher electricity tariff.

Increasing trend of inverse correlation between difference in modification cost (arising from both increasing all internal condition and low thermal conductivity fabric) with reduction of cooling load was observed. That is, for reduction in cooling load, there is an increasing cost in modification respectively. For example, reduction of cooling load of 40% from Case 1 to Case 3, resulted in a corresponding increase in modification cost of 79%.

In Case1, low benefit in terms of cooling load reduction was achieved for increasing the modification cost arising from both increasing internal condition and low thermal conductivity fabric cost compared to Case 2 and Case 3 for the same percentages.

This implies that, for optimum economic benefit, the appropriate combination of solutions (integration of all internal condition and low thermal conductivity fabric) for the climate under study is important.

❖ Difference vs savings per annum

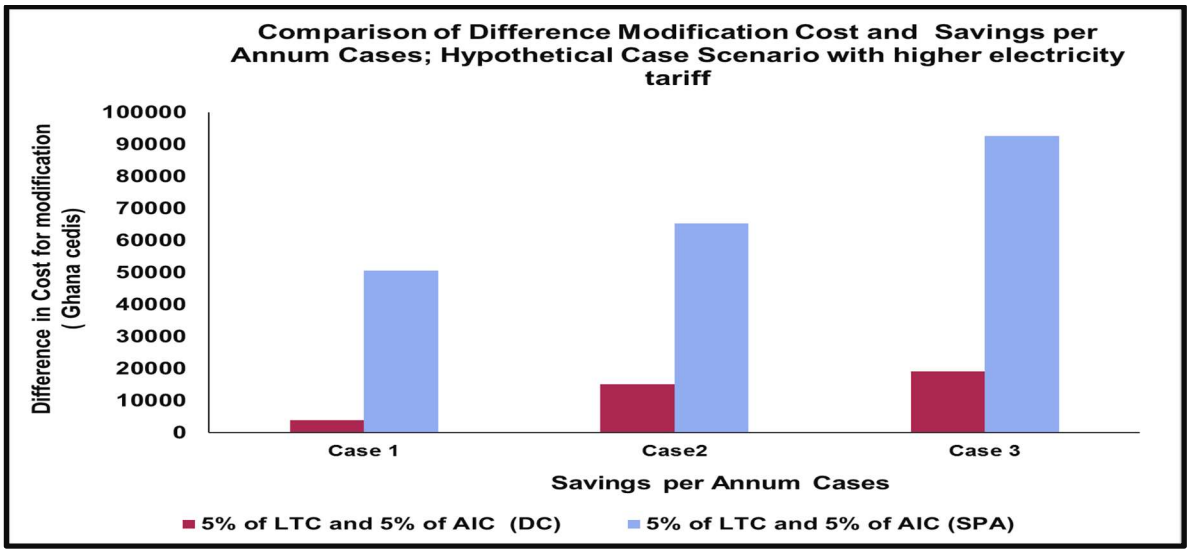

Figure 9.29: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario with higher electricity tariff.

For 5% investment in both low thermal conductivity fabrics and all internal condition variables from case 1 to case 3, there is benefit in savings per annum. More savings per annum was achieved in case 1 than the other cases for the same 5% investment made in both low thermal conductivity fabrics and all internal condition variables. The percentage savings for case 1, case 2 and case 3 are 87%, 63% and 67% respectively. On the other hand, the cooling load reduction was the lowest compared to case 2 and case 3.

Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. On the contrary, from 15% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.30.

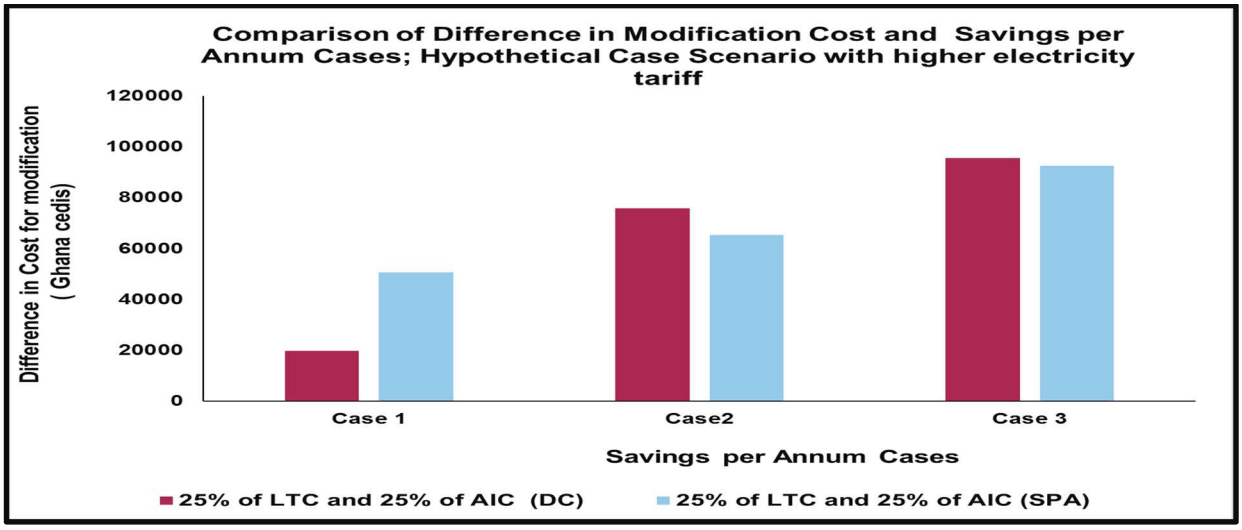

Figure 9.30: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario with higher electricity tariff.

At 25% investment in both low thermal conductivity fabrics and all internal condition variables, the savings per annum for all the three cases decreases with increasing modification cost. In case 1, the savings per annum was higher than the difference in modification cost compared to case 2 and case 3 where it was the reverse.

In conclusion, as the percentage of modification cost (both low thermal conductivity fabrics and all internal condition variables) increases from 5% to 25% of both low thermal conductivity fabrics and all internal condition variables, the savings per annum would decrease. In this research, due to the assumption of constant electricity tariff, the savings per annum remained constant.

❖ **Difference in cost vs simple net return over life cycle**

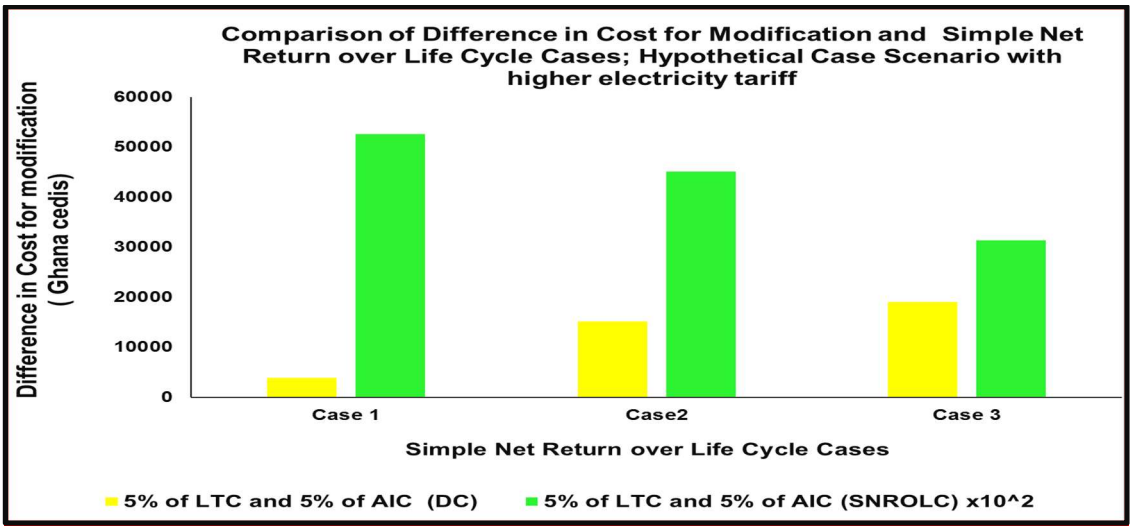

Figure 9.31: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Hypothetical Case Scenario with higher electricity tariff.

At 5% investment in both low thermal conductivity fabrics and all internal condition variables, the simple net return over life cycle for all the three cases decreases with increasing modification cost. Similar trend was observed for an investment of 10%, 15% and 20% of both low thermal conductivity fabrics and all internal condition variables as shown in Appendix C. The 25% investment in both low thermal conductivity fabrics and all internal condition variables is presented in Figure 9.32.

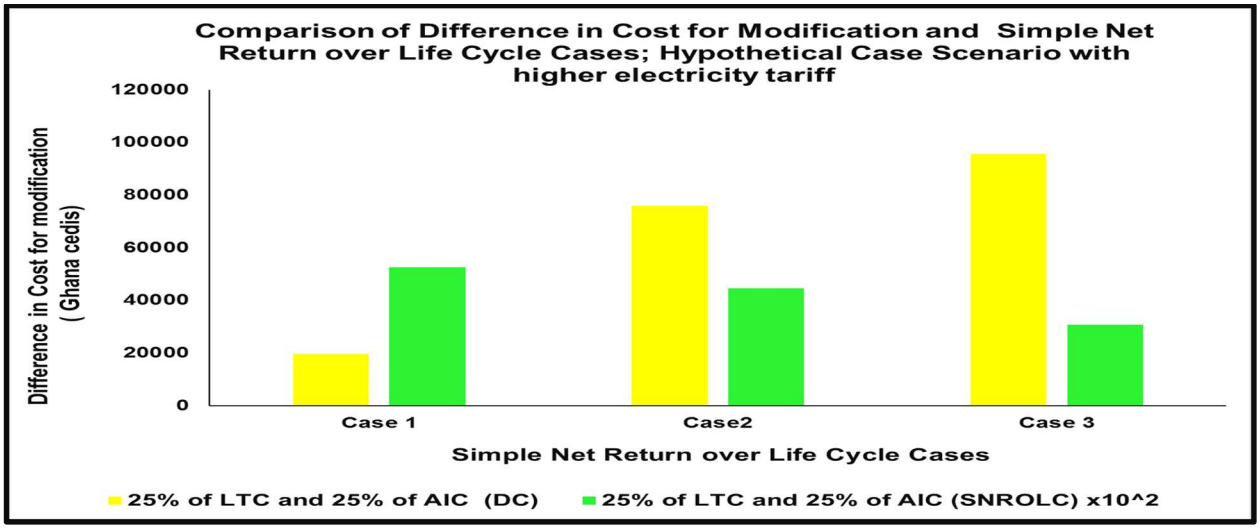

Figure 9.32: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Hypothetical Case Scenario with higher electricity tariff.

Case 3 at 25% of increment of both low thermal conductivity fabrics and all internal condition variables, had the highest difference in modification cost and lowest simple net return over life cycle. Although, in case 3, more money was used in the investment of both low thermal conductivity fabrics and all internal condition variables to produce the optimum combination computer simulation with the best cooling load reduction, yet benefit can be achieved over the life cycle.

Finally, the case 3 has the highest difference in cost of modification for all the parametric percentages considered. On the other hand, it has the highest cooling load reduction and good return per annum as well as simple rate of return over life cycle.

In conclusion, building envelope design before the enactment of Ghana building regulations is economical for all the combinations in case 1, case 2 and case 3.

9.5 Findings and Implications from Economic Benefit Assessment

The summary of findings the comparator economic assessment decision tool are as follows:

- All the scenarios (buildings before the enactment of Ghana regulations, buildings after the enactment of Ghana building regulation and the hypothetical scenario) for low and high electricity tariff considered have simple payback less than a year as in Table 9.2.

Table 9.2: Selected sample of difference in modification cost vs Payback

	Difference in modification cost (Cedis)	Payback (Year)
Case 1	3942.8	0.12
Case2	15367.6	0.37
Case 3	19310.4	0.33

- All the scenarios (buildings before the enactment of Ghana regulations, buildings after the enactment of Ghana building regulation and the hypothetical scenario) for low and high electricity tariff considered have increasing modification cost with decreasing cooling load.
- The economic benefit assessment was sensitive to price variations in building fabric cost and electricity tariff.
- All the scenarios (buildings before the enactment of Ghana regulations, buildings after the enactment of Ghana building regulation and the hypothetical scenario) for low and high electricity tariff considered have increasing modification cost with reducing simple rate of return over the life cycle.
- All the scenarios (buildings before the enactment of Ghana regulations, buildings after the enactment of Ghana building regulation and the hypothetical scenario) for low and high electricity tariff considered have increasing modification cost with reducing savings per annum.

Modification cost have strong correlation on the cooling load reduction, savings per annum and simple net return over life cycle, hence appropriate combination for optimization is paramount to achieving the best economic benefit for any climate.

9.6 Conclusions and Recommendations of Economic Benefit Assessment

In conclusion, the selected optimized design variables combination consisting of both optimum internal condition and low transmittance properties is a viable economic decision to be implemented. As a recommendation, a detailed modification costing including maintenance, transportation, workmanship and miscellaneous should be included in further studies. Finally, an economic benefit model should be developed from the trend of correlations between difference in modification cost, cooling load, simple payback time and simple net return over life cycle.

10 CHAPTER TEN: CONCLUSION AND RECOMMENDATION

10.1 Introduction

Building performance assessment is dominant vital approach in confirming the suitability of building envelope design, integrated technology, impact of design variables specification in codes/regulations on hot-humid climate, building service selection and sizing as well as indoor environmental quality. From this research, impact of low performance assessment by building professionals as well as lack of its implementation by government agencies within permit issuing on energy utilization and indoor environmental comfort in Ghana have been investigated in detail through creative and novel mixed research methodologies. The building professionals consist of building service engineers, architects, building fabric manufacturers and government agencies (building permit regulators, Ghana Standard Boards and Building Regulation Institutions). The creative and novel mixed research methodologies consist of the following:

- Survey questionnaires for building professionals and representative occupants' in institutions in Ghana.
- Experimental assessment of selected building fabrics from Ghana and parametric designed fabrics
- Computer simulation using ESDL Tas for optimized design variables
- Economic Assessment of reduced cooling load modification cost

The summarised purpose of each methodology, findings and the resulting implications of findings on improving energy utilization and indoor environmental conditions have been considered.

10.2 Contribution to knowledge

Several important outcomes have been achieved in solving high cooling energy utilization in representative office building in Ghana to achieving low energy building state at cost effective approaches. Among the major creative and novel contribution to knowledge are:

1. Optimum building fabric specifications and modified properties to enhancing building performance quality in Ghana climate.
2. Novel cooling load comparator and economic benefit decision tool for facilitating decision process on modification of building design variables
3. Technical guidance on achieving recommended thermo-physical properties in Ghana building regulation
4. Practical database of design variables for building performance assessment in Ghana for both future research and local practices.
5. Creative 2-way feedback chart for enhancing compliance assessment using existing method and on site final approval check for commercial building

In summary, all building professionals that is, government agencies, building fabric manufacturers, building service engineers and architects would benefit from this extensive research on these scientific optimized design variables in their practices. Finally, the enhanced cooling energy utilization will further reduce the rising energy utilization in commercial buildings in Ghana thereby contributing to the government efforts in solving energy power crisis.

10.3 Overall Conclusions

The following significant outcomes have been concluded from this research:

1. Government agencies (building permit issuing authorities, Ghana Standard Boards and Housing Ministries) practices are not adequate in monitoring and enforcing Ghana building regulations to enhancing building performance.

2. No single approach can be used to achieving low cooling energy building. Hence, combination of low transmittance building fabrics (window panes, cement blocks and concrete roof) and internal condition (lighting gain, equipment gain, infiltration gain, thermostat setting and ventilation gain) variables were considered.
3. The experimental assessments of the thermo-physical properties for both building fabric from Ghana and the parametric blocks meets the recommended CIBSE guide and are highly correlated with the indicated response by the survey questionnaires participants.
4. From the mixed research methods, the local building professionals' practices especially building fabrics choices of current building design specifications and building fabric selections are contributing significantly to the rising electricity utilization in buildings in Ghana.
5. Proposed redesigned wall and roof systems achieved the u-values outlined in Ghana building regulations, on the contrary, its impact on the overall cooling load reduction was about 15%. The proposed wall system designs considered were (Low Transmittance Single Wall System- (current block thickness), Low Transmittance Single Wall System (propose block thickness) and redesign Double Wall System)
6. The overall appraisal of Ghana building regulations by building professionals shows satisfactory assessment; on the other hand, there was a strong recommendation for modification.
7. The recommended cooling load per floor area for good practice specified by CIBSE Guide, should be reviewed into climate specific. For example, the cooling load specification for hot-humid climate should be different from hot-dry climate.
8. Increasing modification cost in the appropriate solutions for a climate, results in reduced cooling load with resulting benefits in savings per annum as well as simple net return over the life cycle.

Finally, the optimum computer simulation for the proposed building envelope model for Ghana achieved the recommended energy performance in CIBSE Guide and the acceptable indoor environmental quality of ASHRAE standard 55 with viable economic benefits.

10.4 Overall Recommendations

Several recommendations for the various building professionals have been identified as follows:

1. Ghana building regulations, should be modified into performance based regulation. This would encourage building professionals in undertaking performance assessment of design, selection and sizing equipment; integrate technology and minimize high electricity utilization caused by high cooling load.
2. Government should introduce the use of building energy certificate to office building owners to standardize service equipment selection and sizing in Ghana.
3. Building permit issuing authority should adopt the designed creative 2-way feedback chart in this thesis to enhancing building regulations compliance assessments.
4. Building service engineers and building fabric manufacturers should be encouraged to form associations with common aim of sharing knowledge and updating members on new techniques in improving their practices.
5. Government Agencies and building professional associations should have a comprehensive robust up to date accessible research on building performance assessments in Ghana.
6. Future research should integrate desiccant cooling technology and use the economic benefit comparator decision tool to assess its cost effectiveness and the achievement of the recommended good practice cooling load by CIBSE Guide.
7. Future research should use optimization software to verify the optimum proposed design variables achieved in this research.

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Appendices

Appendix A: selected survey questionnaires

6.2.1 Building Regulation Appraisal Questions

3. To what extent are you satisfied with the **government effectiveness** (capability of producing a desired result) in implementing building regulations of Ghana?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

4. To what extent are you satisfied with the **ease** (simple to use) of implementation of the building regulations of Ghana?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

5. To what extent are you satisfied with the **proportionality** (fair representation of key building envelope designers) of all building professional sections in the building regulations of Ghana?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

6. To what extent are you satisfied with the **flexibility** (capable of supporting a wide variety of building envelope design) of implementation of the building regulations of Ghana in practice?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

7. To what extent are you satisfied with the **cost effectiveness** (profitable) in the implementation of the building regulations of Ghana?

- Highly satisfied
- Satisfied

- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

8. To what extent are you satisfied with the **consistency** (free from variation or contradiction) of Ghana building regulation with other building regulation?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

9. To what extent are you satisfied with the **empirical basis** (derived from observation, experience, experiment and not theory) of the building regulations of Ghana?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

10. To what extent are you satisfied with the **adequacy** (sufficient and suitable for climate in Ghana) of the building regulations of Ghana?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

11. If not adequate, to what extent do you agree with the necessity to **modify** (change to improve quality) the building regulation of Ghana which was enacted in 1996?

