KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY
KUMASI, GHANA

DEPARTMENT OF BUILDING TECHNOLOGY

SIMULATION - BASED EXPLORATION OF THE THERMAL PERFORMANCE OF SELECTED MULTI-STOREY OFFICE BUILDINGS IN ACCRA, GHANA

By

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A Thesis submitted to the Department of Building Technology, Faculty of Built Environment, College of Art and Built Environment in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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DECLARATION

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I hereby affirm that this thesis is my own work towards the award of a PhD and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

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Dedicated with the deepest love and gratitude to my family:

Ms. Gladys Sampah, Ms. Elizabeth Sampah, Mr. George Sampah, Nana Asante Sampah and all my brothers, sisters, in-laws, nephews and nieces

For their love and support

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RESEARCH TEAM MEMBERS

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Members of the research team for the thesis include, Prof. Joshua Ayarkwa, Arc. Dr. Christian Koranteng and Dr. Emmanuel Adinyira.

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ABSTRACT

The lack of empirical data and practical advice on thermal performance and efficient use of energy in buildings are gradually becoming a burden to the country. Amidst the recent advancement in the usage of curtain walls for office buildings, high consumption of energy and poor thermal comfort issues have become dominant. Given the warm-humid climatic characteristics of Ghana, energy needs for cooling of office buildings represent an increasing burden on the environment and the economy. In many instances, the building design is not supported by a detailed analysis and evaluation of thermally relevant features as well as options related to orientation, envelope, glazing ratio, shading devices, and thermal mass. Thus, design decision making is not sufficiently informed by relevant expertise pertaining to energy efficient building design methods and technologies.

By adopting subjective thermal comfort models, building performance simulation and experimental approaches, this research aimed at advancing knowledge on how thermal comfort conditions could be enhanced and energy-use reduced in Ghanaian office buildings. In this context, the research had the following objectives:

i. To assess occupants view of their indoor thermal comfort conditions within the selected buildings. ii. To determine the thermal comfort conditions of the indoor environment of the selected buildings.

iii. To identify energy reduction strategies for the indoor conditions of the selected buildings based on validated models.

iv. To identify overheating reduction strategies (passive case-no air conditioners) of the selected buildings.

Adopting a case study research strategy, a number of data collection methods were employed. Both quantitative and qualitative data were collected and analysed in line with a framework designed to examine and extract relevant materials in relation to the research questions. The research database included 4 multi-storey office buildings (Ridge Towers [R.T.], World Trade Centre [W.T.C.], Premier Towers [P.T.], and Heritage Towers [H.T.]) and 195 occupants‘ questionnaires.

From May, 2012 to April, 2013, indoor and outdoor climatic conditions (mainly temperature and relative humidity) were monitored, using data loggers. To evaluate the existing indoor climatic conditions, measured air temperature and relative humidity values were plotted in the psychrometric and bioclimatic charts. A survey (questionnaire) of 195 occupants was conducted to record their views on indoor environment, installed systems and energy use.

At a general level, the study provided insight into the character of occupants within the buildings, their general views and concerns regarding energy use and thermal comfort. It provided evidence of how the buildings could be made comfortable by means of the psychrometric and bioclimatic charts. Significantly, the study showed how building cooling loads could be reduced to the minimum whiles providing comfortable indoors passively. On the psychrometric chart, the monthly hourly temperature and relative humidity values for R.T. and P.T. were within the comfort zone. All the values for W.T.C. were outside the comfort zone whiles H.T. had the months of January, May, June and July inside the comfort zone. This suggests that R.T. and P.T. could operate passively all year round while H.T. could do that within certain months of the year. W.T.C. was found to be very uncomfortable all year round. Plotting both W.T.C. and H.T. values on the bioclimatic charts, 7 months were within the comfort zone of Olgyay‘s chart in the H.T. building.

This gave an indication of five uncomfortable months for the same building. Givoni‘s chart suggests that W.T.C. could be made comfortable by means of comfort ventilation, conventional dehumidication and air-conditioning for the various months. Olgyay‘s chart suggested that air velocity of between 0.1m/s to 1m/s could improve the comfort conditions of the spaces within the W.T.C. In the H.T., Givoni‘s chart recommends high thermal mass and comfort ventilation whiles Olgyay‘s chart proposes air velocity of 0.1m/s to get the other 6 months within the comfort zone.

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Additionally, the analysed data from the questionnaire among others showed that the three most important parameters for occupants‘ satisfaction in the office spaces studied were air quality, thermal comfort and fire safety. Again, the respondents (occupants) were interested in receiving training on the effective and efficient operation of building systems, which could help increase satisfaction, comfort and reduce energy performance of buildings.

The calibrated simulation results suggested that measures regarding building fabric and controls could improve buildings‘ energy performance. Particularly, careful combinations of improvement measures (such as efficient glazing, thermal mass, façade insulation, night ventilation, efficient electrical lighting, form and orientation) have a significant potential to reduce buildings' cooling loads (31% – 49%) in the climatic context of Accra.

When the buildings operated passively, the alternative improvement scenarios considerably reduced the mean overheating in the offices up to about 2.9K, depending on the reference overheating temperature assumption. Though not exactly identical, there is a clear correspondence between the ranking of the scenarios in view of lower cooling demands (active building mode) and lower overheating tendency (passive operation mode).

A significant contribution of this research to the body of knowledge is the provision of empirical evidence with respect to improvement of thermal performance in multi-storey office buildings in Accra, Ghana. Until the current research, the above assertion had not been supported by any empirical study within the localized climate of the capital city of Ghana. Another significant contribution of this research to the body of knowledge is the provision of sufficient evidence to confirm that the procedure for the determination of the comfort zone on the psychrometric chart could be adjusted for tropical climates where people are generally adapted to higher relative humidity and moderate temperatures. Validated simulation models are used in retrofit analysis for improvement in the thermal performance of buildings. Therefore another significant contribution of this research is the achievement of validated simulation models for energy assessment in multi-storey office buildings in Ghana. This provides a reference point for future validated simulation studies involving multi storey office buildings with curtain walls in Ghana. Moreover, this study is the first of its kind in the climatic context of Accra, Ghana

Keywords: Thermal Comfort, Simulation, Energy Performance, Cooling Loads, Occupants, Behaviour, Office Buildings, Passive, Exploration, Psychrometric, Bioclimatic Chart.

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KNUST

TABLE OF CONTENT

Content **Page**

KNUST

KNUST

KNUST

NYANSAPO W ɔ SANE NO BADWEMMA

KNUST

NYANSAPƆ WↃSANE NO BADWENMA

KNUST

LIST OF TABLES

KNUST

Page

LIST OF TABLES CONT'D

KNUST
NYANSAPƆ WƆSANE NO BADWENMA

LIST OF FIGURES

KNUST

LIST OF FIGURES CONT'D

KNUST

LIST OF FIGURES CONT'D

KNUST
NYANSAPO WO SANE NO ADWENMA

LIST OF FIGURES CONT'D

KNUST
NYANSAPO WOSANE NO BADWENMA

LIST OF FIGURES CONT'D

KNUST

LIST OF FIGURES CONT'D

KNUST
NYAMPA W J SANE NO BADWENMA

LIST OF FIGURES CONT'D

KNUST
NYANSAPƆ WƆSANE NO BADWENMA

LIST OF FIGURES CONT'D

KNUST

LIST OF EQUATIONS

Equation Number	Description	Page
Eq. 1	$T_{n,o} = 17 + 0.38T_o$	24
	Where: $T_{n,o}$ - neutral temperature based on mean outdoor air temperature. T_o - outdoor air temperature	
Eq. 2	$T_{n,i} = 2.6 + 0.831T_i$	24
	Where: $T_{n,i}$ -neutral temperature based on mean indoor air temperature, T_i - mean indoor air temperature,	
Eq. 3	$T_{n,o} = 11.9 + 0.534T_o$	24
	Same interpretation as Eq. 1	
Eq. 4	$T_{n,i} = 5.41 + 0.731T_i$	24
	Same interpretation as Eq. 2	
Eq. 5	$T_{n,o} = 17.6 + 0.31T_o$	24
	Same interpretation as Eq. 1	
Eq. 6	$T_{n,i,o} = 9.22 + 0.48T_i + 0.14T_o$	24
	Combination of Eq. 1 and 2	
Eq. 7	$T_c = 17.8 + 0.31T_o$	24
	Where: Tc is the comfort temperature	

KNUST
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T_o - outdoor air temperature

LIST OF EQUATIONS CONT'D

Equation Number **Description**

Eq. 8 $Tn = 17.6 + 0.31 * To.av$ 30

Where: Tn is the neutrality temperature

To.av is the mean monthly outdoor temperature

Eq. 9

$$OH_m = \sum_{j=1}^{n} \frac{\theta_{i,j} - \theta_r}{n}$$

109

Where: θi,j represents the mean indoor air temperature (°C) at hour j (averaged over all simulated office zones in the floor),

θr ; the reference indoor air temperature for overheating (°C), and n the total number of occupied office hours. The term θi,j – θr was considered for those hours when θi,j > θr.

KNUST
NYANSAPƆ WƆSANE NO BADWENMA

Page

KNUST

LIST OF PUBLICATIONS EMANATING FROM THE THESIS

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2. Simons, B., Koranteng, C., Adinyira, E., (2014). Indoor Thermal Environment: Occupants Responsiveness in 4 Multi-Storey Office Buildings in Accra, Ghana. **Journal of Environment and Earth Science, 4 (4), pp 122-130. ISSN 2225-0948, (USA, UK and Hong Kong).**
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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

In every country in the world, the built environment normally constitutes more than half of the total national capital investment and construction represents as much as 10% of Gross National Product (Confederation of International Contractors Association: CICA, 2002). The World Watch Institute estimated that buildings consume at least 40% of the world‘s energy (Roodman and Lenssen, 1995). Energy is connected with all aspects of development and has an incredible impact on the well being of urban citizens: on their health, education, productivity, economic opportunities, etc. Unfortunately, the current situation of energy supply and it‘s utilisation in both the developed and the developing world is worrying.

Best buildings are not only exemplars of form, grace, building technology and aesthetics; they also help in the development of the organizations that use them. Well-briefed and well-designed office buildings reflect the value and aspirations of the occupying organisation (Ulrich, 2005). With most of the urban population spending many hours in office buildings, it is imperative to provide a good indoor climate and efficient building systems with less energy usage as possible. According to Pino et al. (2012), many modern buildings have taken advantage of glass transparency in their design to create clear views to the outside. When using a high window-towall ratio (WWR; ratio of the glazed area with respect to the total area of the exposed envelope), occupants commonly might feel thermal and/or visual discomfort and they will apply their own strategies to mitigate this problem.

Thermal comfort is defined as the state of the mind which expresses satisfaction with the surrounding environment (American Society of Heating, Refrigerating and Air- Conditioning Engineers: ASHRAE, 2004). Thermal comfort however requires a subjective evaluation (Szokolay, 2004). The factors affecting thermal comfort depend on four environmental parameters (i.e. dry bulb temperature, mean radiant temperature, relative humidity and air velocity) and two personal parameters (clothing-insulation and physical activity.), though these two can be expanded to include other factors (Szokolay, 2004). The evaluation of thermal satisfaction at workspaces therefore makes use of the above parameters to calculate the Predicted
Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) persons within a building. This (PMV-PPD) is a model developed by Fanger in 1972 based on climate chamber test.
Fanger's PMV-PPD values have been standardized by organisations such as American Society of Heating Refrigerating and Air- condition Engineers (ASHRAE) and the International Standards Organisation (ISO) (Charles et al., 2005). This has formed the basis for a good number of thermal comfort studies around the world. However, Humphrey and Nicol (2002) asserted that field studies on thermal comfort have shown that the PMV-PPD model does not accurately predict the actual thermal sensation of occupants for all environments; basically due to measurement error and contextual assumptions.

In time past, a number of researchers have tried to give temperature and relative humidity ranges best suited for tropical regions. A comfort range of 23°C - 29°C with a relative humidity of 30% - 70% was suggested by Brooks, as cited by Olgyay in 1963. Koenigsberger et al. (1974) also proposed 22°C - 27°C with an optimum temperature of 25°C. In more recent times however, Keneally (2002) is of the opinion that the general consensus of suitable design set point for tropical buildings is 25°C and 60% relative humidity. Charles (2003) also cites ASHRAE Standard 55

(ASHRAE, 1992) to have proposed a comfort range of 23°C -26°C with a relative humidity value of 50%. In addition, Ferstl (2005) suggests 22°C - 26°C and 30% - 80% relative humidity as optimal values for indoor comfort. Architecturally, the hot and humid region is one of the hardest climates to improve through design. This is due to the high humidity and daytime temperatures that result in high indoor temperatures exceeding the ASHRAE summertime comfort upper limit of 26°C for most of the year (Hyde and Sabarinah, 2008).

Degelman (1999) notes that over the last forty years thermal processes in building energy performance simulation have been brought to perfection. However, user behaviour has a much larger influence on the energy performance of a building than the thermal process within the building façade (Huang et al., 2012). Human behaviour and their effect on the thermal process as well as energy performance of a building cannot be underestimated (Degelman, 1999). Mahdavi and Pröglhöf (2009) asserted that it is common knowledge that the presence and actions of building occupants have a considerable impact on the performance of buildings (energy efficiency, indoor climate, etc.).

Hoes et al. (2009) also observed that occupant perception of so-called conserved, centrally airconditioned buildings with open plan floor layouts that provide minimal adaptive opportunity', with no option for opening windows, is negative. Furthermore, Rijal et al. (2007) as cited by Hoes et al. (2009) states that the application of user behaviour models with higher resolution and higher complexity will improve the understanding of the relation between building, user and building performance. Occupant satisfaction and not just preference is not only with respect to thermal comfort but also on the visual and audible environment, the indoor air quality and the office layout. Altogether, these are referred to as individual satisfaction parameters (Wagner et al., 2007).

Eventually this should result in better building designs. Studies on user behaviour and interaction with building systems for comfort reasons are increasing the knowledge and understanding of building performance.

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In Ghana today, it has become a growing trend to design commercial buildings with large or totally glazed facades. Energy requirements for cooling of office buildings therefore represent a growing burden for both the environment and the economy. Most multi storey office buildings have in recent times become heavily glazed. Radiating much heat into the indoors and making them uncomfortable. Consequently, there is a wider use of air conditions (AC) in a great number of commercial and public office buildings and an expansion of the AC market (Santamouris, 2005). Again, in referring to the International Institute of Refrigeration study, Santamouris (2005) revealed that AC use is responsible for about 15% of all electricity consumed worldwide (ibid). In Ghana, projections made by the Volta River Authority (VRA) revealed that in 2012, Ghana_s total electricity generation capacity was 3,491MW, out of which thermal sources contribution increased to 55% (Sackey, 2007). The significant contribution by thermal sources to the national electricity generation capacity suggests that the component that will contribute carbon emissions into the atmosphere will increase. It has been projected that Ghana will need more than 7 times its 2007 electric power capacity by 2020 if it should succeed in developing its economy into a middle income one (Ofosu-Ahenkorah, 2007).

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1.2 Problem Statement

Energy is the most important engine to improve upon the quality of life and fight poverty. Given that by 2020 almost 70% of the world population will be living in cities, 60% will be energy poor

(Serageldim and Brown, 1995). Thus for the next decade, thousands of megawatts of new electrical capacity have to be added to the old power. Der Petrossian (1999) stated that developing countries may avoid spending USD 1.7 trillion on oil refineries, coal mines and new power plants by spending for the next 30 years USD 10 billion annually to improve energy efficiency and conservation. Another estimate by the US Office of Technology Assessment shows that developing countries have the potential to half their electricity production if energy is used more effectively.

In the building sector, the increased use of air-conditioners, inefficient curtain walls and sliding windows, and the lack of sustainable design principles, especially in office buildings have contributed to the energy situation in Ghana (Koranteng, 2010). Moreover, the growth in demand for energy is among other factors caused by the numerous air-conditioned commercial buildings being constructed especially in the Metropolitan cities of Accra and Kumasi. Occupants' behaviour in these multi storey office buildings has always been to abate thermal discomfort. These behaviours have an eventual effect on energy. However, the exact effect has been insufficiently studied, especially in developing countries like Ghana.

Humphreys and Nicol (1998) introduced an adaptive approach to human comfort stating that people retort in ways which tend to restore their comfort, if a change occurs such as to produce discomfort. This study and other similar ones as cited by Mahdavi (2011) have provided a number of valuable insights into the circumstances and potential triggers of occupancy control actions in buildings. However, given the complexity of the domain, additional long-term and (geographically and culturally) broader studies are necessary to arrive at more dependable (representative) models of control-oriented user actions in buildings.

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A study by Koranteng et al. (2011) involving the subjective feelings of thermal comfort in three multi storey office buildings in Accra-Ghana over a period of 1 month, indicated that there was a higher preference for air-conditioned office environment than there was for naturally ventilated office environment. Consequently, all the occupants did not take advantage of the cool morning breeze to ventilate their offices in the morning before using the air-conditioners (in some cases, not all the windows could be opened). Occupants as a result set their thermostats to between 18 and 26°C. Moreover, about 85% of the occupants did not switch off their air-conditioners during absence from their offices. Less than 40% of the respondents also thought about energy conservation when operating building systems. Comfort issues seem to play a key role in the day-to-day operation of commercial buildings. Comfort problems have predominantly settled around the lack of understanding of human comfort and its in situ assessment (Wagner, 2007).

The above study (Koranteng et al., 2011) is worth looking into over a longer period of time in order to assess and validate occupant behaviour, thermal comfort and the eventual implication on energy performance. According to the International Energy Agency (IEA), office buildings among other service buildings consume about 40% of the world‘s energy demand (IEA, 2003).

Thus the high energy utilisation and thermal comfort issues in buildings need to be addressed.

1.3 Aim of the Research

The aim of the research is to assess thermal comfort conditions and to explore design options toward the reduction of energy use in multi-storey office buildings.

1.4 Research Questions

The study answers the following questions:

1. What are the views of occupants concerning their indoor thermal conditions?
2. What effect does the glazed façade (glass box) have on indoor climate of multi storey office buildings?
3. Which design option would be energy efficient for multi storey office buildings?
4. How best can offices be thermally satisfactory in the absence of air-conditioning?

1.5 Research Objectives

The following objectives were formulated to achieve the above research questions:

1. To assess occupants views of their indoor thermal comfort conditions within the selected buildings.
2. To determine the thermal comfort conditions of the indoor environment of the selected buildings.
3. To identify energy reduction strategies for the indoor conditions of the selected buildings based on validated models.
4. To identify overheating reduction strategies (passive case: no use of air conditioners) for the selected buildings.

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1.6 Scope of Research

This study focused on the use of the idealised approach to identify those building design and operation alternatives that would reduce the cooling requirements and overheating tendencies of office buildings in the climatic context of Accra, Ghana. Conceptually, the focal point of the study was on thermal comfort using the Predicted Mean Vote and Percentage of Persons Dissatisfied (PMV-PPD) theory. Again, the adaptive model will be examined by the use of the psychrometric and the bio-climatic charts. Investigations carried out included simulation models to determine the cooling loads and the overheating tendencies of the 4 case study buildings. Further alternative scenarios were be generated to come out with best and worst improvements set-up.

Geographically, the weather file for the simulation was within the dry-equatorial climatic condition of the Greater Accra Region of Ghana. The study was limited to four case study buildings due to the detailed analysis conducted.

Occupants‘ views were solicited on six main areas. These included:

- Indoor Environment, thermal and visual comfort;
- Operation and accessibility of the building systems;
- Awareness on the functionality of building control systems;
- User control actions on energy performance; User preference on workspace organization; and
- Needs and health complaints.

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1.7 Methodology of the Research

The study employed both the objective and the subjective approaches due to the experimental and technical, as well as the field survey nature of the research. The offices used for the survey differed in sizes and energy concepts.

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For the study, a questionnaire which originated from the University of California‘s Centre of Environmental Design Research, Berkeley on thermal comfort was used. The questionnaire had previously been modified and adapted for a number of thermal comfort studies around the world. In the questionnaire, all relevant aspects of occupant satisfaction with indoor environments are addressed. The questions address parameters directly related to the workplace such as air quality, temperature, air velocity, humidity, acoustics and lighting. In addition, more general questions including office layout, well-being at work, general health, operation and accessibility of building systems, user control actions on energy performance as well as general reception of the workplace, are addressed as well. Thermal preference and sensation questions were answered based on the seven-point ASHRAE scale by the occupants. Space for comments and clothing specification was also provided for.

Analyses of occupant responses were conducted with the statistical software program SPSS (Statistical Packages for the Social Sciences). This included the calculation of mean values, frequency distributions and correlation values. Furthermore, the correlations between independent factors were considered.

Additionally, indoor temperature and relative humidity values were recorded with portable data loggers within 10 minutes intervals continuously throughout the survey period. In the buildings, more data (e.g. indoor air quality, air speed, lighting levels, sound levels, etc.) was measured with

PCE instruments. Intensive simulation was carried out afterwards. The analysis of the measured data employed three thermal comfort models (The PMV-PPD, Bioclimatic chart, and the Psychometric chart).

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In terms of the energy reduction and overheating reduction strategies, an intensive and dynamic simulation application was employed using EDSL TAS software. The software has been validated by means of empirical case comparisons and it is scientific and professionally recognized for building dynamic thermal analysis (ESDL, 2013). During the simulation phase, the buildings were validated (attempt to make the models exactly the same as the existing in terms of persisting indoor conditions). Therefore, both the active case (A/C buildings) and the passive case (no A/C buildings) were assessed: to identify those building design and operation alternatives that would reduce the cooling requirements of the selected office buildings within the climatic context of Accra, Ghana.

In general, the following summarizes the methodology for the research: Measured-ObservedPerceived-Simulated (MOPS) (Mallory-Hills et al., 2005).

MEASURED-Monitoring physical performance through data loggers connected to thermal comfort parameters, lighting sensors and spot measurements to determine light levels, carbon dioxide values and energy use.

OBSERVED- Walk through and time utilization studies to track occupant activities and responses.

PERCEIVED-User surveys (questionnaires) and or interviews to capture occupants‘ satisfaction with the indoor environment.

SIMULATED- Computer visualisations to identify those building design and operation alternatives that would reduce the cooling requirements and mean- overheating tendencies of the selected office buildings.

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1.8 Significance of the Study

The connotation of the study was valued on two grounds. Firstly, the study unveiled those building design and operation alternatives that would reduce cooling loads in commercial buildings. Findings from the study will guide the design of new buildings, refurbishment and retrofitting of existing buildings within the climatic context of Accra, Ghana. Secondly, it is of interest to building investors, as it will lead to a diminution in the requirement of installed plant aptitude. The behaviour of occupants was accurately predicted towards the ultimate reduction of cooling loads.

1.9 Thesis Organisation

The thesis is divided into five chapters in a sequential manner from introduction to conclusion. The first chapter presents the background of the study, the problem statement, aim, research questions and objectives.

Chapter Two re-examines pertinent literature on the concept of thermal comfort and its parameters, occupant behaviour and indoor climate. Literature on energy performance and efficiency of buildings is also re-evaluated.

Chapter Three outlines the methods and procedures used in the survey and field study. Data analysis techniques are also discussed in this chapter. It also explains the data acquisition methods, the model development and the simulation process as well as the validation process employed.

Results of this study are presented in Chapter Four together with discussion where similarities and differences between the study and other studies are documented.

Lastly, Chapter Five concludes the thesis with a summary of major insights into improving indoor temperature conditions whiles reducing the cooling requirements and overheating tendencies of office buildings in Ghana. This is followed by a synthesis of recommendations and proposed direction for future research.

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CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Chapter Outline

This chapter presents a review of literature on thermal comfort, occupants behaviour and energy efficiency strategies of commercial buildings. The purpose is to provide the necessary background, to demonstrate the significance of the study and to identify the specific knowledge gaps associated with thermal comfort and the reduction of cooling requirements in the climatic context of Ghana. The review provides current concepts, theories and data relevant to the subject of the study. In order to demonstrate that all the main concepts and theories relevant to the topic have been identified, understood and critically evaluated, the review covers a rather wide scope. More than 100 documents including refereed journal papers, conference papers, as well as various project documentations have been examined. The majority of the reports are published in journals such as the Energy and Buildings, Solar Energy, Energy Conversion and Management, Building and Environment, Applied Thermal Engineering, Renewable Energy, IBPSA proceedings, PLEA proceedings, etc.

2.2 The Concept of Comfort

Comfort and discomfort within an environment is of major concern to occupants and managers of buildings since it can increase or reduce productivity as well as increase or decrease the cost of products and services. The definition for comfort from generation to generation has been very complex and has varied widely from different disciplines.

The concept of comfort has always been associated with spirituality and moral (Crowley, 2001).

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Using the early Anglo-American and British domestic environment as case studies, it was not until the nineteenth century that the idea of comfort included values, consumption patterns, and behaviours in which all people were believed to be entitled to the same physical comforts (ibid). It was perhaps the first time that the term was used to refer to physical environmental comforts such as light, heat, and ventilation (Rybczynski, 1986) as cited by Inkarojrit (2005).

Brager and De Dear (2003) asserted that Simple or single-dimensional definitions of comfort are almost guaranteed to be inadequate in explaining the concept of comfort. The authors further explained that, historically, the notion of comfort referred to domestic attributes such as privacy, convenience, leisure, and ease (Brager and De Dear, 2003).

Elzeyadi (2002) in his studies showed that comfort is a complex perception which reflects the interaction between objective stimuli and cognitive/emotional processes in which the general perception of comfort is a result of the overall comfort appraisal through humans' senses .These senses act as the sub-systems of indoor comfort. Elzeyadi (2002) illustrated this in what is called the semi-lattice relationship of environmental parameters of indoor comfort.

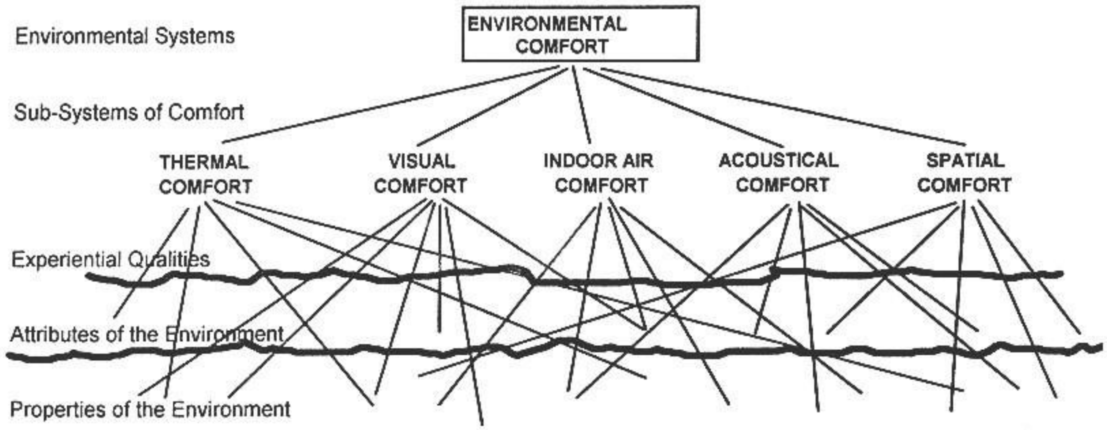

Fig. 2.1: The semi-lattice relationship of environmental parameters of indoor comfort

(Source: Inkarojrit, 2005)

2.3 Thermal Comfort

The answer to the question ―what is thermal comfort?‖ has attracted a good number of studies which try to give a good understanding of the concept and analyse how it affect occupants and their productivity.

In 1979, Benzinger as cited by Van Treeck (2011) defined thermal comfort as ―the absence of driving impulses‖ from cutaneous and hypothalamic receptors causing the body to counteract with physiological adaptations. This definition leans more on the fact that thermal comfort is related to the body settings and is biological. Also, thermal discomfort which may differ from body to body causes one to react in a way so as to bring oneself to a point where they may feel satisfied. In recent times, other authors have defined thermal comfort in very simplistic terms. Szokolay (2004) defined thermal comfort as the condition of mind that expresses satisfaction with the thermal environment which requires subjective evaluation. Szokolay (2004) also underlines three variables that affect thermal comfort which are: environmental, personal and contributing factors. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) in 2004 defined thermal comfort as the state of the mind which expresses satisfaction with the surrounding environment. Pino et al. (2012) also in their study on thermal and lighting behaviour of office buildings in Santiago of Chile, defines thermal comfort as the physical and psychological wellness of an individual when temperature, humidity, and air movement conditions are favourable for the activity that has to be developed.

All of the above definitions are synonymous since they all include the environmental factors (air temperature, air velocity, relative humidity and radiation) and the behavioural or personal factors (activity and clothing insulation). Van Treeck (2011) in his book, _Indoor thermal quality performance prediction‗ asserts that the thermal comfort perception for people all over the world (living in different climates and in cultural diversities) appears to be statistically uniform if similar environmental and personal parameters are taken into accounts (ASHRAE 2005; De Dear et al. 2002; Busch 1992; Fanger 1972). The above - stated assertion is only _if‗ but in reality, there are different climatic features all over the world and culturally, (way of dressing, eating, working, etc.) people all over the world are not the same and therefore thermal comfort will continue to differ from Country to Country and Region to Region (localized climate) except in areas where studies have shown otherwise (similar climate). Even in those areas, there might be some localized differences.

In agreement with the fact that there exist different climate and different cultural groups in the world are Brager and De Dear who in their 2003 study did not uncover the definition of thermal comfort by ASHRAE (2000) to convey the complexity of comfort and all of its contextual and cultural influences. Over the past few decades, the adaptive principle of thermal comfort (Humphreys & Nicol, 1998) has gained more popularity among building science researchers as the model that helps in explaining the complexities of the subject. The adaptive principle suggests that comfort, sensation, and preferences are influenced not only by climate but also culture and expectation. According to this principle, the definition of indoor comfort is extended beyond physical environmental conditions.

2.4 Thermal Comfort Parameters

Van Treeck (2011) found air temperature to be the primary environmental parameter to influence thermal comfort; likewise air velocity (Rohles et al., 1974), the average radiant temperature of the adjoining surfaces, and the ambient water vapour pressure (Rohles et al., 1971). According to Koranteng (2010), the main factor is the body's capability of balancing its own temperature with the thermal environment. This thermal balance depends on the internal heat load and energy flow (thermal exchange) of the body, which is executed through the processes of conduction, convection, radiation and evaporation (perspiration and respiration) (Gut and Ackerknecht 1993).

The main conditions allowing heat to be lost are air temperature, relative humidity, air velocity and average radiant temperature (Lechner, 2001). Other minor factors are age, sex, clothing, health and activity (Charles, 2003). The above factors are in agreement with Szokolay (2004) who also lists **Environmental** (air temperature, air movement, humidity, radiation); **Personal** (metabolic rate, clothing insulation, state of health, acclimatization) and **Contributing factors** (food and drinks, body shape, subcutaneous fat, age and gender) as the factors affecting thermal comfort. Thus, six parameters are necessary for thermal comfort assessment and calculations especially where the heat-balance theory is used. These are: air temperatures, relative humidity, mean radiant temperature (which is equivalent to the air temperature), metabolic rate, and clothing insulation (Charles, 2003).

Whiles the air temperature and relative humidity values within a space can be measured with instruments, the metabolic rate as well as the clothing values have been studied and documented for various levels of activities (Olesen, 1982). Below is a table of various activities and their corresponding metabolic rates in Mets (units for metabolism) and in W/m² (watts per meter squared).

KNUST

Table 2.1: Examples of Metabolism rates for various practical activities

Activity	Met	W/m²
Lying down	0.8	47
Seated, quietly	1.0	58
Sedentary activity(home, school, office, laboratory)	1.2	70
Standing relaxed	1.2	70
Light activity standing (shopping, laboratory, light industry)	1.6	93
Medium activity standing (shop assistant, domestic work, machine work)	2.0	117
High activity (heavy machine works, garage work)	3.0	175

(Source: Olesen, 1982)

Olsen (1982) again sums up clothing values for various activities that can be used in the calculation of thermal comfort. Below is a table for the clothing values (in units of clo).

Table 2.2: Values of thermal insulation of clothing for various practical combinations

Clothing Combination	Clo	m²K/W
Naked	0	0
Shorts	0.1	0.016
Typical tropical clothing outfit: Briefs (underpants), shorts, open- neck shirt with short sleeves, light socks and sandals	0.3	0.047
Light summer clothing: Briefs, long light-weight trousers, open-neck shirt with short sleeves, light socks and shoes	0.5	0.078

Table 2.2: Values of thermal insulation of clothing for various practical combinations Cont'd.

Clothing Combination	Clo	m²K/W
Working Clothes: Underwear, cotton working shirt with long sleeves, working trousers, woollen socks and shoes	0.8	0.124
Typical indoor winter clothing: Underwear, shirt with long sleeves, trousers, sweater with long sleeves, heavy socks and shoes.	1.0	0.155
Heavy traditional European business suit. Cotton underwear with long legs and sleeves, shirt, suit comprising trousers, jacket and waistcoat (US vest), woolen socks and heavy shoes.	1.5	0.233

(Source: Olesen, 1982)

2.5 Thermal Comfort Theories

Reviewed literature indicates two main theories of thermal comfort. Further, there are other theories which are borne from these two. These are the heat-balance approach (PMV-PPD) and the adaptive approach.

2.5.1 The heat –balance approach

The heat-balance approach is based on experiments in climate chambers, developed around the1960s. It was first propounded by Fanger (1970) and then studied again by Gagge et al. (1986) and modified by Mayer (1998). This approach combines the theory of heat transfer with the physiology of thermoregulation to establish a range of temperatures which occupants of buildings will feel comfortable. The range is determined by a _Predicted Mean Vote' (PMV, scale or index of +3 to -3 indicating hot to cold conditions) and a _Predicted Percentage of Dissatisfied persons' (PPD), derived from studies of individuals in tightly controlled conditions.