- Strongly agree
- Agree
- Turn to agree
- Neither agree or disagree
- Turn to disagree
- Disagree
- Strongly disagree

6.2.1 Government Agencies

1. Is Energy Performance Certificates (EPCs) needed for commercial building (office) in Ghana before building permit is issued?

- ○ Yes
- ○ No
- ○ Other *(please specify)*:

If yes, what is contained in the Energy Performance Certificates? *(select all that apply)*

- ☐ Information about a property's energy(electricity) use
- ☐ Typical energy costs
- ☐ How to reduce energy (electricity) bills
- ☐ How to save energy (electricity)
- ☐ Energy efficiency ratings
- ☐ All of the above
- ☐ Other *(please specify)*:

2. During the certification of building permit; what is the **most** important Factor that is considered?

- ○ Structural strength
- ○ Energy consumption of the building
- ○ Certified architectural drawings
- ○ Site plan
- ○ All of the above

Other *(please specify)*:

F

Yes

No

Other *(please specify)*:

3. What is the origin of the values stated in the building regulation of Ghana?

Simulated values

Adjustment values from international standards

From experience

From experiments

All of the above

Other *(please specify)*:

From your experience, if the values in Ghana building regulation were based on adjusting international standards; what is the basis of this adjustment factor?

4. What are the **most commonest** things in the building regulation that people do not comply with during your inspection/review of building permit application? *(select all that apply)*

- ☐ Building envelope sealing
- ☐ Building envelope insulation and infiltration
- ☐ Properties of materials (thermal, optical etc.)
- ☐ Lighting controls
- ☐ HVAC systems
- ☐ Fenestration (window and door)
- ☐ Moisture penetration retarders
- ☐ Detailed building drawing
- ☐ All of the above
- ☐ Other *(please specify)*:

5. Would government be willing to support and implement research findings conducted on building materials?

- ○ Yes
- ○ No
- ○ Other *(please specify)*:

6.2.1.1 Building Regulation and Standards

1. Do you apply any adjustment factor to ASHRAE standards and CIBSE Guide when designing office building equipment?

- ○ Yes
- ○ No
- ○ Other *(please specify)*:

If yes, please explain how you obtain the adjustment factor.

2. From your experience, are you able to achieve the recommended cooling load stated in the CIBSE Guide in kWh/m2 at a comfortable indoor environmental comfort?

- ○ Yes
- ○ No

If no, please select all that is/are applicable in your practice.
(select all that apply)

- ☐ Resetting the thermostat
- ☐ Reducing the ventilation gain
- ☐ Reducing the infiltration gain
- ☐ Integrating dehumidifiers into the air-condition system
- ☐ Incorporating automatic sensor into air-conditioning

☐ Other *(please specify)*:

6.2.3.2 Sizing Building Service Equipment and Client know-how

3. Do you use software in sizing the air-condition equipment?

○ Yes

○ No

◉ Other *(please specify)*:

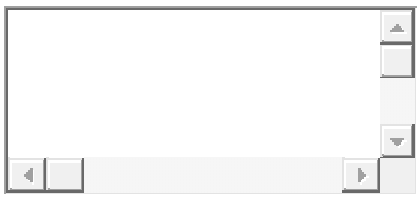
If yes, can you explain the equations used in sizing the air-condition system.

4. From your design considerations, what are the factors you consider in sizing air-conditions for office building?
(select all that apply)

☐ Building envelop materials

☐ Occupants metabolic activities

- [ ] External weather conditions
- [ ] ASHRAE standards for indoor environment comfort specification
- [ ] CIBSE Guides for indoor environment comfort specification
- [ ] Affordability
- [ ] Aesthetics
- [ ] Building efficiency
- [ ] Function of the office space
- [ ] Ghana Building regulation
- [ ] Other *(please specify)*:



6.2.3.3 Building Performance and Life Cycle

5. Do you conduct post-occupancy survey in offices you have designed and installed building service equipment to ensure that the office is efficient, comfortable and functioning as desired?

- ○ Yes
- ○ No
- ○ I do not know
- ○ Other *(please specify)*:

6. From your experience, are clients of office buildings willing to pay for improved efficient building service equipment design?

- ○ Yes
- ○ No
- ○ Other *(please*

6.2.4.1 General questions Ghana Building Regulation

1. Which of the following building regulation/code do you **typically** apply in designing office building envelopes in Ghana?
(select all that apply)

- ☐ Ghana Building Regulations
- ☐ British Standards
- ☐ ASHRAE Standards
- ☐ All of the above
- ☐ Other *(please specify)*:

In your design consideration, do you **typically** apply any adjustment factor

to any of the codes/regulation listed above?

- ○ Yes
- ○ No
- ○ Other *(please specify)*:

i. If yes; please explain the basis of the adjustment factor.

2. Do you perform Whole Building Simulations to assess the building performance before handling the building to clients?

- ○ Yes
- ○ No
- ○ I do not know
- ○ Other *(please specify)*:

If yes, please select the **typical** performance assessment carried out. *(select all that apply)*

- ☐ Energy
- ☐ Thermal comfort
- ☐ Psychological comfort
- ☐ Visual Comfort
- ☐ Acoustic comfort
- ☐ Carbon dioxide emission

☐ All of the above

☐ Other *(please specify)*:

i. What **typical** whole building simulation software do you use?

○ Ecotect

○ EnergyPlus

○ ESDL Thermal Analysis simulation Software (TAS)

○ TRNSYS software

○ ESP-r

○ All of the above

○ Other *(please specify)*:

ii. What typically do you use in validating the simulation results?

○ Building regulation

○ ASHRAE Standards

○ British Standards

○ Electricity Bills

○ Monitored Building results

○ Other *(please specify)*:

6.2.4.2 Building Envelop Design

3. What is the typical range of window-to-floor ratio do you use in your designs? *(select all that apply)*

- ☐ 20 - 25%
- ☐ 25 - 30%
- ☐ 40 - 45%
- ☐ 50 - 55%
- ☐ Other *(please specify)*:

a. What are the main reasons behind the selected percentage(s) above? *(select all that apply)*

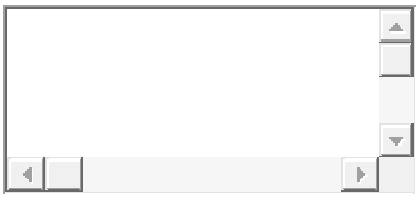
- ☐ Clients specification
- ☐ Maximizing day lighting
- ☐ Aesthetics
- ☐ Enhancing indoor environmental performance
- ☐ Cost implications
- ☐ Weather climate
- ☐ Other *(please specify)*:

b. From your experience, which percentage is best preferred percentage considering

Ghana weather climate?

4. What is the trend of office building designs since the first electricity crisis in Ghana?

- Complicated building design with about 70% glass
- Simple building design with about 30% glass
- There is no change
- Sustainable building design with bioclimatic and passive technology incorporated
- Other *(please specify)*:



6.2.4.3 Building Envelop improvements

5. Which of the following building envelop design process have you incorporated into your designs since 2007(Ghana worse electricity crisis). (*select all that apply)*

- Full Bio-climatic designs
- Full Passive designs

- ☐ High performance controlled ventilation
- ☐ Shading
- ☐ Passive solar building such as compact shape, window orientation
- ☐ Elimination of thermal bridges
- ☐ Insulation into building elements such as floor, wall, roof.
- ☐ Improved window pane and frame technologies
- ☐ Day lighting
- ☐ Airtightness
- ☐ Increased roof insulation
- ☐ Increased wall insulation
- ☐ Increased ground and floor insulation
- ☐ Using materials with low thermal conductivity
- ☐ Using moisture retarding systems
- ☐ Reducing floor-to-window ration
- ☐ Reducing floor-to-ceiling ratio
- ☐ None of the above
- ☐ Other *(please specify)*:

6. If the building performance assessment of an existing typical multi-story office building is not acceptable; what would you **most likely** recommenced in future in designing efficient building?
(select all that apply)

- ☐ Change building design of wall, roof and window pane
- ☐ Use bio-climatic materials in compliance with building regulation
- ☐ Use efficient building service equipment
- ☐ Educate occupants on building usage behaviour
- ☐ Use building management systems
- ☐ Improve building sealing to minimize infiltration
- ☐ Other *(please specify)*:

7. To what extent do you agree with the energy savings through efficient office building design in Ghana could help mitigate the electricity crises in Ghana?

- ○ Strongly agree
- ○ Agree
- ○ Turn to agree
- ○ Neither agree or disagree
- ○ Turn to disagree
- ○ Disagree
- ○ Strongly disagree

6.2.5.1 Building Standards and Regulations

1. If you apply any adjustment factor on standards/regulations in manufacturing your products in Ghana, would clients be willing to pay for material products which complies exactly with the building regulation/ standards?

- Yes
- No
- I do not know

2. If local building construction materials bill is enforced for building professionals in Ghana to use for office building, would you produce them?

- Yes
- No
- I do not know
- Other *(please specify)*:

If no, please explain.

3. Does Ghana Standards Board ensure that the products are in compliance with the building regulation/British Standards?

- Yes
- No

6.2.5.2 Products Specification

4. What **typical** factors do you consider in selecting building construction materials for office building envelope products in Ghana?
(select all that apply)

- ☐ Affordability
- ☐ Aesthetics
- ☐ Building efficiency
- ☐ Function of the office space
- ☐ Durability
- ☐ Climate suitability
- ☐ Availability
- ☐ Cultural practices in Ghana
- ☐ Economy of Ghana
- ☐ Available local technology
- ☐ Available equipment
- ☐ Workmanship
- ☐ Material properties
- ☐ Environmental issues (climate change, indoor comfort)
- ☐ All of the above

☐ Other *(please specify)*:

5. What is the typical mixing ratio of cement: sand: gravel for concrete roof, floor and concrete block in Ghana?

- ○ 1:1:3
- ○ 1:4:1
- ○ 1:5:1
- ○ 1:6:1
- ○ Other *(please*

a. What is the **typical** thermal conductivity(W/mK)of your concrete products?

- ○ 0.03 - 0.3
- ○ 0.3 - 0.7
- ○ 0.7 - 1.0
- ○ 1.0 - 1.6
- ○ 1.6 - 2.2
- ○ I do not know
- ○ Other *(please specify)*:

b. If the answer is different than that of CIBSE Guide/Standard value, then do apply any adjustment factors?

- Yes
- No

c. If yes, following your design considerations, how do you calculate the adjustment factor?

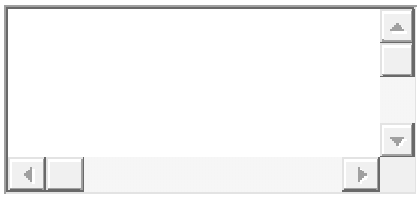
6. What is the typical mixing ratio (cement: sand) of cement mortar blocks in Ghana?

- 1:2
- 1:3
- 1:4
- 1:5
- 1:6
- Other *(please*

a. What do you use in measuring the thermal and moisture properties of your products? *(select all that apply)*

- C-Therm TCi, Thermal Conductivity analyser
- Heat flow meter
- Transient Plane Source TPS 2500 S, Thermal Conductivity Instrument
- Use of thermocouple and test box experiment

☐ Other *(please specify)*:



b. What is the **typical** range of thermal conductivity(W/mK)of the cement mortar products that you produce?

○ 0.03 - 0.5

○ 0.5 - 0.75

○ 0.75 - 0.95

○ 0.95 - 1.2

○ 1.2 - 1.6

○ Other *(please specify)*:

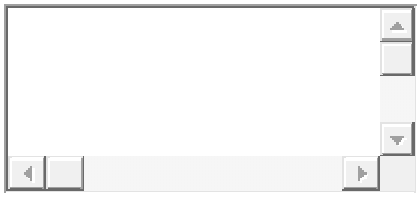
c. Which of the following standards/regulations do you compare your values obtained with? *(select all that apply)*

☐ Ghana building regulation

☐ ISO standards

☐ British Standard?

☐ Other *(please specify)*:



7. Do you test the blocks that you produce for moisture content?

- Yes
- No
- Other *(please*

If yes, how do you measure the moisture content in the blocks *(select all that apply)*

- Hygrometer test
- Electrical resistance test
- Gravimetric moisture content test
- Calcium chloride test
- Rubber mat test
- Other *(please specify)*:

8. Do you consider the fact that, building construction material properties you manufacture affects building envelop overall efficiency?

- Yes
- No
- Other *(please*

If yes, please select all the material properties that directly affect the building envelop overall efficiency. *(select all that apply)*

- Thermal conductivity
- Specific heat

- ☐ water vapour permeability
- ☐ compressive strength
- ☐ Diffusion
- ☐ Density
- ☐ All of the above
- ☐ Other *(please specify)*:

6.2.5.3 Sustainable Building Materials

9. How do you enhance the properties (hydraulic diffusivity, permeability and vapour transfer coefficient) in the materials you produce?
(select all that apply)

- ☐ Using dry construction materials
- ☐ Reducing capillary rise of ground moisture
- ☐ Reducing vapour diffusion
- ☐ Reducing vapour permeability
- ☐ Addition of moisture retarders (asphalt products, polyolefin, cement

sheathings)

☐ Other *(please specify)*:

10. Do you access the environmental suitability of the construction materials?

○ Yes

○ No

If yes, how do you access the environmental suitability? *(select all that apply)*

☐ Compliance with Ghana Building regulation

☐ Compliance of British Standards on construction materials production

☐ In house experimental assessment

☐ From experience of modified standards

☐ Assessment by Government agencies

☐ Other *(please specify)*:

11. In your opinion, are building construction materials used in Ghana suitable for the weather climate?

- Yes
- No

12. Are customers be willing to pay for high quality materials which complies with the **low energy building regulation**?

- Yes
- No
- I do not know

6.2.6 Occupant's Satisfaction and Comfort

The questionnaire for Occupants Satisfaction and Comfort were subdivided into General Occupant's information, Indoor Environmental Comfort and Overall Occupants Satisfaction; there were 43 questions in total. The detail of the questionnaires are outlined in detail in the appendix A; however some selected questions in each subsection are detailed in the following. General occupant's information was extracted for the building simulation in chapter 8.

6.2.6.1 General Occupant's information

1. How many occupants are there in your room?

- 1
- 2
- 4
- 6

Other *(please*

2. In a **typical** working day, what time does your work schedule start and end?

8 am to 5 pm

8 am to 12 noon

9 am to 5pm

Other *(please specify)*:

3. Does your office close down on all the 13 statutory holidays in Ghana?

Yes

No

Other *(please*

4. Was the building constructed before 1996?

Yes

No

I do not know

6.2.6.2 Indoor Environmental Comfort

5. Who control the thermostat settings in the room?

- ○ Centrally controlled
- ○ Occupants controlled
- ○ Automatically controlled
- ○ I do not know
- ○ Other *(please specify)*:

If the thermostat setting is occupant controlled, what temperature and relative humidity do you set the air condition to?

- ○ 20 degrees and 50%
- ○ 26 degrees and 60%
- ○ 18 degrees and 40%
- ○ I do not know
- ○ Other *(please specify)*:

Overall Occupants Satisfaction

6 How satisfied are you with Thermal Comfort?

- ○ Highly satisfied
- ○ Satisfied
- ○ Turn to be satisfied

- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

7 How satisfied are you with Psychological comfort?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

8 How satisfied are you with the perception of indoor air quality?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

9 How satisfied are you with the perception of Acoustic comfort?

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

10 How satisfied are you with the perception of visual (electric lighting and daylighting) Comfort

- Highly satisfied
- Satisfied
- Turn to be satisfied
- Neither satisfied nor dissatisfied
- Turn to be dissatisfied
- Dissatisfied
- Very Dissatisfied

Appendix B Characteristic cost estimates of proposed modifications

FIRST SCHEDULE

Tariff Category	Effective 1st July 2015
BGC VRA - (GHp/kWh)	14.6047
Composite BGC (VRA and IPPs) (GHp/kWh)	23.7405

SECOND SCHEDULE

Tariff Category	Effective 1st July 2015
TSC (GHp/kWh)	4.2956

THIRD SCHEDULE

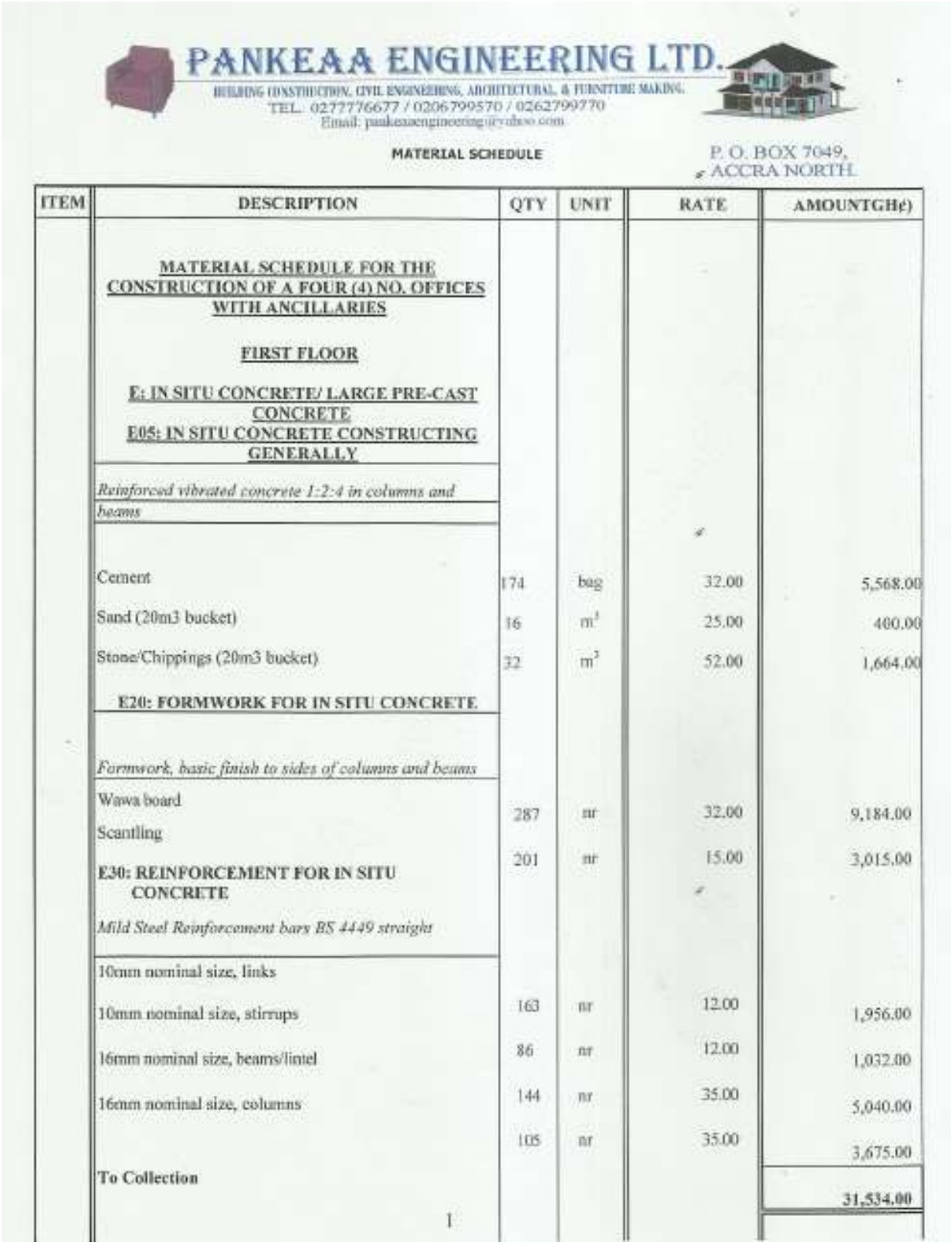
Tariff Category	Effective 1st July 2015
DSC (GHp/kWh)	16.4575

FOURTH SCHEDULE

EUT Tariff Category		Effective July 2015, Billing Cycle	
Residential			
0-50 (Exclusive)	(GHp/kWh)	21.0795	
51-300	(GHp/kWh)	42.2910	
301 – 600	(GHp/kWh)	54.8855	
601+	(GHp/kWh)	60.9839	
Service Charge (GHp/month)		397.7209	
Non-Residential			
0-300	(GHp/kWh)	60.7983	
301 – 600	(GHp/kWh)	64.6959	
601+	(GHp/kWh)	102.0617	
Service Charge	(GHp/month)	662.6662	
Tariff Category		**Effective July 2015, Billing Cycle**	
SLT-LV			
Max. Demand	(GHp/kVA/month)	3712.0621	
Energy Charge	(GHp / kWh)	63.3702	
Service Charge	(GHp / month)	2651.4729	
SLT-MV			
Max. Demand	(GHp/kVA/month)	3181.7675	
Energy Charge	(GHp / kWh)	49.0522	
Service Charge	(GHp / month)	3712.0621	
SLT-HV			
Max. Demand	(GHp/kVA/month)	3181.7675	
Energy Charge	(GHp / kWh)	45.0750	
Service Charge	(GHp / month)	3712.0621	
SLT-HV MINES			
Max. Demand	(GHp/kVA/month)	3712.0621	
Energy Charge	(GHp / kWh)	71.5696	
Service Charge	(GHp / month)	3712.0621	

Samuel K. Sarpong, Executive Secretary
(for) Dr. Emmanuel K. Annan
Chairman, Public Utilities Regulatory Commission

Figure 0.1: Sample Electricity Trarrif from PURC Ghana



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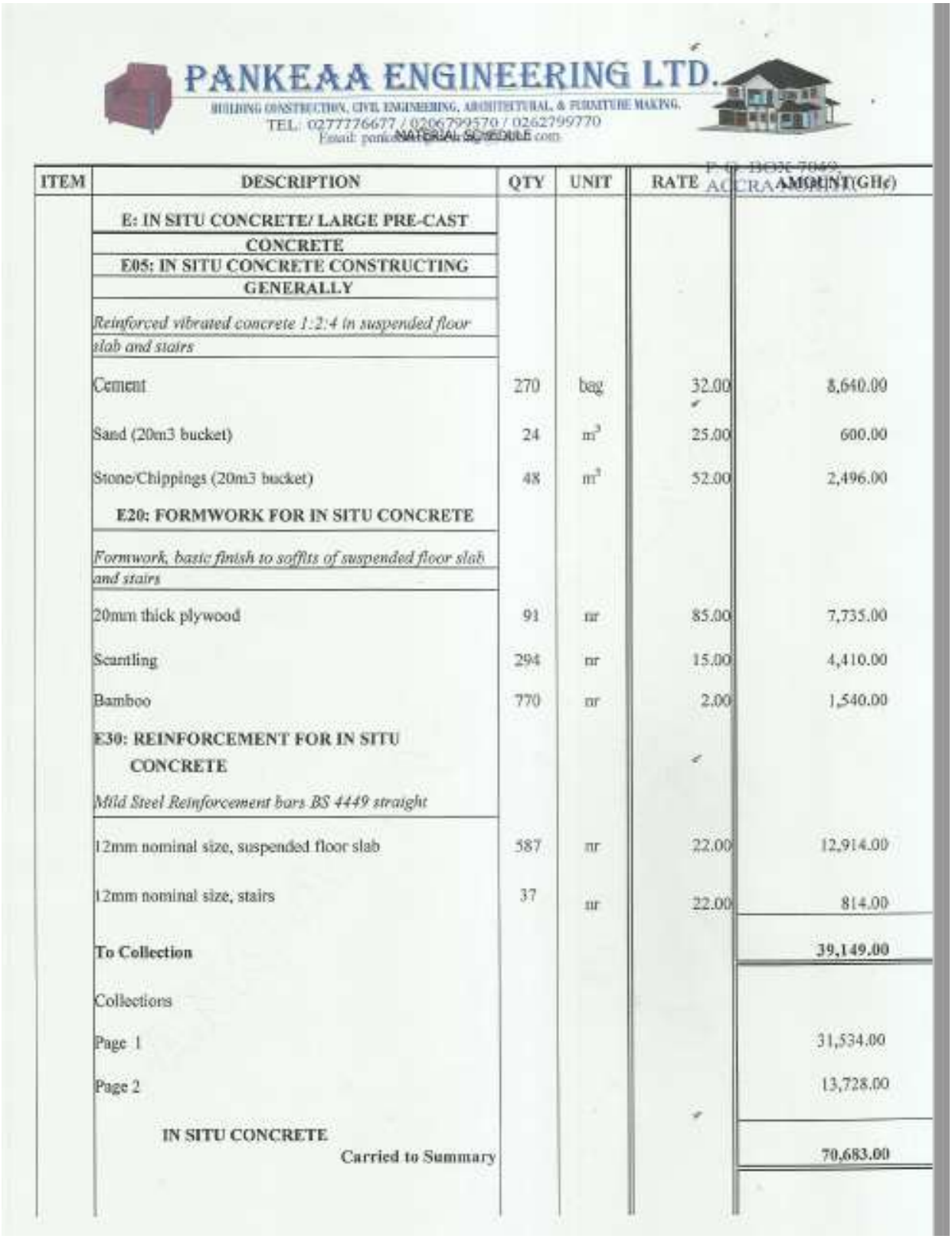
Email: pankeaaengineering@yahoo.com

P. O. BOX 7049,
ACCRA NORTH.

MATERIAL SCHEDULE

ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNTGH¢)
	MATERIAL SCHEDULE FOR THE CONSTRUCTION OF A FOUR (4) NO. OFFICES WITH ANCILLARIES				
	FIRST FLOOR				
	E: IN SITU CONCRETE/ LARGE PRE-CAST CONCRETE				
	E05: IN SITU CONCRETE CONSTRUCTING GENERALLY				
	Reinforced vibrated concrete 1:2:4 in columns and beams				
	Cement	174	bag	32.00	5,568.00
	Sand (20m3 bucket)	16	m^3	25.00	400.00
	Stone/Chippings (20m3 bucket)	32	m^3	52.00	1,664.00
	E20: FORMWORK FOR IN SITU CONCRETE				
	Formwork, basic finish to sides of columns and beams				
	Wawa board	287	nr	32.00	9,184.00
	Scantling	201	nr	15.00	3,015.00
	E30: REINFORCEMENT FOR IN SITU CONCRETE				
	Mild Steel Reinforcement bars BS 4449 straight				
	10mm nominal size, links	163	nr	12.00	1,956.00
	10mm nominal size, stirrups	86	nr	12.00	1,032.00
	16mm nominal size, beams/lintel	144	nr	35.00	5,040.00
	16mm nominal size, columns	105	nr	35.00	3,675.00
	To Collection				**31,534.00**

Figure 0.2: Selected Cost Estimates, 1 of 8



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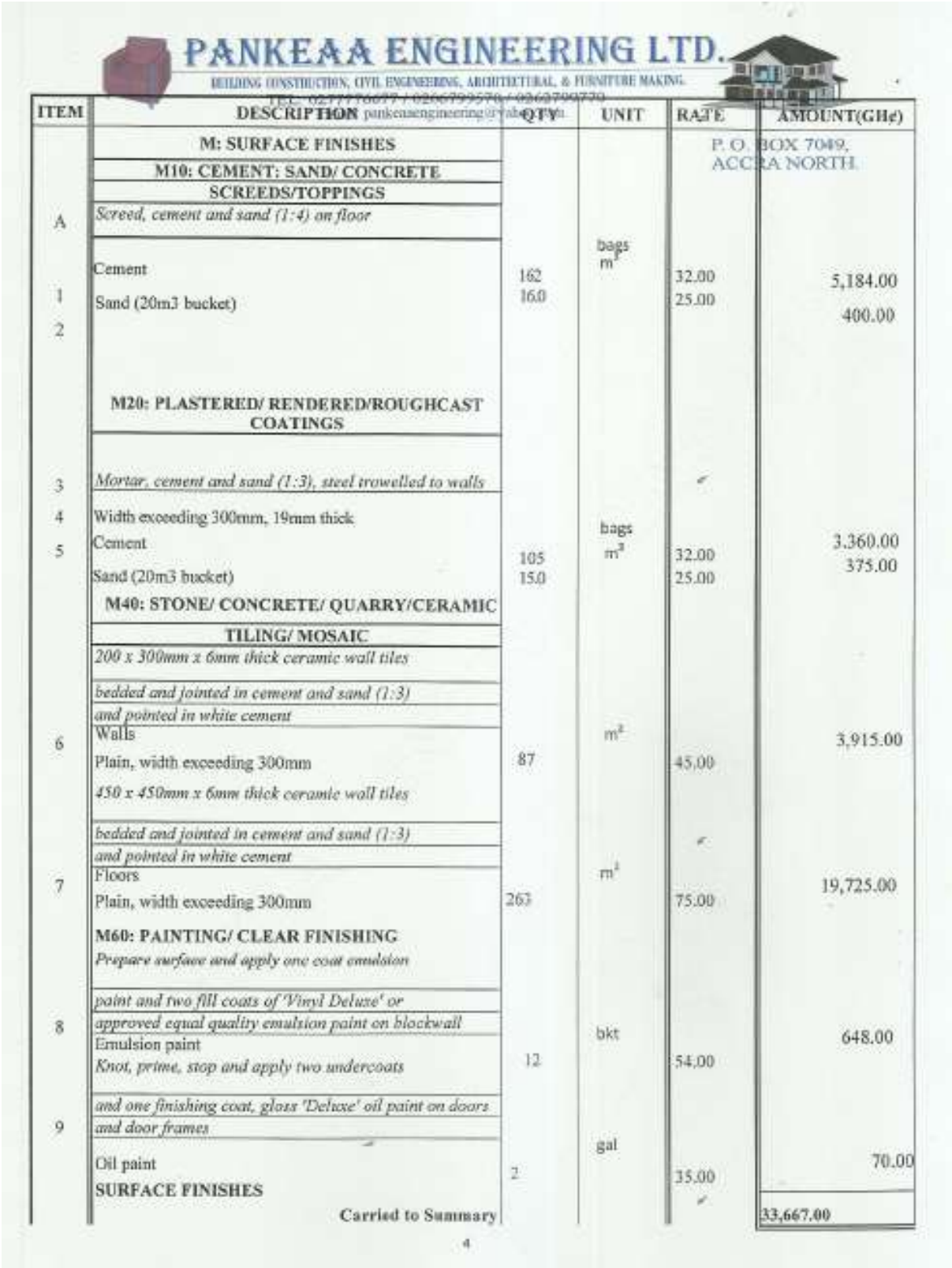
Email: pankeaa@yahoo.com

MATERIAL SCHEDULE

ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNT(GH¢)
	E: IN SITU CONCRETE/ LARGE PRE-CAST CONCRETE				
	E05: IN SITU CONCRETE CONSTRUCTING GENERALLY				
	Reinforced vibrated concrete 1:2:4 in suspended floor slab and stairs				
	Cement	270	bag	32.00	8,640.00
	Sand (20m3 bucket)	24	m^3	25.00	600.00
	Stone/Chippings (20m3 bucket)	48	m^3	52.00	2,496.00
	E20: FORMWORK FOR IN SITU CONCRETE				
	Formwork, basic finish to soffits of suspended floor slab and stairs				
	20mm thick plywood	91	nr	85.00	7,735.00
	Scantling	294	nr	15.00	4,410.00
	Bamboo	770	nr	2.00	1,540.00
	E30: REINFORCEMENT FOR IN SITU CONCRETE				
	Mild Steel Reinforcement bars BS 4449 straight				
	12mm nominal size, suspended floor slab	587	nr	22.00	12,914.00
	12mm nominal size, stairs	37	nr	22.00	814.00
	To Collection				**39,149.00**
	Collections				
	Page 1				31,534.00
	Page 2				13,728.00
	IN SITU CONCRETE Carried to Summary				**70,683.00**

Figure 0.3: Selected Cost Estimates, 2 of 8



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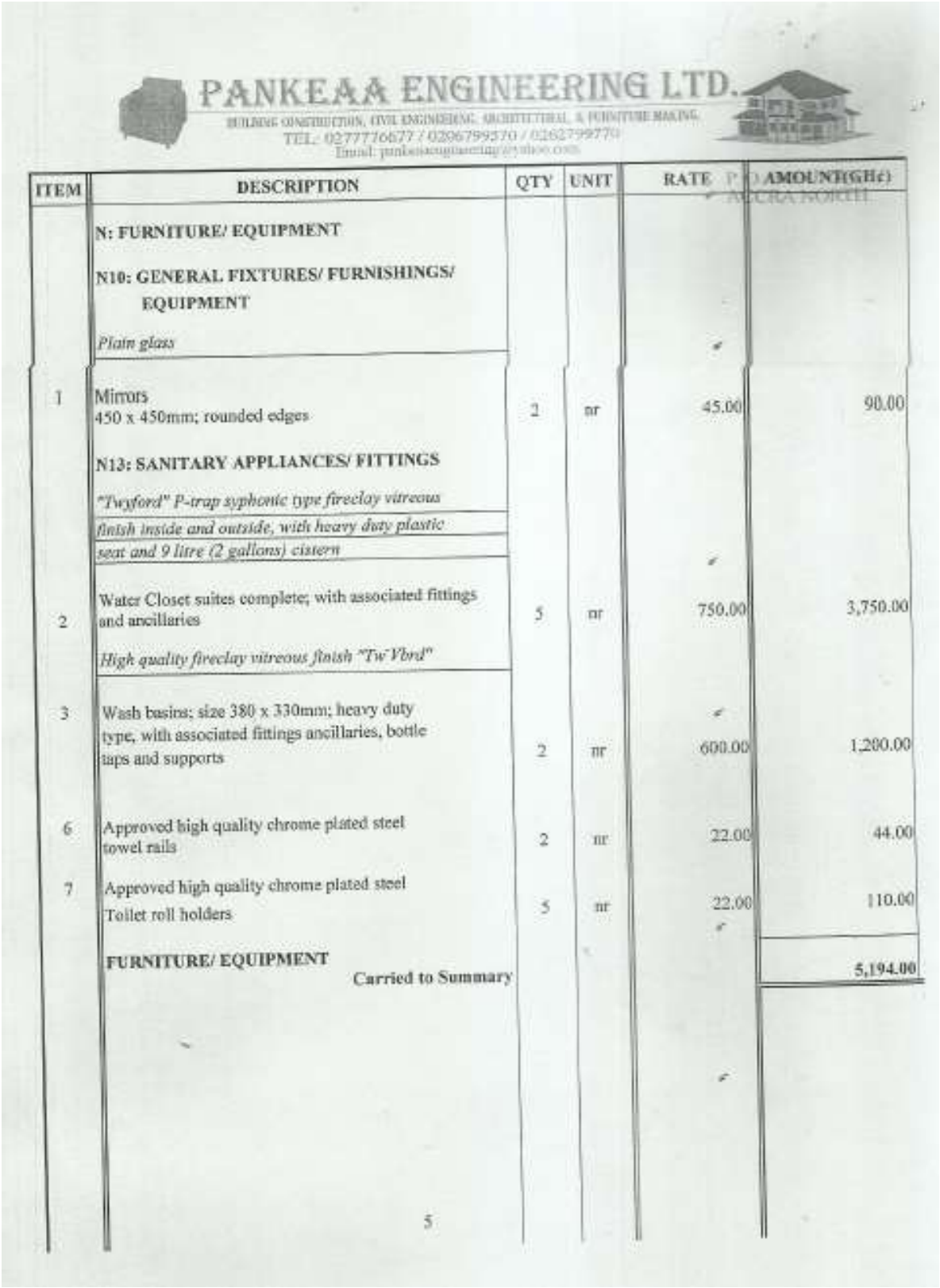
pankeaaengineering@yahoo.com

P. O. BOX 7049,
ACCRA NORTH.

ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNT(GH¢)
	M: SURFACE FINISHES				
	M10: CEMENT: SAND/ CONCRETE SCREEDS/TOPPINGS				
A	*Screed, cement and sand (1:4) on floor*				
	Cement	162	bags	32.00	5,184.00
1	Sand (20m3 bucket)	16.0	m^3	25.00	400.00
2					
	M20: PLASTERED/ RENDERED/ROUGHCAST COATINGS				
3	*Mortar, cement and sand (1:3), steel trowelled to walls*				
4	Width exceeding 300mm, 19mm thick				
5	Cement	105	bags	32.00	3,360.00
	Sand (20m3 bucket)	15.0	m^3	25.00	375.00
	M40: STONE/ CONCRETE/ QUARRY/CERAMIC TILING/ MOSAIC				
	200 x 300mm x 6mm thick ceramic wall tiles				
	bedded and jointed in cement and sand (1:3)				
	and pointed in white cement				
6	Walls		m^2		3,915.00
	Plain, width exceeding 300mm	87		45.00	
	450 x 450mm x 6mm thick ceramic wall tiles				
	bedded and jointed in cement and sand (1:3)				
	and pointed in white cement				
7	Floors		m^2		19,725.00
	Plain, width exceeding 300mm	263		75.00	
	M60: PAINTING/ CLEAR FINISHING				
	Prepare surface and apply one coat emulsion				
	paint and two fill coats of Vinyl Deluxe' or				
8	*approved equal quality emulsion paint on blockwall*		bkt		648.00
	Emulsion paint	12		54.00	
	Knot, prime, stop and apply two undercoats				
	and one finishing coat, gloss 'Deluxe' oil paint on doors				
9	*and door frames*		gal		70.00
	Oil paint	2		35.00	
	SURFACE FINISHES				
	Carried to Summary				33,667.00