The PMV is a function of the set of environmental conditions that include: air temperature, mean radiant temperature, relative humidity, air velocity, and the personal variables of clothing insulation, and rate of production of metabolic heat. The PPD is the difficulty in achieving thermal neutrality for all occupants, thus, at the neutral temperature as defined by the PMV index (comfortable condition); PPD indicates that 5% of the occupants will still be dissatisfied with the thermal environment. The index provides a score that has been standardised by ASHRAE into a thermal sensation scale and represents the average thermal sensation felt by a group of people in a space (ASHRAE, 2004: 2001; Fanger, 1970). Below is the seven point ASHRAE thermal sensation scale.

Table 2.3: ASHRAE thermal sensation scale after Fanger (1972)

-3	-2	-1	0	+1	+2	+3
cold	cool	Slightly cool	neutral	Slightly warm	warm	Hot

According to De Dear and Brager (1998), the static heat balance models (heat-balance approach) are grounded in a fairly linear, deterministic logic, and are tested with extensive and rigorous laboratory experiments yielding fairly consistent, reproducible results. The PMV-PPD model (ISO 7730) was modified by Mayer in 1998. Mayer investigated the relation between PMV and PPD by not only asking for thermal sensation but for thermal preference in addition. Thermal comfort standards use the PMV model to recommend acceptable thermal comfort conditions (Charles, 2003). The recommendations made by ASHRAE Standard 55 (ASHRAE, 1992) are presented below. These thermal conditions should however ensure that at least 90% of occupants feel thermally satisfied.

Table 2.4: Thermal Comfort Conditions – ASHRAE Standard 55

Season	Optimum Temperature	Acceptable Temperature conditions	Assumptions for other PMV inputs
Summer	24.5°C	23-26°C	Relative humidity:50% Mean relative velocity:<0.15m/s Mean radiant temperature: equal to air temperature Metabolic rate:1.2 met Clothing insulation:0.5 clo

(Source: ASHRAE, 2004)

Darby and White (2005) asserts that this approach can be used in air-conditioning as well as a heating environment and can provide better temperature control than could be obtained from opening windows. Loomans et al. (2008), assert that this approach has a larger flexibility and a wider applicability. The aforementioned approach is the basis of the method adopted in several building design standards, such as the Chartered Institution of Building Services Engineers (CIBSE) Guide A (CIBSE 2006); International Standard Organisation (ISO) 7730 (ISO 2005; 1994); ASHRAE 55 (ASHRAE 2004; 1992) to estimate thermal comfort levels in buildings. These standards have come to be regarded as unanimously applicable across all building types, climatic zones, and populations (Parsons, 1994).

Field studies on thermal comfort have shown that the PMV model does not give correct predictions for all environments (Humphreys and Nicol, 2002). Therefore in the face of evidence from real-life conditions, the argument goes; the controlled PMV method of estimating comfort levels can be seriously misleading and needs revising (ibid). Hoes et al. (2009) also noted in their studies that occupants‘ perception of so-called sealed, centrally air-conditioned buildings with open plan floor layouts that provide minimal adaptive opportunity, with no option for opening windows, is negative. Researchers have cited measurement error and contextual assumptions as the two factors contributing to the discrepancies/ bias found with the PMV model (De Dear and Brager, 2002; 1998: Oseland, 1994).

KNUST

Measuring of the Physical variables with reliable instruments, Clothing insulation, Activity levels, Individual and Building differences, Outdoor climate, Behavioural and Psychological adaptation are all factors that have been mentioned by thermal comfort researchers as factors contributing to the incongruity found with the use of the PMV model (De Dear and Brager, 2002, 2001; Humphreys and Nicol, 2002; Morgan et al., 2002; Cena and de Dear, 2001; Brager and De Dear, 1998; Baker and Standeven, 1996; Cena, 1994, Humphreys, 1994; and De Dear et al, 1993). However, a good number of studies have also recommended that the PMV model predictions agree better with actual thermal sensation in air-conditioned buildings as compared to naturally ventilated buildings (Beizaee et al., 2012; Brager and De Dear, 1998; Oseland, 1996; De Dear et al. 1991; and De Dear and Auliciems, 1985).

Darby and White (2005) again in their studies concluded that there is some evidence that individuals dislike being confined in air-conditioned spaces for long periods of time, and that they often prefer natural ventilation for overall comfort: thus, the need for other approaches to be developed. De Dear and Brager (1998), concludes that the adaptive perspective/approach complements rather than contradicts the static heat- balance view. The heat-balance model is more correctly regarded as a partially adaptive model, since it acknowledges the effects of behavioural adjustments made by occupants to thermal environmental parameters, clothing, and metabolic rate.

Despite all the shortcomings of this approach, it still remains one of the strongest approaches for the measurement of thermal comfort in buildings especially those with mechanically ventilation devices. A number of thermal comfort studies from literature have used this approach (Beizaee et al., 2012: Humphreys and Nicol, 2002: Brager and De Dear, 1998) in combination with the other approaches (the adaptive approach). In conclusion, the static heat balance approach is a very renowned approach as far as thermal comfort measurements are concerned .When combined with the other approach; it gives a very precise and accurate indication of thermal comfort analysis within building environments with mechanically ventilation and or heating equipment.

2.5.2 The Adaptive thermal comfort Approach (ATC)

The ASHRAE Standard 55 defines adaptive model as one that relates indoor design temperatures or acceptable temperature ranges to outdoor climate (ASHRAE, 2004). Over the last few years, adaptive models have been applied to define neutral temperature as a function of outdoor, indoor, or both temperatures (Orosa and Oliveira, 2011). Based on the shortcomings of the static heat balance approach, thermal comfort researchers, De Dear and Brager (1998) developed the adaptive model of thermal comfort and preference. The major reason for the introduction of this approach is the fact that the static heat balance approach ignores important cultural, climatic, social, and contextual dimensions of comfort, leading to an exaggeration of the need for air conditioning (Kempton and Lutzenhiser, 1992).

Many more researchers have conducted studies to confirm the need for the adaptive approach for thermal comfort analysis, especially in free-running buildings (Roaf and Nicol, 2005; Nicol, 2004; De Dear and Brager, 2002; Nicol and Humphrey, 2002; Cena and De Dear, 1998; De Dear et al., 1997). Most of these researchers have proposed models and equations for the adaptive approach.

Nicol and Roaf, (1996) recommended the model of *Eq. (1)* for occupants of naturally ventilated buildings. Many other adaptive models have also been proposed. For example,

Humphreys (1976) developed two models for neutral temperature, as given by *Eqs. 2* and *3*, and Auliciems and De Dear (1985) developed relations for predicting group neutralities based on mean indoor and outdoor temperatures, as shown in *Eqs. 4, 5* and *6* which were employed by ASHRAE (2004) in *Eq. 7*.

$$Tn,_{o} = 17 + 0.38T_{o} \ldots\ldots\ldots \quad \text{Eq. 1}$$
$$Tn,_{i} = 2.6 + 0.831T_{i} \ldots\ldots\ldots \quad \text{Eq. 2}$$
$$Tn,_{o} = 11.9 + 0.534T_{o} \ldots\ldots\ldots \quad \text{Eq. 3}$$
$$Tn,_{i} = 5.41 + 0.731T_{i} \ldots\ldots\ldots \quad \text{Eq. 4}$$
$$Tn,_{o} = 17.6 + 0.31T_{o} \ldots\ldots\ldots \quad \text{Eq. 5}$$
$$Tn,_{i,o} = 9.22 + 0.48T_{i} + 0.14T_{o} \ldots\ldots\ldots \quad \text{Eq. 6}$$
$$T_{c} = 17.8 + 0.31T_{o} \ldots\ldots\ldots \quad \text{Eq. 7}$$

Where: T_c is the comfort temperature, T_o
- outdoor air temperature,
T_i - mean indoor air temperature,
$Tn,_{i}$ -neutral temperature based on mean indoor air temperature,
$Tn,_{o}$ - neutral temperature based on mean outdoor air temperature.

Baker and Standeven (1995) explain adaptive opportunity as the measure of opportunity the building offers for the occupants to make themselves comfortable, whiles De Dear and Brager (1998) as cited by Darby and White (2005) explains the adaptive approach to be based on field surveys of thermal comfort and revealed that people are more tolerant to temperature changes than laboratory studies suggest: they consciously and unconsciously act to affect the heat balance of the body (behavioural thermoregulation). These actions may change metabolic heat production (changing activity or doing something more or less vigorously), the rate of heat loss from the body (clothing, posture) or the thermal environment (windows, doors, blinds, fans, thermostat adjustment) (Humphreys, 1994). Comfort may therefore be achieved in a wider range of temperatures than predicted by ASHRAE when it is something that individuals achieve for themselves.

Adaptive variables are extremely important in naturally ventilated (free running) buildings – those without active heating or cooling systems (Nicol, 2004; Raja et al., 1999). People in these buildings need to be able to take charge of their immediate environment by opening and closing windows, dressing in such a way as to maximise comfort indoors and outdoors, and using shading as necessary. Advocates of the adaptive approach hold that, it will eventually be possible to produce thermal standards for buildings that do not resort to specifications of the indoor climate, but uses characteristics of the building such as materials, orientation, moveable shading, heating system and controls (Nicol & Humphreys, 2002). If buildings are designed and built to incorporate the right mix of these characteristics, the occupants will be able to make themselves comfortable within them.

The premise for the adaptive approach according to De Dear and Brager (1998) is that occupants are no longer regarded as passive recipient (as is the case with the heat-balance approach) of the thermal environment but rather, play an active role in creating their own thermal preferences. Contextual factors and past thermal history are believed to modify expectations and thermal preferences. Satisfaction with an indoor climate results from matching actual thermal conditions in a given context and one‘s thermal expectations of what the indoor climate should be like in that same context (De Dear 1994a, Nicol 1993 and Auliciems 1989,1981). In this case, satisfaction of the occupant can only occur through appropriate adaptation to the indoor climatic environment. Researchers have therefore distinguished three categories of thermal adaptation (Edholm, 1985: Folk 1981; 1974: and Goldsmith, 1974) to be: behavioural adjustment, physiological and psychological adjustments.

KNUST

Behavioural Adjustment. This include all alterations a person might deliberately or instinctively make that in turn modify heat and mass fluxes governing the body‘s thermal balance. Adjustment can be further sub-classified into personal (e.g., removing an item of clothing), technological (e.g., turning on an air conditioner), and cultural responses (e.g., having a siesta in the heat of the day). This offers the greatest opportunity for people to play an active role in sustaining their own comfort (Humphreys, 1994a; Nicol and Humphreys, 1972).

Physiological. The most all-inclusive definition of physiological adaptation would include changes in the physiological responses that result from exposure to thermal environmental factors, and which lead to a gradual attenuation in the strain induced by such exposure. Physiological adaptation can be broken down into genetic adaptation (intergenerational) and acclimatization (within the individual‘s lifetime).

Psychological. The psychological dimension of thermal adaptation refers to an altered perception of, and reaction to, sensory information due to past experience and expectations. Personal comfort set points are far from thermostatic. Relaxation of expectations can be likened to the notion of habituation in psychophysics (Frisancho, 1981; Glaser, 1966) where repeated exposure to a stimulus diminishes the magnitude of the evoked response. The ATC approach according to

Loomans et al. (2008) is less flexible and limited in its application range compared to the PMV/PPD approach. Buildings with poor adaptive opportunities often produce intolerable indoor conditions within (Baker and Standevan, 1996) and eventually become power guzzlers (Nicol and Humphreys, 2004). This is probably so since occupant perception of so-called conserved, centrally air-conditioned buildings with open plan floor layouts that provide minimal adaptive opportunity, with no option for opening windows, is negative (Hoes et al., 2009).

In conclusion, the adaptive thermal comfort (ATC) approach offers a natural way for occupants to thermally satisfy themselves within a building, by giving them the opportunity to operate building systems and with the outdoor climatic condition in consideration. With some evidence that individuals dislike being confined in air-conditioned spaces for long periods of time, and that they often prefer natural ventilation for overall comfort (Darby and White, 2005), it becomes imperative for researchers to conduct (micro-level) thermal comfort studies into the mixed approach to make building occupants comfortable.

2.6 Comfort indices, Comfort zones and Comfort scales

The range of acceptable comfort conditions is generally referred to as the comfort zone (Szokolay, 2004). Thermal comfort standards define the acceptable temperatures, humidity, and air velocity conditions, usually inside buildings, and thus delineate the comfort zone (Givoni, 1998). Fanger (2003) further notes that because of biological variance, establishing a condition that will satisfy everyone is not likely to be achievable. Rather, the designer or the builder should seek to create a condition that will satisfy the largest number of occupants. In which case the standard define temperature values that should result in thermal satisfaction for at least 80% of occupants in a space (Charles, 2003).

KNUST

Thermal comfort studies have attracted a good number of researchers from centuries. A great number of these studies significantly dedicated their studies to the development of standards or indices and these have been the basis of recent studies in defining and calculating comfort in buildings. The very first single figure comfort index was proposed by Houghten and Yagloglou (1923) as the _effective temperature' cited in Szokolay (2004). Over the years, at least 30 different such indices have been produced by various studies, all with different derivations and names (ibid).

Whiles some studies established charts: ASHRAE comfort charts since the 1920's (ASHRAE, 2005;1985;1981 and 1967), Olgyay_s Bio-climatic Chart (Olgyay, 1963), Givoni_s Building Bioclimatic Chart (Givoni, 1976), and Fanger_s Predicted Mean Vote (Fanger, 1970), others also established models, (De Dear, 1998; Fanger, 1970) and indices (Gagge et al, 1986) using climate chamber experiments (Fanger, 1970) and undertaking field survey to establish thermal comfort standards and evaluation methods (Lin and Deng, 2008; Han et al., 2007, Olesen and Parsons, 2002; De Dear and Brager, 2002, 1998). The most important findings are now the basis of national and international standards; ASHRAE standards and the International Standards Organization (ISO) are almost exclusively based on theoretical analyses of human heat exchange (Djongyang and Tchinda, 2010). They focused on correlations for thermal comfort criteria or on health issues as the Sick-Building-Syndrome (Wagner et al., 2007).

Comfort indices that evaluates the combined effect of comfort of several climatic factors, and demarcating comfort zone, have been developed by various researchers (Szokolay, 2004; Evans, 2003; Givoni, 1976; Fanger, 1972; Olgyay, 1963). In more recent years, modified versions of these comfort indices are generally accepted (Ogbonna and Harris, 2008). These include operative temperature (To), (AT_a + (1 _ A) Tr), effective temperature (ET), standard effective temperature

(SET*), Thermal sensation (TSENS), Discomfort (DISC), Weighted ThermalSensation Vote (WTSV), Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfaction (PPD). It must be noted that each of these indices do calculate thermal comfort values either using the heat –balance approach (PMV-PPD) or the adaptive approach (neutrality temperature, standard effective temperature, Olgyay‘s bioclimatic chart, etc). The most broadly used indices in recent studies on outdoor thermal comfort according to Xi et al. (2012) are SET*, PMV, and PET (physiologically equivalent temperature).

Some of these studies also have concluded on comfort zone that will provide occupants satisfaction. A comfort range of 23ºC - 29ºC with a relative humidity of 30-70% was suggested by Brooks (1963), as cited in Olgyay (1963) for tropical conditions, whiles ASHRAE recommends 23ºC - 26ºC as temperature range for summer comfort within which the mechanical system has to maintain the indoor climate for sedentary activity (Stein and Reynolds, 2000).

Koenigsberger et al. (1974) also proposed 22°C to 27°C with an optimum temperature of 25°C. Ferstl (2005) suggests 22°C to 26°C and 30% to 80% relative humidity as optimal values for indoor comfort.

In a related study by Koranteng (2010) in Kumasi, Ghana, it was found that occupants in lowrise office buildings had adapted to high relative humidity levels and therefore found maximum relative humidity levels of 80% – 85% acceptable, if temperature values did not exceed 29°C. This, the author concluded that an adjustment of the comfort scale for the climatic context of Kumasi, Ghana is necessary. In view of this and many other thermal comfort studies, one can state categorically that the thermal comfort scales which have been accepted worldwide like that of ASHRAE does not always seem to be accurate and therefore the need for empirical evidence to validate or otherwise these scales.

According to Hyde (2000), the neutrality temperature is the temperature at which a person should be neither too hot nor too cold and the comfort zone is 2°C below and above the neutrality temperature. Szokolay (2004) has set the comfort zone for 90% acceptability to be 2.5°C above and below the neutrality temperature, after Auliciems (1981) who did set the comfort zone for 90% acceptability to be Tn (+ -) 2.5K and 80% acceptability to be Tn (+ -) 3.5 K for both naturally ventilated and artificially ventilated spaces.

$$Tn = 17.6 + 0.31 * To.av \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 8}$$

Where: Tn is the neutrality temperature
To.av is the mean monthly outdoor temperature

There are also the sensation scales which have been developed by thermal comfort researchers. Due to the subjective nature of measuring thermal comfort, the wording for applying these scales is frequently not precise (Van Treeck, 2011). The following definitions have been distinguished: In 1936, Bedford used mixed expressions in order to combine thermal sensation and comfort perception. This became known as the Bedford scale and reads :(*much too warm, too warm, comfortably warm, comfortable, comfortably cool, too cool, much too cool*), with ratings from one to seven. Bedford further showed a linear relationship between comfort assessment and equivalent temperatures in his scaling. Moreover, it was also found that the influence of relative humidity is insignificant for temperatures below 24°C. Gagge et al. (1967) also introduced the unpleasantness scale with the four terms :*(pleasant, indifferent, slightly unpleasant, and unpleasant)*. The level of discomfort according to Van Treeck (2011) can be expressed by the sequence: (*comfortable, slightly uncomfortable, uncomfortable, and very uncomfortable).*

However, thermal sensation as a rational experience was suggested by Rohles et al. (1971) with the seven-point scale: *(cold, cool, slightly cool, neutral, slightly warm, warm, hot).* Statistically this seven-point scale correlates with the range (-3,-2,-1, 0, 1, 2, 3) with zero being the neutral point (AHSRAE Standard 55, 2004). There is yet another scale which is the mean thermal vote (MTV) which was developed by (Nilsson et al., 2007, Wyon et al., 1989). This scale is similar to the Bedford scale in terms of counting from -3 to +3 (much too cold, too cold, cold but comfortable, neutral, hot but comfortable, too hot, much too hot). Again, it also have zero as the neutral point just as the ASHRAE scale. Unlike ASHRAE however, this scale clearly distinguishes between acceptable, thus comfortable ratings (-1, 0, +1) and ratings which are unacceptable. Van Treeck (2011) stress that sometimes, difference in language and in the subjective observations can cause misinterpretations in the experimental data and thus the experiments performed by different authors should be handled as such even if the same scales has been used.

2.7 Bioclimatic Charts

Building Bioclimatic Chart gives an indication that, whenever an ambient condition is within the designated limits of a control strategy, then the outdoor temperature and relative humidity conditions fall within the interior conditions of a building and the indoor of the building is said to be comfortable (Watson and Labs, 1983). Since, the selection of building passive thermal design strategies is based heavily on the local climatic conditions: suitable strategy for a given location can be determined by the use of bioclimatic charts.

According to Al-Azri et al. (2012), Oglyay‘s chart (Fig. 2.2) has a constant comfort in the range from 20°C to 30°C. This comfort zone also corresponds to a relative humidity value of around 30% to 67% (medium humidity). The level of comfort is applicable to indoor spaces with the

KNUST

indoor level of clothing. The comfort zone is shown at the centre of Olgyay‘s chart in an aerofoil shape. The chart takes into consideration levels of comfort that can be felt outside the comfort zone but in combination with ranges of the other environmental factors: mean radiant temperature, wind speed and solar radiation. Above the lower boundary of the zone, shading is necessary to maintain reasonable level of comfort. Up to 10°C below the comfort zone, comfort can be retained provided that there is enough solar radiation to offset the decrease in temperature. Likewise, to retain comfort up to around 10°C above the zone, wind speed can offset the increase in temperature. Evaporative cooling according to this chart is another means to retain comfort at high temperature and low relative humidity values. The effect of 0.5 m/s air-movements on thermal comfort has been reported by Gut and Ackerknect (1993) to have a cooling effect of 1°C to 1.7°C at a corresponding ambient temperature of 25°C to 30°C. Thus the chart is not limited to only identifying whether a particular condition falls within the comfort zone, but it also provides recommendations on the speed of wind required to restore comfort at temperatures above the comfort zone (Fig.2.2) and the quantity of solar radiation needed under lower temperatures.

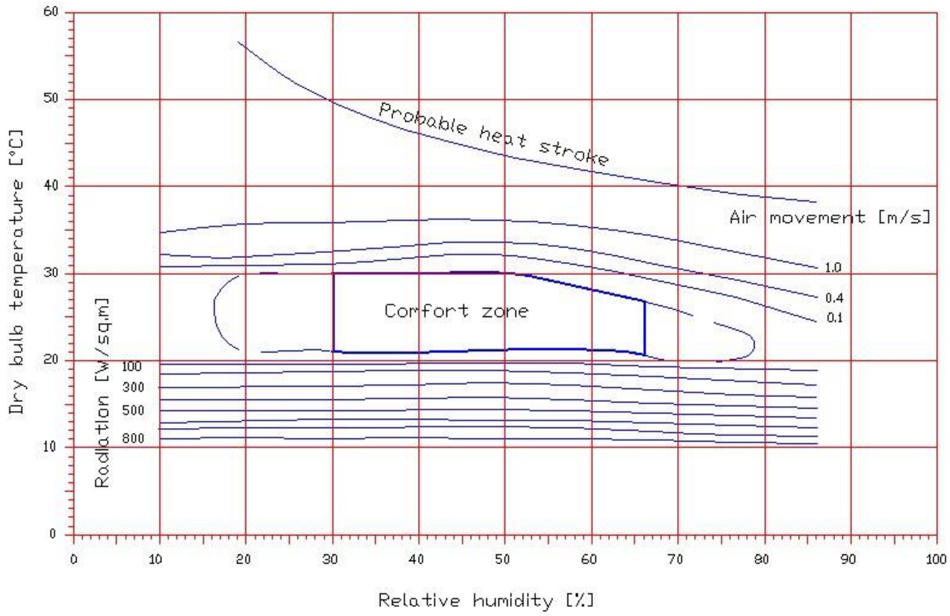

Fig. 2.2: Olgyay’s Bioclimatic Chart (Szokolay, 2004)

Since Olgyay‘s chart (1923) only considers the outdoor conditions disregarding the indoor physiological considerations, it is only applicable for hot humid climates where there is minimal fluctuations between the indoors and the outdoors temperatures (Sayigh and Marafia, 1998). Conversely Olgyay‘s original chart was inappropriate for use in hot and dry regions where the indoor temperatures are significantly different from the outdoor temperatures. However, Givoni, 1976; Arens et al., 1980 [ref. Watson and Labs, 1983, pp. 33-34] updated the chart using the original format of the Olgyay‘s chart based on a comfort model developed by the J.B. Pierce Foundation.

By 1969, significant improvement of the bioclimatic chart had been completed by Givoni (1969).This chart is based on the linear relationship between the temperature amplitude and vapour pressure of the outdoor air. Givoni‘s chart identifies the suitable cooling technique based on the outdoor climatic condition. In 1979, Milne and Givoni combined the different design strategies of the previous study of Givoni (1969) on the same chart. The resultant chart (Milne and Givoni, 1979) is currently used by many researchers and hence the motivation for this research. Five zones are identified on Givoni – Milne chart: thermal comfort, natural ventilation, high thermal mass, high thermal mass with night ventilation and evaporative cooling. Below is the new Givoni-Milne chart.

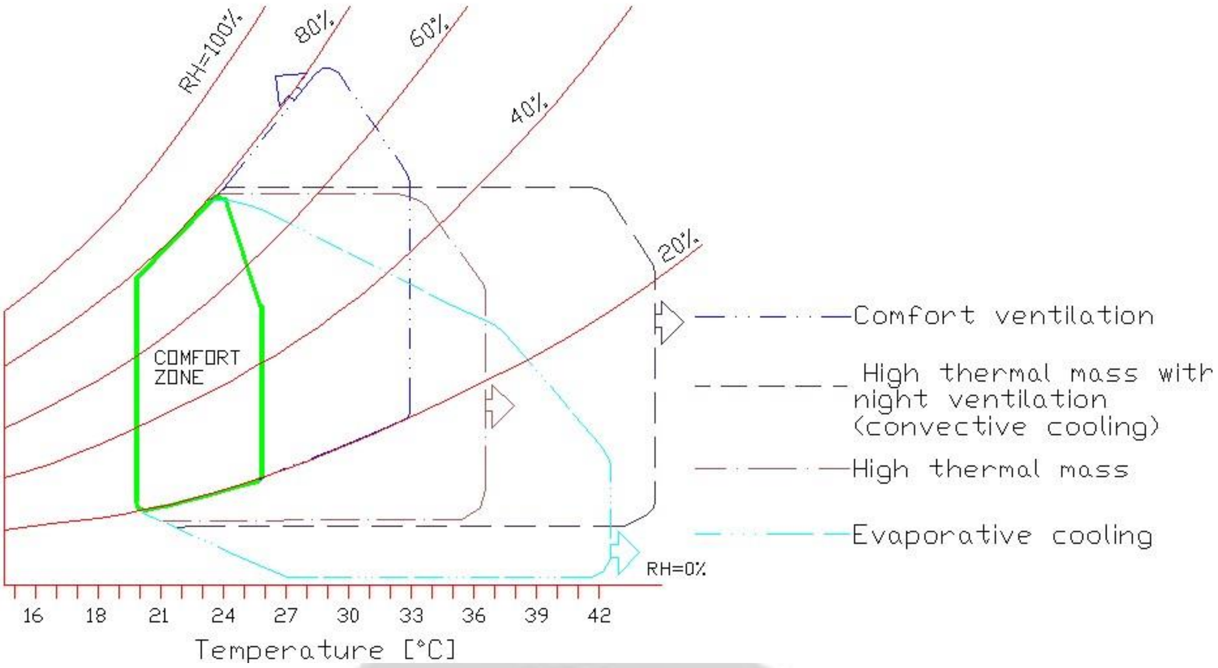

Fig.2.3: Comfort zone with recommended design strategies (Givoni, 1979)

Givoni's chart (Fig. 2.3) is mainly applicable to buildings where heat gain is minimal (Watson, 1981). The current study is based on the bioclimatic chart modified for warm countries (Szokolay, 2004) and design strategies recommended by Givoni and Milne in Lechner (2001).

2.8 Thermal Comfort Studies around the world

A great number of thermal comfort studies have been conducted around the world since the development of the PMV model and the adaptive model (Pino et al., 2012; Xi et al., 2012; Bluyssen, 2011; Buswell and Loveday, 2010; Koranteng, 2010; Lin and Deng, 2008; Taylor, 2008; Tian and Love, 2008; Barlow and Fiala, 2007; Han et al., 2007; Van Hoof and Hensen, 2007; Wang, 2006; Cheng and Ng, 2005; Darby and White, 2005; Heschong, 2002; Liu and Tian, 2002; Nicol and Humphreys, 2002; Cena and De Dear, 2001; Nicol, 1994; Brager et al, 1994; De Dear and Fountain, 1994; and Busch, 1992). These studies cut across temperate, hot– arid, tropical and cold climatic zones. Office buildings, classrooms, residential apartments are few of the structures within which thermal comfort studies have been conducted. Several locations in England and Wales, Bangkok, Thailand, several Californian locations, Montreal and Ottawa in Canada, six cities across Australia, five cities in Pakistan, Athens in Greece, Singapore, and Grand Rapids in Michigan (De Dear and Brager, 1998).

In most thermal comfort studies, temperature have been indicated as the most important parameter since it is temperature that actually determines how occupants feel within spaces. Most authors have confirmed this assertion. Air temperature is often recognised as the main design parameter for thermal comfort. Hence, it is essential for occupants‘ well-being, productivity and efficiency (Adebamowo and Akande, 2010). Heidari and Sharples (2002) have suggested that air temperature alone is a good indicator of occupants‘ indoor thermal comfort. Beizaee et al. (2012) in their study in UK during the summer found a mean temperature value of 23.9°C in office buildings with a range of 21.6°C to 26°C. This value is well within the ASHRAE (2004) summer comfort zone. Additionally, there was an average PMV value of -0.25 with a range of -1.6 to 0.5 (between cool to neutral). Oseland (1995) also found lower mean temperatures of 23.8ºC in offices he studied in London.

Heidari and Sharples (2002) conducted a study in Iran. The study comparatively analysed long and short term thermal comfort surveys. By the end, the authors reported that during the two short-term studies, the indoor air temperatures ranged from as low as15.4 °C to as high as 32.7°C with an average of around 30°C in the hot season and around 20°C in the cool season. For the long-term study, the mean indoor temperatures during each month of the survey, ranged from approximately 20°C during January to 29°C during August. The results indicated that in Iran, there are two main seasons; the cool season around January to March and the hot season occurring from June to August. Ghana‘s climatic condition is contrary to that of Iran. There are two major seasons in the country: the rainy/cool season (around June to late September) and the dry/hot season (November to late April). In the southern part of Ghana, the hottest month of the year is March/April just before the rainy season whiles August is the coolest. Again in the south, the highest mean monthly temperature of about 30°C occurs between March and April and the lowest is 26°C in August (Amos-Abanyie, 2009). Furthermore, comfort temperature as seen from above tends to be higher in tropic Regions (Li et al., 2010).

Wagner et al. (2007) studied thermal comfort and workplace occupant satisfaction in German low energy office buildings. The authors‘ conclusion was that votes of _just right‘ and _slightly warm‘ covered operative temperatures of above 27°C. Again, the authors‘ noted that PMV was very wide spread on the sensation scale and only changed slightly, depending on the class of the individual votes.

Thermal comfort within indoor spaces has also been accounted for by the glazing to wall ratio of a building. In Santiago of Chile, Pino et al. (2012) observed that _when using a high window-towall ratio (WWR; ratio of the glazed area with respect to the total area of the exposed envelope), occupants commonly might feel thermal and/or visual discomfort and they will apply their own strategies to mitigate this problem‘. Another study conducted in Sweden (Bulow-Hube, 1998), showed that glazing type and WWR have strong impact on cooling and heating demands. The use

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of modern glazing, with low solar transmittance and U values, can mitigate this problem but it does not necessarily solve it. However, for external glazing, orientation and shading does help in the transmission of solar radiation into the indoor spaces. Whiles high WWR triggers thermal discomfort in indoor spaces, the same can help in the provision of high amount of day lighting.

Heschong (2002) substantiated that WWR plays an important role in the admittance of natural lighting into an interior space. It has been studied that working with suitable natural lighting can improve job performance of workers (ibid). Tzempelikos and Athienitis (2007) studied an office module located in Montreal, Canada, and concluded that a 30% WWR is good enough to guarantee useful natural lighting on the working area, during 76% of working time. Moreover, they reiterated that increased sizes of windows do not produce significant increase of useful daylight for a South-oriented office. Thus, glazing for other orientations also has considerable effect on indoor thermal comfort. Charles et al. (2005) also in their study of _Indoor Air Quality and Thermal Comfort in Open-plan Offices, Canada' corroborated early assertions that _occupants seated next to a window tend to be less satisfied with thermal conditions. Though workstations located next to windows benefit from natural lighting and views, their occupants often experience a wider range of temperatures because of the warm or cool radiant temperatures from the windows'. The aforesaid observation therefore agrees more with other studies averring negative effect of a wide WWR on the indoor environment. Several supposed constraints influence thermal comfort such as: illumination, draughts, temperature variations, acoustics, olfactory quality, glare and perceived control as well as for air which is perceived as stale and dry. The impact of these parameters depends on the type of ventilation and the perception of the indoor environment temperature (whether it's hot or cool).

In a study reported by Hellwig et al. (2012), their indication was that, in spite of the type of ventilation, 85% of the entire occupants‘ would yearn to have control over their indoor climate. In naturally ventilated offices, 87% of persons feel they have control over the indoor temperature. The percentage of the same group in partially air conditioned buildings is half as much (46%). In air-conditioned buildings, the value is even lower (36%). In naturally ventilated offices, the proportion of occupants perceiving they have control over air movement is just as high as for indoor temperature. In buildings with air-conditioning and sealed windows, this proportion is only 7% (Hellwig et al., 2012; Darby and White, 2005).

Most comfort standards (the PMV-PPD for instance) is suitable mainly for static, uniformly thermal conditions. The assumption here is that, human beings are thought to feel comfortable in a narrow, well-defined range of thermal conditions, regardless of race, age and sex (Han et al., 2007). De Dear and Brager (2001) noted that current thermal comfort standards and models underpinning them purport to be equally applicability across all types of buildings, ventilation, climatic zones and occupancy pattern.

But in reality, thermal comfort is climate specific and even if a particular model is applicable across all types of building in the same country, the question of localized climate come into play and needs to be taken into consideration. In other words, thermal comfort studies needs to be carried out specifically across all buildings, ventilation, occupancy pattern and age to determine similarities and otherwise between different climates and buildings. Roaf and Hancock (1992) suggest that laboratory based predictions may not be entirely reliable, as they do not allow for people_s adaptive responses, such as taking off a shirt or drawing curtains or closing windows or their need for some variety in the environmental conditions.

Thermal comfort field studies have also shown that occupants are susceptible to a wider range of indoor temperature most of which they feel comfortable by acclimatizing (Simons et al., 2014). This thus follows from Roaf and Hancock‘s (1992) assertion that there is no need for uniformity for indoor temperatures worldwide. Field studies also allow for analyses of other factors other than those that can be simulated in chambers, as the subjects provide responses in their everyday habitats, wearing their everyday clothing and behaving without any additional restrictions (Cena and De Dear, 2001).

In Ghana and Africa in general, very few thermal comfort studies have been conducted. With its hot and humid climates and its people used to living in naturally ventilated buildings, Wu (1988) demonstrated that for people acclimatized to hot and humid climates in developing countries, the suggested upper temperature limit with indoor airspeed of 2m/s would be higher and about 32°C would be appropriate. Koranteng and Mahdavi (2010) also recommend that suitable design set point for tropical buildings should be 29°C.