4

Figure 0.4: Selected Cost Estimates, 4 of 8



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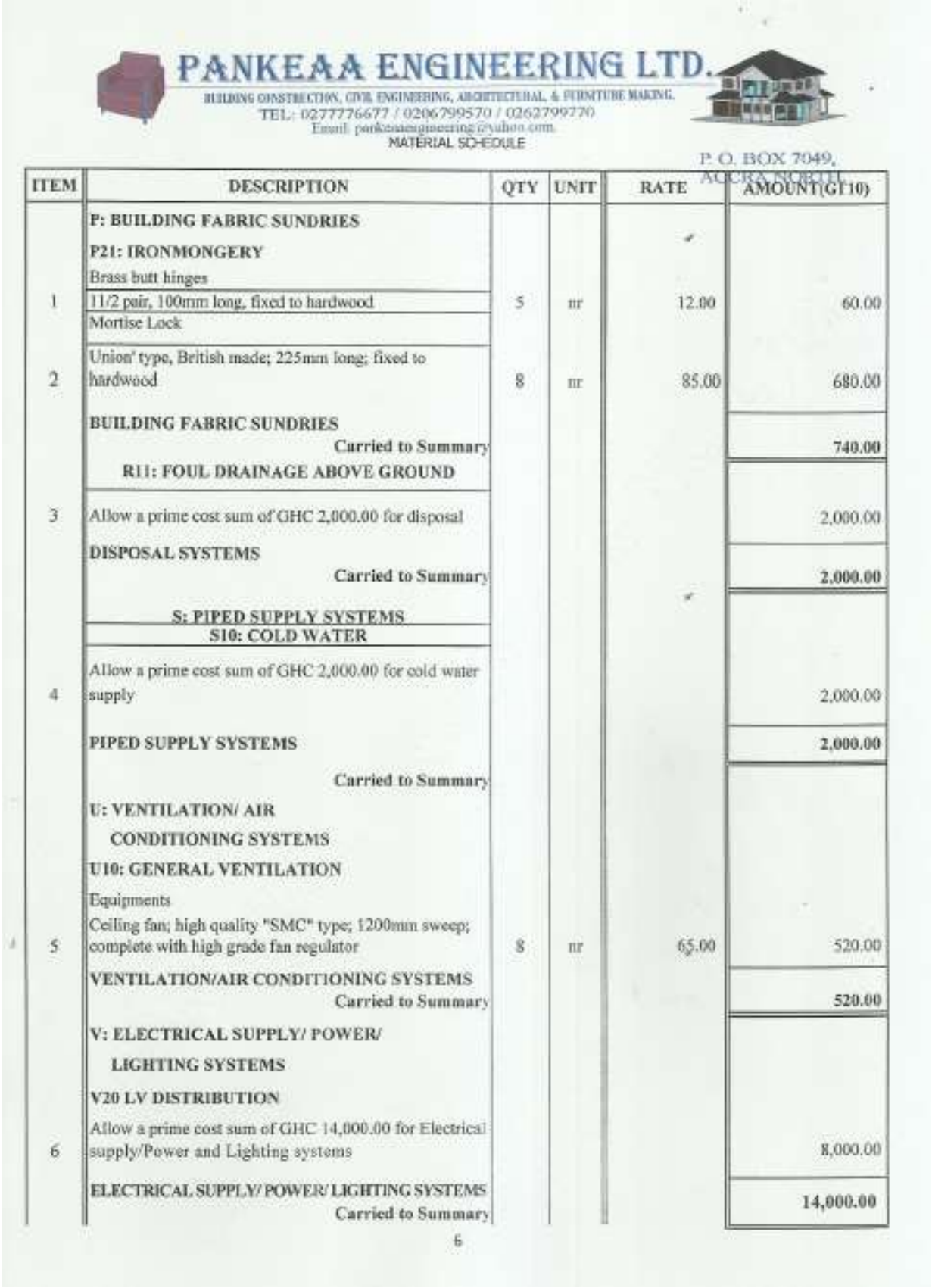
ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNT(GH¢)
	N: FURNITURE/ EQUIPMENT				
	N10: GENERAL FIXTURES/ FURNISHINGS/ EQUIPMENT				
	Plain glass				
1	Mirrors 450 x 450mm; rounded edges	2	nr	45.00	90.00
	N13: SANITARY APPLIANCES/ FITTINGS				
	"Twyford" P-trap syphonic type fireclay vitreous finish inside and outside, with heavy duty plastic seat and 9 litre (2 gallons) cistern				
2	Water Closet suites complete; with associated fittings and ancillaries *High quality fireclay vitreous finish "Tw Vbrd"*	5	nr	750.00	3,750.00
3	Wash basins; size 380 x 330mm; heavy duty type, with associated fittings ancillaries, bottle taps and supports	2	nr	600.00	1,200.00
6	Approved high quality chrome plated steel towel rails	2	nr	22.00	44.00
7	Appeoved high quality chrome plated steel Toilet roll holders	5	nr	22.00	110.00
	FURNITURE/ EQUIPMENT Carried to Summary				5,194.00

5

Figure 0.5: Selected Cost Estimates, 5 of 8



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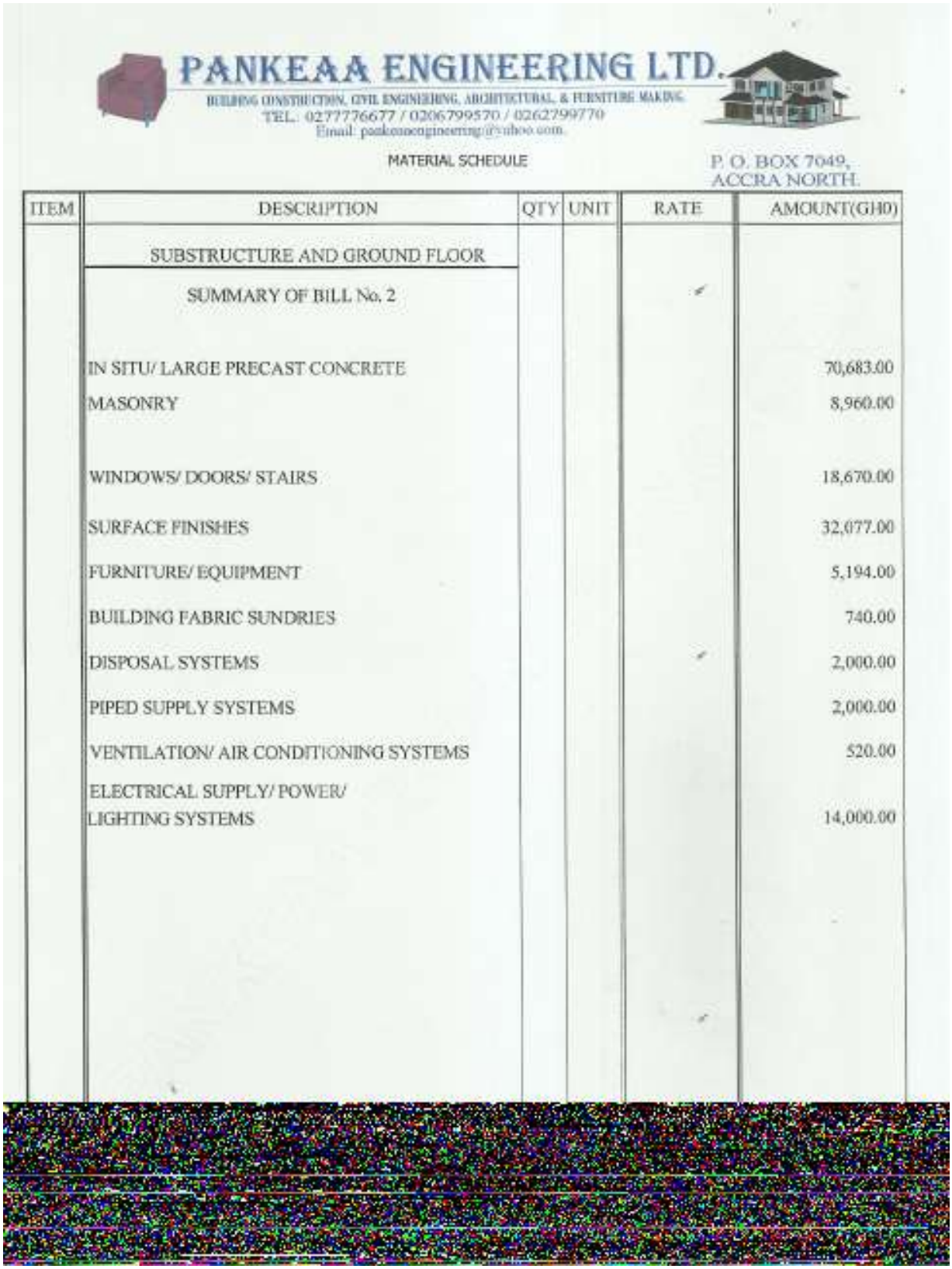
MATERIAL SCHEDULE

P. O. BOX 7049,
ACCRA NORTH

ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNT(GH¢10)
	P: BUILDING FABRIC SUNDRIES				
	P21: IRONMONGERY				
	Brass butt hinges				
1	11/2 pair, 100mm long, fixed to hardwood	5	nr	12.00	60.00
	Mortise Lock				
2	Union' type, British made; 225mm long; fixed to hardwood	8	nr	85.00	680.00
	BUILDING FABRIC SUNDRIES				
	Carried to Summary				**740.00**
	R11: FOUL DRAINAGE ABOVE GROUND				
3	Allow a prime cost sum of GHC 2,000.00 for disposal				2,000.00
	DISPOSAL SYSTEMS				
	Carried to Summary				**2,000.00**
	S: PIPED SUPPLY SYSTEMS				
	S10: COLD WATER				
4	Allow a prime cost sum of GHC 2,000.00 for cold water supply				2,000.00
	PIPED SUPPLY SYSTEMS				**2,000.00**
	Carried to Summary				
	U: VENTILATION/ AIR CONDITIONING SYSTEMS				
	U10: GENERAL VENTILATION				
	Equipments				
5	Ceiling fan; high quality "SMC" type; 1200mm sweep; complete with high grade fan regulator	8	nr	65.00	520.00
	VENTILATION/AIR CONDITIONING SYSTEMS				
	Carried to Summary				**520.00**
	V: ELECTRICAL SUPPLY/ POWER/ LIGHTING SYSTEMS				
	V20 LV DISTRIBUTION				
6	Allow a prime cost sum of GHC 14,000.00 for Electrical supply/Power and Lighting systems				8,000.00
	ELECTRICAL SUPPLY/ POWER/ LIGHTING SYSTEMS				
	Carried to Summary				**14,000.00**

6

Figure 0.6: Selected Cost Estimates, 6 of 8



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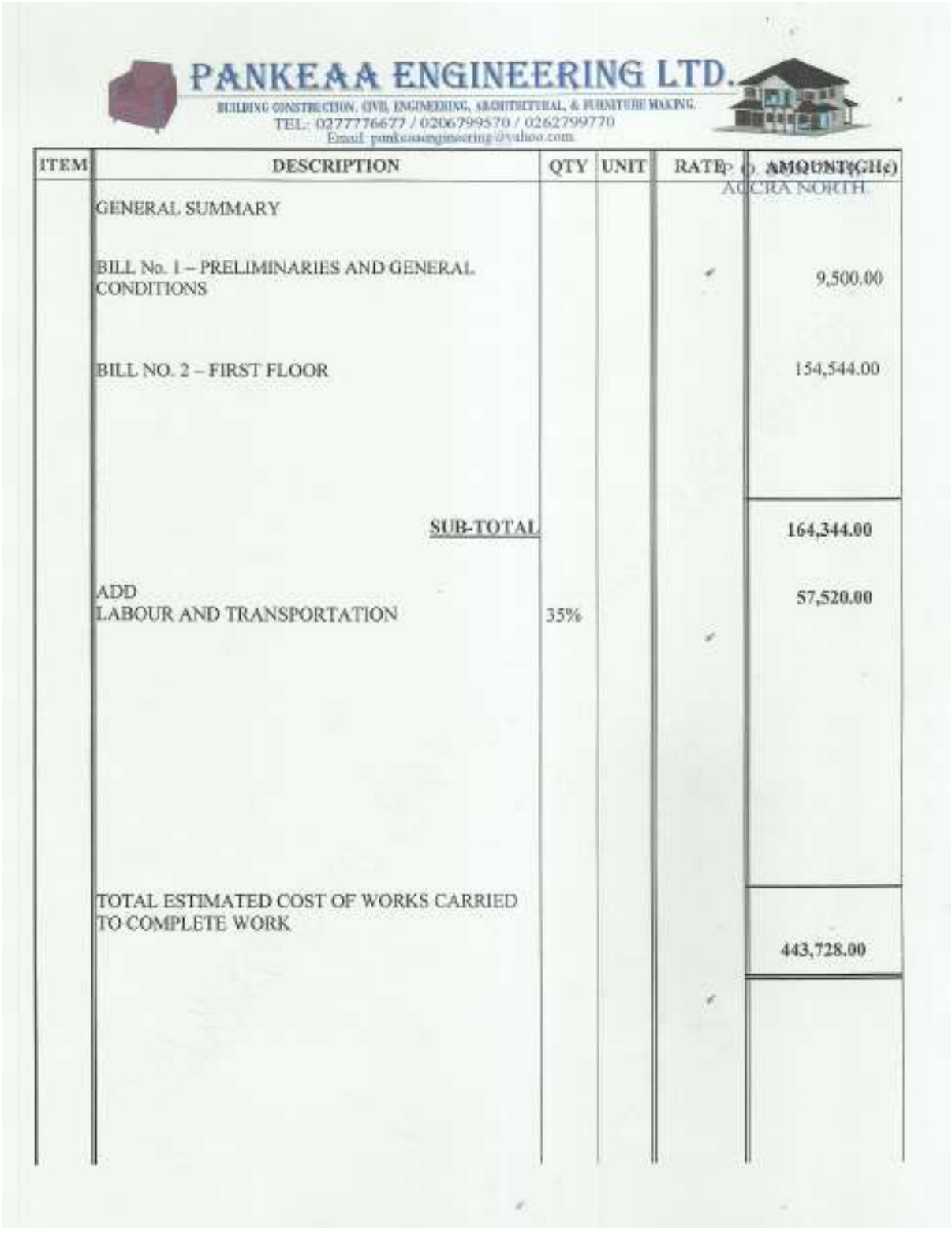
MATERIAL SCHEDULE

P. O. BOX 7049,
ACCRA NORTH.

ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNT(GHO)
	SUBSTRUCTURE AND GROUND FLOOR				
	SUMMARY OF BILL No. 2				
	IN SITU/ LARGE PRECAST CONCRETE				70,683.00
	MASONRY				8,960.00
	WINDOWS/ DOORS/ STAIRS				18,670.00
	SURFACE FINISHES				32,077.00
	FURNITURE/ EQUIPMENT				5,194.00
	BUILDING FABRIC SUNDRIES				740.00
	DISPOSAL SYSTEMS				2,000.00
	PIPED SUPPLY SYSTEMS				2,000.00
	VENTILATION/ AIR CONDITIONING SYSTEMS				520.00
	ELECTRICAL SUPPLY/ POWER/ LIGHTING SYSTEMS				14,000.00

Figure 0.7: Selected Cost Estimates, 7 of 8



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Email: pankeaaengineering@yahoo.com

P. O. BOX AD
ACCRA NORTH.

ITEM	DESCRIPTION	QTY	UNIT	RATE	AMOUNT(GH¢)
	GENERAL SUMMARY				
	BILL No. 1 – PRELIMINARIES AND GENERAL CONDITIONS				9,500.00
	BILL NO. 2 – FIRST FLOOR				154,544.00
	SUB-TOTAL				164,344.00
	ADD LABOUR AND TRANSPORTATION	35%			57,520.00
	TOTAL ESTIMATED COST OF WORKS CARRIED TO COMPLETE WORK				443,728.00

Figure 0.8: Selected Cost Estimates, 8 of 8

Appendix C

Parametric Scenarios using low electricity tariff for:

Building design before enactment of Ghana regulations

- **Difference in cost vs savings per annum**

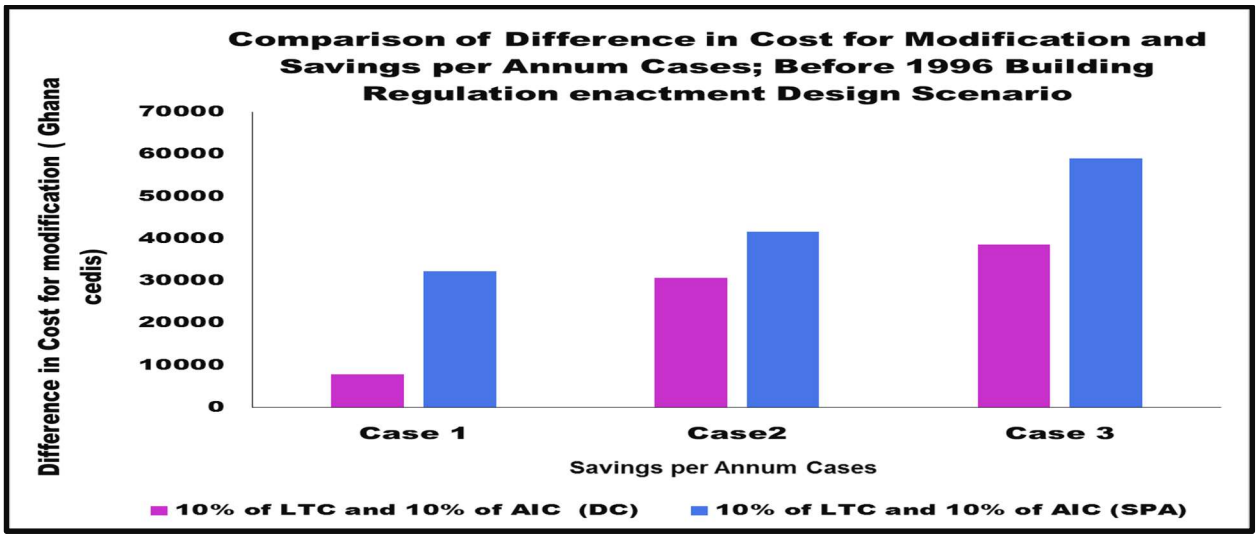

Figure 0.9: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario.

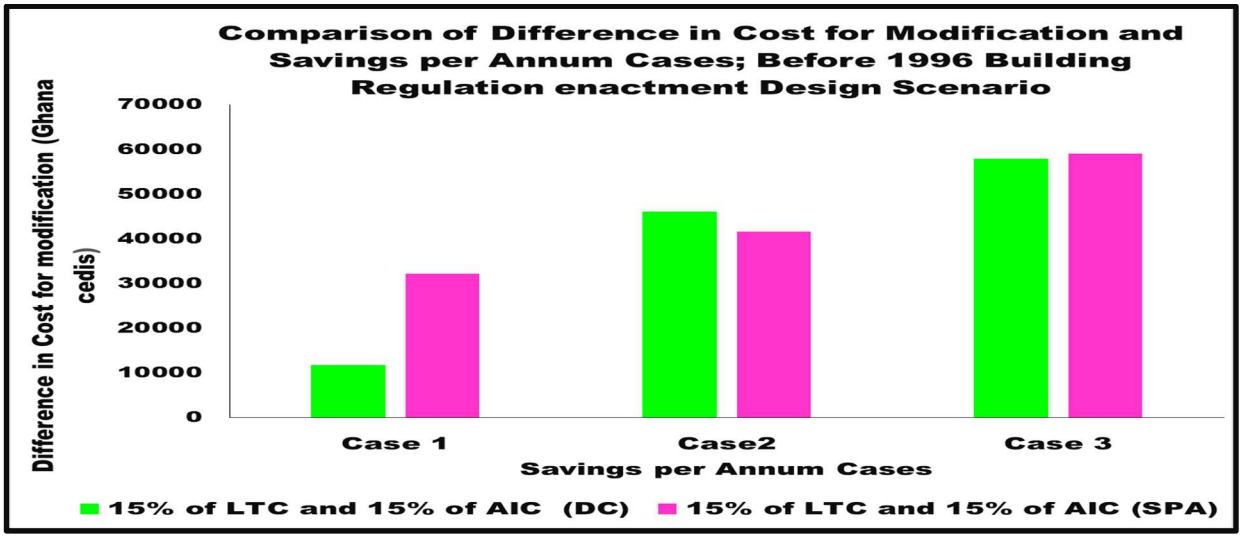

Figure 0.10: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario.

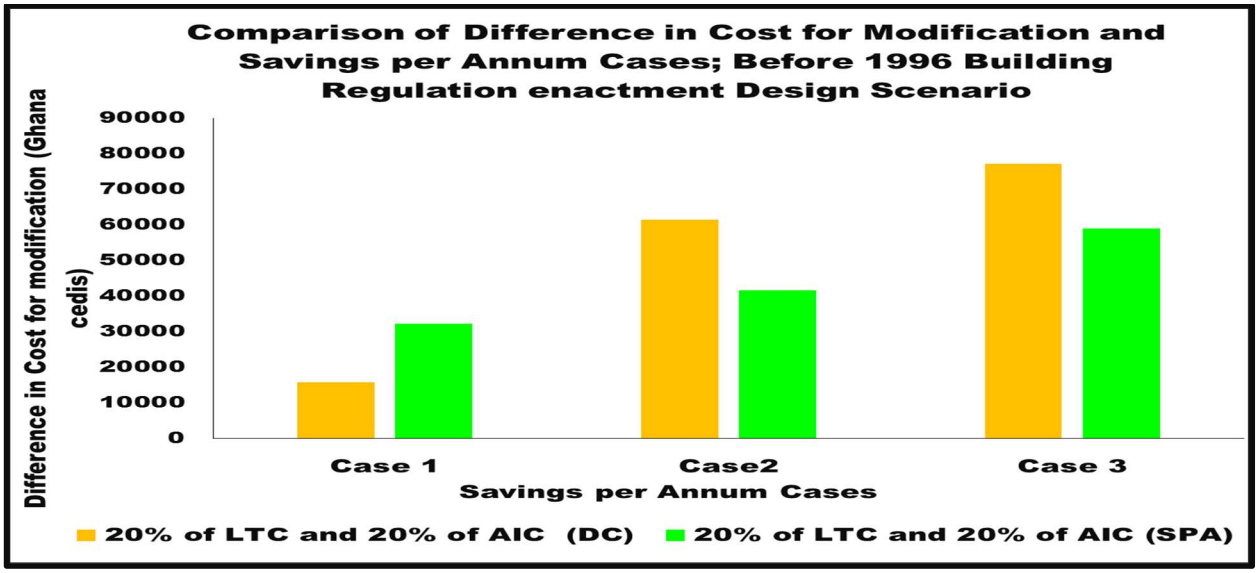

Figure 0.11: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario

- **Difference in cost vs simple net return over life cycle**

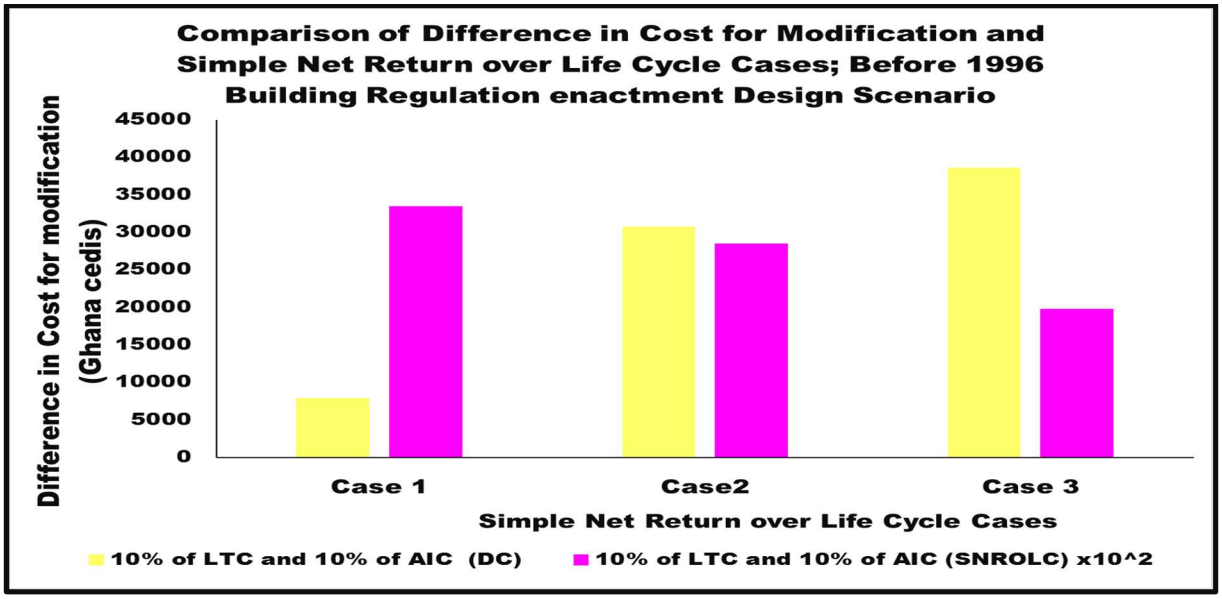

Figure 0.12: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario.

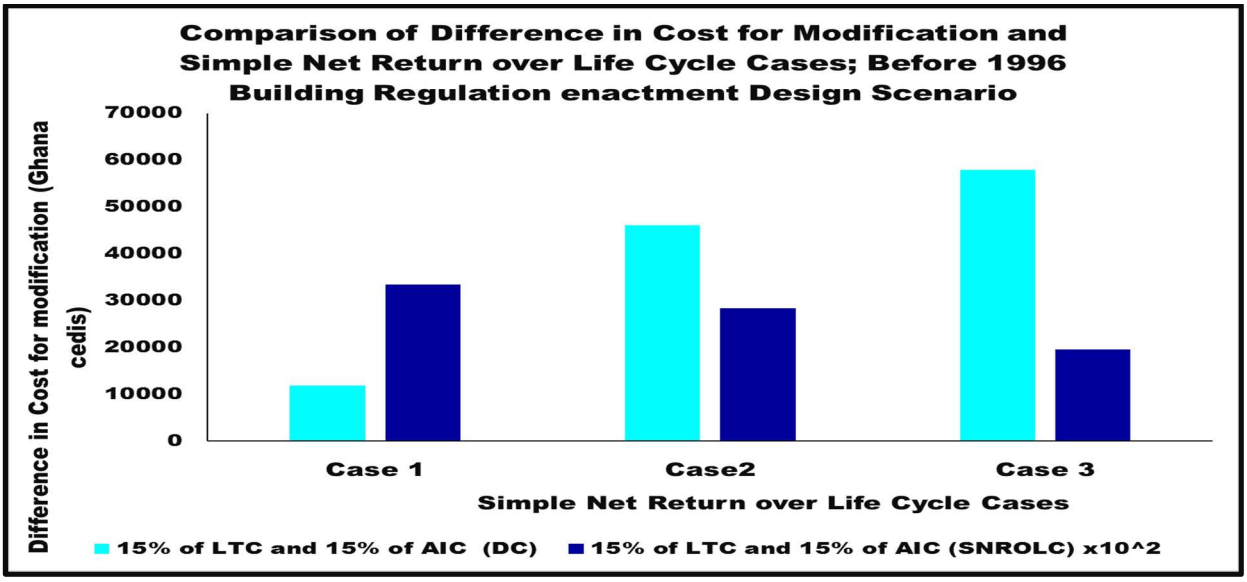

Figure 0.13: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario.

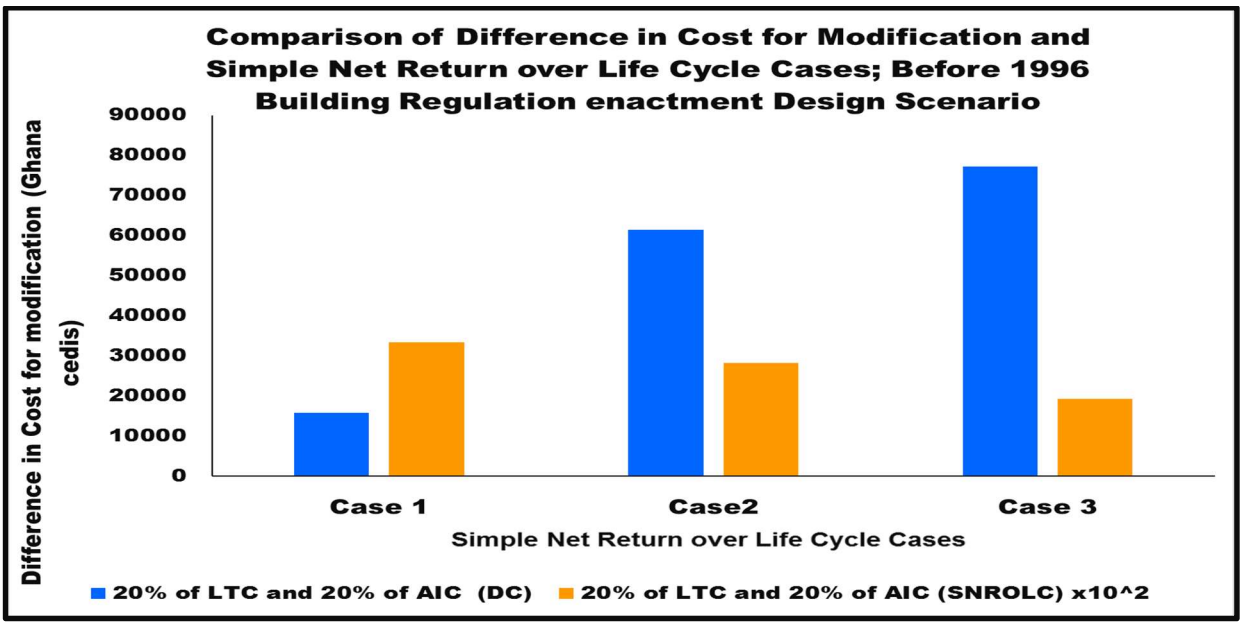

Figure 0.14: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario.

Building design after Building regulation

- Difference in cost vs savings per annum

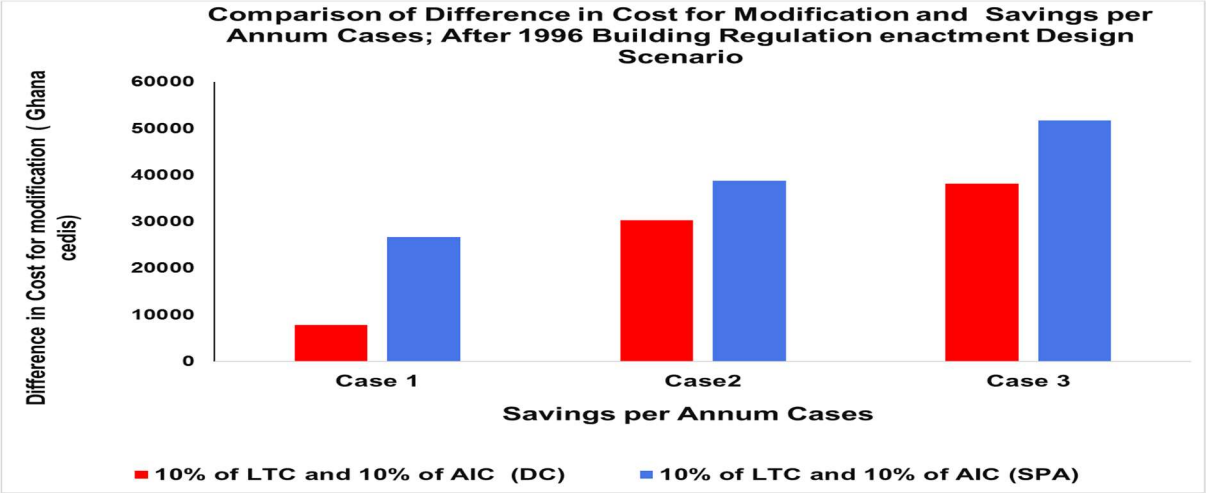

Figure 0.15: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation enactment Design Scenario.

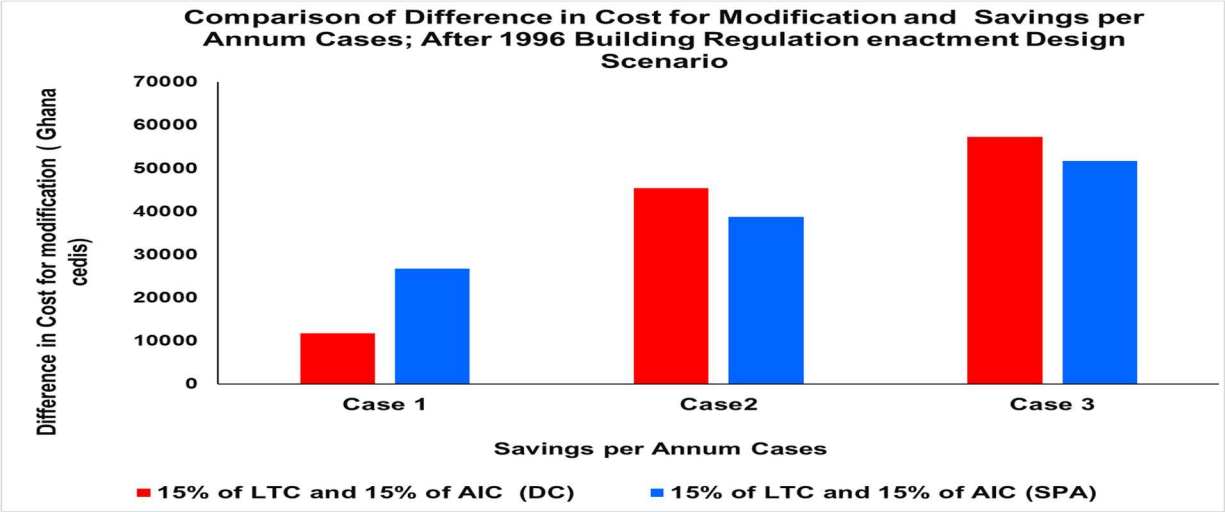

Figure 0.16: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation enactment Design Scenario.

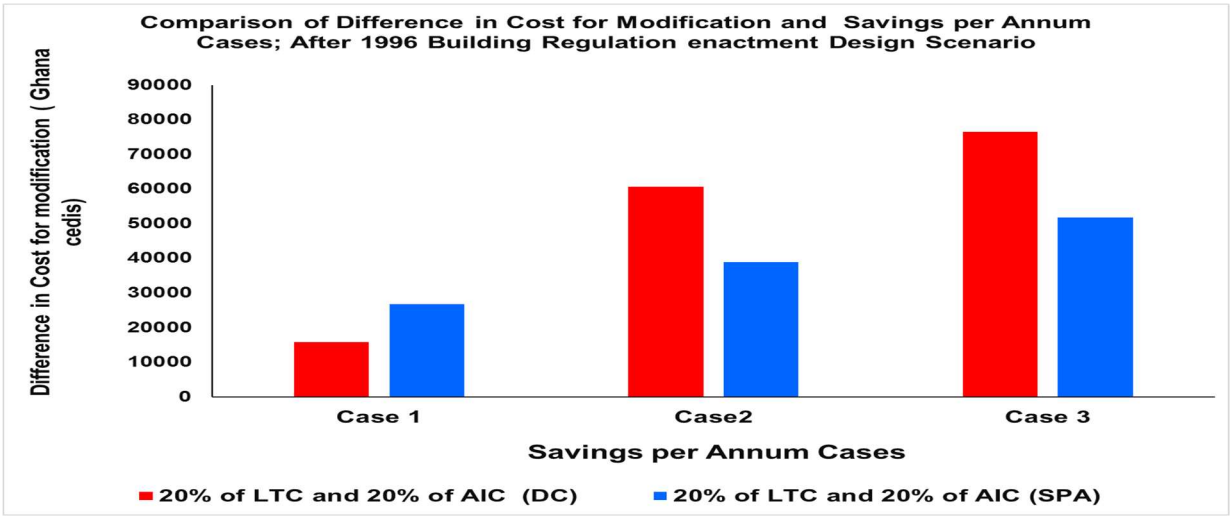

Figure 0.17: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation enactment Design Scenario.

c. Difference in cost vs simple net return over life cycle

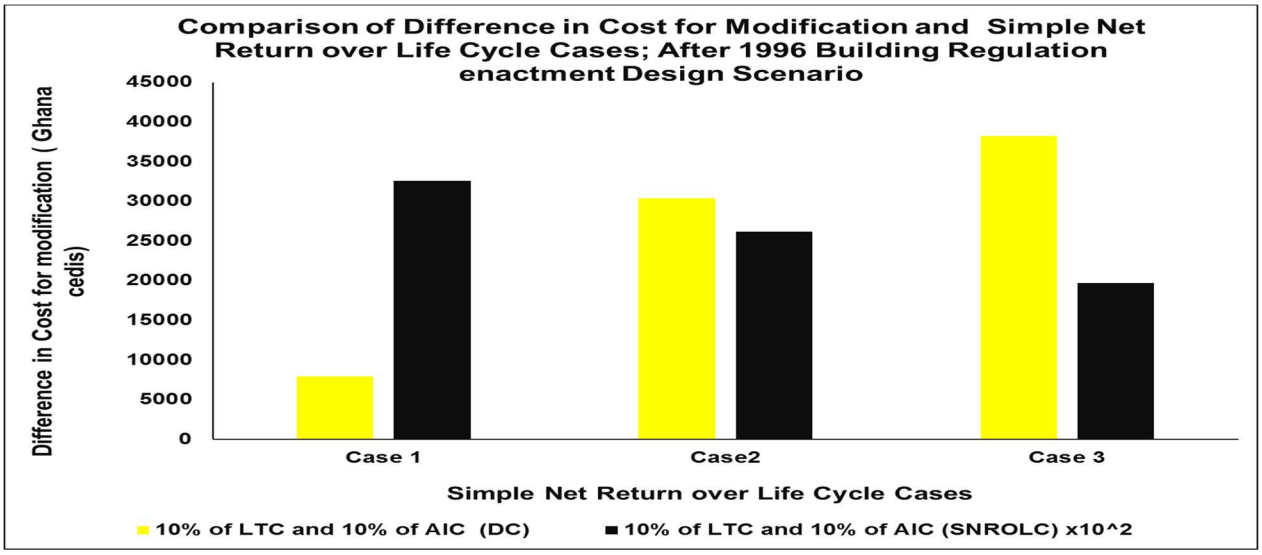

Figure 0.18: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario.