Adebamowo (2007) carried out a study to examine the thermal characteristics of the external (outdoor) and internal (indoor) spaces and the suitability of the Predicted Mean Vote (PMV) and the adaptive models in naturally ventilated houses in the tropical climate of Lagos, Nigeria. The study showed that houses in Lagos were not thermally comfortable. Based on ASHRAE and Bedford scales, occupants in naturally ventilated houses show higher comfort levels as compared to what PMV had predicted. Equally, a field survey was carried out by Ogbonna and Harris (2008) in Jos, Nigeria to obtain a broad understanding of occupants_ thermal comfort sensations within buildings as a contributory factor to energy-services_ demand and use.

The adaptive thermal comfort paradigm was employed based on the theory that physiological and adaptive factors play evenly vital roles in the perception and interpretation of thermal comfort (Amos-Abanyie, 2012). A total of 200 subjects in naturally-ventilated buildings (with operable windows) provided 200 sets of cross-sectional thermal comfort data for the months of July and August, 2006 (Ogbonna and Harris, 2008). Moreover, indoor climatic data were collected by hand-held portable laboratory-grade instruments, with accuracies and response times in tandem with the recommendations of ANSI/ASHRAE 55 and ISO 7726. In their results, thermal neutrality, using the ASHRAE 7-point scale, occurred at 26.27°C. The thermal neutrality was in general agreement with most of the adaptive models, varying the least from Humphrey_s 1981 model and the most from the Nicol and Roaf model by 0.33ºC and 0.72°C, respectively. The derived comfort range was between 24.88ºC and 27.66°C. The comfort range varies by about 1.39ºC on either side of the optimum temperature. This comfort range was less than the 2°C to 3°C suggested by the standards, but may be due to the effects of elevated relative humidity. The PMV determined neutrality was much higher than the direct votes suggested: confirming the suggestion by previous researchers about the limitations of the PMV for predicting thermal comfort in naturally- ventilated buildings (Hensen, 1991).

Promoters of the adaptive approach hold that it will ultimately be achievable to produce thermal standards for buildings that do not resort to specifications of the indoor climate, but use characteristics of a building such as materials, orientation, moveable shading, heating system and controls (Nicol and Humphreys, 2002). It therefore follows that if buildings are designed and built to incorporate the right mix of these features, the occupants will be able to make themselves comfortable within them. The shape, fabric, fenestration and ventilation systems are all factors that affect the thermal performance of a building (Szokolay, 2004).

In the sub-Saharan African city of Cameroon thus; Ngaoundere and Kousseri areas, an investigation into thermal comfort and residential thermal environment during the harmarttan was conducted by Djongyang and Tchinda (2010). Their approach was the adaptive thermal comfort paradigm with field study of the area. Their findings among others include the following. The thermo neutral temperatures in both Climatic Regions range from 24.69°C to 27.32°C. In Ngaoundere, it is approximately 2.63°C less than Kousseri. The thermo neutral temperatures in traditional living rooms differ from that of modern living room by approximately 1°C. In Ngaoundere, about 58% of the occupants' considered their thermal environments acceptable. In Kousseri, just about 47% found their environment thermally acceptable. Again, the minimum values of PPD are 6.31% and 6.81% respectively for Ngaoundere and Kousseri. This indicates that the agreement between the expression of thermal comfort proposed by climatic chamber experiments and field studies is not perfect.

Koranteng et al. (2010) studied indoor temperature and relative humidity conditions of five office buildings that were representative of existing low-rise buildings with different functions and locations in Kumasi, Ghana. The adaptive model based on the work of Auliciems (1981) and recommendations by Szokolay (2004) for 90% adaptability was used to derive the comfort zone for Kumasi. The generated mean maximum, minimum and hourly values during the working hours were then plotted on psychrometric charts to analyse the conditions within the office spaces in relation to the comfort zone. The indoor conditions of the buildings in almost all the months fell outside the comfort zone. The study attributed the above finding (shift above the comfort zone) to high relative humidity values, even though the temperature values in some of the cases were below 29ºC. The study concluded that occupants had adapted to higher relative humidity levels and therefore found humidity levels of around 80% comfortable, provided temperature values were not above 29ºC.

The difference between the study in Cameroon and Ghana lies in the types of buildings used. Whiles in Cameroon, residential buildings were studied; low- rise office buildings were studied in Ghana. In office buildings, a uniform attire is worn throughout the working hours whiles in the residential building more loose clothing can be worn which reduces the clothing insulation values. Again, the difference in the climate for both countries seems to have altered the results. It brings to fore that, due to high relative humidity levels, high wind speeds, and acclimatisation, no single universal comfort index has been developed for people all over the world that does not need adjustment. The literature also reveals that most of the studies carried out in the Tropical Sub-Saharan Africa, have been evaluation of human thermal comfort from the physiological, adaptive and conventional paradigms.

2.9 Climatic Overview of Ghana

Ghana is located between latitudes 5°N and 11°N and longitudes 3°W and 1°E. It is predominantly a tropical country with climate that varies from a Warm Humid South - West corner to a Warm dry Coastal belt in the southeast to a Hot dry Savannah in the Northern part (Boateng, 1982) as cited in Amos-Abanyie et al. (2006). According to Abass (2009), there are four distinct Climatic Regions in Ghana as shown in Fig. 2.4. I- South Western Equatorial; II – Dry Equatorial; III- Wet semi Equatorial and IV – Interior Savannah.

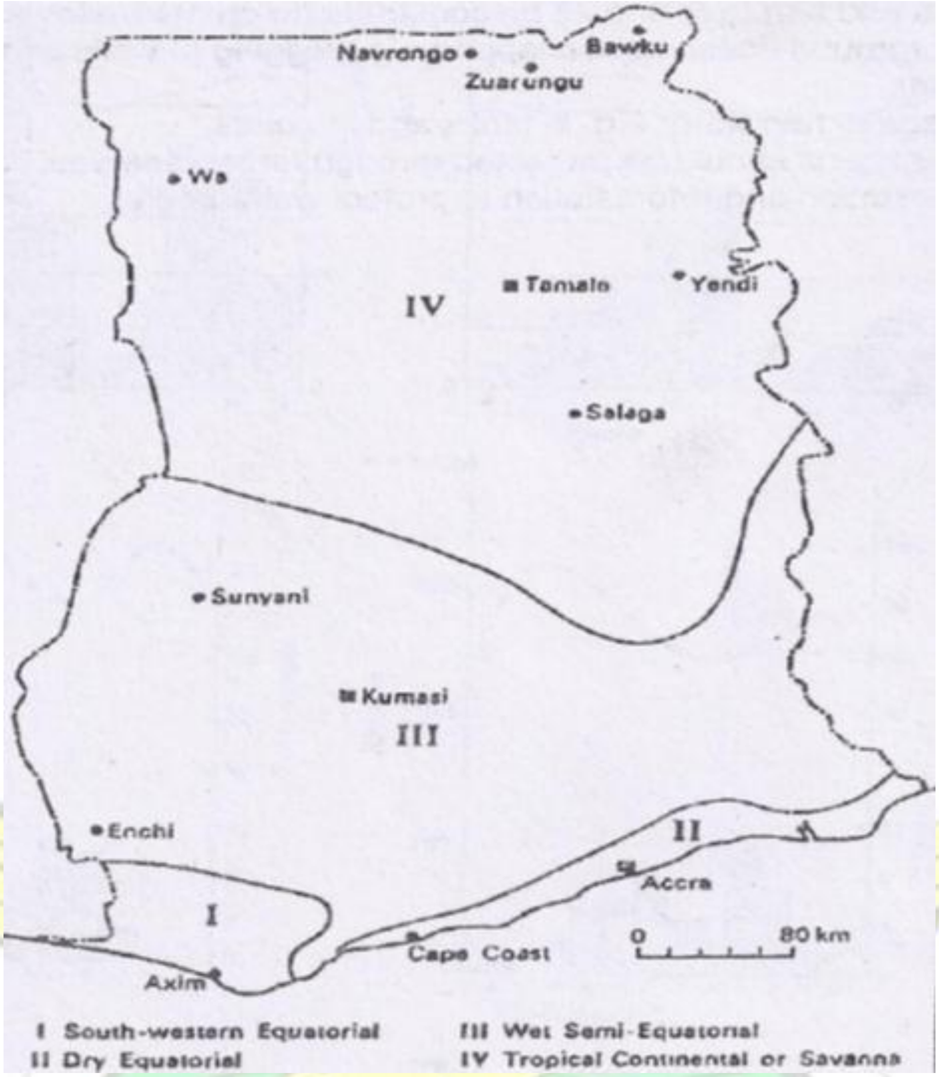

Fig. 2.4: Climatic Regions of Ghana (Source: Abass, 2009)

Temperatures are generally high with mean monthly temperature always above 25°C. There are however variations over different parts mostly due to the effect of altitude and, more importantly to the effect of distance from the sea (Abass, 2009).

Two major seasons exist in the country: the rainy season (around June to late September) and the dry season (November to late April). In Ghana, the hottest month of the year is March/April just before the rainy season whiles August is the coolest. In the southern part of the country, the highest mean monthly temperature of about 30°C occurs between March and April and the lowest of 26°C in August. The Southern part has a mean diurnal range of temperature between 6°C and 8°C which is increased in the case of the Northern sector by as much as 11°C and 12°C.

Climatic data obtained from the Ghana Meteorological Agency (GMA) validates the affirmation by Dickson and Benneh (1988) that relative humidity values along the Coastal belt in the South is generally between 95% and 100% during the night and early morning when the air over land is cooler than over the sea. In the afternoons however, the relative humidity falls to about 75% in the south West and 65% in the South East. Relative Humidity values in the Northern part of the country are about 20% to 30% during the dry season from November to April. It is extremely high during the rainy season at about 70% to 90% from May to October.

Annual mean rainfall levels decreases Northwards across the country. The wettest part of Ghana is the extreme South Western part. It receives more than 190cm of rain in a year (Amos-Abanyie, 2009). The driest part however is found in the South East plains where the mean annual rainfall is less than 75cm. Though the above represent the climatic overview of the country, localised climate within the various Regions contribute to the uniqueness of the study.

2.10 User behaviour and Indoor Climate

Research has demonstrated that the quality of the indoor environment has considerable impact on human health, stress, productivity and wellbeing (Agnieszka and Mats, 2013). The aforementioned authors also suggested in their study on Sweden apartment homes that, individual and building characteristics contribute significantly on how occupants perceive their indoor comfort. In their research, air quality was ranked first to have a great impact on occupant satisfaction followed by thermal comfort and sound (acoustic) comfort. Although the data used carries certain subjectivity, the subjective ratings proved to predict overall comfort better than the objective indicators

(Fransson and Vastfjall, 2007). Since the presence and actions of building occupants have a significant impact on the performance of buildings (Mahdavi and Pröglhöf 2009), building users have to know how to operate and control their systems. The mere existence of a control system cannot improve the adaptive opportunity in a building (Nicol and Humphreys, 2002). Therefore control systems have to be operated and done rightly to save energy.

Thermal controls in office buildings are used to adjust the climate for comfort and are achieved through the manipulation of environmental control systems, such as air- conditioners, windows, shades, etc. (Nicol and Roaf, 2005). Occupants in office buildings dress in standardized clothing and show up in their offices to carry out activities that have been assigned them by their superiors. In their quest to fulfilling these tasks, they are often disrupted by the way they thermally, visually as well as acoustically feel. Assigned tasks may be delayed or at worst not done. It is also known that technological and cultural pressures (building design, dress codes, heating and cooling control systems) are in danger of producing convergence on a very limited range of temperatures that are professed as ‗comfortable', particularly in public buildings such as offices (Shove 2003). This implies both increased indoor temperature control and increased energy use. In office buildings for instance, thermal comfort may not be the only parameter that has to be right for occupants. Visual comfort is defined as ―a subjective condition of visual wellbeing induced by the visual environment‖ (EN, 2002). Visual conditions are characterized by such parameters as luminance distribution, illuminance and its uniformity, glare, colour of light, colour rendering, flicker rate and amount of daylight (EN, 2002).

Navai and Veitch (2003) defined acoustic comfort as ―a state of contentment with acoustic conditions‖. The acoustic environment is influenced by such physical room properties as sound insulation, absorption and reverberation time (Cowan, 1994). Frontczak and Wargocki (2011) in their literature survey conducted showed that thermal, visual, acoustic and air quality is the main indoor environmental parameters contributing to satisfactory indoor environment. Frontczak et al. (2012) used panel data collected by the Centre for Built Environment (CBE) through postoccupancy surveys sent to office buildings to investigate which Indoor Environment Quality (IEQ) parameters affect occupants' satisfaction most. The results suggested that the three most important parameters for occupant satisfaction were space available for individual work, noise level and visual privacy. The impact of the main indoor environmental parameters, i.e. thermal, visual, acoustic and air quality, on office occupants' satisfaction was as follows: noise level, sound privacy, temperature, amount of light and air quality. More often than not, occupants in office buildings have different answers when it comes to the most important parameters for their satisfaction. Depending on how secure the building is, safety against fire, space allocated for individual workers, circulation spaces, break-off zones etc, occupants' tends to make various choices.

Kim and De Dear (2012) used the Kano Model to differentiate between IEQ factors that impact overall satisfaction in negative, positive or in both directions. They concluded that ‗temperature' and ‗noise' had predominantly negative impact on occupants' overall satisfaction when expectations were not met. According to Huang et al. (2012) in relation to temperature and relative humidity values, the thermal environment affects occupants' sensation of ―warm‖ or ―cool‖ and ―humid‖ or ―dry‖, and is considered to be the environmental factors to which people pay the most attention to. Comparative risk studies performed by the United States Environmental Protection Agency (USEPA) ranked Indoor Air Quality (IAQ) as one of the top five environmental risks to public health (Lai et al., 2009).

Alternatively, studies conducted on commercial spaces in Hong Kong by Lai and Yik (2009, 2007) showed fairly different results, indicating that thermal comfort had the highest impact on overall IEQ acceptance, followed by air, noise and visual quality. An investigation conducted in China also suggested that thermal comfort has the highest impact on overall satisfaction (Cao et al., 2012). Similar results were also found when a study based on Indoor Environment evaluation of occupants living in Hong Kong apartments was performed. The results indicated that thermal comfort had the highest importance impact on overall IEQ (Lai et al., 2009, Lai and Yik, 2009). This was followed by noise and air quality. Choi et al. (2009); Astolfi and Pellerey (2008) both investigated the importance of environmental conditions only in terms of the subjective evaluations by building users. They examined the importance of indoor environmental conditions for comfort by asking the building users to rank the parameters according to their importance. The results of both studies showed that thermal comfort was ranked to have slightly higher importance than acoustic comfort and satisfaction with air quality, and considerably higher importance compared with visual comfort.

One of the factors that are known to affect occupants' perception of their indoor environment is the climatic difference. McIntyre (1980) as cited by Djongyang and Tchinda (2010), observed that people of warm climates may prefer what they call a __slightly cool" environment and on the contrary, people of cold climates may prefer what they call a __slightly warm" environment. Apart from the main climatic difference, contextual variables such as localized climate do impact on occupants' thermal adaptation and perception of comfort (Becker and Paciuk, 2009).

The mode of ventilation of the building also affects the indoor environmental quality. The construction (materials and WWR) of the building is also a factor contributing to occupants‘ perception. A study of educational and office buildings in the UK and in India (Steemers and Manchanda, 2010) showed that occupants‘ overall satisfaction varies depending on the ventilation mode applied in the buildings. Moreover, dwelling quality, size and design were also demonstrated to have significant impact on residents‘ satisfaction (Lee et al., 2012, Dekker et al., 2011 and Mohit et al., 2010).

The recommendations of most agreed standards and codes of practice for office lighting criteria is 500Lux (Burberry, 1997). A study conducted by Yufan and Hassim (2011) on the comparison of occupant comfort in a conventional high-rise office block and a contemporary environmentally-concerned building showed that more than half of the illuminance records gave figures less than 500Lux (54.3%). Although this meant the working stations did not meet the lower limit of the visual requirement, only 26.5% (N - 34) of the occupants‘ clearly showed that their spaces were dark from _little‘ to _fairly‘. Moreover, since occupants‘ perception of their visual environment also depends upon the illuminance they are accustomed to (Tregenza and Leo, 1998), the aforementioned finding is possible.

The recommended criteria and suggested values for general office space sound is less than 45 dB as suggested by Reid (1984) in Yufan and Hassim (2011). The neutral sound pressure level for aural comfort in typical air-conditioned offices was found to be between 45 dB and 70 dB, with a mean of 57.5 dB (Mui and Wong, 2006). Studies have showed that physical environmental parameters are all interrelated, and the feeling of comfort is a composite state involving an occupant‘s sensation of all these factors (Naganoa and Horikoshib, 2005; Eduardo et al., 2004).

As cited by Huang et al. (2012), the Chinese code for the design of sound insulation of civil buildings suggests that the noise level in offices should not be higher than 55 dB. In their survey however (Huang et al., 2012), when the noise level was below 49.6 dB, subjects felt satisfied with the acoustic environment. When the noise level increased above this threshold, subjects felt increasingly uncomfortable.

Lighting represents a major energy-user in commercial buildings (around 15%), and large amounts of energy can be saved by using well designed lighting controls that can take advantage of the natural light available (Galasiu and Veitch, 2006). Cuttle (1983) as averred by Galasiu and Veitch (2006) administered questionnaires in England and New Zealand to investigate the perceived attributes of windows. The sample of participants consisted of 471 office workers who were asked whether they considered windows to be an important feature of a workplace and, if so, how important that was to them and why. Almost all respondents (99%) thought that offices should have windows, and 86% considered day lighting to be their preferred source of lighting. The preference for day lighting was attributed to the belief that working by daylight results in less stress and discomfort than working by electric light, but this belief was not based so much on the fact that daylight was beneficial but that electric light was harmful to health (Galasiu and Veitch,2006).

Heerwagen and Heerwagen (1986) as cited by Galasiu and Veitch (2006) surveyed occupants of an office building in Seattle, USA, in winter and summer. More than half of the occupants reported that they believed that daylight is better for psychological comfort, for office appearance and pleasantness, for general health, for visual health, and for colour appearance of people and furnishings. The authors further reported that occupants of naturally ventilated buildings had a more forbearing thoughts in relation to indoor thermal conditions compared with the occupants of air-conditioned buildings. They accepted higher indoor temperatures in the dry season and lower temperatures in the wet season, and they also accepted wider temperature ranges. This observation is in tandem with Frontczak and Wargocki (2011) who found similar results in their research. Frontczak et al. (2012) again in their study asserted that, respondents valued natural ventilation highly and it was very important for them that they could open a window in their home.

A study in Denmark showed that people did not feel confident in regulating heating equipment in their homes and felt that they needed more information (Gram-Hanssen, 2010). Kempton et al. (1992) and Lutzenhiser (1992) as alluded to in Frontczak et al. (2012) reported that people experience difficulties in using other systems, e.g. room air-conditioners, as shown in studies in the U.S. In Japan, occupants' only used a limited number of features of the air conditioners (Fujii and Lutzenhiser 1992). In contrast, Finnish occupants felt quite confident about their knowledge of heating and ventilation systems in their homes (Karjalainen, 2009). The above results show that understanding how people behave indoors and how they operate the systems for controlling the indoor environment demands an in-depth knowledge which is crucial for developing systems that provide comfort for building occupants (Frontczak et al., 2012).According to Price and Sherman (2006), people felt quite confident regarding their knowledge on how a ventilation system works and how to operate it properly. However, the authors concluded that respondents were not familiar enough with mechanical ventilation systems to meaningfully respond to questions about them. Other studies have also showed that people lack understanding on how to use systems properly for controlling the indoor environment and experience problems when operating them (Gill et al., 2010; Xu et al., 2009; Peeters et al., 2008).

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2.11 Energy Performance and Efficiency of Buildings

According to Yang et al. (2014), buildings account for about 40% of the global energy consumption and contribute over 30% of the CO_2 emissions (ibid). A large proportion of this energy is used for thermal comfort in buildings which are controlled by occupants. In the last decade, there has been an increasing interest in building energy performance enhancement, due to the shortage in energy supply and the benefits from reducing the energy costs of buildings (Yan et al., 2012). It has been estimated that, by 2020 energy consumption in emerging economies in Southeast Asia, Middle East, South America and Africa will exceed that in the developed countries in North America, Western Europe, Japan, Australia and New Zealand (Perez-Lombard et al., 2008).

Energy efficiency is one of the main tools that are highlighted when discussing the possibility of realising sustainable development (MSD, 2006). As the energy situation in the world all over is not getting any better, current trend of buildings is partly to blame for this situation. Energy is the most important engine to improve upon the quality of life and fight poverty. Given that by 2020 almost 70% of the world population will be living in cities, 60% will be energy poor (Serageldim and Brown, 1995). Thus for the next decade, thousands of megawatts of new electrical capacity have to be added. Der- Petrossian (1999) state that developing countries may avoid spending $ 1.7 trillion on oil refineries, coal mines and new power plants by spending for the next 30 years $ 10 billion annually to improve energy efficiency and conservation.

Lighting represents a major energy-user in commercial buildings (around 15%), and large amounts of energy can be saved by using well designed lighting controls that can take advantage of the natural light available (Galasiu and Veitch, 2006). In the UK, lighting account for between

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13% and 16% of energy-use and 18% and 25% of CO_2 emissions in a typical office building (Energy Consumption Guide, 2000). Literature search has shown that occupant actions in buildings greatly contribute to the energy problem. For instance, Webber et al. (2006) studied office equipment after-hours usage in different commercial buildings in the US, and showed that less than 50 percent of equipment is switched off by the building occupants‘ during non operating hours. In a more general study, Masoso and Groblera (2010) showed that more than half of the total building energy is typically consumed during the non-working hours mainly due to occupancy related actions.

An office building study performed in London however showed benefits in energy use when window size, solar protection, and internal gains were optimized (Kolokotroni et al., 2006) Barlow and Fiala (2007) however substantiate that the conventional response of installing air conditioning into existing offices to maintain comfort conditions results in increasing levels of energy, CO_2 emissions and pollution. Heating, Ventilation and Air-Conditioning systems (HVAC) in developed countries are confirmed to be the largest energy end-use, accounting for about half of the total energy consumption in buildings especially non-domestic buildings (Chua et al., 2013; Chung, 2011; Lam et al., 2010,2009). All over the world, refrigeration and air conditioning are responsible for about 15% of the total electricity consumption (UNEP, 2002). In the United States (US), lighting alone accounts for 25% of the energy usage (Buildings Energy Data Book, 2009). From the above, lighting is seen to be a major energy consumer and as such effort to conserve energy cannot be entire without lighting conservation.

Based on the above discussion, Salvalai et al. (2013) classifies all building end-users into three categories, i.e., HVAC-consumers, internal consumers (consisting of electric lights, office

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equipment and appliances) and other-consumers (e.g., lift, mechanical ventilation fans, water heaters, etc.). For a building to be energy efficient, its envelope (exterior façade) design must take into consideration both the external and internal heat loads as well as day lighting benefits (USAID Project, 2009). External loads mainly include solar heat gains through windows, heat losses across the envelope surface and unwanted air infiltration in the building. Internal loads on the other hand include heat released by the electrical lighting systems, equipment and the people working within the building space. Limiting air infiltration and ex-filtration is important to energy efficiency. The American Society of Heating, Refrigeration and Air-condition Engineering (ASHRAE) Standard 189.1 (2009), states that energy efficient designs must be evaluated on the following parameters: Orientation, Shape of building, Aspect ratio, Number of stories, Thermal mass, Natural ventilation, Wind, Colour and Shading. Other researchers suggest that window size and glazing types, envelope of the building are also parameters to pay attention to (Kolokotroni et al., 2006; Levine et al., [n.d]).

2.11.1 Orientation

The orientation of a building eventually determines how much energy it would use to provide thermal comfort for its occupants‘. Seok-Hyun et al. (2013) affirms that the amount of sunshine is affected by the orientation of a building. During summer, the amount of sunshine at the East and West is small but the west requires a larger cooling load in the afternoon because of the afternoon sunshine. The South has a larger amount of sunshine but the solar radiation can be blocked easily by shading. Salmon (1999), establishes the fact that ―buildings should be able to respond to changes in climate by the rejection of solar heat and have the thermal integrity to maintain internal comfort, despite the influence of climatic forces acting on the building envelope. In addition, the building should be able to retain cool, in order to maintain comfort. In this regard, the exact solar orientation is not critical (ibid). Salmon (1999) however establishes that, analyses of sun paths and wind directions have shown that elongated buildings should be oriented to the South. In addition, the best orientation for wind is the Southwest whilst a compromise of 22.5° (south-southwest) should give the best orientation.

KNUST

Contrary to Salmon‘s view, Lauber‘s (2005) recommendation was that the best orientation for buildings in the Warm and Humid countries should be +/- 30° from the prevailing wind direction. The author further states that the shell of air-conditioned buildings must be insulated, windproof and made airtight. This suggests an orientation away from the prevailing wind direction, but there is no precise direction for air-conditioned buildings from Lauber.

Szokolay (2004) also has a different proposal from the above mentioned authors. Szokolay suggested that in order to ensure maximum cross ventilation in a building, the major openings should face within 45° of the prevailing winds. All the above suggestions from these authors are for free- running (naturally ventilated) buildings since in mechanically ventilated buildings, the outdoor conditions do not fully have any effect on the indoor. Hawkes (1996) categorises buildings into two groups; the exclusive and selective modes. The exclusive mode has an automatically artificial environment. The shape is compact and tries to minimise the influence of the external environment, therefore, orientation is not important. In addition, the environment of the selective mode is controlled by automatic and manual means with a mixture of natural and artificial variables. The shape is dispersed and seeks to maximise the use of ambient energy. Orientation is an important factor in this mode. This implies that buildings in the exclusive mode are most likely to orient spaces anyhow and could have higher energy performance levels. Those in the selective mode would orientate spaces to the direction of the prevailing winds; functions of spaces are

important and could be a factor in the determination of the orientation as corroborated by the other authors. Aspect ratio which is the ratio of the longer dimension of an oblong plan to the shorter (Szokolay, 2004), is seen to have a relationship with the orientation of a building. Szokolay further explains that depending on the temperature and radiation conditions, North and South walls should be longer than the East and West with an aspect ratio of about 1.3 to 2.0 (op
cit).

2.11.2 Building Envelope

The envelope of any building is the exterior fabric that protects the building‘s interior from the harsh conditions of the outdoor climate. In other words, the envelope of a building acts as a shell in the transfer of heat from the external (exterior) to the internal (interior) and vice versa. A building‘s envelope therefore is constituted by the glazing or window area, the door, and the outer wall areas. According to Levine et al. (n.d), the effectiveness of the thermal envelope depends on

(i) the insulation levels in the walls, ceiling and ground or basement floor, including factors such as moisture condensation and thermal bridges that affect insulation performance;

(ii) (ii) the thermal properties of windows and doors; and

(iii) (iii) the rate of exchange of inside and outside air, which in turn depends on the airtightness of the envelope and driving forces such as wind, inside-outside temperature differences and air pressure differences due to mechanical ventilation systems or warm/cool air distribution.

On air- tightness of an envelope, Seok-Hyun et al. (2013) point out that air tightness is important to the performance of windows because this blocks the air flow causing a difference in the indoor and outdoor temperature of buildings. In particular, the windows and outer wall must be of an integrated construction. If it is not an integrated construction, air flow can occur as a result of the different pressures, which can cause heat loss. In modern day construction, it is unfortunate that building envelope designs are developed to meet the client's requirements without much concern to the local climate and with no objective to conserve energy (Al-Tamimi et al., 2011). An analysis of the building energy consumption in Hong Kong, Singapore and Saudi Arabia for example gives a result that, the building envelope design, accounts for 36%, 25% and 43% of the peak cooling load respectively (Grace - Cheok, 2008; Al-Najem. 2002; Lam and Li, 1999).

2.11.3 Thermal Mass, Night and Natural Ventilation

The thermal mass of a building material describes the ability of that material to absorb heat, store, and later release it either outdoor or indoor. Thermal mass can delay heat transfer through the envelope of a building, and help keep the interior cool during the day when the outside temperature is relatively higher (Amos- Abanyie, 2012). When thermal mass is exposed to the interior, it absorbs heat from internal sources and dampens the amplitude of the indoor temperature swing (Chenvidyakarn, 2007). This is particularly beneficial during warm periods, when the internal heat gains during the day is absorbed, and help to prevent an excessive temperature rise and reduction in the risk of overheating (Yam et al, 2003). A building with high thermal mass has the ability to absorb heat and provide a cooling effect which comes from the difference between the surface (radiant) temperature and that of the internal air. Szokolay (2004) accounts that absorptance/

reflectance will strongly influence the solar heat input. Reardon (2010) agrees with Szokolay (2004) by asserting that porous materials with low specific heat exhibit low thermal mass effects. Good thermal conductivity and low reflectivity are also required for effective passive cooling by thermal mass.

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Apart from high thermal mass, other strategies such as night ventilation and natural ventilation are known to reduce the energy use in buildings around the world. For instance, Pfafferott et al. (2003) confirmed that night ventilation reduced the mean room temperature by 1.2 K during working hours for a building in Freiburg/Germany and so did Geros et al. (1999) who also found the average reduction of the temperature in an office building in Greece to be between 1.8 and 3 K after using night ventilation.

Natural ventilation on the other hand can reach much higher ventilation rates than mechanical ventilation systems, which are especially designed for fresh air supply (Aggerholm, 2002). However, energy savings by natural ventilation can mostly only be evaluated when simulation tools are used as reported by Schulze and Eicker (2013). A range of studies using measurements and simulations in schools and offices showed air change rates between 5 and 22 per hour for cross ventilation and 1 and 4 for single-sided ventilation (Fisch and Zargari, 2009; Breesch,2006 and Eicker et al.,2006). Schulze and Eicker (2013) in their studies reported that _simulations showed that natural night ventilation is only suitable in buildings with sufficient and accessible thermal mass of about 75–100 kg/m^2 of floor space. The internal gains have to be limited to 30 W/m^2 of floor area‘. In a tropical climate, Al tamimi et al. (2011) observed that the improvements in comfort by natural ventilation ranged between 9% and 41% (Kuala Lumpur in

April). According to the authors, in a temperate climate, the improvements may vary between 8% and 56%; a result which showed that natural ventilation has a good potential in tropical and temperate climates according to (Haase and Amato, 2009).

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2.11.4 Windows and Glazing

Windows in buildings helps in several ways to keep the building comfortable. Windows provide building occupants with the opportunity to view outside, it also allow fresh air into a building when it is opened. Al-Saadi, (2006) and Datta, (2001) together gives an apt description of glazed windows. They describe glazed windows as components that allow natural light; offer a visual communication with outdoors; reduces the structural load and enhances the aesthetic appearance of buildings. A shaded and well positioned window on a building can go a long way into reducing the energy usage of the building as reported by Szokolay (2004). Furthermore, the area of exterior wall to the area of windows/glazing can also affect the thermal conditions within a building, thus the window-to wall ratio (WWR) of the building. In our part of the world today,

(Ghana) the use of extensive glazing is the order of the day. Commercial buildings with high WWR have a damaging consequence on energy conservation. Seok-Hyun et al. (2013) confirms the aforesaid assertion and comments that ‗the WWR is increased by the trend in curtain wall because of its attractiveness. This increases the cooling loads but decreases the heating load because of the season and solar radiation, which means that the proper WWR should be considered'. Manz and Menti (2012) commented on glazing in their report. They stated that ‗in terms of energy flows, glazing can be characterised by two parameters: Firstly, the total solar energy transmittance ‗g', which denotes the share of the incoming solar energy, which is converted into heat inside the indoor space. Secondly, the thermal transmittance ‗U' that describes how much heat is transferred through the glazing per square meter and Kelvin temperature difference between inside and outside.

Whiles the WWR of a building plays an important role by aiding day lighting into a space (Tzempelikos and Athienitis, 2007); it is known to be the most influential parameter on energy demand (Pino et al., 2012). Bokel (2007) studied the effect of window position and window size on the energy demand for heating, cooling and electric lighting. The total energy demand was calculated with the dynamic thermal program ‗Capsol' which simulates the total yearly energy demand for lighting, heating and cooling. The study concluded that facades should have a WWR of about 30 % of the façade area, where the window is positioned on the top half of the facade. WWR between 20 to 40% is also very acceptable whiles greater WWR does not have any effect on the lighting loads. The study further asserted that when a window position is considered, it does have a significant effect on the primary energy demand for lighting.

Shading is one of the methods for reducing the energy consumption of buildings while ensuring the outside views. Shading can be inside or outside. According to Seok-Hyun et al. (2013), ‗the ideal shading is to block solar radiation but achieve acceptable ventilation and view. In this regard, outside shading has more efficiency than inside shading. Inside shading leads to radiation between the shading and window. Outside shading blocks solar radiation before it reaches the window (ibid). The install option of the outside shading can be limited by high rise buildings or the characteristics of buildings. The design of the outside requires the azimuth of the sun, view, ventilation and maintenance to be considered'.

2.12 Energy Use Quantification Methods and Conservation in Buildings

In buildings, energy use should be calculated in order to know how much energy a building is using so for interventions to be made towards it reduction. It is possible to quantify energy use both in

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proposed designs and existing buildings. Typical energy classification instruments include energy bench-marking, energy rating, energy labelling and energy certification, which provide uniform or authorised means to communicate a building‘s relative energy efficiency and carbon emissions to both the owners and the public to encourage ongoing efficiency and conservation gains (Pérez-Lombard et al., 2009).

According to Yan et al. (2012), there are three energy quantification approaches that can be used to assess the energy performance of existing buildings, i.e., the calculation-based approach (e.g., via simulations), measurement based approach (e.g., via sub-metering) and the hybrid approach. Hybrid methods combine the features of calculation-based and measurement-based methods.
Maile et al. (2012) also observed in their studies that, _to assess the energy performance of all levels of detail in a building, a comparison that ranges from the component of the building levels and a systematic methodology are needed‘. Simulating the energy performance of a building helps in determining the energy usage and the reduction process through the components of the building. There is however a lack of a generic, effective and user-friendly tool for practical energy performance assessment and diagnosis in existing buildings as mentioned by Yan et al. (2012). For instance, Lee et al. (2003) developed a bottom-up estimation method to disaggregate the total energy consumption into four major end-uses, i.e., air-conditioning, lighting, office equipment and miscellaneous equipment. The individual energy consumption of each facility is calculated by multiplying the number, rated consumption, utilization factor, and the estimated operation hours. Salvalai et al. (2013) also states that electrical energy bill is a type of reliable and high quality measurement which provide an easy access to analyse the energy use characteristics of existing buildings.

Pfafferott et al. (2003); Turrent and Barlex (1997) showed a high potential of reducing energy use and costs, by up to 80% of the air conditioned solutions, in some energy efficient buildings with low energy cooling strategies coupled with natural ventilation. Kalz et al. (2009) and Henze et al. (2008) demonstrated that buildings with Thermo Active Building Systems (TABS) showed higher occupant satisfaction with low energy consumption, about 20% less, compared to traditional cooling system solutions. Miriel et al. (2002) and Imanari et al. (1999) also investigated water ceiling panels in terms of comfort and energy consumption and demonstrated that they are suitable technology for office buildings with low thermal loads. Tsikaloudaki et al.

(2012) reported in their study that ‗to avoid excessive use of the energy that is ever dwindling, passive cooling in naturally ventilated buildings should be encouraged. This can be achieved under the framework that is widely accepted: prevention of heat gains (solar shading devices, modulation of heat gains (thermal mass) and heat dissipation (natural ventilation). These methods have also been confirmed by Mosaffa et al., 2013; Artmann et al., 2008; Santamouris and Argiriou, 1994. Wang et al. (2014) also reported that enhancing the insulation and airtightness of the building envelopes, adding effective sun-shading systems, taking full advantage of natural ventilation and day-lighting, installing energy-saving lamps and intelligent control systems could enhance the energy efficiency of the building. Once the building envelope is airtight with a high thermal mass, indoor temperatures could be reduced as reported by AmosAbanyie (2012).

2.13 The Energy Situation in Ghana

The population of Ghana has increased over the years and economic growth rates have also increased steadily but the energy supply base has not caught pace with the growth (AmosAbanyie, 2012). In the wake of modernism, the current trend of architecture with large glazed areas has not been supported with the much needed energy to provide comfort in commercial buildings. The energy Commission of Ghana (2006) confirmed that indeed Ghana‘s energy situation is dwindling which is a challenge manifested in her expanding economy and growing population. Ghana‘s energy situation over the years have suffered major setbacks with the most recent being in 2006 where the water levels in the Volta lake reservoir (Ghana‘s main and only source of electric power) did fall below the ―Minimum Reservoir Elevation‖ of 240 feet which is safe for operation of the Akosombo power plant (Brew-Hammond and Kemausuor, 2007). Since then, Ghana has added unto its power generation plants but the situation is barely okay with the increase growth of urbanisation.

According to Frazier (2010) Ghana‘s sole sources of power supply until recently was from the Volta River Authority (VRA) owned hydroelectric plants of Akosombo (1038 MW, commissioned in 1965) and Kpong (160MW, commissioned in 1982), and imports from Cote d‘Ivoire. Since demand was outstripping the supply from the two hydro generation stations and poor hydrologic conditions were increasingly resulting in severe power shortages (such as in 1997 and 1998), the Government commissioned a 330-MW Combined Cycle thermal plant at Takoradi in 1999. The Government followed this by further diversifying its electricity production capabilities with a second thermal plant at the same site in 2000. This second plant, which was developed through a joint-venture partnership between the VRA and CMS Energy from the United States of America, is a 220-MW simple cycle thermal plant, with the option for an additional 110-MW steam turbine, once natural gas becomes available. Currently both plants are run on light crude oil imported from Nigeria. (Energy Commission of Ghana, 2006; Nexant Inc., 2004b).

The Ghana Grid Company Limited (GridCo) (2013) published in its electricity supply plan that allowing for periods of shutdown of generators for maintenance purposes, the total available

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hydro generation for 2013 was 7,577 GWh, and was made up of 6,088GWh from Akosombo; 1,011 GWh from Kpong and 478 GWh from Bui. Similarly, the total thermal generation for 2013 according to GridCo (2013) was 5,794 GWh which was made up of generations from : Takoradi Thermal Power plant 1 (TAPCo) (1,531 GWh), Takoradi Thermal Power plant 2 (TICO) (1,217 GWh), Takoradi- T3 (541 GWh), Tema Thermal Power plant 1 (TT1PP) (695 GWh), Tema Thermal Power plant 2 (TT2PP) (234 GWh), Mines Reserve Plant (MRP) (57 GWh), Sunon Asogli Power Plant (SAAP) (804 GWh) and CENIT (715

GWh). The VRA's Solar PV plant as at 2013 was expected to generate 2GWh.

Table 2.5: Ghana's Plant availability and Energy Generation

Plant	2013 Availability (%)	Dependable Capacity (MW)	2013 Generation (GWh)
Akosombo Hydroelectric Plant	94	900	6088
Kpong Hydroelectric Plant	94	140	1011
Takoradi Thermal Power Plant-T1 (TAPCO)	85	300	1531
Takoradi Thermal Power Plant-T2 (TICO)	85	200	1217
Takoradi Thermal Power Plant-T3	85	120	541
Tema Thermal Power Plant-(TT1PP)	85	100	695
Mines Reserve Plant (MRP)	75	80	57
Tema Thermal Power Plant-T2 (TT2PP)	85	49.5	234
Sunon Asogli Power Plant (SAPP)	90	170	804
CENIT Thermal Power Plant	85	100	715
Bui Hydro	94	345	478

(Source: GridCO, 2013)

Projections made by the Volta River Authority of Ghana revealed that in 2012, Ghana_s total electricity generation capacity was 3,491MW, out of which thermal contribution was 55% (Sackey, 2007). In the capital city of Accra alone, Frazier (2010) estimates that commercial land use experienced slightly higher consumption rates, averaging from 10,000 kWh per month upwards to 50,000 kWh per month. According to the Resource Centre for Energy Economics and Regulation (RCEER, 2005), urbanisation in Ghana was expected to increase from around 40% in 2000 to about 55% in 2012 and eventually to 60% by 2020. A little more than a third of the urban population lives in Greater Accra and is expected to reach around 40 percent by 2020. It has been projected that Ghana will need more than 7 times its 2007 electric power capacity by 2020 if it should succeed in developing its economy into a middle income one (OfosuAhenkorah, 2007).

A study carried out by the Energy foundation (1997) in the Ministry of Mines and Energy (MOME) building in Accra revealed that air-conditioners were responsible for 50% of the total energy consumed in the building annually. It was followed by office equipment (17.7%), internal lighting (17.1%), Miscellaneous (8.8%) and external lighting (6.4%). Altogether, the building consumed a total annual energy of 238,090kWh. Occupants actions were reported to have contributed to the aforementioned energy use by citing the following reasons: ―in 20% - 30% of the time, the air-conditioners and lights were left _on' when the offices were not occupied or sometimes left till the next morning. Cleaners who organise the offices in the mornings turn on the lights and air-conditioners as early as 6.00am and leave them _on' when they have completed cleaning till the staff gradually come in around 8.00am, and settle down to start the day's work. Sometimes, officers leave their offices for meetings or even lunch breaks and could proceed from there to other meetings or even home, leaving the air-conditioners and lights running for all those periods. Office operations consume almost 20 percent on the average, of electricity per year (Energy Commission, 2006).

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2.14 Thermal Simulation Techniques in Building Design

Over the past years, literally hundreds of building energy programs have been developed, enhanced and in use. These programs are based on information presented by software developers about: general modelling characteristics, outdoor climatic elements (day lighting, the sun, ventilation, and air flow), as well as studying the electrical systems and equipment, HVAC systems, etc. (Crawley et al., 2009). Simulation codes generally calculate dynamic heat transfer through building materials and evaluate overall building performance (Strachan, 2008). BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, Energy Plus, eQUEST, ESP-r, IDA ICE, IES/VES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS are all building energy simulation programs that have been developed for building thermal and energy calculations. In the current study, TAS simulation program was used as a design and analysis tool for the thermal and energy performance investigation.

2.14.1 The Thermal Analysis Software Programme (TAS)

Thermal Analysis Software (TAS) is a tool developed by the EDSL Company, used to simulate the day lighting, the sun, ventilation, and air flow in buildings. Tas is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems. It has a 3D graphics-based geometry input that includes a CAD link. Tas Systems is a 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 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. TAS is a program for the assessment of thermal behaviour. It calculates the heating and cooling loads resulting from inside and outside of buildings. The program adopts the mechanical simulation principle, by tracking the thermal behaviour of the building via various snapshots taken every hour. This gives users a detailed image of the way the building performs (Lee, 2010). The software has heating and cooling, plant sizing procedures, which include optimum start. The programme has 20 years of commercial use in the UK and around the world.

Fig. 2.5: The normal sequence of using TAS (adapted from Ahmed, 2012).

The Figure above shows the normal sequence of performing simulation for each application in the triple TAS package. First, the 3D model-maker is used for building the geometrical shape of the building, and specifying the borders of each space. Then the geometrical shape, the building elements, zones, and surfaces are sent to the building simulation application. In the course of sending, different calculations may be performed (EDSL, 2008).

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2.15 Validation of the Simulated Models

Validation involves creating a model of the test component and undertaking simulations using measured climatic data, and then comparing to the measured test environment to ensure that the model predictions align with the measured data over a realistic range of operating conditions spanning a period of several days to several weeks (Strachan and Baker, 2008). If successful, it gives confidence that the simulation program can correctly model the component characteristics when integrated into a full-scale building. The process can be improved by using simulation for the design of experiments, to ensure that all the main influencing factors are measured. A more pragmatic approach is to define the comparisons to be made and compare measurements with model predictions and modify the model if necessary. Once validated, it is considered that the simulation program can then be used to model the performance of a component. Ryan and Sanquist (2012) assert that for a building energy model to contribute to a sustainable energy future, the accuracy of the models needs to be assured so that the results of the models can be trusted. Comparison of models to empirical data allows for an ―absolute truth standard‖ within the uncertainty of the experiment; however empirical data requires expensive and time consuming experiments to be conducted (Loutzenhiser et al., 2007).

Empirical data is considered a very powerful validation tool since you are able to compare the model to the _true' metering and auditing data (Jensen, 1995). Therefore both the building parameters (Heating, Ventilation and Air-conditioning systems, the building materials and the architectural layout) and the occupants' behaviour (amount of cooling being used, additional electricity load due to appliances, etc.) have to be considered. Literature identifies two main types of validating energy efficiency models: the idealized and the realistic studies (Ryan and Sanguist, 2012). The idealized validation studies of building energy models, aim to validate the coupled physics of the models and the engineering assumptions which go into the models. In this case, idealized test cells are often modelled. Usually, a test cell typically consists of a single room, which is well insulated from its surroundings on all but one of its walls (Hoes et al., 2009; Loutzenhiser et al., 2009; Loutzenhiser et al., 2007). In realistic validation studies, building energy models are compared to metering and auditing data from actual residential and commercial buildings. Additionally, buildings and building energy models are often designed on the assumption that occupants will use the building in the way it is designed, i.e. maintaining temperature set points, utilizing passive day lighting controls, etc. In reality, the occupants of a building do not care about energy conservation as much as personal comfort and convenience. Furthermore, the operators of a building are not always as knowledgeable as designers assume them to be and therefore do not always operate the building in the way it was designed (Norford, et al., 1994).

In a study by Newsham et al. (2009), the authors investigated 100 Leadership in Energy and Environmental Design (LEED) buildings and compared them to a database of typical building energy use from the Commercial Building Energy Consumption Survey of 2003 (CBECS). The results of their statistical analysis show that on average, LEED buildings uses 18% – 39% less energy than CBECS buildings (Newsham et al., 2009). However 28% – 35% of the LEED buildings considered, used more energy per floor than the CBECS buildings. Although on average the LEED buildings performed better than the CBECS buildings, on individual basis, the LEED buildings did not always lead to energy savings. Some of the key factors that affect a building‘s energy use and which are difficult to account for accurately include changes in occupancy hours, different as-built versus initial design conditions, new energy-saving technologies not performing as expected, and buildings being poorly commissioned (ibid). All of these factors can affect a LEED building, thus, actual versus expected performance.

For the current research, the realistic validation process was followed through to ensure the building energy modelling accuracy. Empirical data was collected in all the case study buildings comprising of the building parameters, the occupants and their behaviour. Occupant‘s behaviour is typically included in building energy modelling by setting the heating, cooling, equipment and lighting schedules and temperature set points based on the hours of use by the occupants and local weather conditions. Significant time and effort was devoted in the modelling of the building. This was to ensure that accurate experimental test results were achieved to calibrate the simulation model in order to confirm the simulation model of the tested component can accurately predict its performance.

2.16 Gaps in the literature

The literature reviewed has identified some gaps concerning the various subject areas:

i. Thermal comfort and building performance studies are climate specific and as such will have to be conducted in various climatic regions due to micro-climatic difference. This study is conducted within the dry equatorial climatic region of Ghana which is the first of its kind. The collection of empirical data from the case study buildings add to the exceptionality of the research.

ii. Previous studies on the behaviour of occupants and indoor climate was not conclusive. For instance, studies carried out on occupants satisfaction with their indoor climate (Cao et al., 2012: Frontczak et al., 2012: Lai and Yik, 2009 and 2007) all drew conclusions on the rankings of existing parameters at the time of the research. They did not go further to determine the preferences of the occupants‘ as far as those thermal parameters were concern. This study probes further into determining occupants preferences.

iii. Very little has been done to verify the use of building energy models in real life situations (realistic approach) where many factors need to be modelled, such as the efficiency of the HVAC equipment, the effect of occupants etc. This study takes these factors into account.

iv. The current study is unique since it uses the realistic approach in finding alternatives that could reduce the energy use of multi-storey commercial buildings in Accra, Ghana whiles providing a better thermal comfort for occupants. This is the first of such study in the country. Though two previous studies were identified, Amos-Abanyie (2012) was purely idealised in its approach whiles Koranteng (2010), though realistic in approach did not concentrate on curtain wall multi-storey commercial buildings. Again Koranteng‘s study was carried out within the wet- semi equatorial region of Kumasi.

v. Whiles many thermal performance studies have concentrated on the reduction of indoor temperature, very few studies have looked at the reductions in terms of cooling loads. Within the study area, no such studies have been conducted.

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CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 Chapter Outline

This chapter discusses the method used in the research. It covers a presentation on the overall research design. The main aim and objectives of the study is also reiterated here. Object description: thus the buildings and the subjects from whom information was elicited. Data collection procedure, development of the ESDL Tas simulation models, data processing, data analysis and the limitation of the research are all expressed in this chapter.

3.2 The Purpose and Objectives of the Study

The purpose of this research is to assess thermal comfort conditions and to explore design options towards the reduction of energy use in multi-storey office buildings. Given the purpose, the objectives, research questions and the data collection methods are presented in Table 3.1.

Table 3.1: Research Objectives, Questions, Data Collection Methods, Actions and Outputs.

Research Objectives	Research Questions	Data Collection Methods, Actions and Outputs
1. To assess occupants views of their indoor thermal comfort conditions within the selected buildings.	What are the views of occupants concerning their indoor thermal conditions?	Questionnaire survey, Observation, perceived actions.

Table 3.1: Research Objectives, Questions, Data Collection Methods, Actions and Outputs Cont'd.

Research Objectives	**Research Questions**	**Data Collection Methods, Actions and Outputs**
2. To determine the thermal comfort conditions of the indoor environment of the selected buildings.	What effect does the glazed façade (glass box) have on indoor climate of multi storey office buildings?	Measured data (Thermal comfort models: PMV-PPD, Psychrometric chart and the Bioclimatic chart).
3. To identify energy reduction strategies for the indoor conditions of the selected buildings based on validated models.	Which design option would be energy efficient for multi storey office buildings?	Parametric simulation (experimental research).
4. To identify overheating reduction strategies (passive case- no air conditioners) for the selected buildings.	How best can offices be thermally satisfactory in the absence of air- conditioning?	Parametric simulation (experimental research).

3.3 Research Objective 1:

To assess occupants views on their indoor thermal comfort conditions within the selected buildings.

Data for this objective was collected through a thermal comfort questionnaire developed by the University of California's Centre for Environmental Design Research, Berkeley. The questionnaire had been adopted, modified and tested on 64 subjects in a similar study in Kumasi

(Koranteng, 2010). In this situation, people's answers refer to the very thermal environments to which they are subjected to in their everyday life (Paula and Lambert, 2000). Samples were drawn from all the monitored offices. Analysis was conducted based on the occupants'

subjective feelings within their indoor environment. This objective was aimed at finding out the occupants' judgment about the perception of their indoor environment.

3.3.1 Research Objective 2:

To determine the thermal comfort conditions of the indoor environment of the selected buildings.

The thermal environment was analysed by means of field measurement; where thermal comfort parameters were measured. The parameters were measured continuously throughout the study period of 12 months at a height of 1.1m above the floor, according to the ISO 7726 (1998) standard for seated persons. The measurement grid included at least four measurement spots, uniformly distributed in the spaces monitored. This was done to ensure reliability of the measurements. Data loggers were mounted within the selected offices which were located from the fifth floor to the fifteenth floor in all buildings. The measured data was used as inputs into 3 thermal comfort models for analysis. The models are: PMV-PPD (Fanger, 1970), Psychrometric chart (Szokolay, 2004) and the Bioclimatic chart (Olgyay, 1963; Givoni and Milne, 1976).

Findings were related to literature and conclusions drawn.

3.3.2 Research Objective 3 and 4:

To identify energy reduction strategies for the indoor conditions of the selected buildings based on validated models; and

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To identify overheating reduction strategies (passive case-no air conditioners) of the selected buildings.

Objective two provided the necessary data for objectives three and four. Objectives three and four employed the use of a simulation tool: ESDL Tas, to run experimental scenarios for the best fit strategy towards the reduction of energy use in the offices. The chart below (Fig. 3.1) describes the process for the achievement of the two objectives.

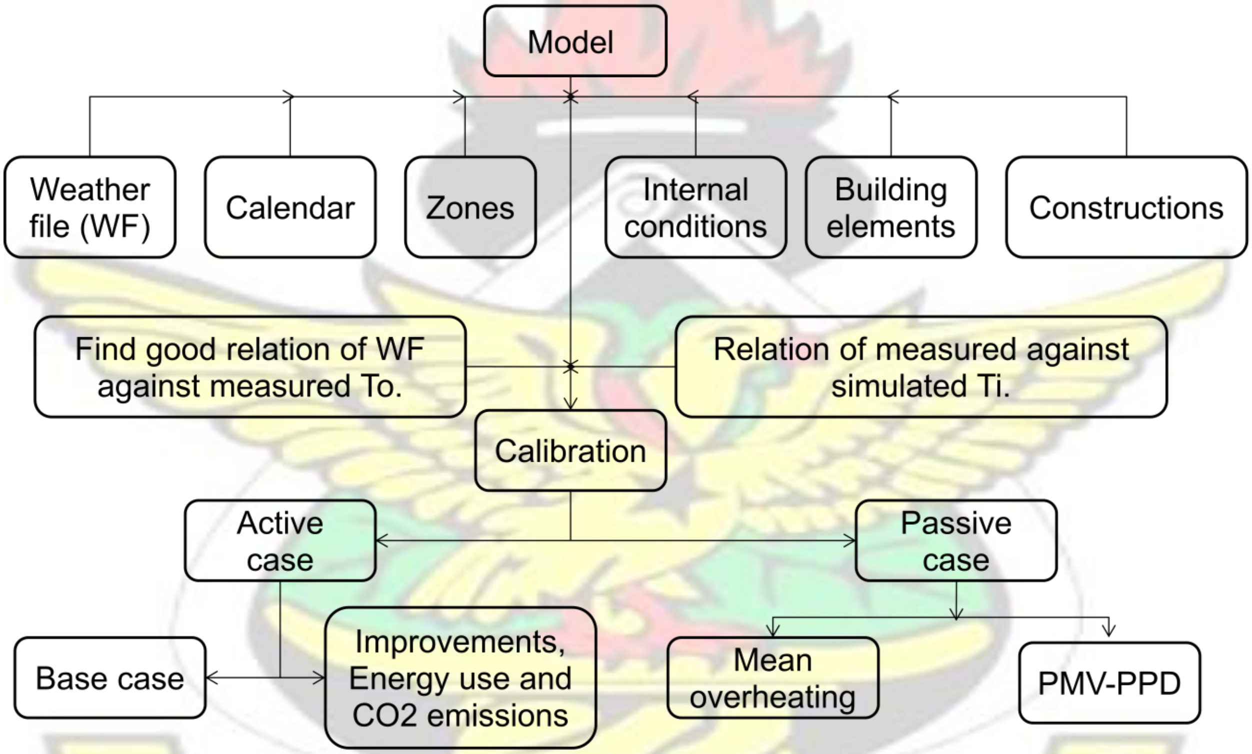

Fig. 3.1: Systematic process of the simulation steps (Author‘s construct)

Using the plans of the buildings, the models were built using the Tas 3d modeller. The weather file (synthetic weather file from meteotest) was applied within the simulator. The calendar specifies the study period (12 months). The office spaces were segregated from the circulation spaces, zoning. All internal conditions (occupancy sensible and latent gains, equipment sensible gain, lighting gain, infiltration etc) in the office spaces was calculated and applied in the simulator. The building elements in the form of the floors, external and internal walls, window frames and panes, ceiling and blinds were all identified. The constructions of these elements were then applied. Calibration/Validation of the models (finding a good agreement between the weather file and the measured data) was performed after which the active and the passive case simulations were run.

3.4 The Research Process and Design

The research process gives a detailed account of the research strategy utilised in the research. With a clear theoretical framework established in Chapter Two, Fig. 3.2 describes a generic research process that supported the researcher to ―depict the issues underlying the choice of data collection methods (Saunders et al., 2007).

The layers of Saunders ―Research Onion‖ correspond to the following aspects:

- Research philosophy;
- Research approach;
- Research strategy/methodology;
- Time horizons; and
- Data collection methods;

Yin‘s (2003) research design criterion is also used to check the flawlessness of the method arrived at by using Saunders‘ model. The magnitude of research design comes from its role as a critical link between the theory and argument that informs the research and the empirical data collected (Nachmias and Nachmias, 2008). A choice of research design _reflects decisions about the priority being given to a range of dimensions of the research process (Bryman and Bell, 2007).

It is therefore a blueprint that enables researchers to find answers to the questions being studied for any research project. Along with clear research plan, it provides constraints and ethical issues that a study will inevitably encounter (Saunders et al., 2007).

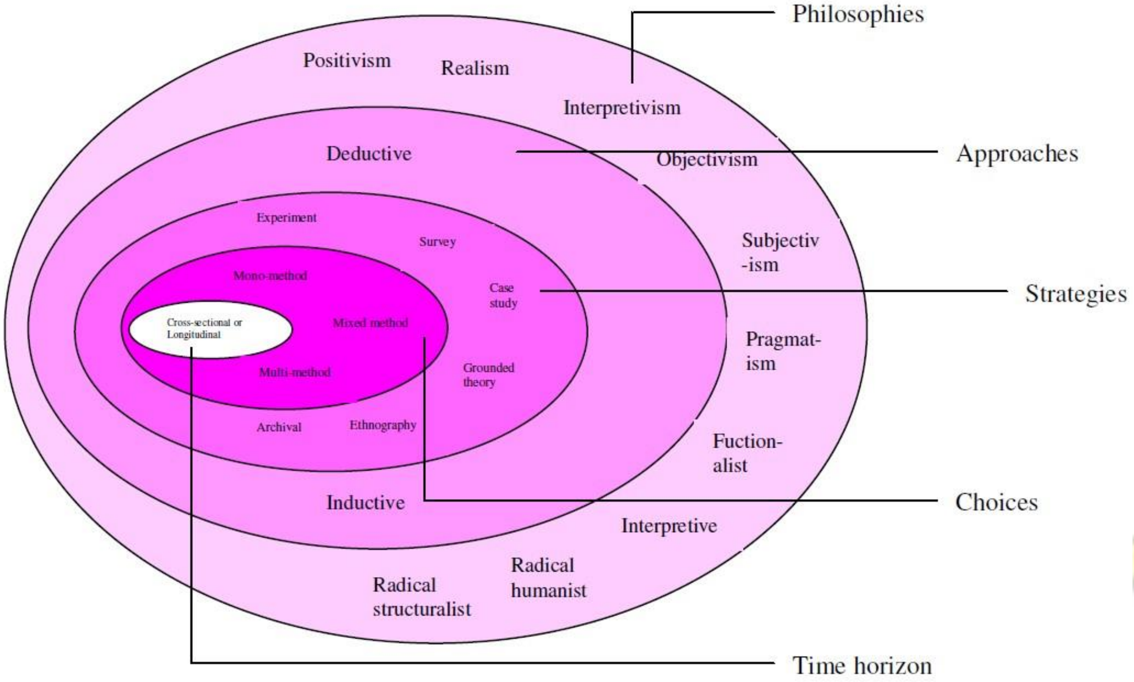

Fig. 3.2: The research onion (Saunders et al., 2007)

Figure 3.3 shows how the ―Research Onion‖ as applied in this study. The specific research philosophy, research approach, research strategy/methodology, time horizons and data collection methods are shown in boxes. These selections and methods culminate in the research design.

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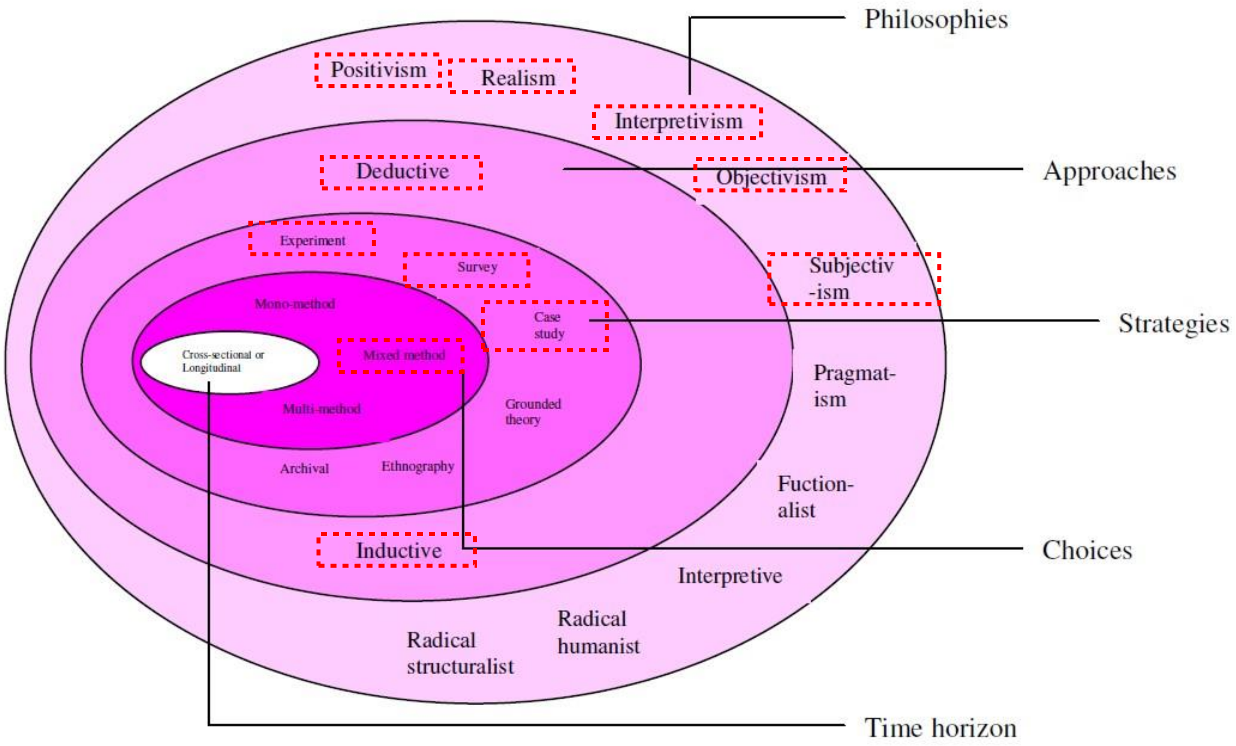

Fig. 3.3: The Research process onion adapted for the studies (Saunders et al., 2007)

3. 5 Research Philosophy

A research philosophy is a belief about the way data about a phenomenon should be collected and analyzed (Levin 1988). It fundamentally concerns the assumptions or the standpoint that the researcher brings to an investigation. Sexton (2003) argues that research philosophies are characterized by contrasting views on the ontological, epistemological and axiological assumptions. Abbott, (1998) also states categorically that in whatever manifestation, for a theoretical model to explain anything, there must be an appropriate relationship between the statements made, the methods used to make such statements, and the philosophical perspective deployed to inform the methods; thus issues pertaining to ontology, epistemology and methodology. Ontology is concerned with the nature of reality. Its central question is whether social entities can, or should, be considered social constructions built-up from the perception and action of social actors (Limpanitgul, 2009). Epistemology, on the other hand, concerns what constitute acceptable knowledge in an area of study. The key epistemological question is ―can the approaches to the study of the social world, be the same as the approach to studying the natural sciences? (Saunders et al., 2007). Epistemology provides the philosophical underpinning to the credibility which legitimises knowledge and the framework for a process that will be produced through a rigorous methodology. In summary, ontology is _being', epistemology is _knowing', and methodology is _studying' (Limpanitgul, 2009).

In behavioural sciences, the positivist posits that human behaviours can be explained and predicted in terms of cause and effect (May, 1997). Positivists believe that the collection of data has to be performed in the social environment and involves reactions of people (ibid). Principal positivist methods consist of observations, experiments and survey techniques. From the purpose and objectives of the current study, there are clear signs of theory confirmation through both the deductive and inductive approaches. The defence of the field study approach to thermal comfort depends largely on what has been named __experimental realism" of the field methodology (De Dear and Auliciems, 1985) as cited by (Corgnati et al., 2007). This philosophical position entails all the views indicated in Fig. 3.3 used for the study.

As per each objective, the research parameters involved in the study were transformed into observables or indicators to facilitate quantitative empirical testing leading to the use of objective methods in gathering information; which leans more towards positivism as well as objectivism.

Additionally, literature reviewed informed the presence of human actions and interactions, thermal comfort and energy use in office buildings. This also gives an indication of subjectivism, realism and interpretivism.

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3.6 Research Approach/Strategy and Time Horizon

Deriving from the research philosophy is the determination of research approach, strategy, and time horizon. It is normally argued that research approaches are attached to different research philosophies (Saunders et al., 2007). Mason (2002) describes the research approach as ―deciding what theory does for your arguments‖.

For the current research, the mixed approach is appropriate where the inductive emphasises:

- The collection of qualitative data;
- Gaining access to understanding of meanings human attach to events;
- A close understanding of the research context; and
- A more flexible structure to permit changes of research emphasis as the research progress (Saunders et al., 2000).

Again, as per the positivist stance which has been established to be used for some objectives, there is a more deductive approach along with this since the identification of measured variables facilitates quantitative empirical testing (Saunders et al., 2003).

Another research approach described as the ―abductive research strategy‖ is the process of moving between everyday concepts and meanings and laying accounts to social explanations (Blaikie, 2000).

Scott and Usher (1999) also state that, abduction is applied as a research approach when the researcher ―can only know social reality through the eyes of the social actors involved in it‖. In the current study, the author generating a questionnaire to the building occupants to know their concerns align well with the scenario created by the cited authors.

The literature on research methodology identifies experiments, survey, case study, grounded theory, and ethnography and action research as major research strategies within the spectrum from deductive to inductive approaches (Saunders et al., 2007; Yin, 2003; Easterby-Smith et al., 2002). The research strategy is a general plan of how the research questions will be answered (Saunders et al., 2000).

Figure 3.3 below represents the research strategy adopted for the current research (circled). It shows how the research strategy can be positioned within the epistemological, axiological and ontological continuums.

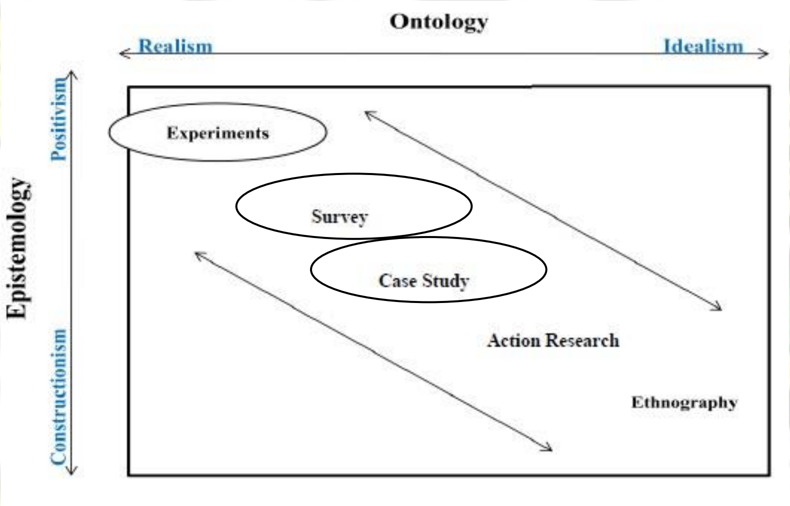
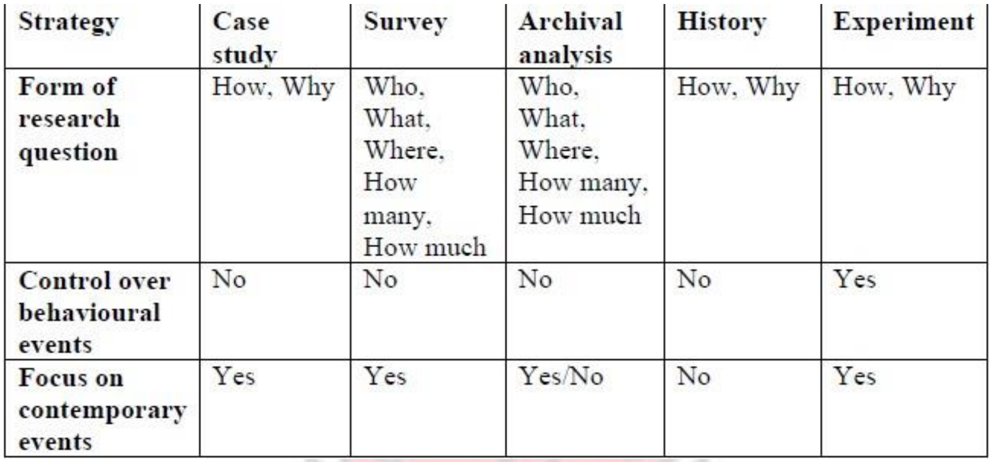


Fig. 3.3: Continuum of Research Approaches (Adapted *from Sexton, 2004*)

The choice of the strategy circled above as pertaining to the current research is substantiated using Yin's research design selection criteria (Yin, 2003). In his work, Yin (2003) identified certain factors that have to be taken into consideration in carrying out any research and put these factors into three main conditions in his framework for choice of research strategies.