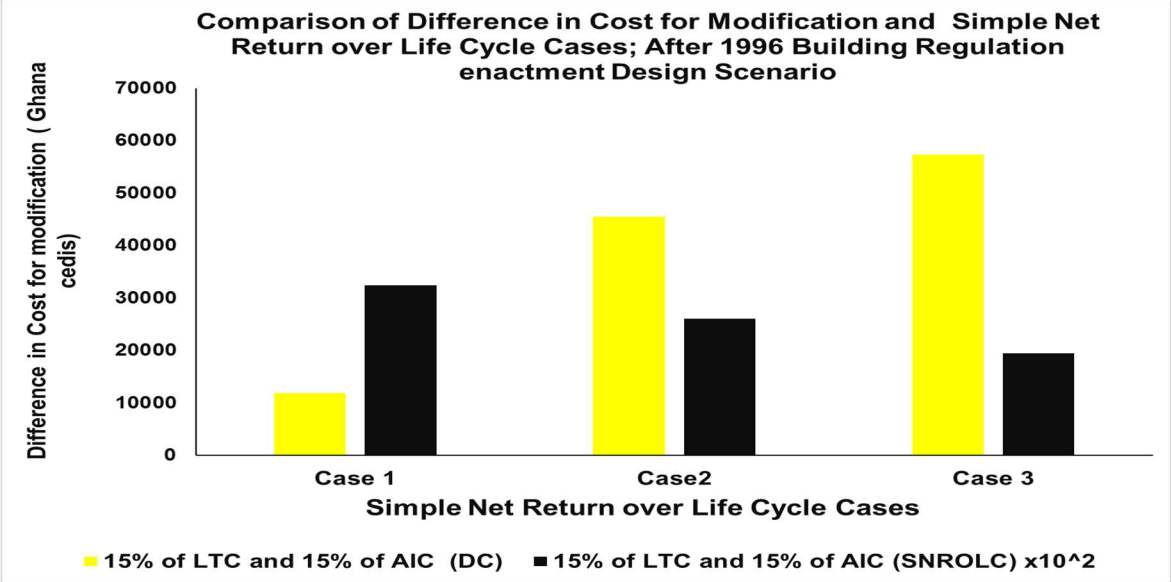

Figure 0.19: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario.

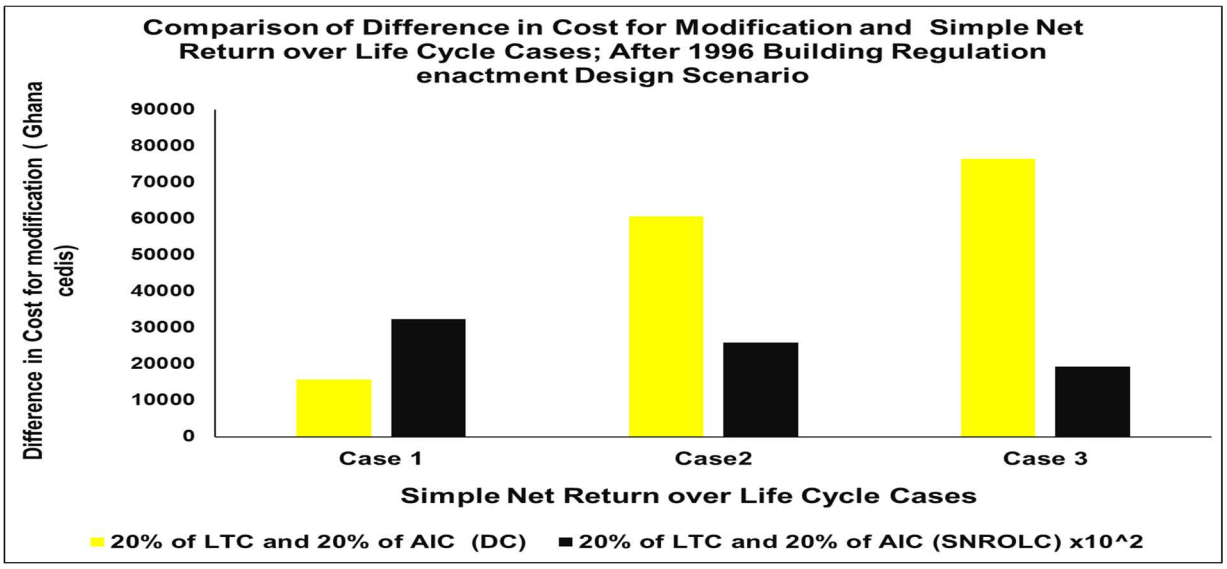

Figure 0.20: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario.

Hypothetical Case

- ✓ Difference vs savings per annum

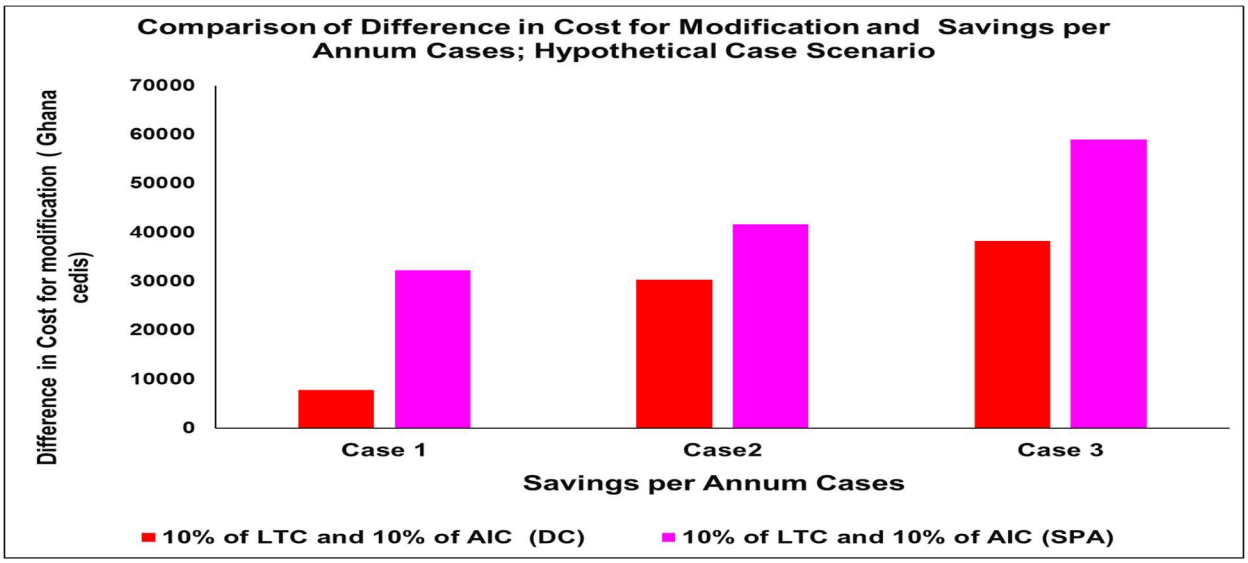

Figure 0.21: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario.

Figure 0.22: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario.

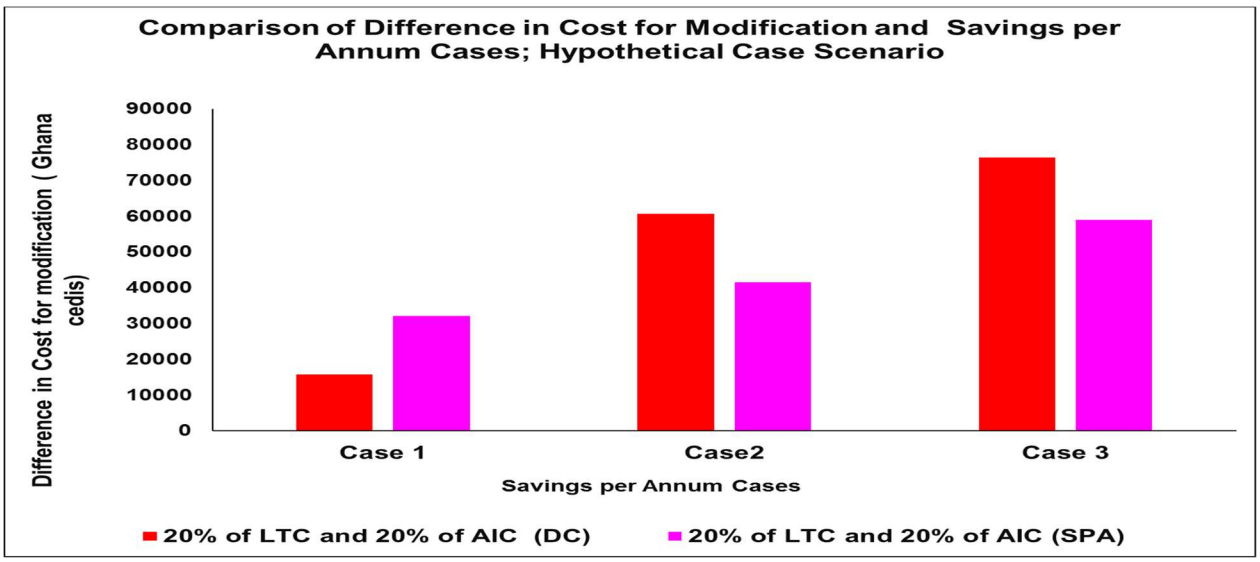

Figure 0.23: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario.

- **Difference in cost vs simple net return over life cycle**

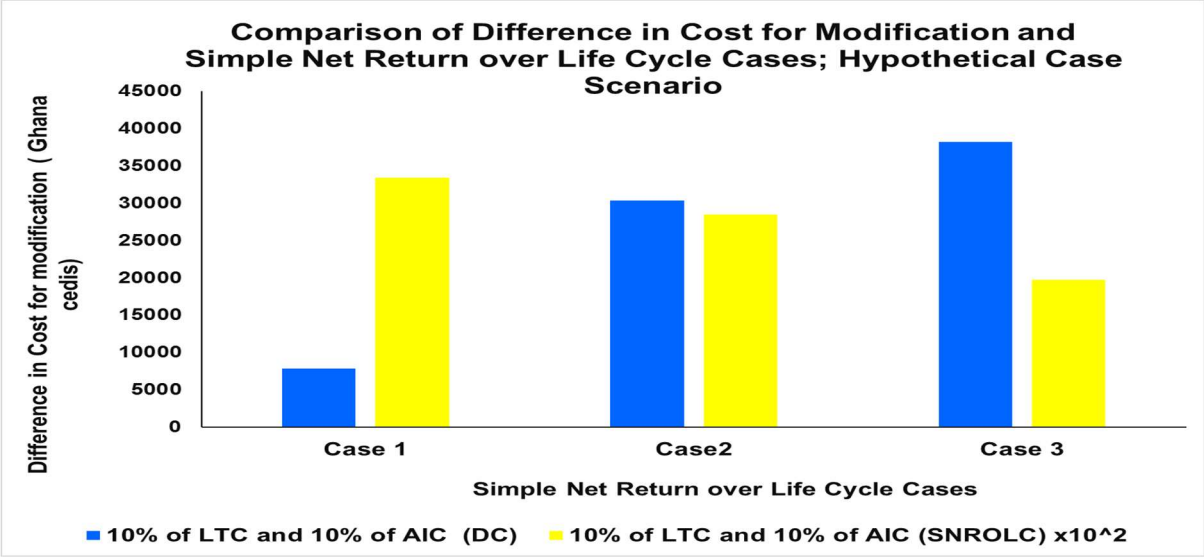

Figure 0.24: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cases; Hypothetical Case Scenario

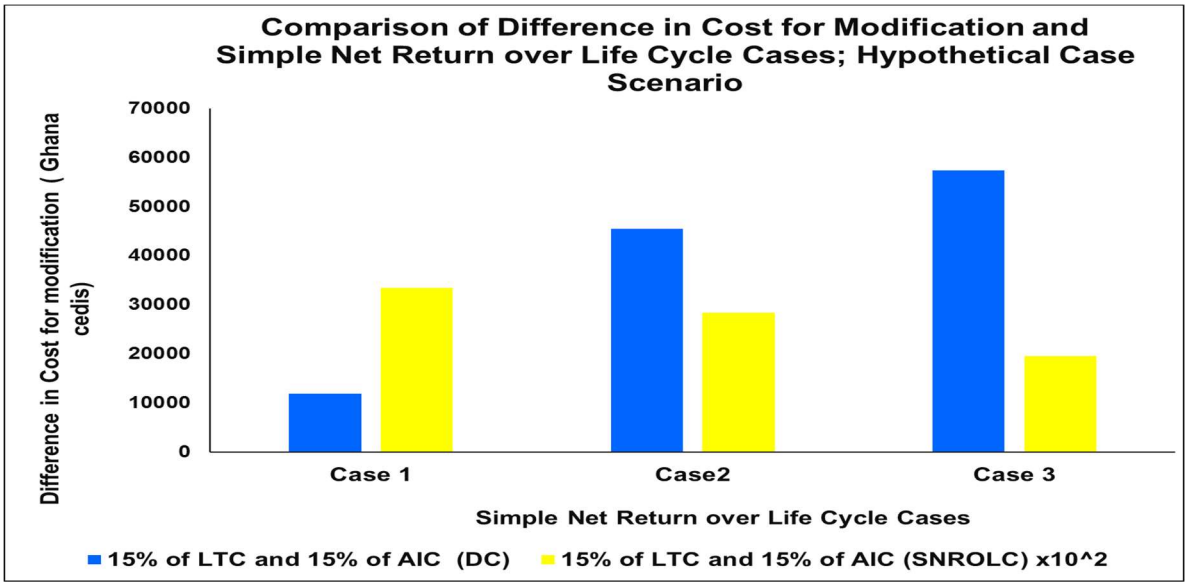

Figure 0.25: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cases; Hypothetical Case Scenario.

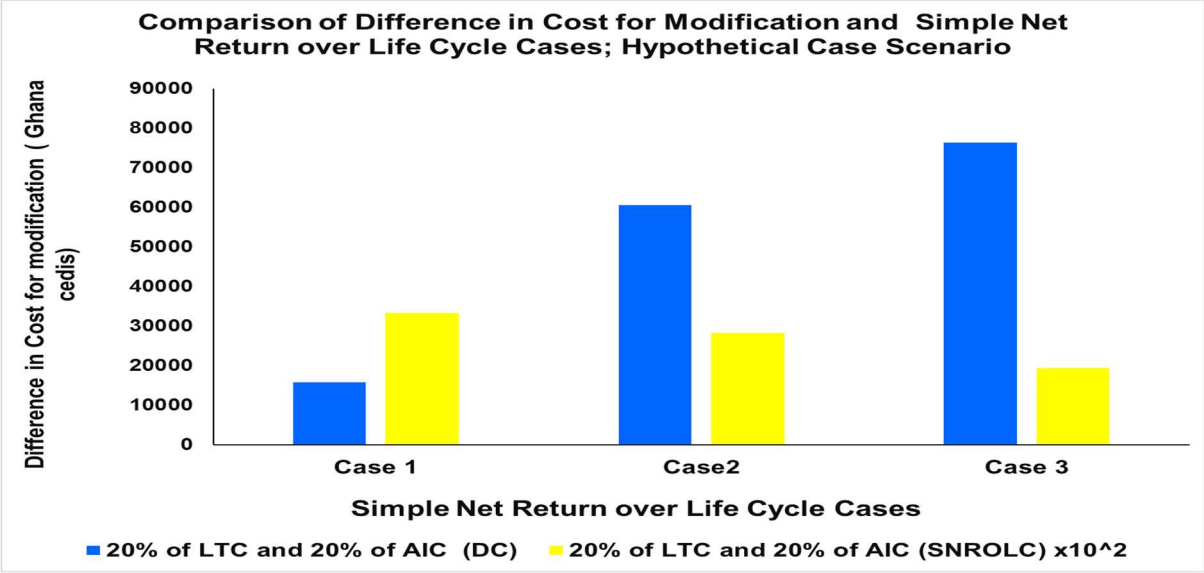

Figure 0.26: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cases; Hypothetical Case Scenario.