Table 3.2: Research design selection criteria



Strategy	Case study	Survey	Archival analysis	History	Experiment
Form of research question	How, Why	Who, What, Where, How many, How much	Who, What, Where, How many, How much	How, Why	How, Why
Control over behavioural events	No	No	No	No	Yes
Focus on contemporary events	Yes	Yes	Yes/No	No	Yes

(Source: Yin 2003)

The time horizon for the current study was limited to a specific period of time the study was conducted (cross sectional). The measurement and the questionnaire were given to the subjects (occupants) of the study during the period of May, 2013 after all the measurements had been taken (May, 2012 to April, 2013). This was so because the researcher did not want the occupants to be influenced by the presence of the data loggers in their offices in the answering of the questions.

Measurement-Observation-Perceived-Survey-Simulation (MOPSS) adapted from Mallory- Hills et al. (2005) was used as data collection methods/tools whilst the methods of analysing the data included three thermal comfort models (PMV-PPD, Psychrometric chart, and Bioclimatic charts), descriptive statistics and simulation.

A research design is the logic that links the data to be collected to the initial questions of the study (Yin, 1989). The logical sequence of the research design should help the researcher to ensure that the evidence addresses the initial questions (Mouton, 2002). The research design for this study is formulated according to the following perspective;

- Research strategy;
- Data collection methods;
- Data collection instrument or process;
- Data sources;
- Timing in terms of when the instrument is administered;
- Qualitative or quantitative nature of the data; and
- Trustworthiness and continuity of the data (adapted from Korpel, 2005).

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Table 3.3: Summary of the Research Design for the current Study

Research Strategy				
Data collection methods	**MEASUREMENT**	**OBSERVATION/ PERCEIVED**	**SURVEY**	**SIMULATION**
Data collection instrument/process	Data loggers, anemometers, digital light meters	Observation notes	Thermal comfort questionnaire	-
Data source	From the selected office spaces	Within the monitored office spaces	From literature	From the selected office buildings
When administered	After identification and permission from the office managers	In the course of the measurement	After the measurement	-
Qualitative and Quantitative	Quantitative	Qualitative	Quantitative Qualitative	Quantitative

Table 3.3: Summary of the Research Design for the current Study Cont'd.

Research Strategy				
Data collection methods	**MEASUREMENT**	**OBSERVATION/ PERCEIVED**	**SURVEY**	**SIMULATION**
Who administers	Researcher	Researcher	Researcher	Researcher

Trustworthiness and continuity	Continuous measurement	Peer examination triangulation	The investigator‘s position Triangulation	Continuous simulation
Data type	Thermal comfort parameters	Behavioural patterns, office ethics	Personal, indoor environment …	-

(Adapted from Korpel, 2005)

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3.7 Object Description

The object description describes the case study buildings. Four multi-storey office buildings in Accra, Ghana were selected for the study. The buildings are: Premier Towers (P.T.), World Trade Centre (W.T.C.), Heritage Towers (H.T.) and Ridge Towers (R.T.). The selection was based on the following rationale;

- Their common features; thus exposed glazing (curtain walls) on all or a greater part of the facades;
- Representative of current design trends in Ghanaian high-tech office buildings; and
- Located within the same neighbourhood, thus within the central business district of the capital city of Ghana, Accra.

Below is the map of the area within which all the buildings are found.

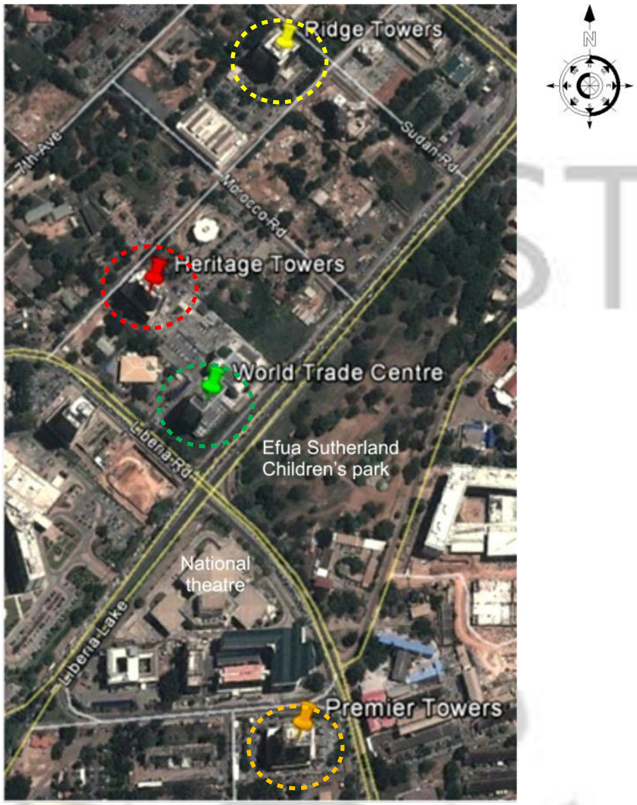

Fig. 3. 4: Location of Case Study buildings (Source: Goggle Maps, 2014)

The buildings accommodated different organisations, had varied sizes and occupants in different age groups as well as educational levels.

3.7.1 Premier Tower (P.T.) Building

The Premier Towers building has a pyramidal form but a simple plan with an atrium in the middle. The external fabric is made up of fixed curtain wall systems with no external windows and a North-South orientation. There are no external shading systems. The entrance is located in the middle of the space and linked to the various spaces through a veranda in front of the offices and a lift to the other floors. There are two stair cases for use to the other floors as well (Fig. 3.5). The building operates on central air-conditioning systems with each office unit ventilated based on centrally located on/off switch. All four sides of the building have glazed windows exposed to direct sunlight without any external shading devices. The 5th floor was monitored for the study.

Fig. 3.5: Outdoor and indoor view of selected space in building P.T.

Originally, all floors were designed and developed as open floor plans with modifications made by the various corporate entities occupying them. The area of the monitored office measures 169m² with five enclosed spaces for the management of the firm. A sample enclosed office measured 11m² with carpeted floor. The interior spaces have blinds which are deployed when the direct sunlight becomes a nuisance. Each office has three to four 40 watts florescent tubes depending on the size of the office with manual control. With the exception of the enclosed offices, occupants within the open floor plan need permission from their colleagues before they could operate the blinds, the lights and or the air-conditioners. For detailed properties of the building elements, see appendix F.

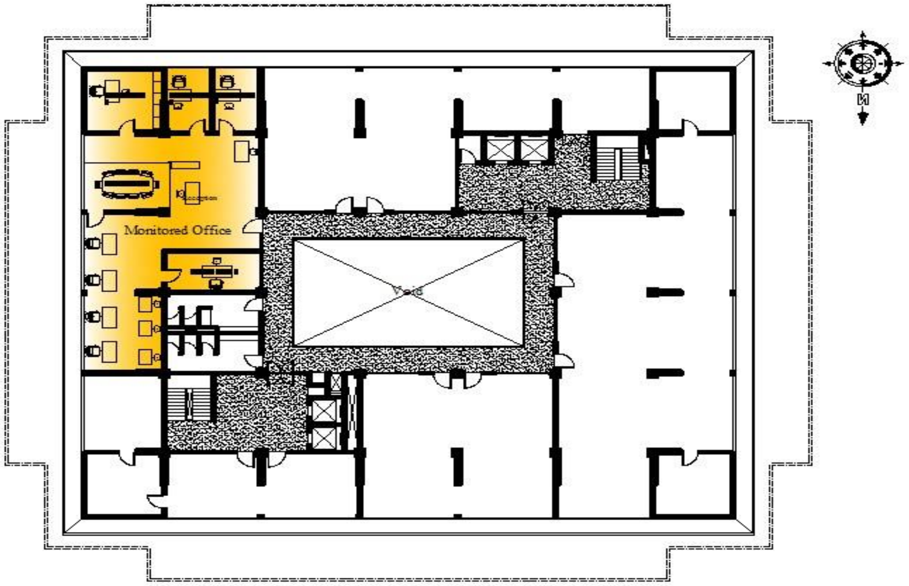

Fig. 3.6: Schematic plan of offices on the 5th floor in the P. T. Building

3.7.2 World Trade Centre (W.T.C.) Building

The World Trade Centre is a multipurpose 15 storey block with a North -West and a South-East orientation. The building is rectangular in shape with a total area of 14,556.78m². The entrance of the building is located at the middle on the ground floor with a first floor space for meeting/conferencing (Fig. 3.7) on top. The various floors are accessible via 6 lifts and a staircase. The exterior fabric is made up of operable double pane windows without external shading; an exception is the 15th floor which has a balcony with the windows recessed. The office spaces have been rented out to various national and international companies who have organised the interior spaces according to their taste and style. Each office space has manually controlled interior blinds. Currently, the first through the fourteenth floors operate on central aircondition units with thermostat controls whiles the fifthteenth floor is a naturally ventilated floor with air-conditioners yet to be fixed. The 15th floor was the monitored floor for the study.

Fig. 3.7: External view of the building W.T.C.

Fig. 3.8: Schematic plan of offices on the 15th floor in the W.T.C. building

A sample office space is occupied by five to eight staff and measures about 35.5m². Each office space has three twin florescent tubes of 40watts each which is manually controlled. As a result of the ventilation type (natural ventilation), there exist different adaptive opportunities (opening windows, using personal standing fans, etc.) which could be operated based on the collective agreement of the occupants. The floor material within the monitored offices is tiles with acoustic panels as the ceiling material. Gypsum board cladding which goes up to the ceiling separate one office space from the other. The structural support for the building is a 300mm x 300mm at 5000mm c/c reinforced columns. See appendix F for the properties of the building elements.

3.7.3 Heritage Tower (H.T.) Building

The Heritage Tower is a fully glazed rectangular office block occupied by different companies. It is a 15 storey building and 9,340.86m² in area. The tower has an East-West orientation without any external shading for its extensively single pane glazed facades; thereby, allowing direct solar radiation into the interior spaces. This gives an indication of the amount of energy that must be used to maintain comfort. There are however internal blinds which are manually deployed by occupants when they feel disturbed by solar radiation. Floors monitored were the 10th, 11th and the 12th. The space is cooled by split air-condition units and there are virtually no operable windows in the curtain walled façades. The outdoor units are kept on the balconies of each floor.

The structural support for the building is columns and beams arranged at not more than 4800mm.

Fig. 3.9: External and internal view of monitored office in the H.T. building

Offices located within the middle part of the tower have manually controlled blinds on the inside whiles those at the wings are without blinds probably because of the balconies (Fig. 3.9). Nonetheless, there is still indirect solar radiation that hits the envelope of the building and finds its way to the inside of these offices through the various elements. A sampled office monitored measures 23.2m² for top management personnel. Each enclosed office has two twin 40watts florescent tubes which are manually controlled. The floor is made up of tongue and groove timber pieces with no carpet.

Fig.3.10: Schematic plan of offices on the 11th floor in the H.T. building

3.7.4 Ridge Tower (R.T.) Building

The Ridge Tower building, designed with the swastika symbol as its concept (Fig. 3.11), is a 15 storey high structure accommodating different multi-national companies. It has a North WestSouth East orientation. Structurally, the building is supported by columns and beams with column centres of not more than 6000mm. Appendix F gives a full description of the building elements.

Fig. 3.11: Exterior and internal view of selected space in the R. T. building

Ridge Towers has a net area of 14.355.68 m^2. The glazing arrangement on the building facade is 100% wall to window ratio and alternates on the walls (Fig. 3.11). On the seventh floor however, there is a recession which serve as a balcony and protects the glazing. One compartment of the seventh floor contains the company that manages the whole building (Fig. 3.12). The building operates fully on centralized air-condition systems with thermostats. In a typical open plan office, occupants do not have access to the thermostats since they cannot change the settings on their own accord. A classic closed office within the management company‘s floor is 12.6m^2. There is also privacy for telephone conversations as well as in the operating of the airconditioners and the lights. There are no external shading devices, thus, in an attempt to reduce the amount of solar ingress into the various spaces, occupants have resorted to internal blinds which are manually operated in the afternoons. The light within the various offices range from

36 to 40Watts and differ in numbers depending on the size of the office space.

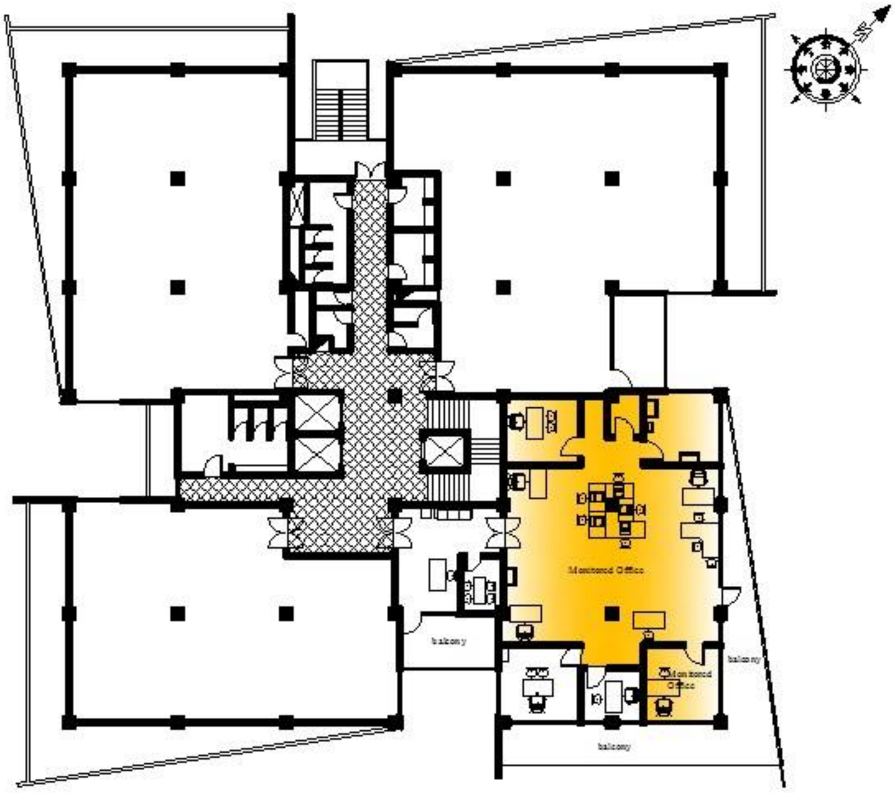

Fig. 3.12: Schematic plan of offices on the 7th floor in the R. T. Building

3.8 Data Collection

The data collected included climatic data, building and operational parameters. With the decision to undertake the investigation with the Tas simulation program, the first step entailed the skill and knowledge in the use of the software. This was possible through sections and information available on the ESDL website.

3.8.1 Overview

The data collected includes climatic data, building and operational parameters. The building parameter data was collected from May, 2012 until April 2013. Within this period, external weather information was gathered from the Accra Meteorological Department. Data loggers (Hobo sensors) were installed inside and outside of the buildings and consequently, data-points were read out every

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30 days. Building plans and information on the materials used were collected within the same period.

3.8.2 External environment

Data loggers (Hobo sensors, U12-012) produced by ―Onset Inc.‖ were mounted on the outside of the buildings to record air temperature and relative humidity values (see Table 3.4). Since detailed and comprehensive outdoor weather information was not available, the author identified segments of a synthetic weather file for Accra (generated via Meteotest 2008). The Accra weather station provided some daily mean minimum and maximum temperature and relative humidity values which were compared to the measurement from the data loggers.

Table 3.4: Accuracy of the Sensors

SENSOR	Range	Error
Air temperature	-20 to 70 ºC	± 0.4 ºC
Relative humidity	5 to 95 %	± 3%
Air velocity	0.1 to 25.0m/s	± 5% ± 0.1m/s
Light intensity	12 to 32.000 lux	-

3.8.3 Internal environment

Indoor temperature, relative humidity, light intensity, and air velocity values were measured with the aforementioned data loggers within the same date as the external measurements were started. The sensors were mounted near the workspace to avoid occupants from depositing items on them (Fig. 3.12). Care was taken to avoid direct solar radiation on the sensors. They recorded the parameters every 10 minutes and the recordings were downloaded by connecting the sensors to a computer using the hobo-ware pro and the green-line software. For further information on the data loggers see Appendix A. The sensors were named as follows: ―building name _ floor and room number _ sensor ID _ installation date‖. For instance, ―R.T. _701_701_010512‖ means Ridge Tower building _ seventh floor, room one _ first sensor on the seventh floor _ installed on May 1st, 2012.

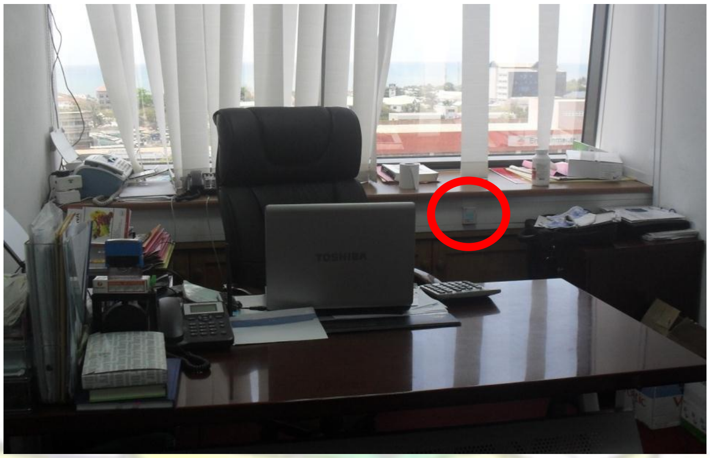

Fig. 3.13: Position of data logger in a sample office

3.8.4 Survey

At the end of the observation period, the occupants were interviewed by filling a comprehensive questionnaire. They were to provide information on their profile and their views on the under listed areas:

- Indoor Environment, thermal and visual comfort;
- Operation and accessibility of building systems;
- Awareness on the functionality of building control systems;
- User control actions on energy performance;
- User preferences on workspace organization; and
- Needs and health complaints.

In all, 195 occupants completed the questionnaire out of a possible 294 occupants. Forty-two of the respondents‘ were from the Ridge Towers, 60 from the Heritage Towers, 39 from the World Trade Centre and 54 from the Premier Towers. Their perceptions were based on long term aggregate opinion on the aforesaid parameters. For information on the questionnaire, see Appendix C.

3.8.5 Energy performance

Monthly electricity bills, providing information on monthly electricity consumption of the buildings for all the months under review were available for the R.T. building. The W.T.C, P.T. and H.T. buildings did not have all their monthly bills available.

3.9 Data Processing

At the beginning and end of the observation period, the hobo sensors were tested to verify their reliability and performance. This was done by launching them in a test bed and processing the data in MS Excel (Fig 3.13). The calculated standard deviation resulted in an accuracy of +/- 0.09 and +/- 0.02 which showed the closeness of the measured data points when compared to the mean values.

Fig.3.14: Examining the performance of the loggers/sensors

Data gathered was processed with Microsoft Excel, because of its high compatibility with a number of other applications. Other software applications used in the study were Green-line, Hobo-ware pro, AutoCAD, Meteotest, Tas simulation tool, Psychrometric chart pro, and PMVcalc v2. Green-line was used to launch and read the files from the data loggers. The downloaded data points were screened in Hobo-ware pro software, after which the data points were exported to a MS Excel file for further processing. Below is an interface of the hobo-ware pro application (Fig. 3.14). In all, there was a total of 867, 214 set points recorded.

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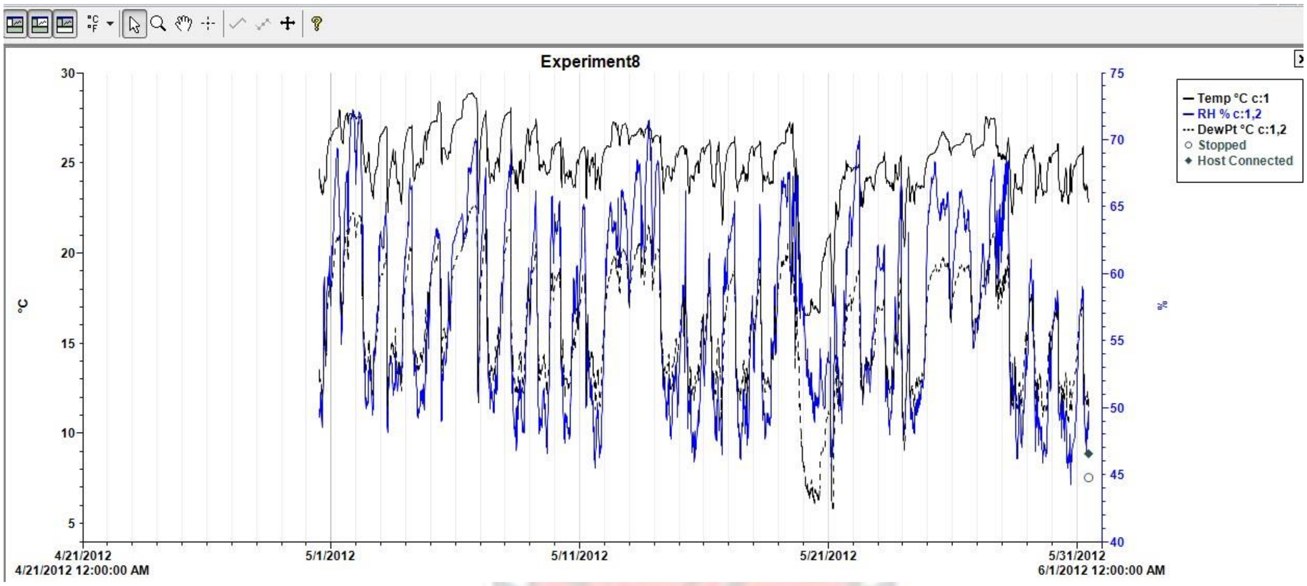

Fig. 3.15: Hobo-ware Pro Interface

In MS Excel, the text files were imported, screened, and built together into monthly tables. Since the data recorded was in an interval of minutes, a formulae sheet was generated to produce mean hourly values, making it easier to compare them with the data generated from the Meteotest weather file. Various options for the data were generated (e.g. minimum, maximum, mean values, etc.) and graphs drawn for pre-analysis. In the Tas simulation programme, the 3D modeller was used to model the buildings by first drawing out the building plans with the information gathered on the building elements and spaces as well as the original drawn out designs of each building (Fig. 3.15). The weather file from Meteotest was used to run the simulation and the output data was exported back into the MS Excel application to calculate mean and hourly sums.

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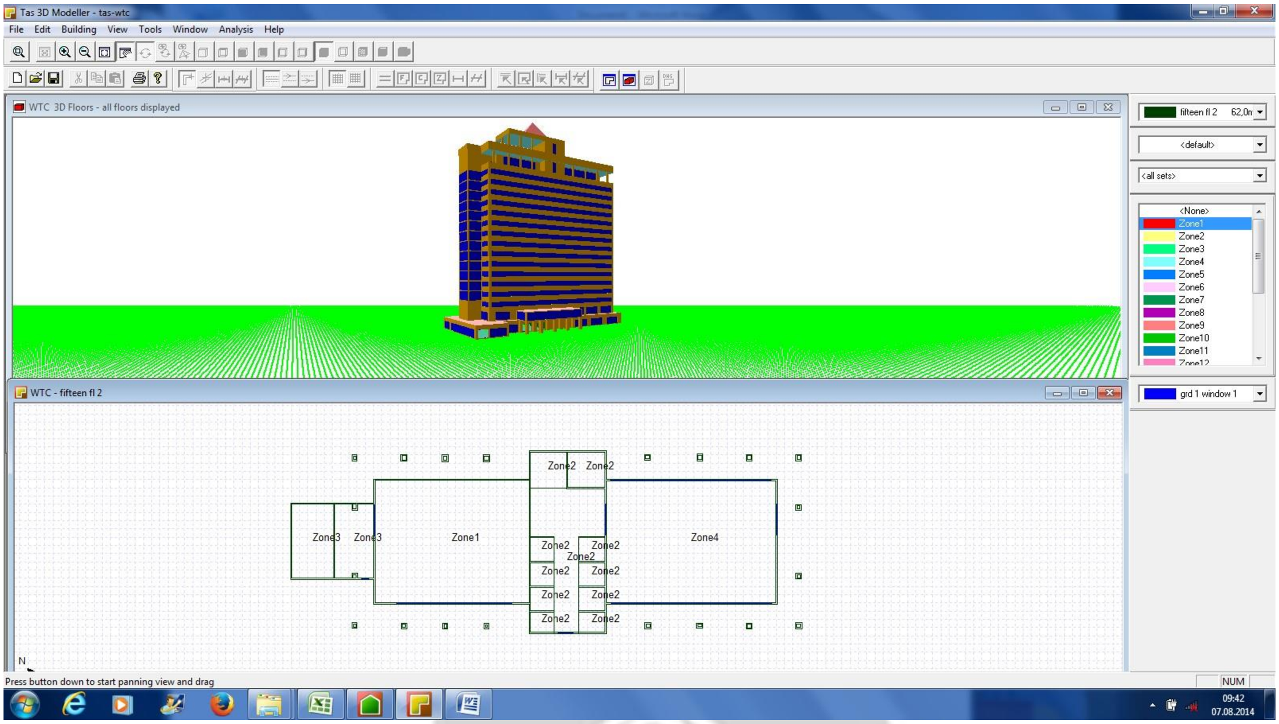

Fig. 3.16: Model of the W.T.C. building in TAS

In Psychrometric chart pro, data from the MS excel output file was used to generate a graphical representation of the comfort zone with the monthly data points (Fig. 3.17).

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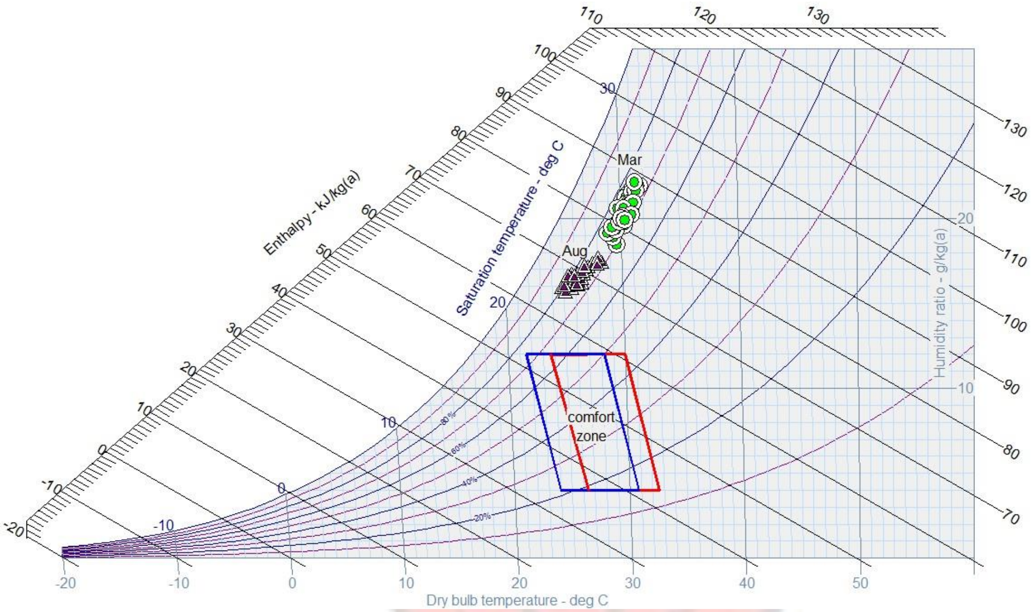

Fig. 3.17: Mean hourly outdoor temperature and relative humidity values (for a reference day) in Accra for representative days in the months of March (hottest) and August (coolest)

This was achieved by using a method described by Szokolay (2004 pp.21-22). Briefly, the measurements of the mean monthly outdoor temperatures were used to calculate the neutrality temperature (Tn). The range of acceptable comfort conditions (warmest and coldest temperature) for 90% acceptability (Tn – 2.5) °C to (Tn + 2.5) °C were used as lower and upper temperature limits. These values were plotted on the 50% relative humidity curve on the psychrometric chart, as the Standard Effective Temperature (SET) coincides with the Dry Bulb Temperature (DBT) on this curve. The gradient of the SET lines shows that at higher relative humidity, temperature tolerance is reduced and vice versa. The two points thus define the boundaries for the warmest and coolest month with the corresponding SET lines. The upper and lower humidity limits were taken as 12 and 4 g.kg^{-1}. This completes the boundaries of the comfort zone. Mean hourly data points (temperature and relative humidity) were plotted on the psychrometric chart to consider the relationship between the points and the generated comfort zone.

The software, PMV calc v2 was used to calculate the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied occupants (PPD) after Fanger (1973). This was achieved by inputting the clothing values, metabolic rates of the occupants, air velocities, indoor temperatures and relative humidity values of the occupied spaces. The output results were tabulated and analysed. In correspondence to the psychrometric chart and PMV methods above, Olgyay‘s bioclimatic chart illustrated the effects of physiological cooling resulting from air movement (also see Szokolay 2004, pp. 40-41). Givoni-Milne‘s bioclimatic chart was also used.

3.9.1 Validation of the Simulation Models

In order to make the process of exploring possible measures that could improve the thermal performance of office buildings in Ghana more reliable, the simulation models needed to be validated, thus had to conform with the existing building. Segments of the synthetic weather file (generated via Meteotest 2008) that matched measurements taken from the outdoor around the buildings were identified. Indoor air temperature values were then simulated using the above mentioned weather file segments and compared with the measured indoor air temperature values. The energy information provided was used in the calibration of the R.T. building. To this effect, the billed electric energy was compared to the simulated electric energy where the difference was expected to be negligible thus zero. Predictions of the simulated calibration models had to compare well with the measured values, therefore the relationship between measured and simulated indoor air temperature in terms of regression lines was calculated.

3.9.2 Parametric study of Thermal Improvement Scenarios

Parametric simulation was selected as a means of comparing the thermal performance of the buildings. Two kinds of simulations were performed: thus, simulation of cooling loads (active building operation assumption) and mean overheating (free-running building operation assumption). The calibrated thermal performance simulation models of the aforementioned four office buildings were used for the improvement scenarios. Various improvement options concerning glazing types, efficient electrical lighting, night ventilation, day time ventilation, shading (type, position and schedule), thermal mass and façade insulation that could reduce cooling loads and the need for extensive active devices for air-conditioning (26°C set point temperature) were explored.

The performance indicator for the thermal analysis, in this case the active scenario, was cooling (sensible and latent) energy loads ($kWh.m^{-2}a^{-1}$).The above options were considered as single cases to know how much cooling loads could be reduced before it was combined by a matrix as scenarios. Information regarding the various scenarios considered for the simulations is summarized in Table 3.5 and 3.6. Table 3.5 provides the base case (B.C.) scenarios for the four buildings whiles Table 3.6 refers to the improvement parameters.

Table 3.5: Overview of Base case Simulation Scenarios

Parameters	R.T.	P.T.	H.T.	W.T.C.
Base case temp.(°C)	26	26	26	26
Occupancy Sensible (W/m^2)	7	7	8	4
Occupancy Latent (W/m^2)	1	1	2	0.8
Electric lighting loads (W/m^2)	3	8	7	5
Infiltration-ACH (h^{-1}) Day-Night	1/0.5	1/0.5	1/0.5	1/0.5
Equipment Sensible (W/m^2)	5	8	20	3
Window U_{value} ($W.m_{-2}.K_{-1}$)	2.8 (double glazing)	2.8 (double glazing)	5.6 (single glazing)	2.9 (double glazing)
Window g_{value}	0,5	0.6	0.7	0.6
Thermal mass	Carpet Acoustic ceiling	Carpet Acoustic ceiling	No carpet Acoustic ceiling	No carpet Acoustic ceiling

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Table 3.5: Overview of Base case imulation Scenarios Cont'd.

Parameters	R.T.	P.T.	H.T.	W.T.C.
Shading Options	Internal blinds	Internal blinds	Internal blinds	Internal blinds

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Table 3.6: Overview of Simulated Improvement Options

Parameter	Code	Description
Office Window Orientation	N-W	North-West windows at the R.T. and the W.T.C. buildings
	S-W;N-E	South-West and North East windows at the H.T. building
	S	South windows at the P.T. building
Glazing	$G_{0.5}$	Double glazing; $g=0.5;U=1.7W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{0.4}$	Double glazing; $g=0.4;U=1.8W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{PT0.4}$	Double glazing; $g=0.4;U=2.8W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{0.3}$	Double glazing; $g=0.3;U=2.6W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{0.2}$	Double glazing; $g=0.2;U=1.6W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{S0.3}$	Single glazing; $g=0.3$; $U=5.7W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{S0.24}$	Single glazing; $g=0.24$; $U=5.7W{\cdot}m^{-2}{\cdot}K^{-1}$
	$G_{S0.18}$	Single glazing; $g=0.18$; $U=5.7W{\cdot}m^{-2}{\cdot}K^{-1}$
Efficient electrical lighting loads	L_e	$2W.m_{-2}$
Day Time Ventilation	$DV_{m.1}$	Day/Night ACH = $10/0.5h^{-1}$
	$DV_{m.2}$	Day/Night ACH = $10/10h^{-1}$
Night Ventilation	$NV_{m.1}$	Mode 1; Day/Night ACH = $1/10h^{-1}$; 6pm-6am
	$NV_{m.2}$	Mode 2; Day/Night ACH = $1/10h^{-1}$; 9pm-6am
	$NV_{m.3}$	Mode 3; Day/Night ACH = $1/10h^{-1}$; 10pm-6am
	$NV_{m.4}$	Mode 4; Day/Night ACH = $1/10h^{-1}$; 12am-6am
	$NV_{m.5}$	Mode 5; Day/Night ACH = $1/10h^{-1}$; 1am-6am
	$NV_{m.6}$	Mode 6; Day/Night ACH = $1/10h^{-1}$; 2am-6am
Shading Option	SO_e	External blinds
	SO_i	Internal blinds

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Table 3.6: Overview of Improvement Options Cont'd.

Parameter	Code	Description
Blind deployment schedule	BS_{PT11}	11am – 2pm
	BS_{11}	11am – 4pm :South windows
	BS_{HT11}	11am – 5pm
	BS_{PT12}	12pm – 3pm
	BS_{12}	12pm – 5pm :SW windows
	BS_{1}	1pm – 5pm :SW windows
	BS_{2}	2pm – 5pm
	BS_{F}	8am – 5pm (Continuous deployment)
Thermal Mass	TM_{a}	Without carpet and acoustic ceiling (suspended ceiling)
Façade Insulation	I_{51}	With 50mm insulation outside only (U = 0.46)
	I_{101}	With 100mm insulation outside only (U = 0.24)
	I_{52}	With 50mm insulation outside and inside (U = 0.24)
	I_{102}	With 100mm insulation outside and inside (U = 0.12)

Altogether, 120 scenarios (different combinations of options given in Table 3.6) were simulated, thus, 40 scenarios for each building. Table 3.7 lists the 40 improvement scenarios simulated for the R.T. building.

Table 3.7: Overview of Simulated Scenarios for the R.T. building

Scenario	Glazing	Efficient Lighting	Night Ventilation	Shading Option	Blind deployment schedule	Façade insulation
1	$G_{0.3}$	L_{e}	$NV_{m.1}$	SO_{e}	BS_{12}	I_{51}
2	$G_{0.3}$	L_{e}	$NV_{m.2}$	SO_{e}	BS_{1}	I_{101}
3	$G_{0.3}$	L_{e}	$NV_{m.3}$	SO_{e}	BS_{2}	I_{51}
4	$G_{0.3}$	L_{e}	$NV_{m.4}$	SO_{e}	BS_{12}	I_{101}

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5	$G_{0.4}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{51}
6	$G_{0.4}$	L_e	$NV_{m.2}$	SO_e	BS_1	I_{101}
7	$G_{0.4}$	L_e	$NV_{m.3}$	SO_e	BS_2	I_{51}
8	$G_{0.4}$	L_e	$NV_{m.4}$	SO_e	BS_{12}	I_{101}
9	$G_{0.5}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{51}
10	$G_{0.5}$	L_e	$NV_{m.2}$	SO_e	BS_1	I_{101}
11	$G_{0.5}$	L_e	$NV_{m.3}$	SO_e	BS_2	I_{51}

Table 3.7: Overview of cenarios for the R.T. building Cont'd.

Scenario	Glazing	Efficient Lighting	Night Ventilation	Shading Option	Blind deployment schedule	Façade insulation
12	$G_{0.5}$	L_e	$NV_{m.4}$	SO_e	BS_{12}	I_{101}
13	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	BS_1	-
14	$G_{0.3}$	L_e	-	SO_e	BS_{12}	I_{51}
15	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	-	I_{51}
16	$G_{0.4}$	L_e	$NV_{m.2}$	SO_i	-	I_{51}
17	$G_{0.4}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{101}
18	$G_{0.5}$	L_e	$NV_{m.3}$	SO_e	BS_1	I_{51}
19	$G_{0.4}$	L_e	$NV_{m.4}$	SO_e	BS_{12}	-
20	$G_{0.3}$	L_e	-	SO_i	BS_2	I_{101}
21	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	-	I_{51}
22	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	I_{101}
23	$G_{0.3}$	L_e	$NV_{m.3}$	SO_i	BS_1	I_{51}
24	$G_{0.4}$	L_e	-	SO_e	-	-
25	$G_{0.5}$	L_e	$NV_{m.1}$	SO_i	-	I_{101}
26	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{101}
27	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	I_{51}
28	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_1	I_{101}
29	-	L_e	$NV_{m.1}$	-	-	I_{101}
30	-	L_e	$NV_{m.1}$	SO_e	-	I_{51}
31	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	-
32	-	L_e	$NV_{m.4}$	SO_i	BS_1	I_{51}
33	$G_{0.4}$	L_e	$NV_{m.1}$	SO_i	-	I_{51}
34	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	-	I_{101}
35	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	-	-
36	$G_{0.3}$	L_e	-	SO_e	-	-
37	$G_{0.5}$	L_e	$NV_{m.2}$	SO_e	-	-
38	-	L_e	-	SO_e	BS_{12}	I_{51}
39	$G_{0.3}$	L_e	-	SO_e	-	I_{101}

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40	-	L_e	$NV_{m.1}$	SO_i	BS_{12}	-

Table 3.8: Overview of Simulated Scenarios for the P.T. building

Scenario	Glazing	Efficient lighting	Night ventilation	Shading Option	Blind deployment schedule	Façade insulation
1	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{51}
2	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{PT11}	I_{101}
3	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_{51}

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Table 3.8: Overview of cenarios for the P.T. building Cont'd.

Scenario	Glazing	Efficient lighting	Night ventilation	Shading Option	Blind deployment schedule	Façade insulation
4	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{101}
5	$G_{0.4}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{51}
6	$G_{0.4}$	L_e	$NV_{m.2}$	SO_e	BS_{PT11}	I_{101}
7	$G_{0.4}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_{51}
8	$G_{PT0.4}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{51}
9	$G_{PT0.4}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{101}
10	$G_{PT0.4}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_{51}
11	$G_{0.5}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{101}
12	$G_{0.5}$	L_e	$NV_{m.2}$	SO_e	BS_{PT11}	I_{51}
13	$G_{0.5}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_{101}
14	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{51}
15	$G_{0.3}$	L_e	$NV_{m.3}$	SO_i	BS_{PT12}	I_{101}
16	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{PT12}	I_{51}
17	$G_{PT0.4}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-
18	$G_{PT0.4}$	L_e	-	SO_i	BS_{PT11}	-
19	$G_{PT0.4}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_{101}
20	$G_{0.4}$	L_e	$NV_{m.2}$	SO_i	BS_{12}	I_{51}
21	$G_{0.4}$	L_e	-	SO_e	BS_{PT11}	-
22	$G_{0.4}$	L_e	$NV_{m.1}$	SO_i	BS_{PT12}	I_{101}
23	$G_{0.3}$	L_e	-	SO_e	BS_{11}	I_{51}
24	$G_{0.3}$	L_e	$NV_{m.2}$	SO_i	BS_{11}	-
25	$G_{0.5}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{51}
26	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-
27	$G_{PT0.4}$	L_e	$NV_{m.3}$	SO_i	BS_{PT12}	-
28	$G_{PT0.4}$	L_e	-	SO_e	BS_{11}	I_{51}
29	$G_{PT0.4}$	L_e	-	SO_i	BS_{12}	I_{101}
30	$G_{0.3}$	L_e	-	SO_i	BS_{PT12}	I_{51}
31	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	-
32	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{51}
33	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{PT12}	I_{101}
34	$G_{0.4}$	L_e	-	SO_e	BS_{11}	I_{51}
35	$G_{0.5}$	L_e	-	SO_i	BS_{PT11}	-
36	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	-
37	$G_{0.3}$	L_e	$NV_{m.3}$	SO_i	BS_{PT11}	I_{101}
38	$G_{PT0.4}$	L_e	-	SO_e	BS_{PT12}	-
39	$G_{PT0.4}$	L_e	$NV_{m.1}$	SO_e	BS_{PT12}	-

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40	$G_{0.3}$	L_e	$NV_{m.2}$	SO_i	BS_{PT12}	I_{51}

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Table 3.9: Overview of cenarios for the H.T. building

Scenario	Glazing	Efficient lighting	Night ventilation	Shading Option	Blind deployment schedule	Thermal mass
1	$G_{S0.18}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a
2	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
3	$G_{S0.18}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	TM_a
4	$G_{S0.24}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a
5	$G_{S0.24}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
6	$G_{S0.24}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	TM_a
7	$G_{S0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a
8	$G_{S0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
9	$G_{S0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	TM_a
10	$G_{0.2}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
11	$G_{0.2}$	L_e	$NV_{m.1}$	SO_e	BS_{HT11}	TM_a
12	$G_{0.2}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	TM_a
13	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a
14	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
15	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	TM_a
16	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	TM_a
17	$G_{S0.18}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
18	$G_{S0.18}$	L_e	$NV_{m.1}$	SO_e	BS_{11}	TM_a
19	$G_{0.2}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	-
20	$G_{0.2}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
21	$G_{0.2}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	-
22	$G_{S0.24}$	L_e	$NV_{m.1}$	SO_e	BS_{11}	-
23	$G_{S0.24}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	TM_a
24	$G_{S0.24}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
25	$G_{S0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	TM_a
26	$G_{S0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{HT11}	TM_a
27	$G_{S0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
28	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	TM_a
29	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
30	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{11}	-
31	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_i	BS_{HT11}	TM_a
32	$G_{0.2}$	L_e	-	SO_e	BS_{12}	TM_a

33	$G_{0.2}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	-
34	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	TM_a
35	$G_{S0.24}$	L_e	-	SO_i	BS_{HT11}	-
36	$G_{S0.24}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-
37	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-
38	$G_{0.2}$	L_e	-	SO_i	BS_{11}	TM_a
39	$G_{0.2}$	L_e	$NV_{m.3}$	SO_i	BS_{12}	TM_a
40	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_i	BS_{12}	-

Table 3.10: Overview of Simulated Scenarios for the W.T. C. building

Scenario	Glazing	Efficient lighting	Night ventilation	Shading Option	Blind deployment schedule	Thermal mass	Façade insulation
1	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a	I_{51}
2	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_1	TM_a	I_{101}
3	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_2	TM_a	I_{52}
4	$G_{0.3}$	L_e	$NV_{m.4}$	SO_e	BS_{12}	TM_a	I_{102}
5	$G_{0.4}$	L_e	$NV_{m.1}$	SO_e	BS_1	TM_a	I_{51}
6	$G_{0.4}$	L_e	$NV_{m.2}$	SO_e	BS_2	TM_a	I_{101}
7	$G_{0.4}$	L_e	$NV_{m.3}$	SO_e	BS_{12}	TM_a	I_{52}
8	$G_{0.4}$	L_e	$NV_{m.4}$	SO_e	BS_1	TM_a	I_{102}
9	$G_{0.5}$	L_e	$NV_{m.1}$	SO_e	BS_2	TM_a	I_{51}
10	$G_{0.5}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	TM_a	I_{101}
11	$G_{0.5}$	L_e	$NV_{m.3}$	SO_e	BS_1	TM_a	I_{52}
12	$G_{0.5}$	L_e	$NV_{m.4}$	SO_e	BS_2	TM_a	I_{102}
13	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	-	TM_a	-
14	$G_{0.3}$	L_e	$NV_{m.2}$	SO_i	-	TM_a	-
15	-	L_e	$NV_{m.3}$	SO_e	-	TM_a	-
16	$G_{0.4}$	L_e	$NV_{m.4}$	SO_e	-	TM_a	-
17	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	-	-	I_{51}
18	$G_{0.5}$	L_e	$NV_{m.2}$	SO_i	-	-	I_{101}
19	-	L_e	$NV_{m.3}$	SO_i	-	-	I_{52}
20	$G_{0.3}$	L_e	$NV_{m.4}$	SO_e	-	-	I_{102}
21	-	L_e	$NV_{m.1}$	SO_i	-	TM_a	I_{101}
22	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	-	-	I_{51}
23	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-	I_{52}
24	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	-	TM_a	-
25	$G_{0.4}$	L_e	-	SO_e	BS_1	-	-
26	$G_{0.4}$	L_e	$NV_{m.2}$	SO_e	-	TM_a	I_{51}
27	$G_{0.4}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	-	I_{101}
28	$G_{0.5}$	L_e	$NV_{m.3}$	SO_i	BS_{12}	TM_a	I_{52}

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29	$G_{0.3}$	L_e	$NV_{m.4}$	SO_i	-	-	I_{102}
30	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{12}	-	I_{101}
31	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	-	I_{102}
32	-	L_e	$NV_{m.1}$	SO_i	-	TM_a	-
33	$G_{0.4}$	L_e	$NV_{m.3}$	SO_e	-	-	I_{51}
34	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a	I_{101}
35	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_1	TM_a	I_{51}
36	$G_{0.4}$	L_e	$NV_{m.1}$	SO_i	-	-	-
37	-	L_e	$NV_{m.2}$	SO_i	BS_1	TM_a	-
38	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_1	TM_a	I_{51}
39	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_1	TM_a	I_{101}
40	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-	-

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For the computation of the mean overheating (OH_m), the following formula was used:

$$OH_m = \sum_{j=1}^{n} \frac{\theta_{i,j} - \theta_r}{n} \quad \text{…………………Eq. 9}$$

Where: ‗θi, j‘ denotes the mean indoor air temperature (°C) at hour j (averaged over all simulated office zones in the floor);

‗θr‘ the reference indoor air temperature for overheating (°C); and ‗n‘ the total number of occupied office hours.

The term $\theta_{i,j} - \theta_r$ was considered for those hours when $\theta_{i,j} > \theta_r$.

Mean overheating (OH_m) was computed for two different sets of assumptions pertaining to the applicable values for the reference overheating temperature θr. The first set was the concept of Neutrality Temperature (Auliciems, 1981) as cited in Szokolay, (2004). This is derived as a function of the mean monthly outdoor air temperature. The second set was based on a constant reference overheating temperature of 26°C. The design alternatives that were simulated were the base case, the best improvement scenario from the active case combined with different air change rates (ACH 1/0.5: 1/10: 5/10: 10/10) to create a comfortable thermal environment during the passive case.

Table 3.11: Neutral temperature for 90% acceptability (Adaptive model)

	MAY	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**
To.av	29	27.6	26.2	26.2	27.1	28.5	29.8	29.5	29.3	30	30.4	30.2
Tn + 2.5	29.1	28.7	**28.2**	**28.2**	28.5	28.9	29.3	29.2	29.2	29.4	**29.5**	29.4
Tn	26.6	26.2	25.7	25.7	26	26.4	26.8	26.7	26.7	26.9	27	26.9
Tn – 2.5	24.1	23.7	23.2	23.2	23.5	23.9	24.3	24.2	24.2	24.4	24.5	24.4

Where: To.av = the mean monthly outdoor temperature (°C)

Tn = neutrality temperature (°C)

Tn +2.5 = the upper limit

Tn -2.5 = the lower limit

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Table 3.12: The two sets of reference overheating temperature θr (°C)

	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
Tn + 2.5	29.1	28.7	28.2	28.2	28.5	28.9	29.3	29.2	29.2	29.4	29.5	29.4
Constant 26°C	26	26	26	26	26	26	26	26	26	26	26	26

The mean indoor air temperature at hour _j' (averaged over all simulated office zones on the floor) was subtracted from the reference overheating temperature (Table 2) and divided by the total number of occupied office hours. Only cases where the indoor temperature was higher than the reference temperature were considered. The simulated indoor environmental parameters, temperature and relative humidity values, were combined with the clothing values, metabolic rates and various air velocities (after Szokolay, 2004) to determine the predicted mean vote (PMV) and the predicted percentage of dissatisfied occupants (PPD), using the software application ―PMVcalc_V2, (n.d.)‖. The different air velocities used were 0.1m/s, 0.5m/s, 1m/s and 1.5m/s. According to Szokolay (2004), the subjective reactions to air movement includes:

Table 3.13: Subjective reactions to air movement

<0.1m/s	stuffy
0.1 to 0.2	unnoticed
0.3 to 0.5	pleasant
0.6 to 1	awareness
1.1 to 1.5	draughty
>1.5	annoying

3.10: Limitations

The thesis was limited in scope due to a number of reasons. Firstly, as a result of the time frame for the programme (PhD), various in-depth analyses could not be conducted. Various parameters such as probabilities and time of switching on the lights, air-conditioners and blind operation, etc could not be monitored in detailed. Consequently the author had to focus on indoor environmental parameters with the key aim of reducing cooling loads in the buildings.

Secondly, though permission was granted for data to be collected within the various buildings, not all the internal areas were accessible to us. In two of the buildings, prime areas like top official offices were not made accessible by the facility managers. Some of the reasons cited included security issues and some of the occupants (top managers) were incredulous about the data loggers and therefore refused its mounting in their offices.

Thirdly, building energy consumption data could not be obtained from three of the case study buildings; because the managers of these buildings were sceptical about such information being given to a third party.

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CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Chapter Outline

This chapter presents and discusses the results of the studies chronologically according to the set objectives. Out of the 828,974 data points and over 500 graphical and simulated outputs generated, presented here are the summary results which have been grouped into six areas each with its discussion. They are the results of the Survey, PMV-PPD measurements, Psychrometric analysis, Bioclimatic analysis, Simulation - validation results, Energy performance (active case), and Passive case scenarios.

4.2 *Objective One: To assess occupants' views of their indoor thermal comfort conditions.*

The results from the survey are presented here. Altogether, 195 occupants with permanent workstations within the various offices answered the questionnaire out of a total number of 294 (for details on the questionnaire, see Appendix C). The questionnaire was made up of the sections below:

- Indoor environment evaluation (thermal ,visual and acoustics);
- Operation and accessibility of the systems and system controls;
- Awareness of the functionality of the building control systems;
- Energy implications of user control actions;
- Personal preference of organizing the current work space/Ideal workspace; and
- Health complaints.

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4.2.1 Indoor environment evaluation (thermal, visual and acoustics) results

The results on questions pertaining to indoor environment, thermal and visual comfort from the occupants in all the buildings are shown in Figures 4.1 to 4.11.

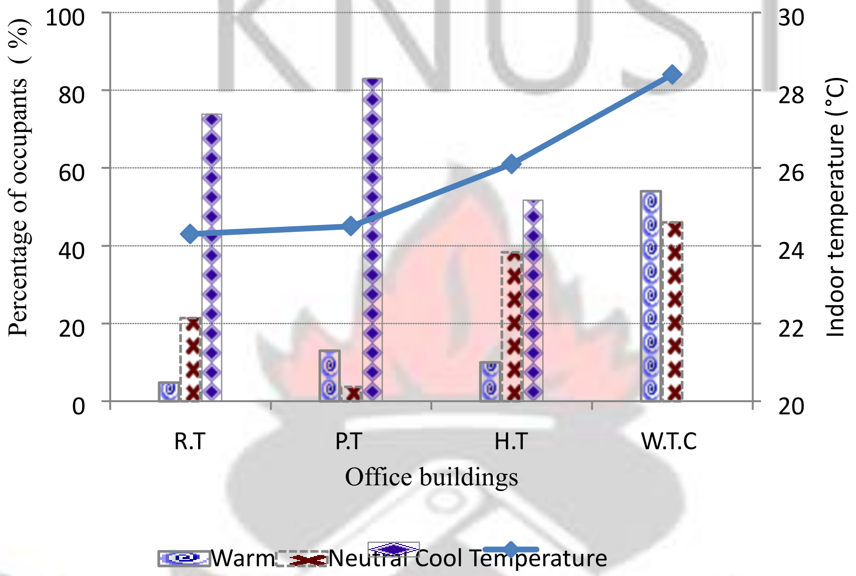

Fig. 4.1: General feeling of occupants concerning their indoor temperature

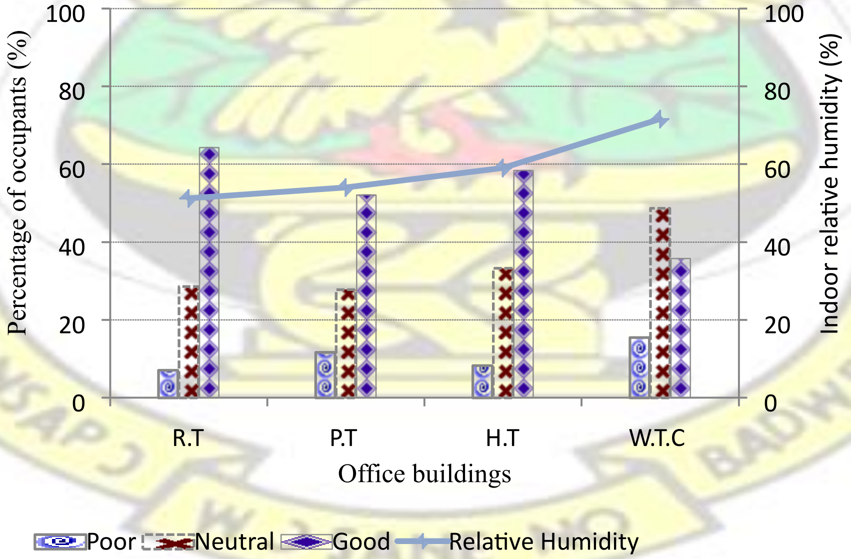

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Fig. 4.2: General feeling of occupants concerning their indoor relative humidity

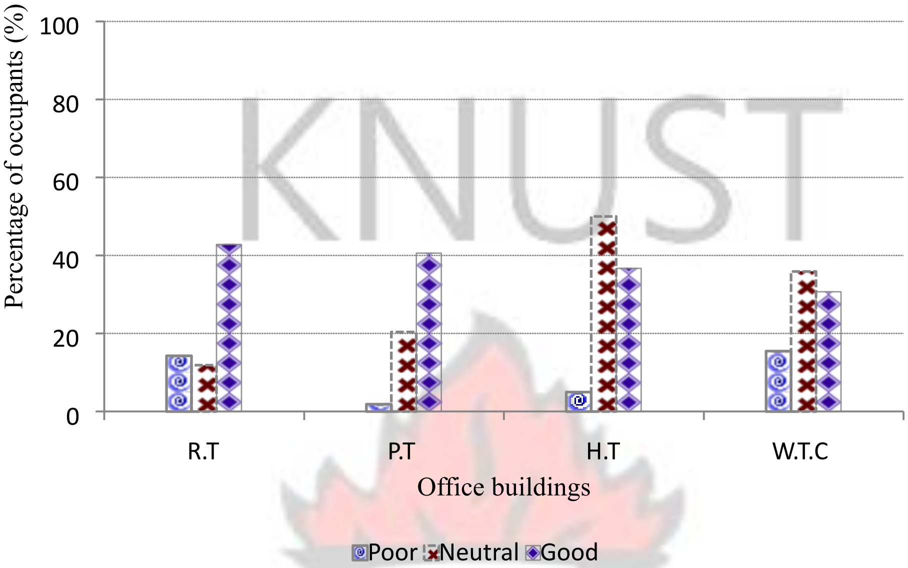

Fig. 4.3: Occupants' general feeling about their indoor air quality

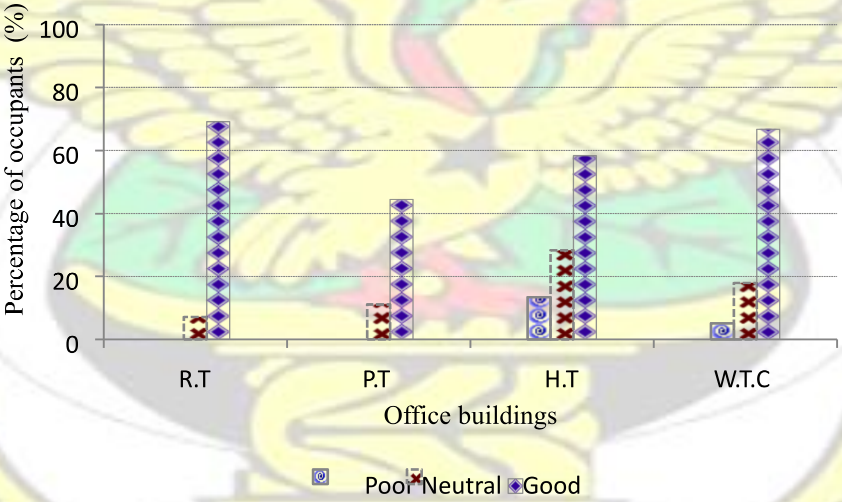

Fig.4.4: Percentage of occupants' opinion about their indoor lighting quality

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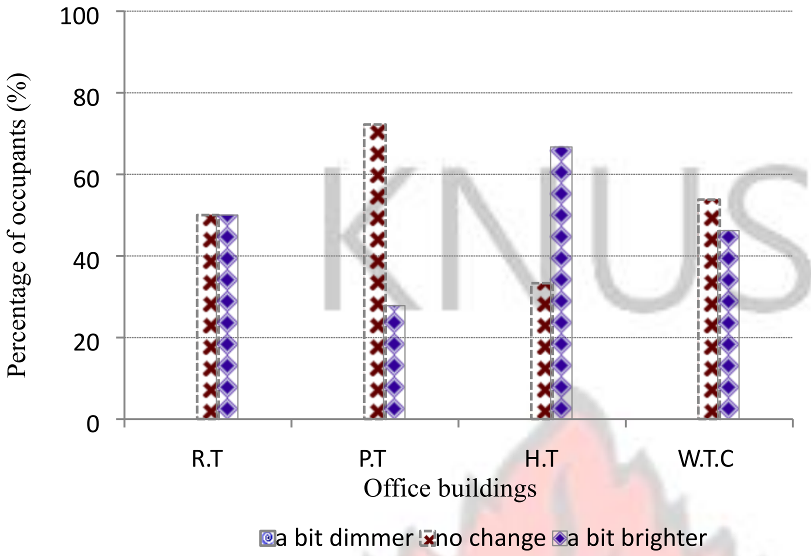

Fig.4.5: Occupants' preference of the lighting levels in their offices

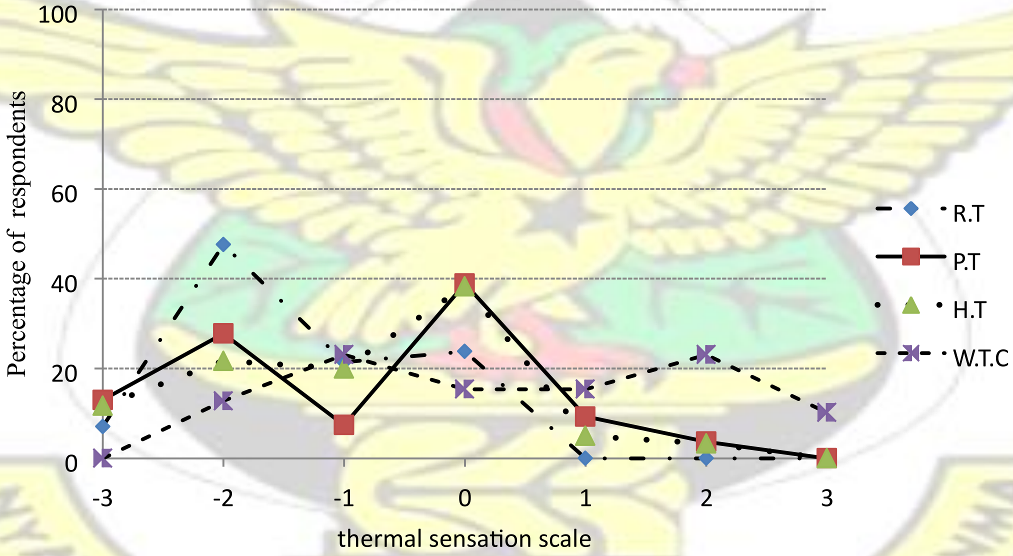

Fig. 4.6: Occupants' thermal sensation levels (-3 for cold, 0 for neutral and +3 for hot) within the offices

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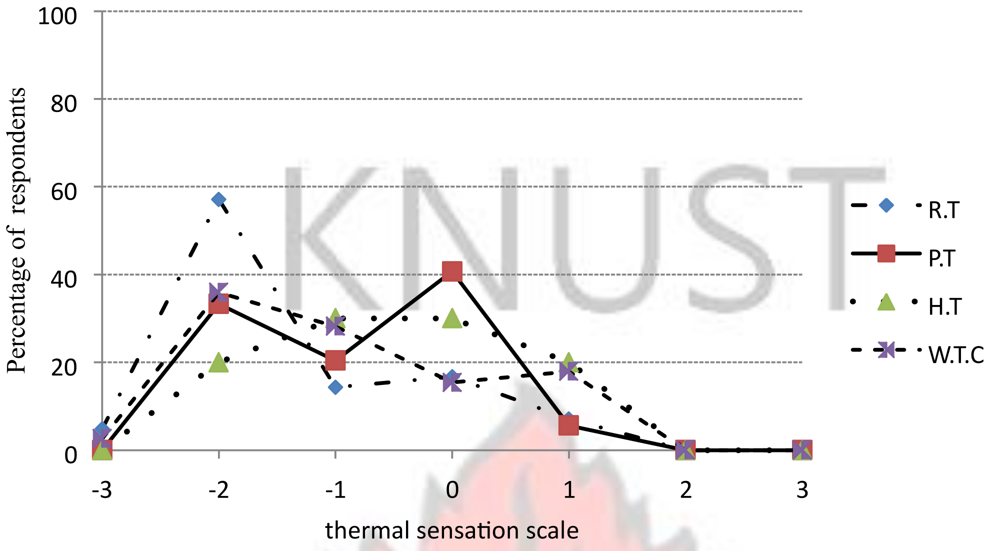

Fig. 4.7: Occupants' thermal sensation (-3 for cold, 0 for neutral and +3 for hot) preferences within the offices

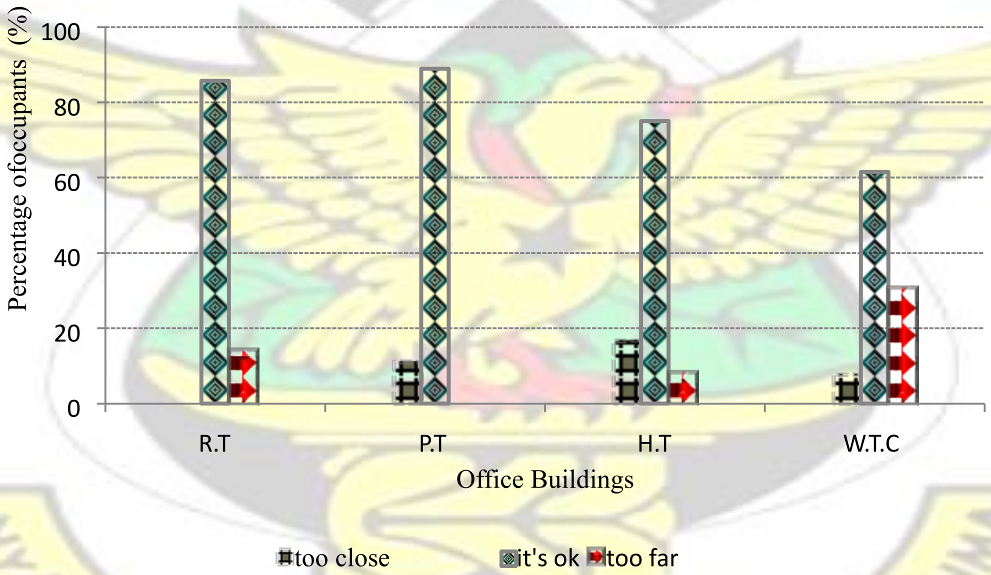

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Fig.4.8: Occupants' evaluation of distance of workstation from the window