Parametric Scenarios using High electricity tariff

Building design before enactment of Ghana regulations

- **Difference in cost vs savings per annum**

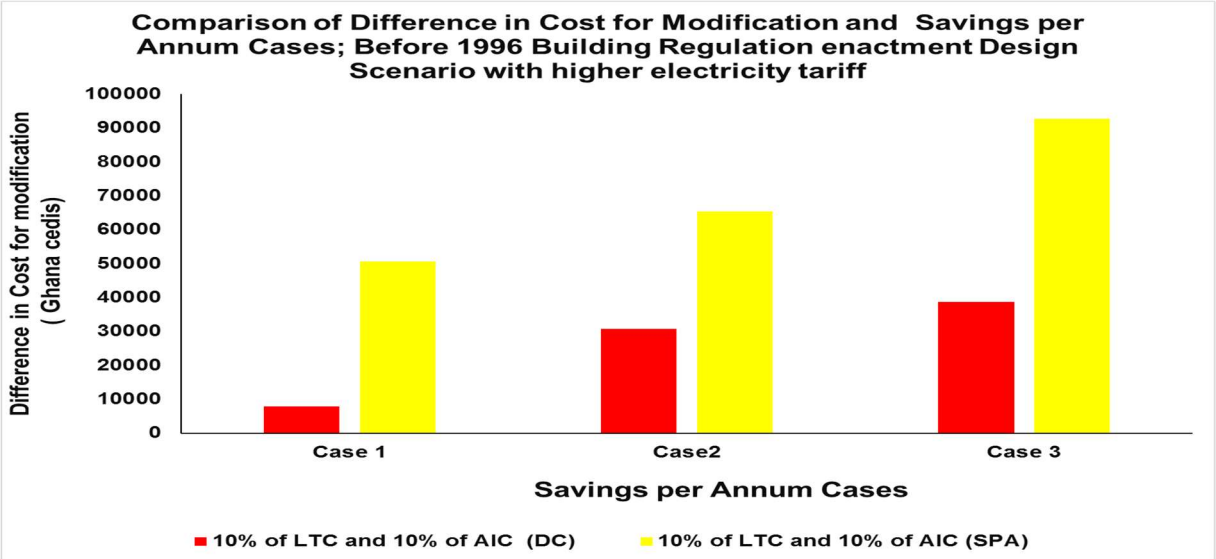

Figure 0.27: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

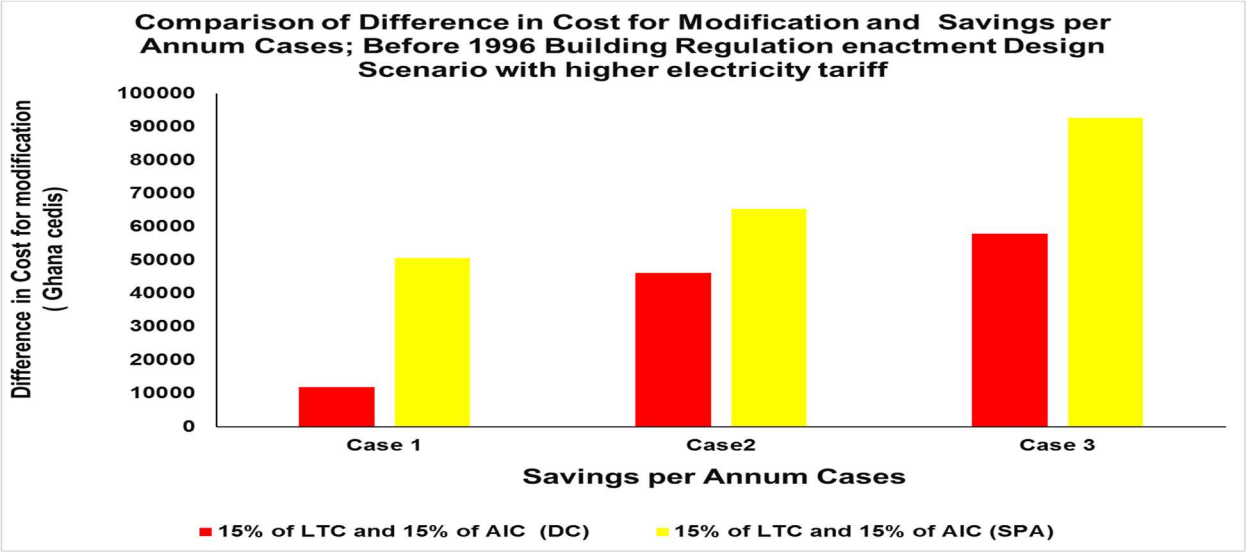

Figure 0.28: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

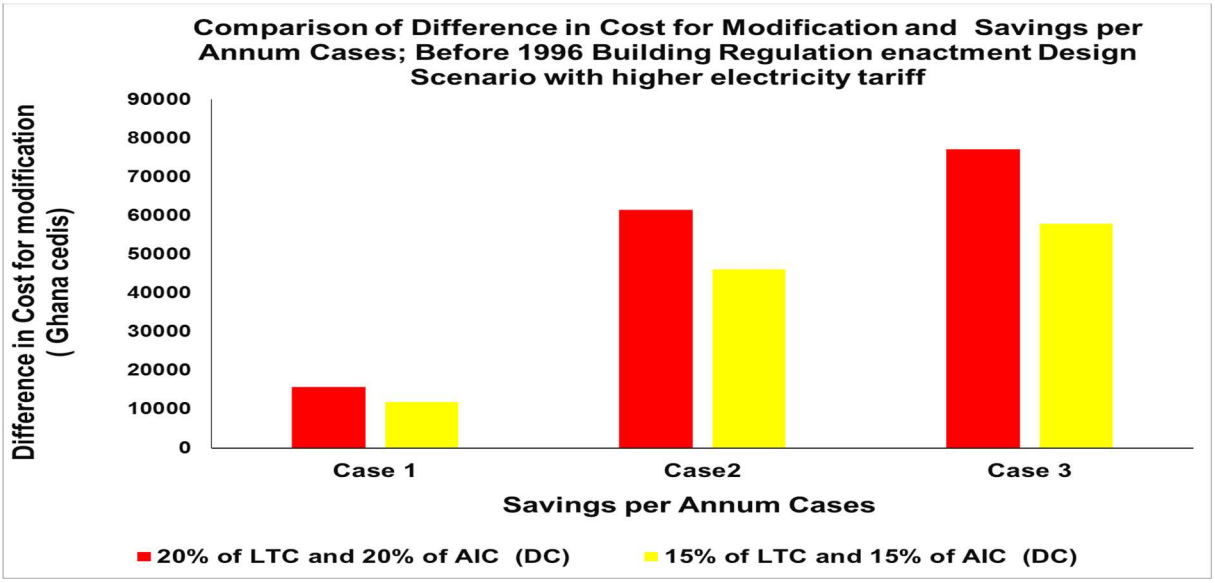

Figure 0.29: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

- **Difference in cost vs simple net return over life cycle**

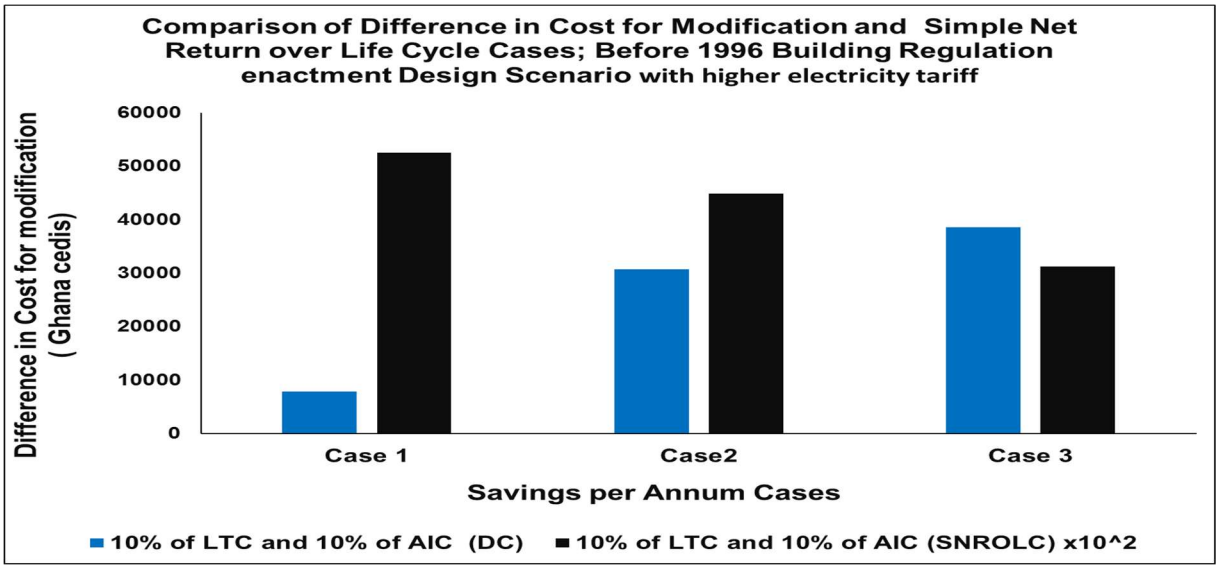

Figure 0.30: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

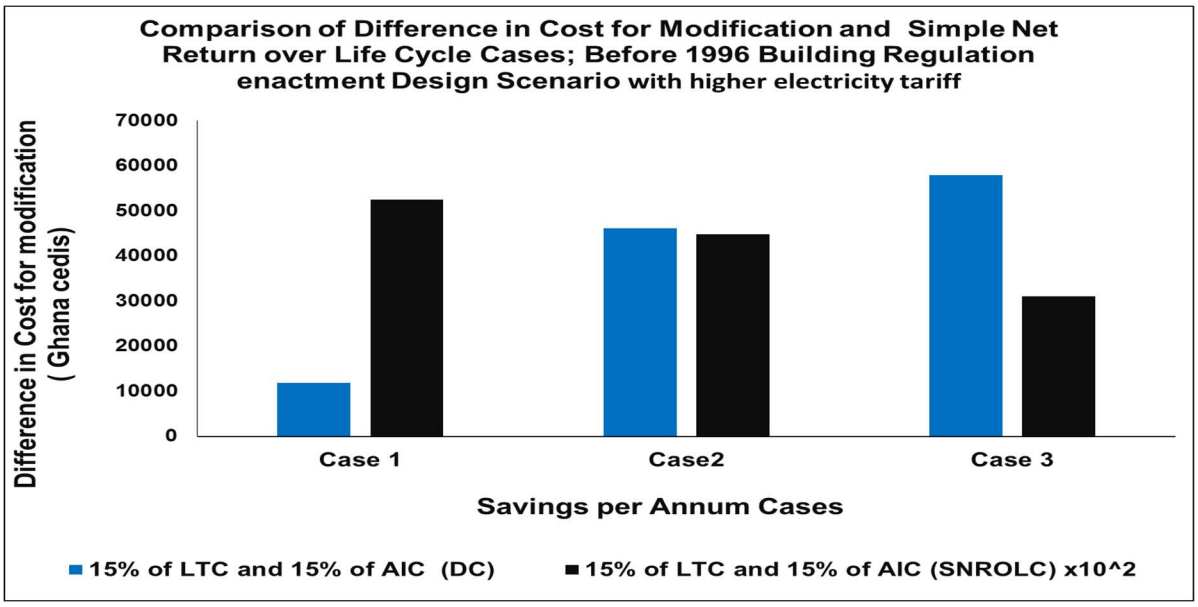

Figure 0.31: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

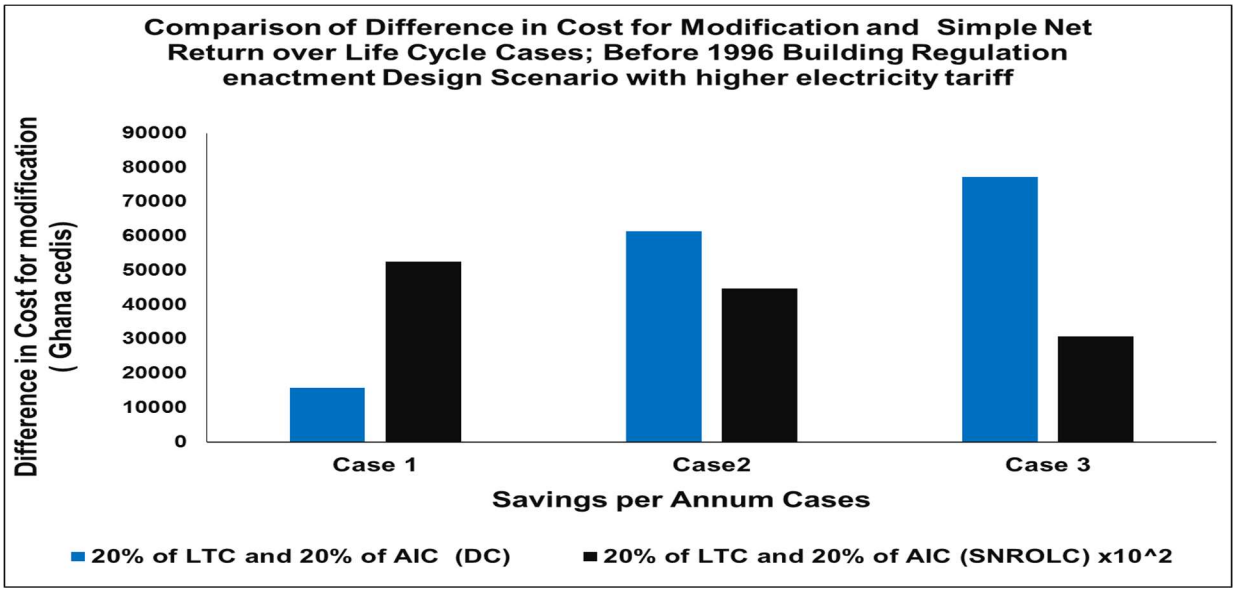

Figure 0.32: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Before 1996 Building Regulation enactment Design Scenario with higher electricity tariff

Building design after Building regulation

- Difference in cost vs savings per annum

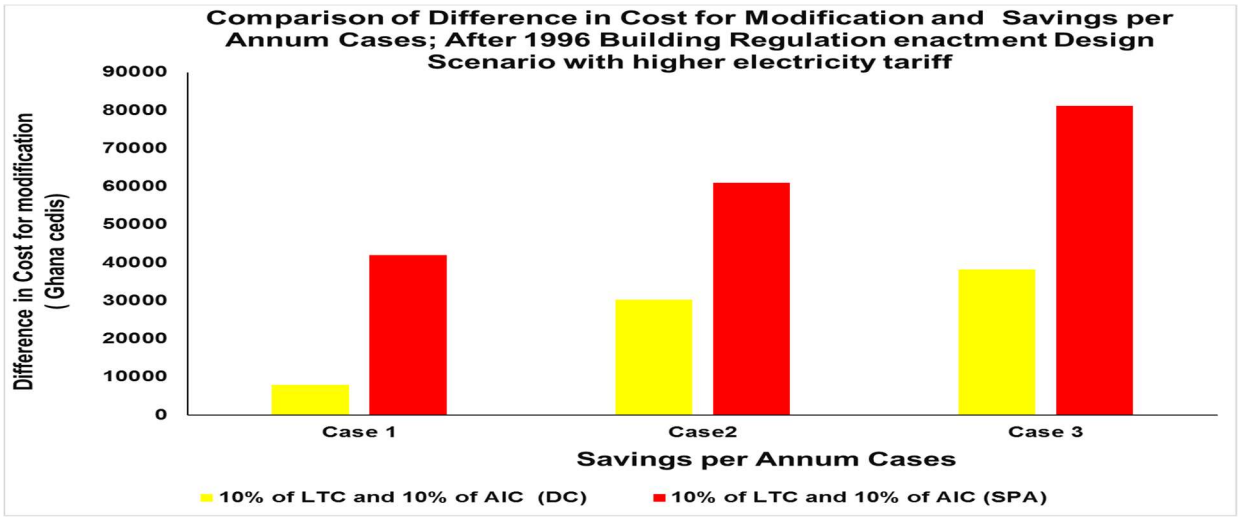

Figure 0.33: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation Enactment Design Scenario with higher electricity tariff.

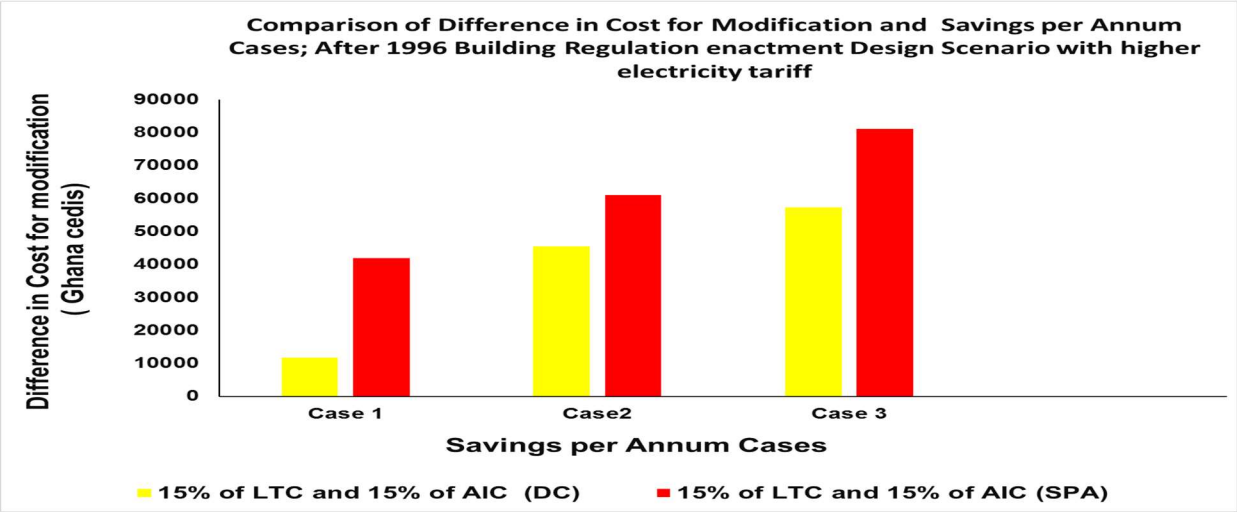

Figure 0.34: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation Enactment Design Scenario with higher electricity tariff.

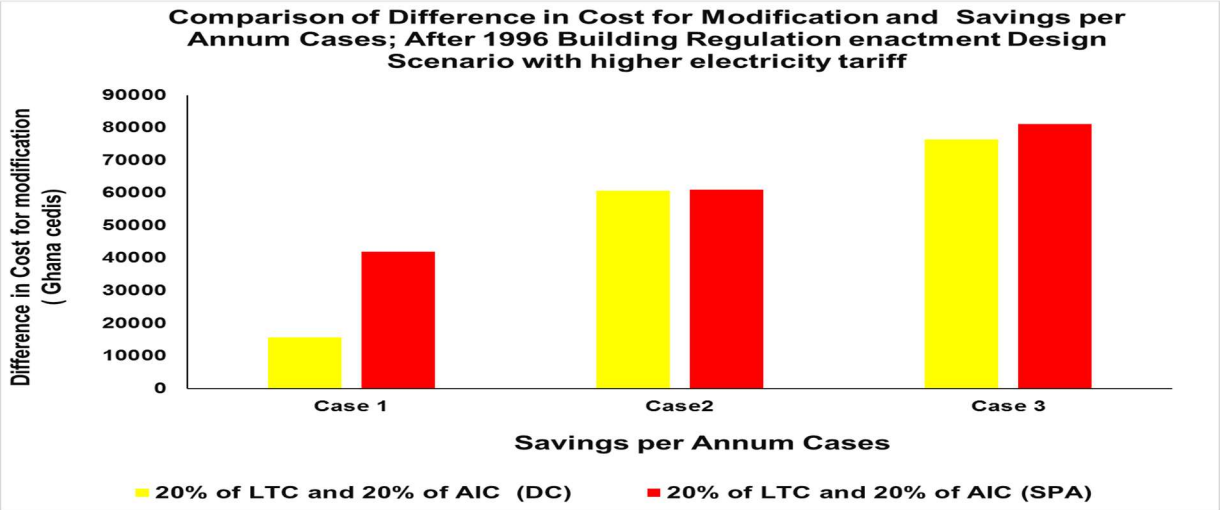

Figure 0.35: Comparison of Difference in Cost for Modification and Savings per Annum Cases; After 1996 Building Regulation Enactment Design Scenario with higher electricity tariff.