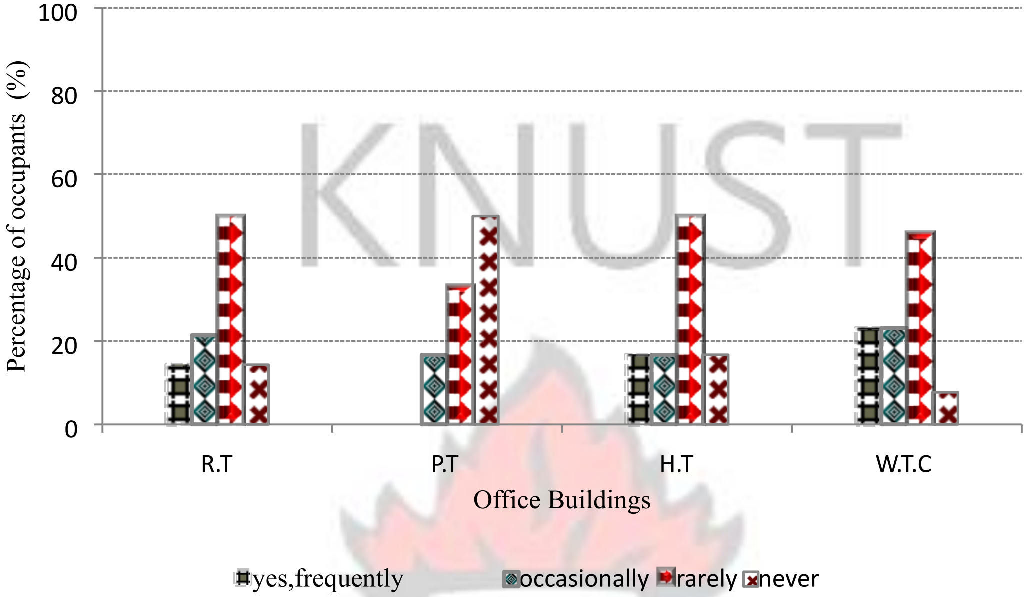

Fig. 4.9: Respondents annoyed by noise in the offices

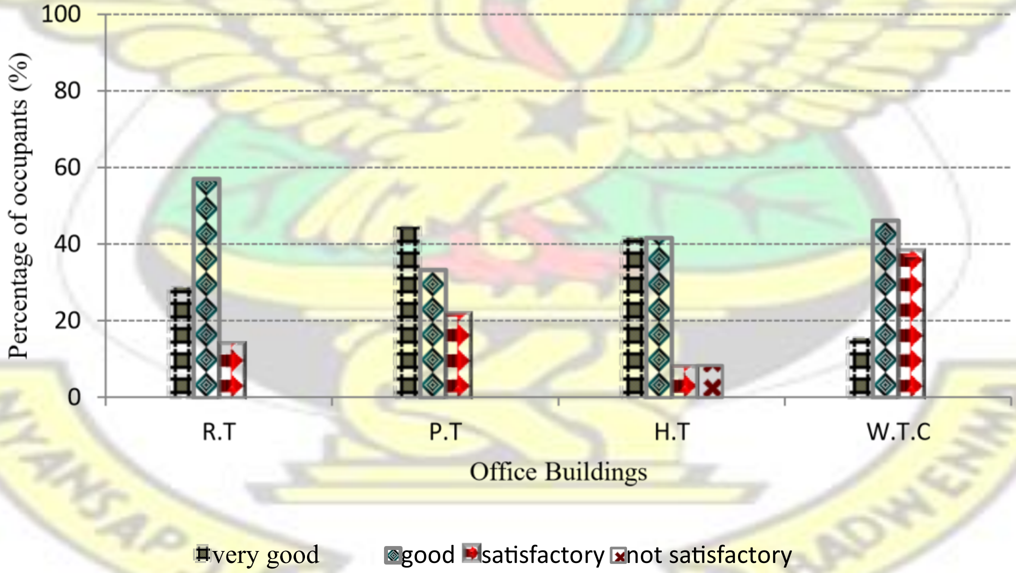

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Fig. 4.10: Occupants' evaluation of the outdoor view from their office windows

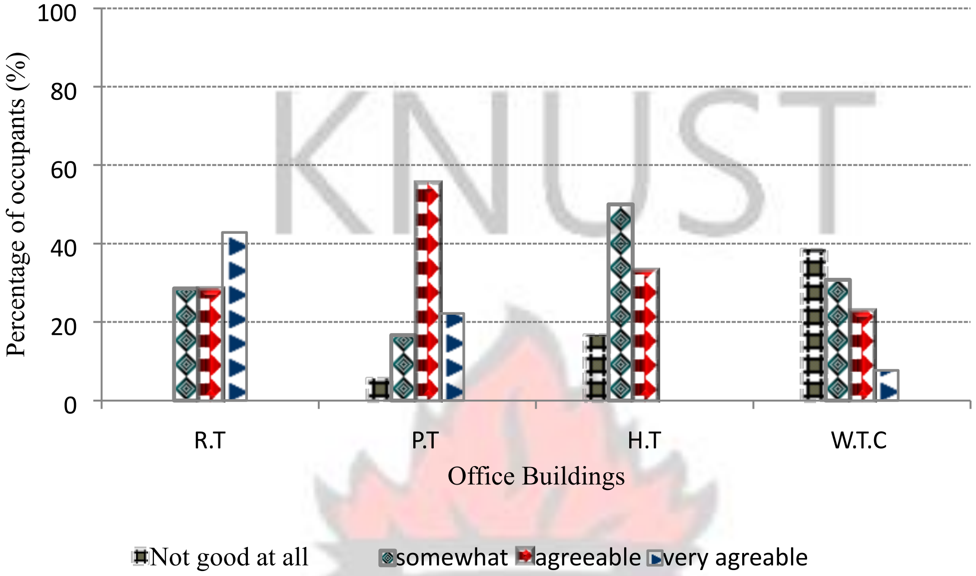

Fig.4.11: Occupants' general perception of the working environment

Table 4.1: On-site measurements within the offices

	R.T	P.T	H.T	W.T.C
Mean Lighting levels (Lux)	640	480	350	220
Mean Sound levels (dB)	54	55	59	55

More than 70% of occupants in building R.T. and P.T. felt that temperature in their offices were cool (Fig.4.1; page 113). This may be due to the use of air-conditioners with comparatively low temperature set points (18°C). Mean temperature values measured within these buildings was 24.3°C and 24.5°C respectively. Although H.T. is also an air-conditioned building, only 51% of the occupants felt their temperature condition was cool. One of the reasons could be H.T.'s Wall to Window Ratio, (WWR) which is about 90%. As a result, there is direct solar radiation into the office spaces, making the indoors warmer than the R.T. and P.T. This reason could be attributed to

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the orientation of the building (East-West) with its unprotected glazing: confirming the assertion of a number of studies that heat gain through the exterior window accounts for 25-28% of the total heat gain within a space (Al-Najem, 2010 and Yu et al., 2008). A similar finding was reported by Pino et al. (2012) on buildings with high WWR. East-West orientation of buildings in the tropics with exposed windows is known to cause discomfort within the internal spaces (Koranteng et al., 2011). All the occupants in the W.T.C. building felt their temperature was cool and okay: this situation may be accredited to the fact that their glazing windows were operable and shaded with a balcony along the glazed facades. Again, 85% of the occupants were out of the office during the hot afternoons with the high outdoor temperature values. Because occupants at the W.T.C. could open their windows (adaptive opportunity), they felt comfortable even with a mean temperature of 28.4°C. This comfort sensation is in conformity with the studies of (Nicol and Humphreys, 2004: Baker and Standevan, 1996) who confirmed in their studies that occupants felt comfortable with mean temperature of 28°C

Air quality evaluation followed similar trend as temperature, where great satisfaction was expressed by occupants in the R.T. and P.T. buildings due to their reliance on air-conditioners to create exclusive environment (Hawkes, 1996).

Occupants‘ thermal sensation and preferences are expressed in Figures 4.6 and 4.7. This was subject to the operative temperature within the offices. These are retrospective subjective judgments. In the naturally ventilated building (W.T.C.), occupants thermal sensation ranges from cool (-2) to hot (3). Whiles 23 % of the occupants felt that their spaces were warm, 10% reported their spaces to be hot. In the study of German low energy office buildings, Wagner et al.

(2007) found 7% of their respondents voting _very warm‘ to their spaces when the temperature was between 25°C to 30°C. In the current study if _very warm‘ is equivalent to _hot‘, then the results are similar. Once more, the air-conditioned buildings have greater number of occupants who feel comfortable: slightly cool to slightly warm (ASHRAE, 2004). Forty-seven percent of the occupants in the R.T. building felt that their offices were cool (-2), a condition which have been created by the low set point of the air-conditioners (16°C to 18°C). This behaviour could have a huge toll on the energy usage of the building. Occupants generally increased clothing (clo-value) which gave an indication of how cool/cold they felt.

On their preferences, all the occupants within the air-conditioned buildings wanted to feel cool to warm (-2 to 2). This was so because of the seasonal differences experienced in Ghana: the wet season where outside conditions are cool (low temperatures) and the dry season where conditions are dry and warm (low humidity).

Occupants in the W.T.C. building had a more forbearing attitude in relation to indoor thermal conditions as compared with the occupants in the air conditioned buildings. They accepted higher indoor temperatures in the dry season and lower temperatures in the wet season, and they also accepted wider temperature ranges; an observation which is tantamount to Frontczak and Wargocki (2011) who found similar results in their work.

The satisfaction with the availability of daylight and electric lighting in the office was generally high (about 60%). However, 58.3% of the occupants in the H.T. building felt that their daylight amount could be more: an expression which some explained as daylight releases stress and is refreshing. Similar finding was reported by Galasiu and Veitch (2006). By observation, the H.T.

offices though with a high WWR lacked enough daylight because of the internal partitions blocking day light from reaching the core of the building. Again, occupants in the H.T. building deployed their internal blinds in an attempt to mitigate the direct solar radiation into their offices thereby compromising on daylight. From Table 4.1, though buildings P.T., H.T. and W.T.C. are all below the standard illuminance level of 500Lux (Burberry, 1997), less than 50% reported that their spaces were dark. This finding agrees with the study by Tregenza and Leo (1998) who concluded that the occupants‘ perception of their visual environment also depends upon the illuminance they are accustomed to.

In terms of the sound levels (acoustic tendency), all the offices were within the mean of 57.5 dB (Mui and Wong, 2006). Buildings R.T., P.T. and W.T.C. recorded 54dB, 55dB and 55dB respectively; a reading similar to the Chinese code for the design of sound insulation of civil buildings which suggests that noise level in offices should not be higher than 55 dB (Huang et al., 2012). Even the H.T. building‘s sound level was just 1dB higher than the suggested values which could be due to the external factors (one major road too close to the building).

Moreover, all occupants cumulatively reported that their working environment were conducive by voting somewhat, agreeable and very agreeable to the general perception of the working environment.

4.2.2 Operation and accessibility of the systems and system control results

Questions relating to the operation and accessibility of the systems and system controls were aimed at finding out how occupants operated the buildings systems, the difficulties they had and their satisfaction with these systems.

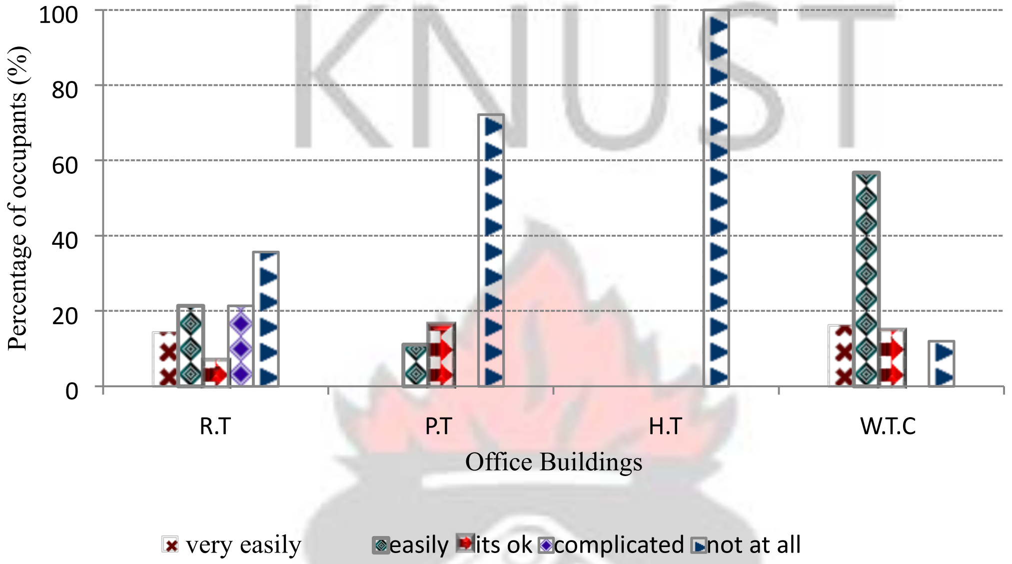

Fig. 4.12: Occupants' who could open their office windows if necessary

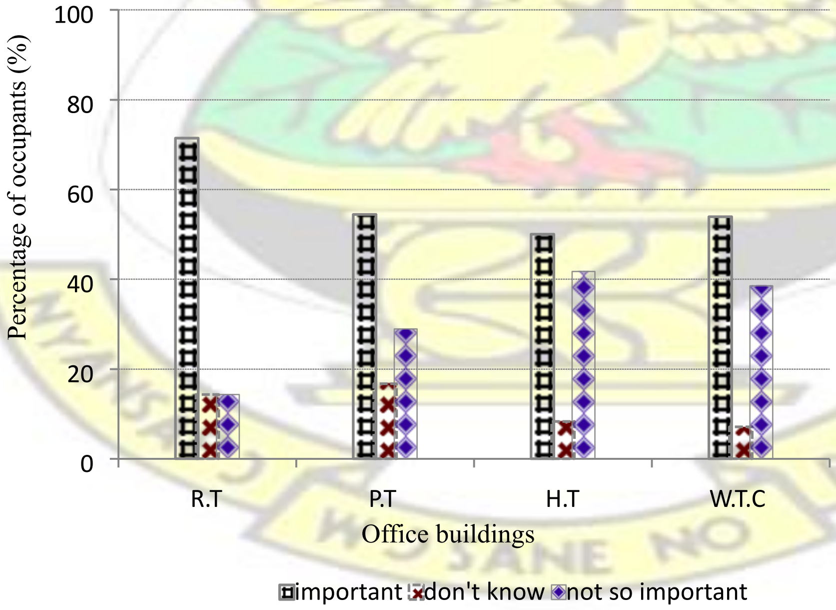

Fig.4.13: Importance of the possibility of occupants' to open their office windows

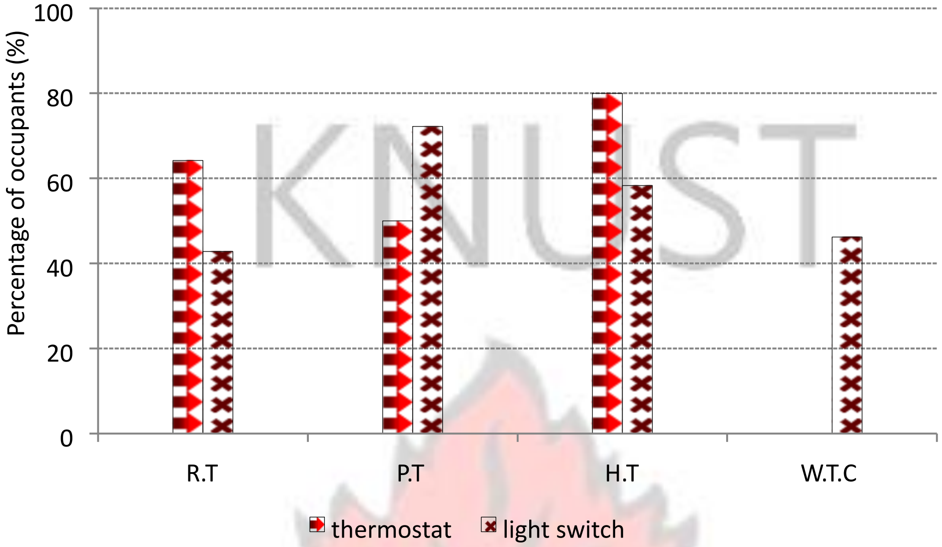

Fig. 4.14: Percentage of occupants' to whom building systems were easily accessible

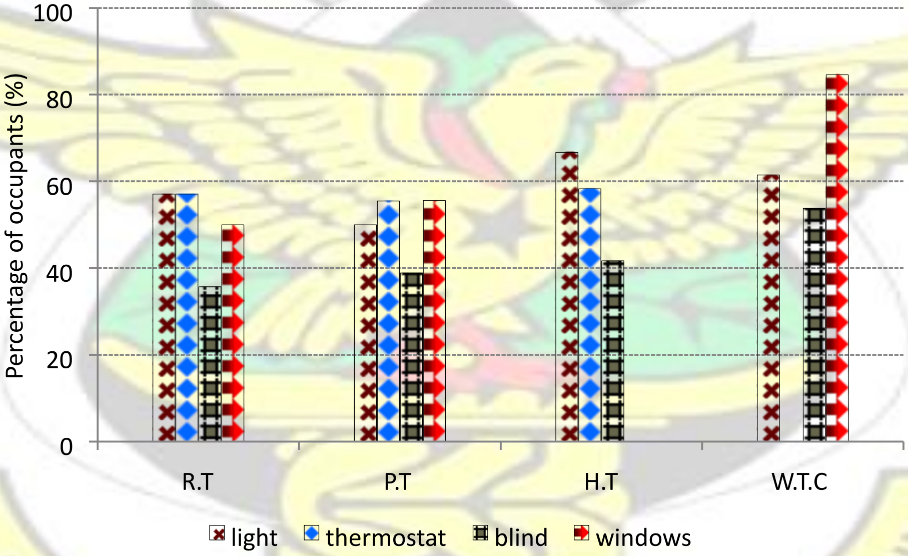

Fig. 4.15: Percentage of occupants' who had to negotiate with colleagues before operating building systems

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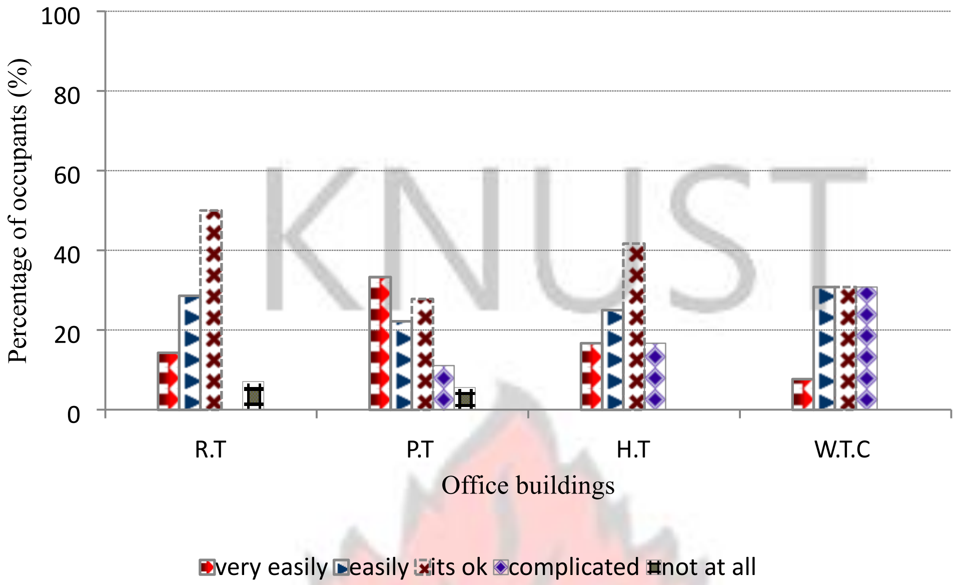

Fig. 4.16: Occupants' ability to operate their office blinds

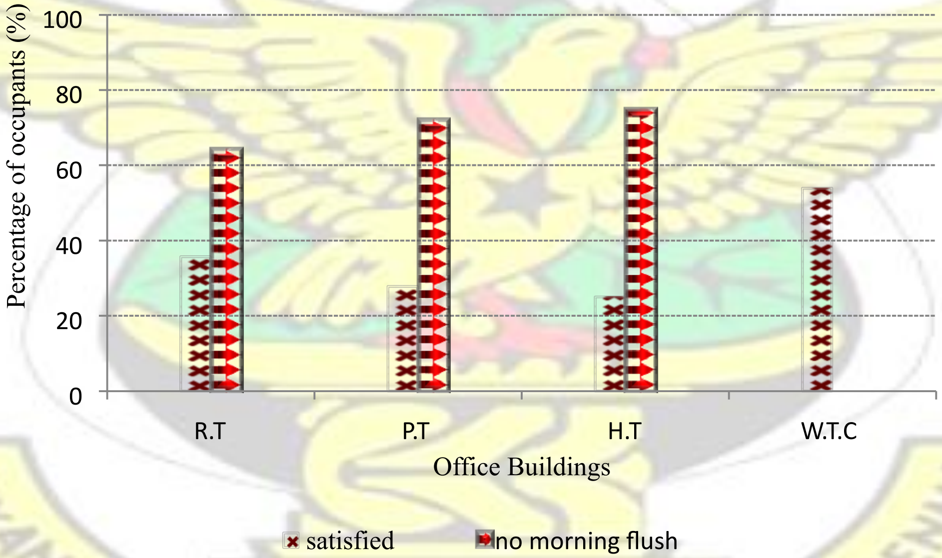

Fig. 4.17: Percentage of occupants' who were satisfied with the possibility to ventilate but rarely/never had a morning flush before using the air-conditioner in their offices

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The H.T. is the only building with fixed glazing without the possibility of opening at all. Perhaps a solution against infiltration and ex-filtration as reported in E-Source (2005). But with the eastwest orientation, no external shading of the building (H.T.), frequent power cut and load shedding, fixed glazing was not a good choice. Even though all the other buildings had operable windows; it was hardly opened as has been presented in Fig. 4.12. The reason for this trend includes the collective decision making to open the windows (Fig.4.15). Not all the occupants‘ showed enthusiasm when it came to opening of windows especially those whose workstations were close to them (windows). They complained that opening of the windows distracted them a lot. They again reported that their workstations was uncomfortable and they felt opening the windows will make the situation worse. This report affirms Al-Najem‘s study (2010) when he concluded that heat gain through the exterior window accounts for 25-28% of the total heat gain of a space. The heat gain is what these occupants‘ feel. These occupants‘ (who sat along the windows and the glazed areas) said they were constrained to pull over the blinds to help in the reduction of the direct solar radiation (Charles et al., 2005) all the time. Fewer than 40% of the occupants in the R.T. building did not at all open their windows whiles in the P.T. building, 72.2% of the occupants did not. Apart from them being insufficiently informed about the positive effects the operation of windows has on building occupants (Koranteng and Mahdavi, 2010: Rijal et al., 2007: Mahdavi et al., 2007; and Herkel et al., 2005), the high dependency on the airconditioners (AC) also account for this trend. The occupants across the three AC buildings however expressed the importance of their building having windows/large glazed portions which aid in clear vision to the outside to catch a glimpse of what was going on.

All the occupants‘ in the three AC buildings did not ventilate their offices in the mornings before using the air-conditioners. H.T. occupants‘ could not do that even if they wanted to. This observation is in congruence with Simons et al. (2012). The poor satisfaction level of the AC in the P.T. building could be due to multi-occupancy office with large numbers.

In the P.T., whiles only 4 workers had enclosed office spaces, the remaining 50 occupants' were allocated open plan workstations measuring a total of 50.4m².

In the W.T.C building, 56.8% of the occupants could easily open their windows and did that in the mornings when they came to work.

Occupants in the H.T building were very dissatisfied about the fact that they could not open their windows at all and wished they could do that sometimes; especially when there were power failures. This agrees with the study about occupants having negative perception about AC buildings with no option for opening windows (Hoes et al., 2009).

Twenty-five percent of occupants across all buildings felt that, it was not at all important to open their office windows and relied solely on the AC's. When asked whether they knew the importance of daylight on their wellbeing? Forty-six percent of the occupants across the buildings said they did not and even if they did, they are always bound to deploy their internal blinds. Occupants' in the W.T.C. building did enjoy daylight as well as open views so much since their windows were protected with a balcony. The work of Mahdavi et al. (2007) confirms the above results with regards to the behaviour of occupants.

Satisfaction with the building control systems in the AC buildings was however higher than in the naturally ventilated building. Though occupants in the free run building (W.T.C.) had a range of adaptive opportunities, more than 50% preferred working in an AC office. But the heavy reliance on artificial lighting in the office spaces could have a negative effect on energy usage since lighting represents a major energy-user in commercial buildings (Galasiu and Veitch, 2006). The percentage of occupants who did not make use of cool outdoor air in the mornings to flush the offices before using the air-conditioners was high. Similar finding was documented in the study of office buildings in Accra (Simons et al., 2012).

4.2.3 Results on the awareness of the functionality of the building control systems

This section demonstrates the level of training and the amount of information occupants have concerning the functionality of the building systems in their offices.

Table 4.2: Summary responses to the question 'are you sufficiently informed about how the following systems work in your office: Ventilation, Air-conditioning, Lighting, and Blind operation?'

Ventilation

	R.T.	P.T.	H.T.	W.T.C.
Very well informed	35.7%	27.8%	10%	15.4%
It's Ok (Averagely informed)	42.9%	44.4%	16.7%	46.1%
Insufficiently informed	21.4%	27.8%	73.3%	38.5%

Air- conditioning

	R.T.	P.T.	H.T.	W.T.C.
Very well informed	50%	33.3%	0%	N.A
It's Ok (Averagely informed)	42.9%	33.3%	58.3%	N.A
Insufficiently informed	7.1%	33.4%	41.7%	N.A

Where N.A is Not Applicable

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Lighting

	R.T.	P.T.	H.T.	W.T.C.
Very well informed	50%	33.3%	8.3%	30.8%
It‘s Ok (Averagely informed)	42.9%	44.4%	50%	46.1%
Insufficiently informed	7.1%	22.2%	41.7%	23.1%

Blind Operation

	R.T.	P.T.	H.T.	W.T.C.
Very well informed	28.6%	33.3%	8.3%	7.7%
It‘s Ok (Averagely informed)	57.1%	33.4%	50%	61.5%
Insufficiently informed	21.4%	33.3%	41.7%	30.8%

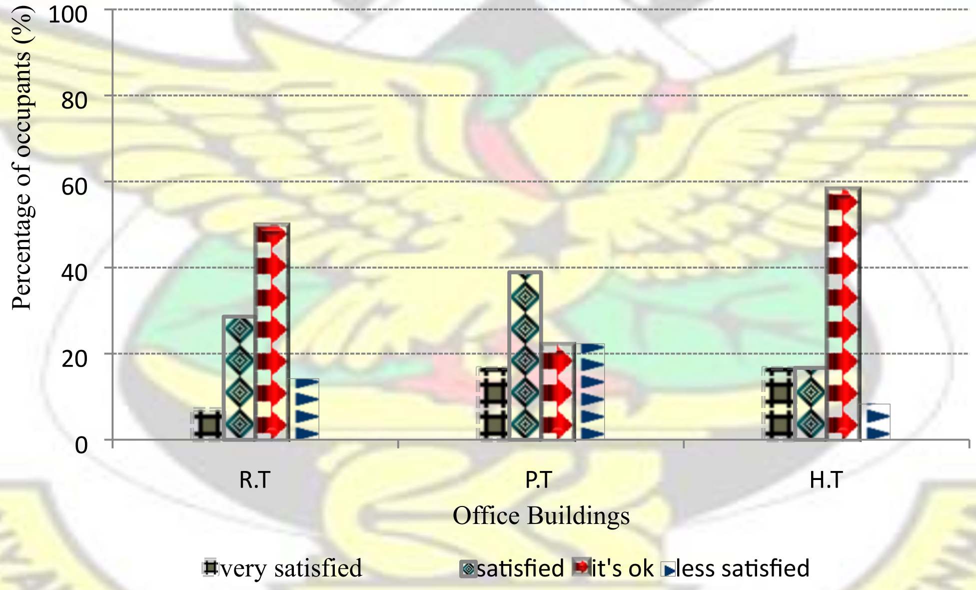

Fig. 4.18: Occupants' level of satisfaction with the A/C in their offices

Occupants responded on how informed they are about their building control systems. Table 4 shows the summary of the responses to the question _are you sufficiently informed about how the following systems work in your office: Ventilation, air-conditioning, lighting and blind protection. Ninety percent of occupants‘ in the H.T. building had very little idea on how ventilation in their office was achieved and therefore voted _it‘s okay‘ and insufficiently informed. Due to the fact that the design of their building had no adaptive opportunity coupled with the east-west orientation, occupants solely relied on ACs which also proved so technical to them and as a result, used only some few settings as also reported by Fujii and Lutzenhiser (1992). There is also a convergence with the study of Price and Sherman (2006).

With lighting and blind protection, H.T. occupants again felt that they were not sufficiently informed about their operation and were willing to attend workshops on how to operate these systems effectively. Building R.T. and P.T. occupants‘ felt more confident and were well informed when they operated their lighting, and air-condition systems. Karjalainen (2009) concluded on a similar finding in his study.

In the P.T. building, as much as those who were informed were also not sufficiently conversant with both their AC‘s and lighting systems. Occupants in R.T. and P.T. buildings were more interested in controlling their systems than in the H.T. and W.T.C. buildings. Most occupants (91%) from all the buildings also indicated that in case of problems concerning the systems, the property managers were referred to. Few offices consulted their maintenance units for faster solutions to such problems.

4.2.4 Results on energy implications of user control actions

The result on energy implications gives an insight into the behaviour of the occupants with regard to control actions and energy implications. Energy conscious behaviour of occupants in office buildings is known to have a positive effect on building energy consumption.

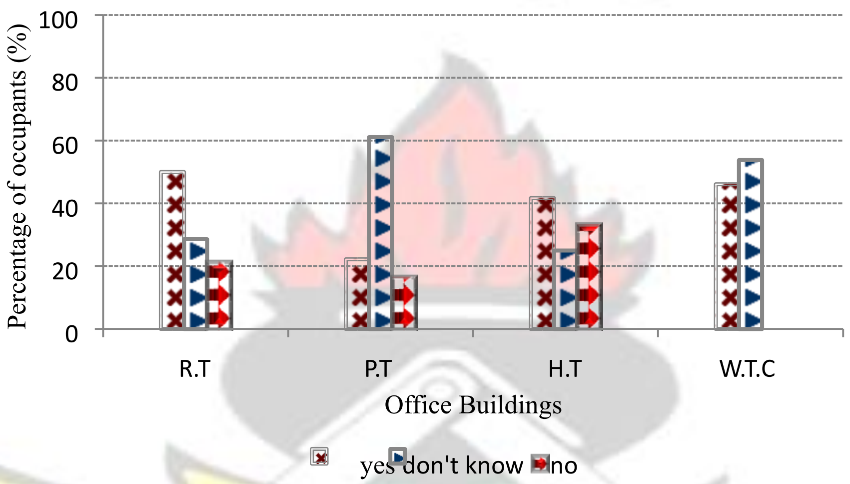

Fig. 4.19: Occupants' perception on whether their actions influence building energy consumptions

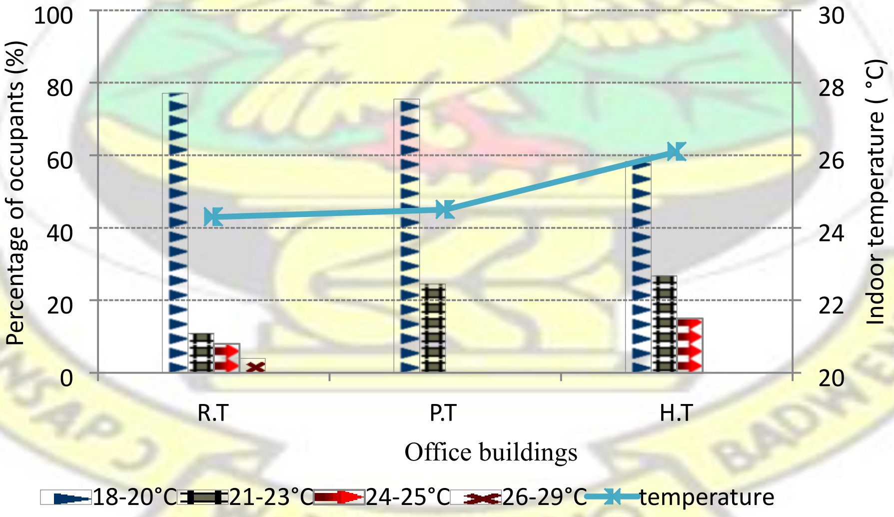

Fig. 4.20: Percentage of occupants', their thermostat settings and mean yearly indoor temperature values

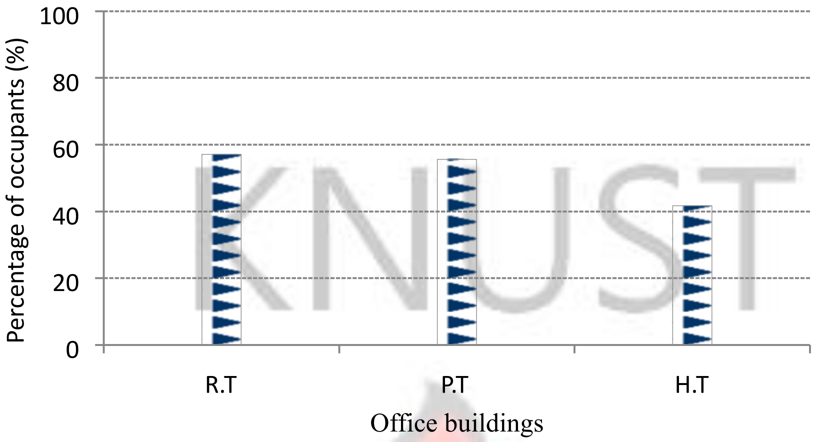

Fig. 4.21: Percentage of occupants' who generally left the air-conditioners on during short absences from the office

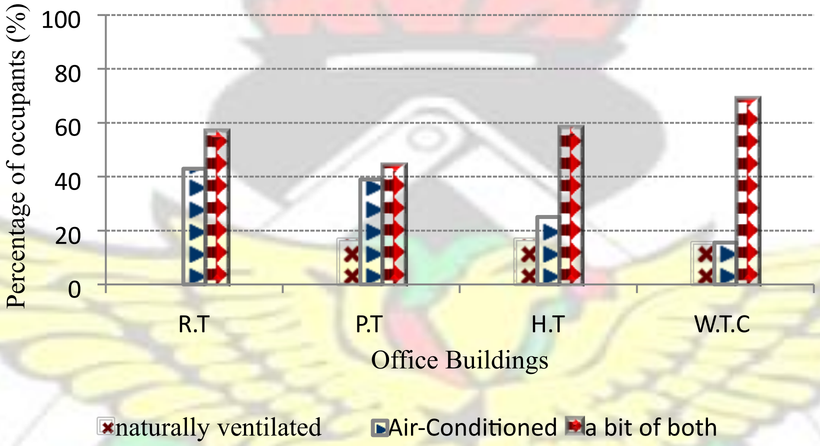

Fig. 4.22: Occupants' preference on type of office environment

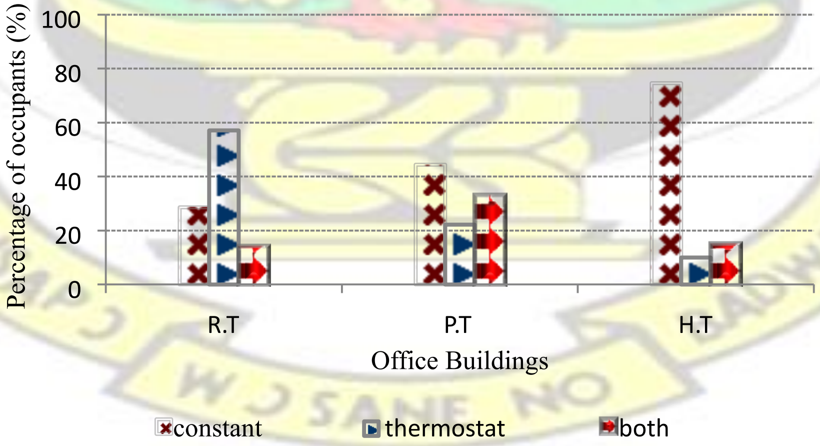

Fig. 4.23: Percentage of occupants' and how they operated their air- conditioners

Due to the fact that nearly 50% of all occupants well insufficiently informed on the functionality of certain control systems, misuse of it (controls) leading to high energy usage and poor performance during operation is frequent. On average, 70% (Fig.4.19; page 130) of all occupants' in the buildings did think about energy conservation when they operated their building systems. Yet their actions had a negative impact on energy usage: a result which could be caused by both direct and reflected solar radiation into the office spaces (Dibra et al., 2011).