Difference vs savings over life time

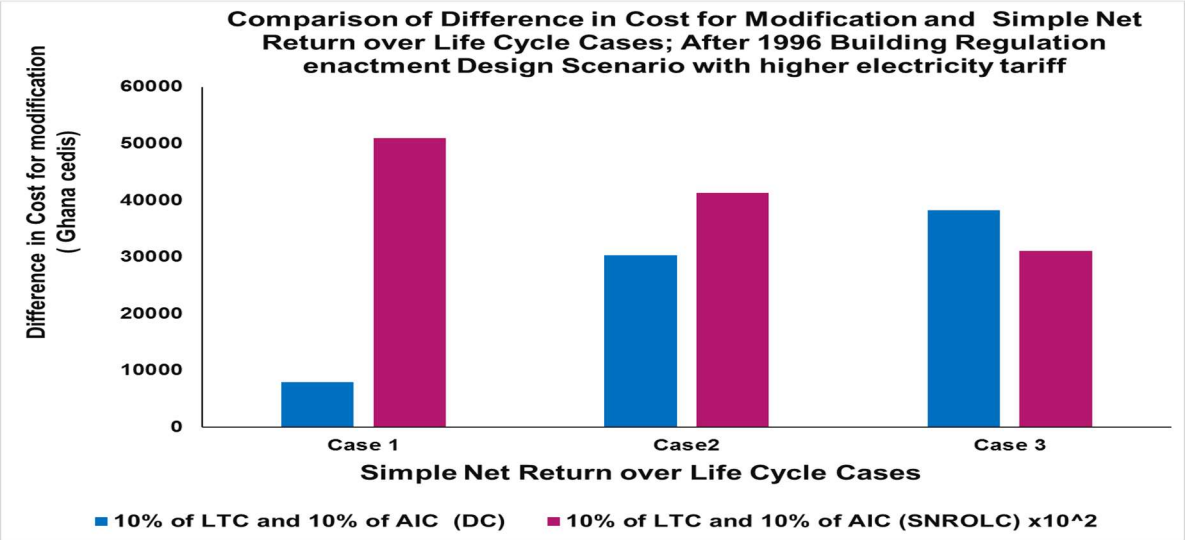

Figure 0.36: Comparison of Difference in Cost for Modification and Simple Net Returns over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

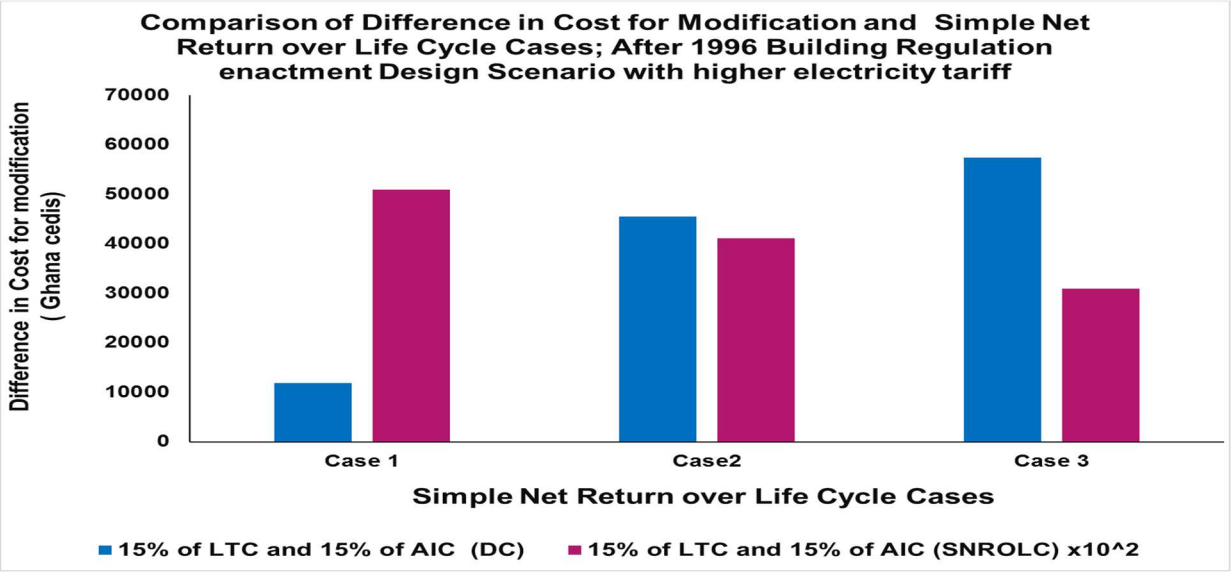

Figure 0.37: Comparison of Difference in Cost for Modification and Simple Net Returns over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario with higher electricity tariff

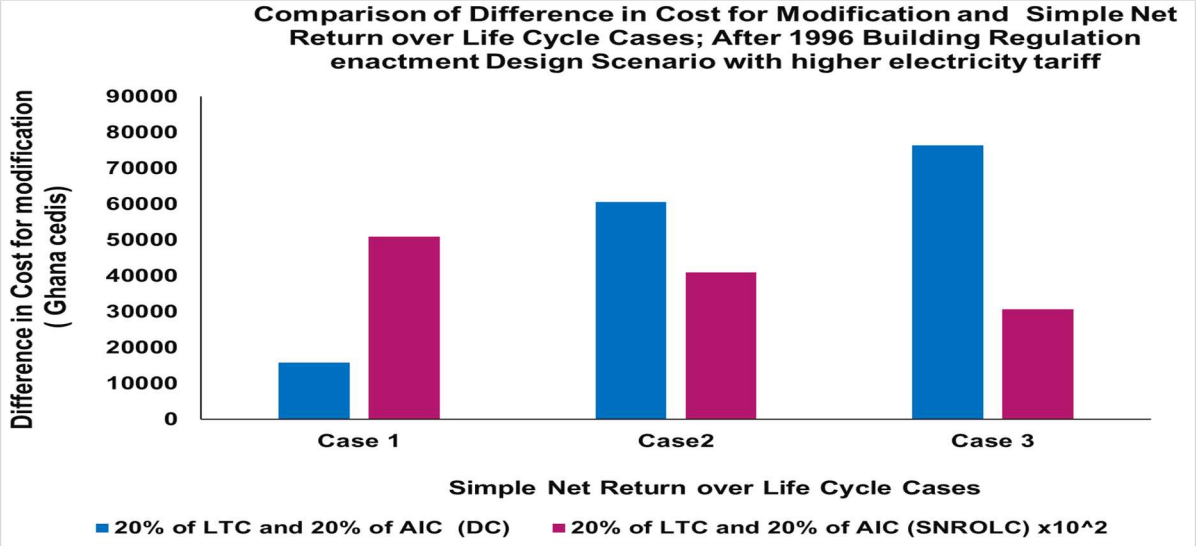

Figure 0.38: Comparison of Difference in Cost for Modification and Simple Net Returns over Life Cycle Cases; After 1996 Building Regulation enactment Design Scenario with higher electricity tariff.

Hypothetical Case

- **Difference in cost vs savings per annum**

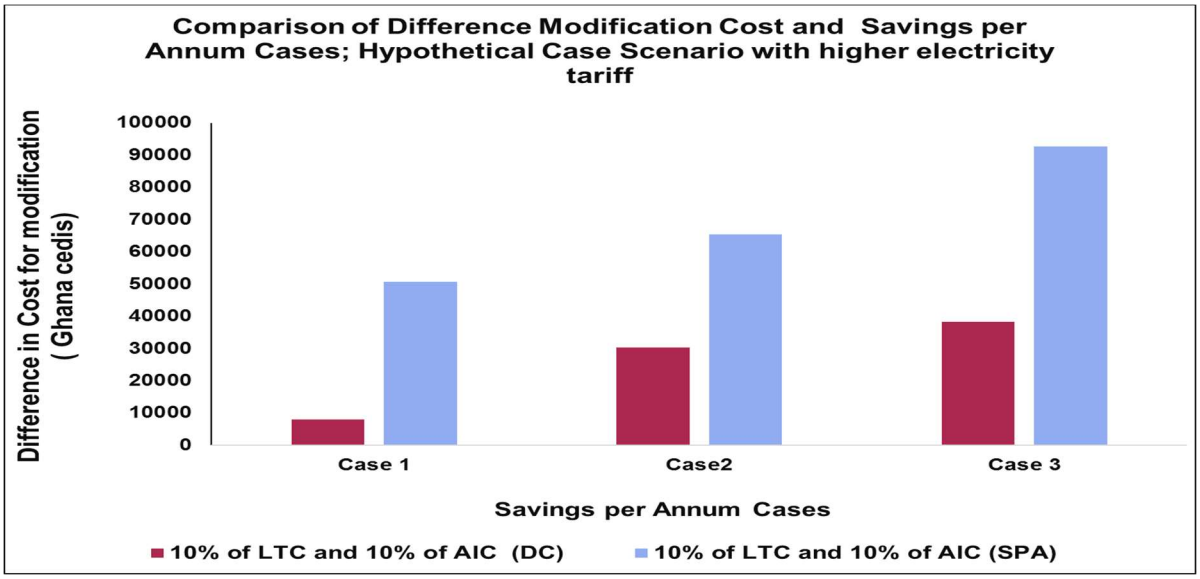

Figure 0.39: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario with higher electricity tariff.

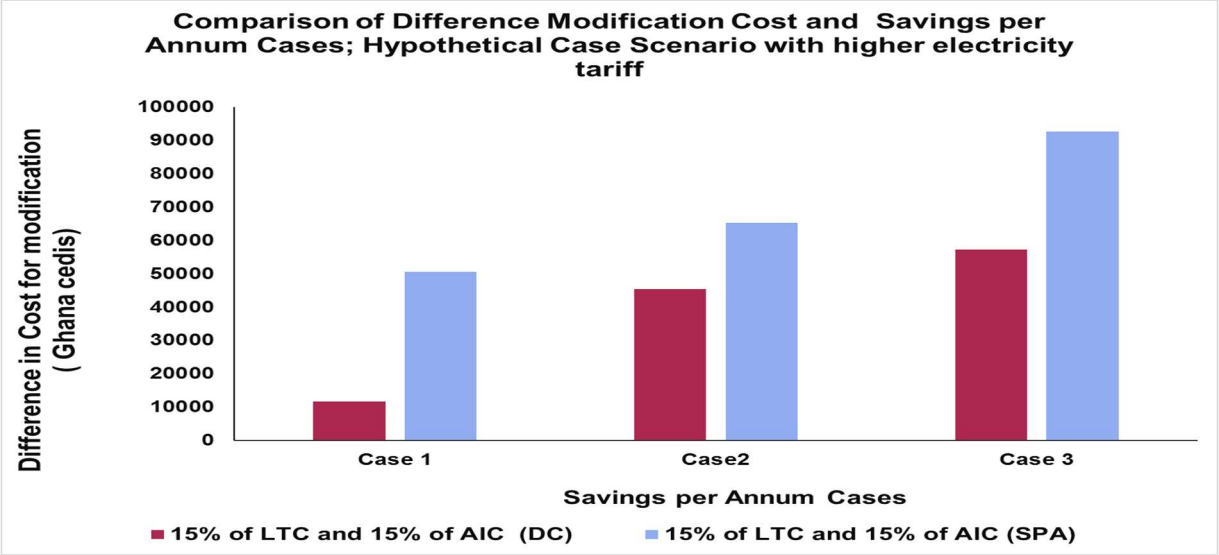

Figure 0.40: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario with higher electricity tariff.

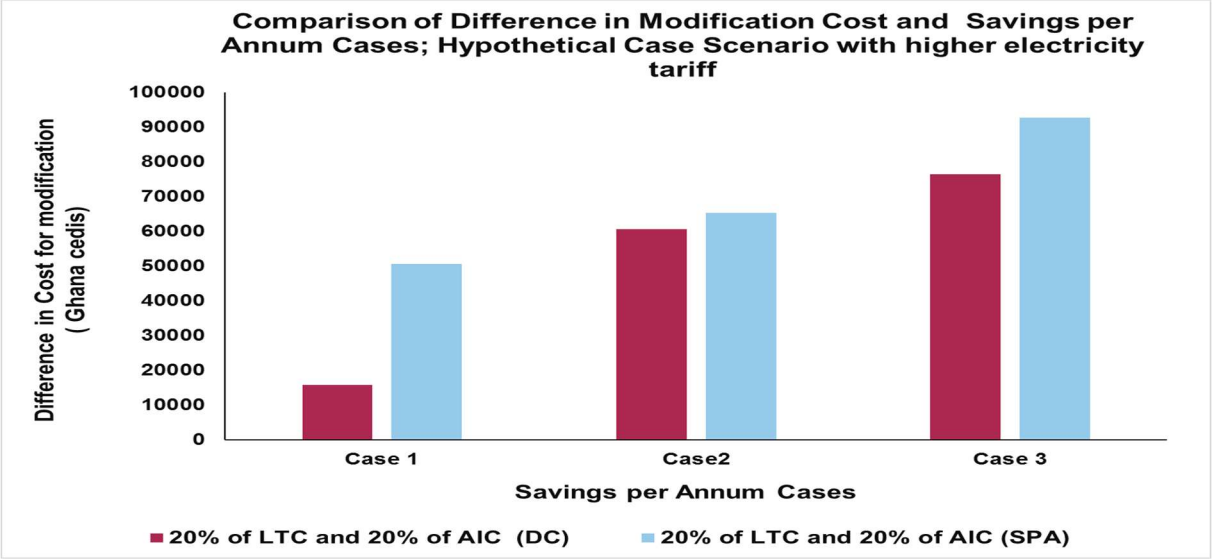

Figure 0.41: Comparison of Difference in Cost for Modification and Savings per Annum Cases; Hypothetical Case Scenario with higher electricity tariff.

❖ Difference in cost vs simple net return over life cycle

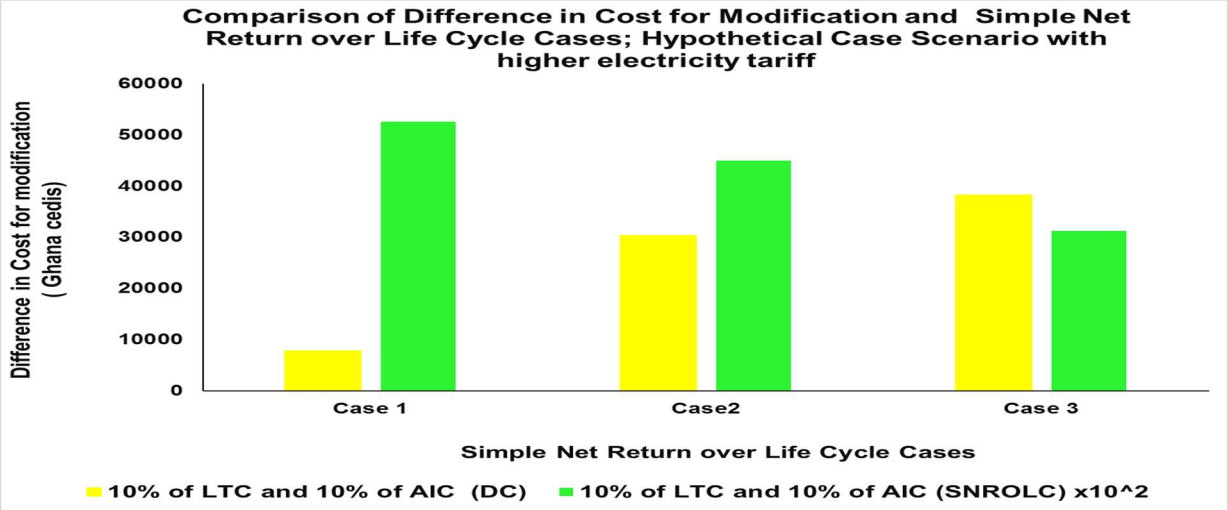

Figure 0.42: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Hypothetical Case Scenario with higher electricity tariff

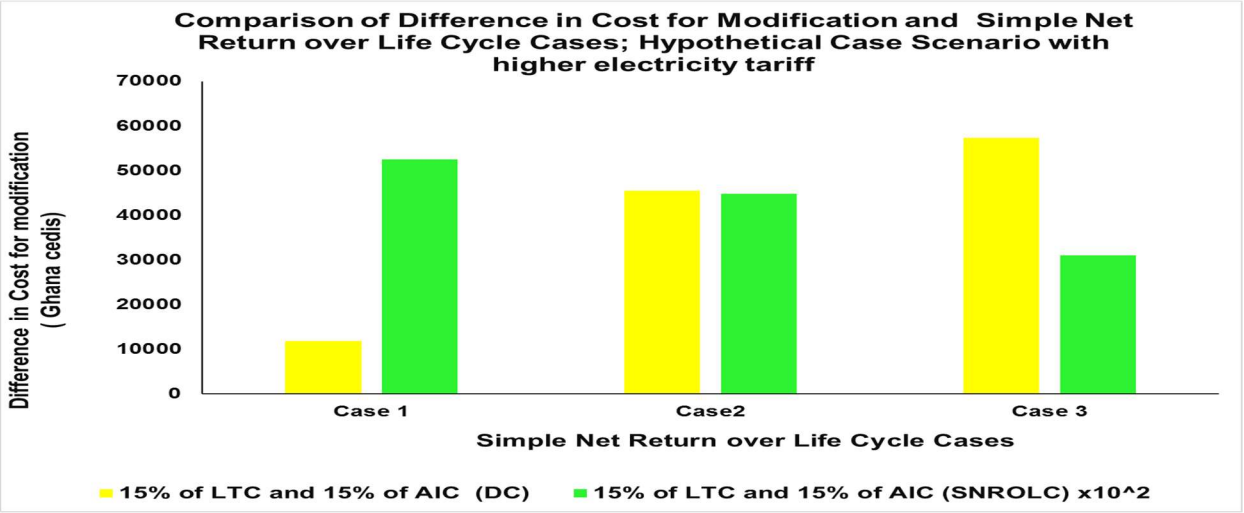

Figure 0.43: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Hypothetical Case Scenario with higher electricity tariff.

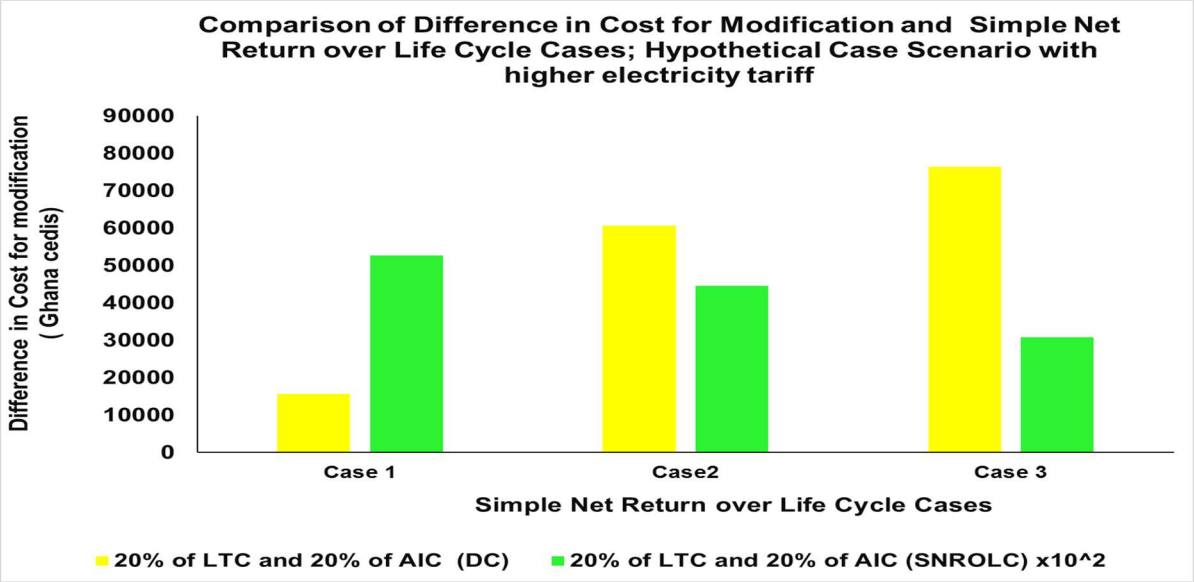

Figure 0.44: Comparison of Difference in Cost for Modification and Simple Net Return over Life Cycle Cases; Hypothetical Case Scenario with higher electricity tariff.