Again, more energy is used up since just 50% of the occupants did have sufficient knowledge on how to operate some of the control systems. Though the occupants knew about the implication of system controls on energy usage in some of the offices, they just did not really care so much since the company will have to pay for the exorbitant electricity bills. All the air-conditioned (AC) buildings had their set points between 18-20°C. These set points show the effect of user behaviour on energy consumption of buildings. In the R.T. building, nearly 80% of the occupants felt cold (-3) to slightly cool (-1) on the thermal sensation scale. When asked of their preference, less than 8% wanted to feel cold (-3). There is therefore a good indication that a higher set point (up to 26°C) could still provide comfort within the spaces. P.T. on the other hand operated the low set point probably due to heat absorption by the excessive glazing and the large number of occupants' on the open plan workstations.

Building H.T. occupants' had their set points that low since they felt very uncomfortable and thought their AC systems were inefficient. There is also a plausible chance that the glazing is not as tight as it should be and therefore infiltration could be the cause. Additionally, the type of glazing used could also cause direct heat transfers through radiation and conduction. Radiation and conduction heat transfer have been reported in E-Source (2005). A significant percentage of occupants (52%) did not switch off their air conditioners when they were out of their offices even for as long as between 30 to 45 minutes.

Whiles 40% of the occupants thought they could influence building energy consumption in the way they operated their building systems, 42% thought otherwise, explaining that they did not really care much about how energy is consumed other than to feel comfortable. This observation could also be as a result of the occupants understanding into the subject area of energy conservation.

In the H.T. building, 74.6% of the offices operated the air-conditioners at a constant temperature which is centrally operated, whiles the rest had split systems. This could account for why they could not switch it (AC) off whenever they were out of their offices on short notices.

In the R.T. building, 57.1% of the offices regulated their AC‘s with a thermostat but in the open plan workstations, permission needed to be sought from colleagues before one could change the settings. Sometimes, this process becomes cumbersome and in most cases proves futile. Due to the above, the AC setting is hardly changed though some occupants feel too cold (uncomfortable) in the course of working hours. The use of intelligent and flexible building control systems in combination with well informed occupants have the potential to reduce cooling loads (Koranteng, 2010).

4.2.5 Results on the personal preference of organizing the current work space/Ideal workspace

Graphs presented here summarize occupants‘ response on the following questions in the order that they appear.

- ‗How important are the effects of plants on indoor climate to you?‘
- ‗Are you satisfied with the available possibilities to personalize your working place (Furniture, Plants, Photos…)?‘
- ‗Generally, how do you find your office climate?‘
- ‗Are you satisfied with your office layout?‘

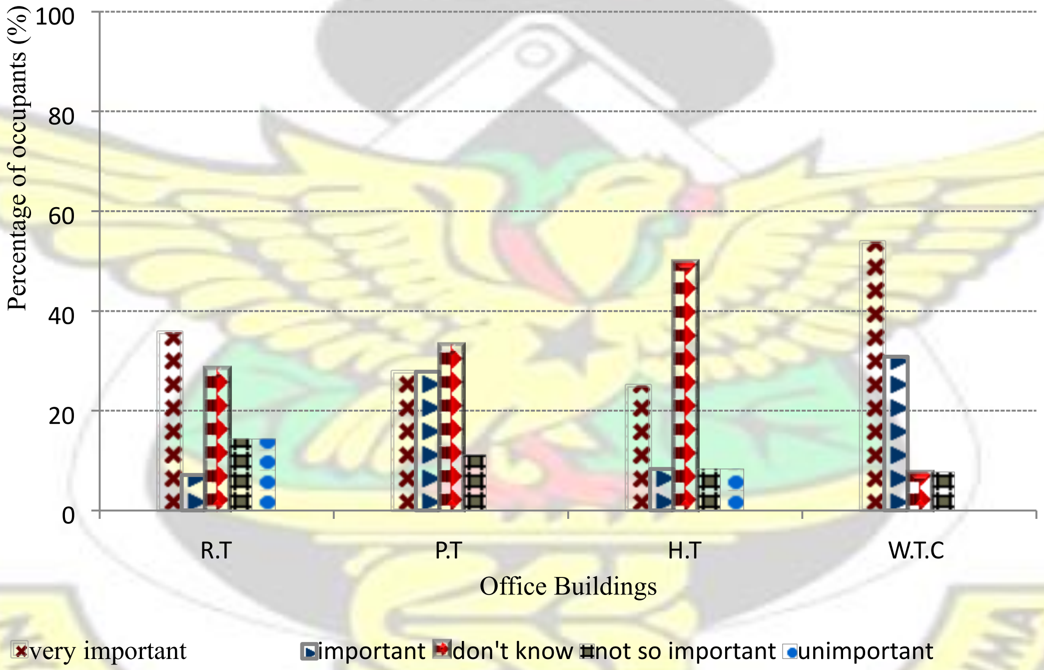

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Fig. 4.24: Importance of the effect of plants on indoor climate

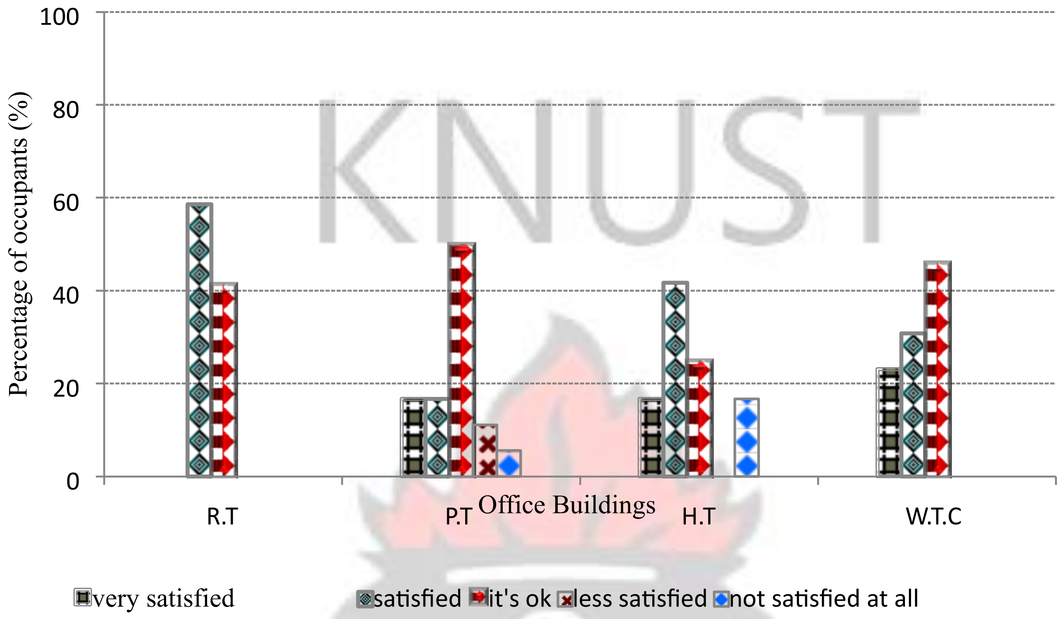

Fig. 4.25: Satisfaction with the available possibilities to personalize workstations

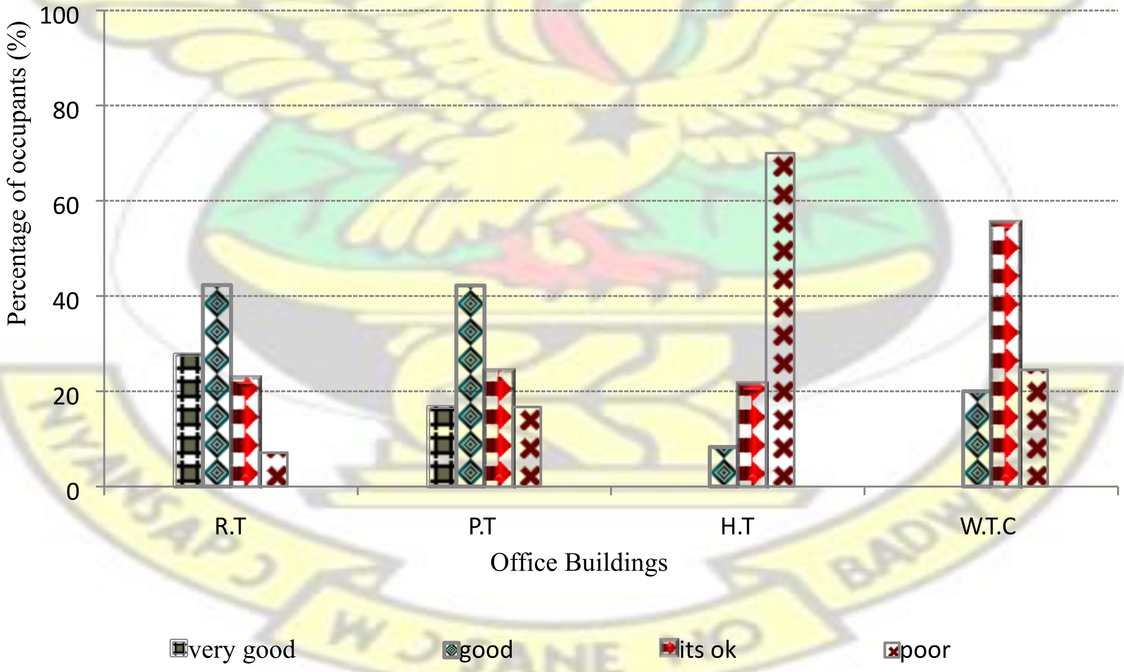

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Fig. 4.26: General perception of office climate by occupants

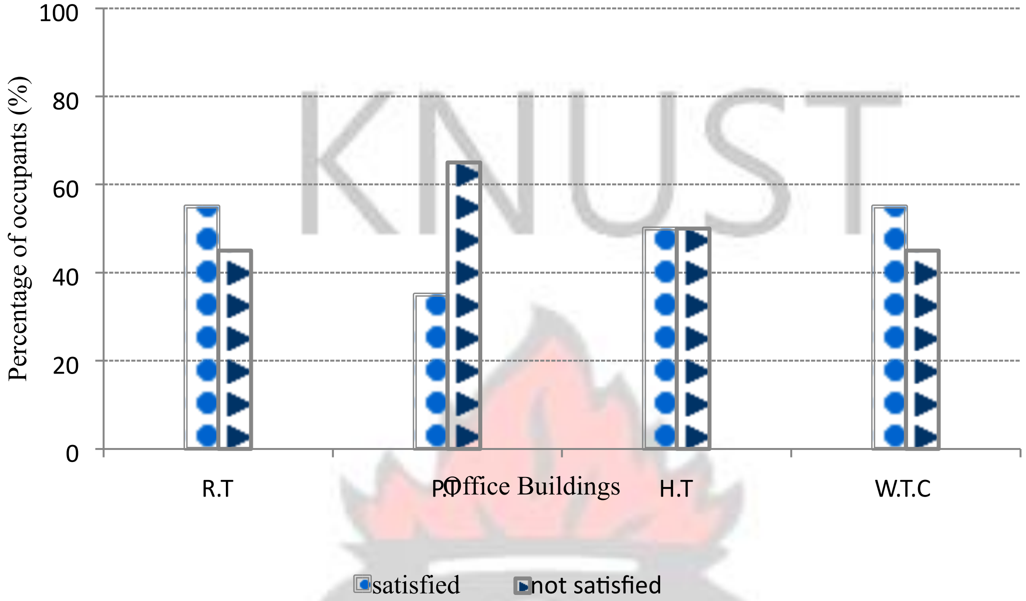

Fig. 4.27: Occupants' satisfaction with their office layouts

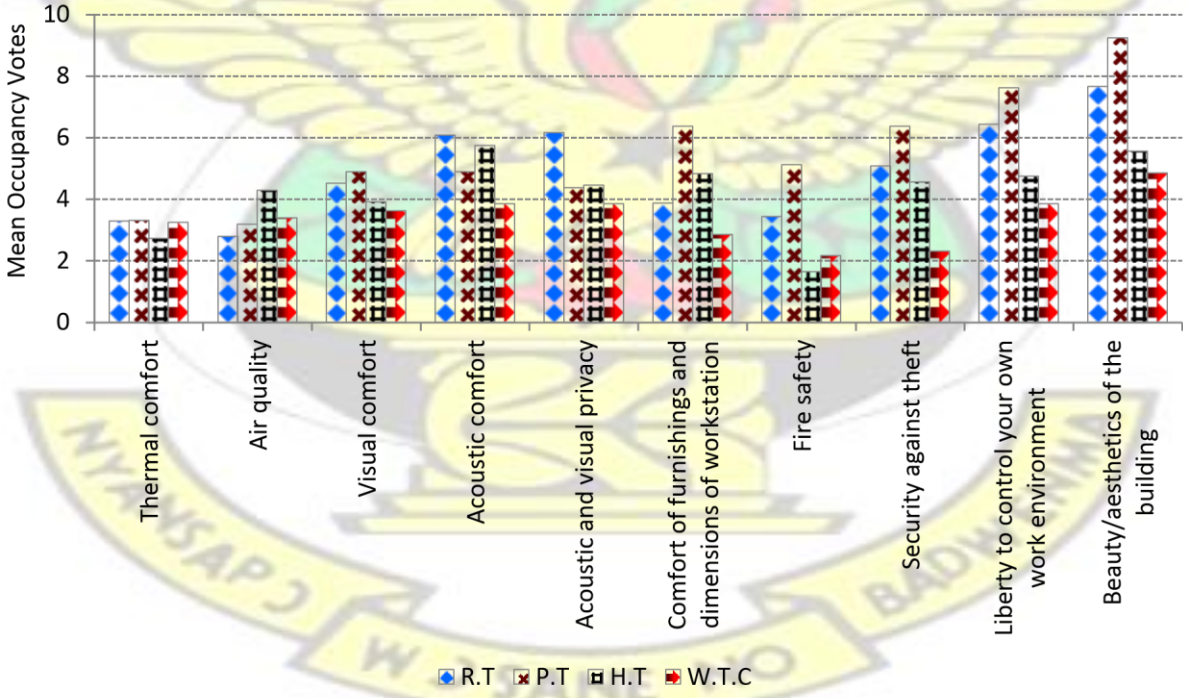

Fig. 4.28: Ranking of features of ideal working place with vote 1 being the most important feature

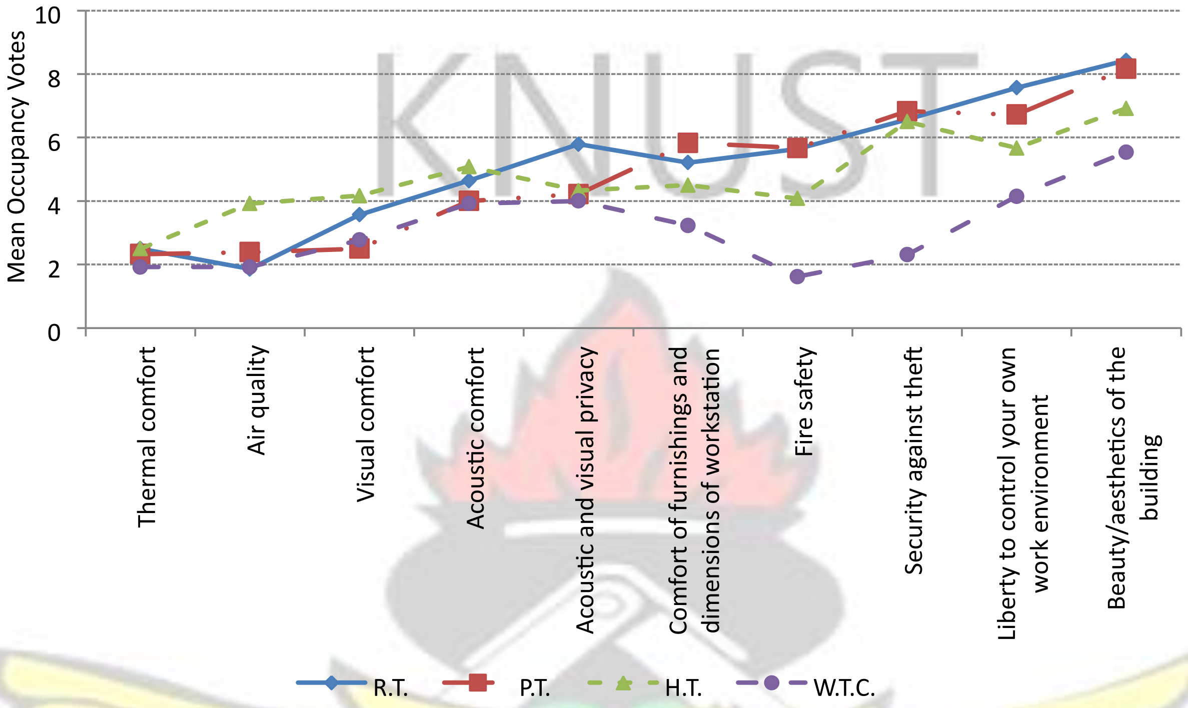

Fig. 4.29: Ranking of improvement measures considered urgent in all the buildings, with vote 1 being the most important feature

Occupants from all the buildings complained about various parameters that could be improved in their offices. As can be seen from Fig. 4.26 (page 135), 58.6% and 41.7% of the occupants‘ were satisfied with their layout in the R.T. and H.T. buildings respectively. This is because though only, 11.9% and 6.7% accordingly had enclosed offices, the open floor workstations were spacious (90.1m² for R.T. and 23.46m² each for H.T.) and the workers felt they had control over their spaces. Most of them had personalized their spaces with photographs and other personal elements.

In the P.T. building, occupants felt uncomfortable as they complained they had no privacy. They could not personalize their spaces and got distracted and interrupted most of the time.

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Situation in the W.T.C. building was quite subtle since each space occupied a smaller group of users. However, they (users) carped about lack of telephone privacy as well as interruptions for those who occupied window side workstations as others wanted them to open and close windows to maximize the thermal conditions within the spaces. Occupants in the enclosed offices across all buildings felt good about their spaces and gave positive comments about it. A similar result was reported by Windsor (2005) in his study on _User satisfaction surveys in Israel‘.

In the H.T. building, because the glazing is fixed and cannot be opened, occupants had negative feelings about their office climate. They complained that the split units are inefficient and as a result preferred opening the inoperable windows when the outside conditions are favourable. Again, due to the east-west orientation of H.T., the late afternoon sun had direct impact on the indoor climate: a situation which the air-conditioning units sometimes fail to set right and therefore occupants‘ become agitated. Shading devices (Koranteng, 2010) should have been provided to counteract the conductive gains from the direct solar ingress in the H.T. building.

From the survey, it was reported that from the design stage, the users‘ needs are not satisfied. The buildings are built as ordinary open plan office blocks with only the vital areas provided for (washrooms, lift areas, staircase areas, and main circulation spaces). Any company who comes in will have to re-organize the interior spaces to suit their workers. This could account for all the buildings having prominent open plan workstations. The few enclosed offices are for the top management staff.

At H.T., 50% of the occupants did not know the importance of the effect of plants on indoor climate. Thirty-three percent responded important/very important whiles 16.6% said it was unimportant. Among the positive effects of plants in the landscape is a more comfortable environment, less energy needed for indoor comfort, reduction of greenhouse gas emissions and filtering potential on pollutants.

Air quality was ranked as the most important parameter with a positive satisfaction on occupants in both the R.T. and P.T. buildings followed by thermal comfort for the same buildings in addition to the H.T. building. This result shows a divergence from the study by Choi et al. (2009) and Astolfi and Pellerey (2008) who both reported that thermal comfort was ranked to have slightly higher importance than acoustic comfort and satisfaction with air quality. In the present study, thermal comfort does have a higher importance than acoustic comfort but not air quality. Acoustic comfort was ranked 4th, 7th, and 7th in P.T., R.T. and W.T.C. respectively. The least ranked parameter for P.T., R.T. and W.T.C. was _Beauty/aesthetics of the building', whiles H.T. ranked acoustic comfort as the least important parameter. Occupants from P.T., R.T. and W.T.C. all commented that the beauty of the building did not really matter to them as much as their indoor conditions as well as how the building responded against fire and the options it gave them to feel comfortable at their work stations.

In the W.T.C. building, occupants reported that when it came to issues concerning thermal comfort, air quality, acoustic comfort etc., they were less informed and always thought about fire safety, security against theft, etc. These two they believe were talked about more and could be fatal if attention is not paid to them. Across all the buildings, fire safety, air quality and thermal comfort were the top three parameters the occupants voted as the most important. This result diverges from Frontczak and Wargocki (2011) study which concluded that thermal, visual, acoustic and air quality is the main indoor environmental parameters contributing to satisfactory indoor environment. Agnieszka and Mats (2013) also stressed in their study that air quality had a great impact on occupant satisfaction followed by thermal comfort and sound (acoustic) comfort.

In terms of preference however, the occupants' most important parameter was thermal comfort, then air quality and fire safety.

Fire safety seems to be a new parameter which is peculiar to the study. Occupants may have been psychologically affected by the emergence of the frequent fire outbreaks in Ghana (commercial buildings, markets, etc).

4.2.6 Health needs and complaint results

The negative effects of poor indoor environment on health are widely known. The aim of this section of the questionnaire was to trace possible health problems to inefficient building systems.

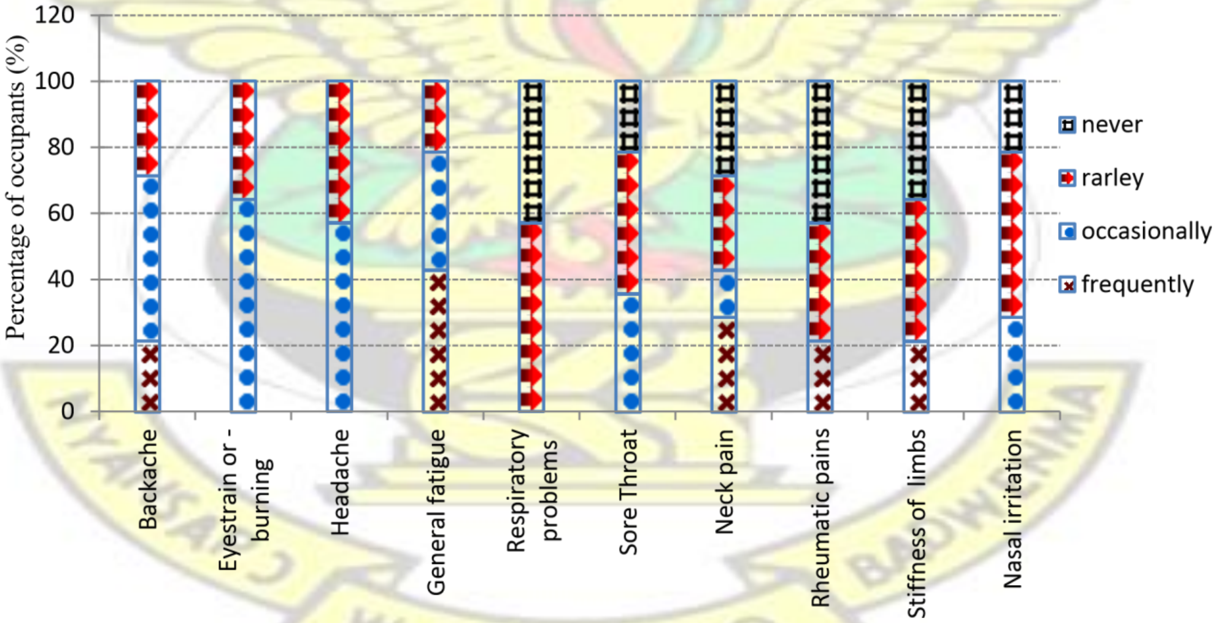

Fig. 4.30: Health complaints at the R .T. building

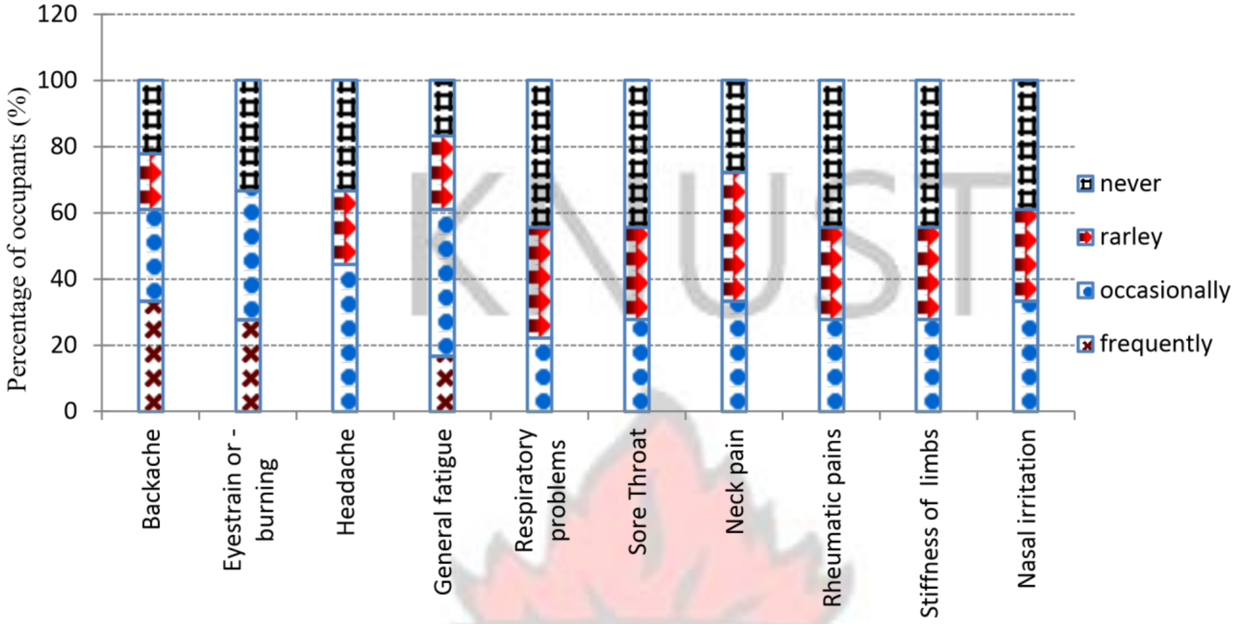

Fig. 4.31: Health complaints at the P.T. building

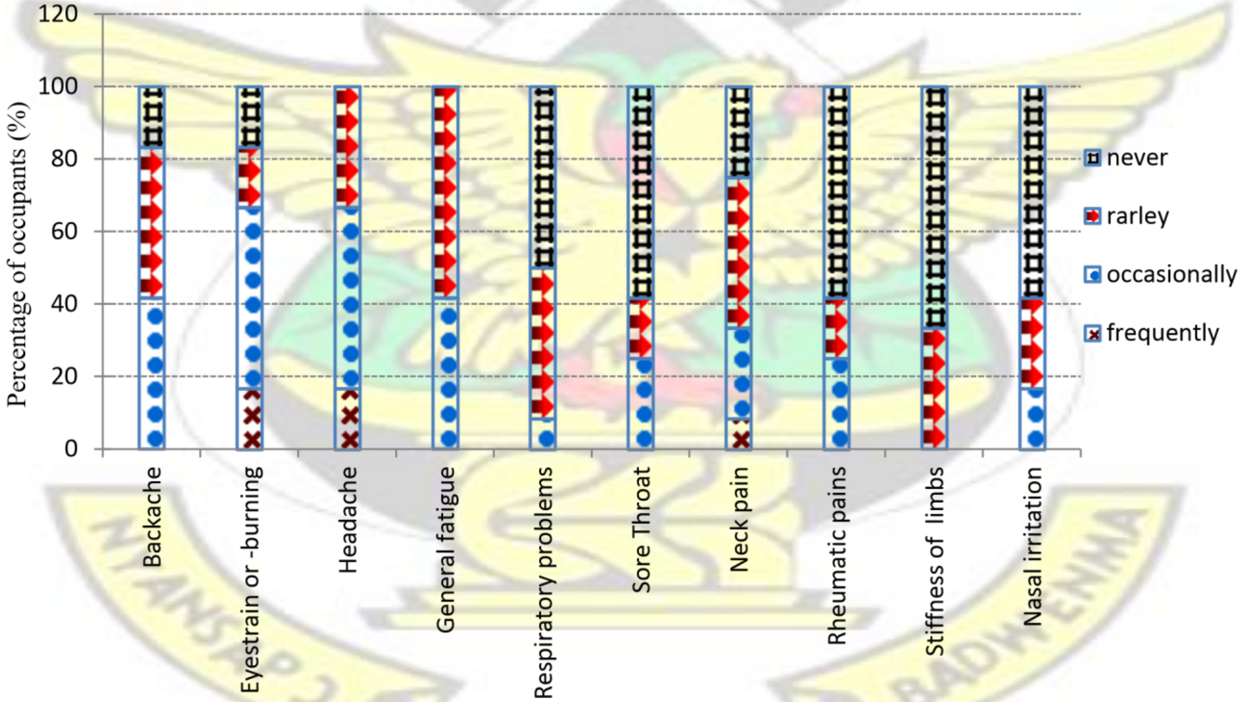

Fig. 4.32: Health complaints at the H.T. building

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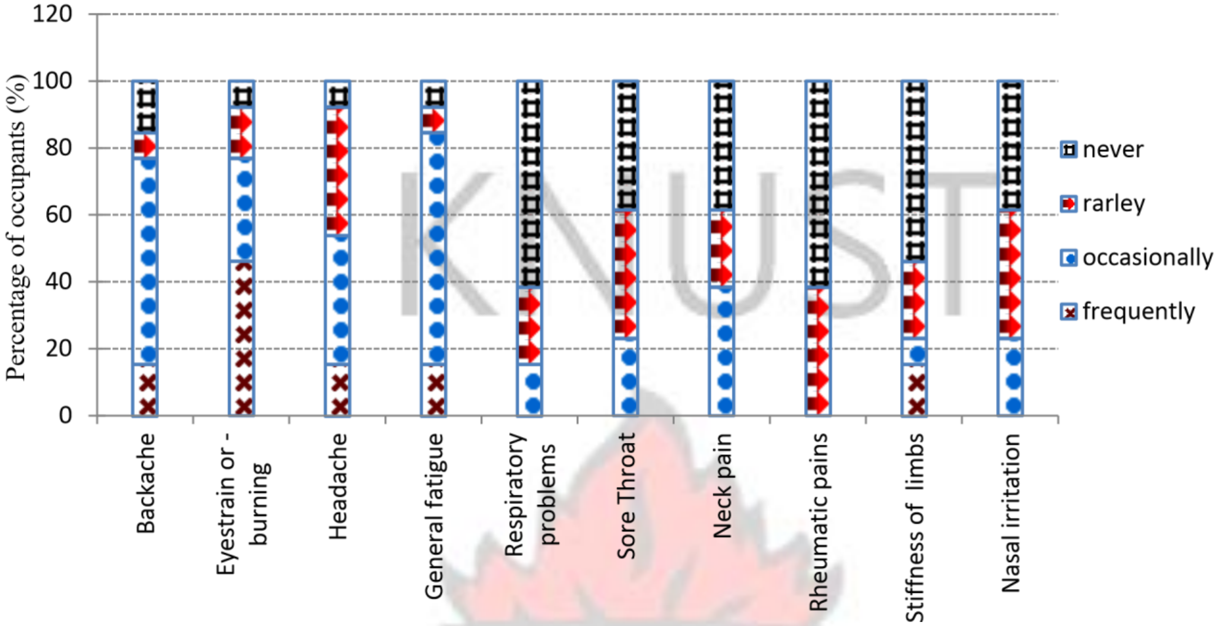

Fig. 4.33: Health complaints at the W.T.C. building

Results concerning health complaints from occupants are presented in the illustrations below. As many as 28.6% and 33.3% of the respondents at the R.T. and P.T. respectively (air-conditioned buildings) reported of nasal irritation occasionally, perhaps due to the effect of the airconditioning systems. Frequently experienced health complaint from all the buildings included backache: 33.3% in the P.T. building, 21.4% in the R.T., 15.4% in the W.T.C. Higher percentages were recorded by Koranteng (2010) in a similar study of low rise office buildings in Kumasi. In his study, the author reported that 60% of occupants on the average reported of backache in three air-conditioned buildings and suggested that lack of proper ergonomics might be the cause.

Other frequently reported health problems at the R.T. included general fatigue, neck pains and stiffness of limbs. Since occupants complained of feeling cool/cold in the R.T. building, this could be the reason for the above health complaints. In P.T., it was eyestrain/burning and general fatigue. H.T. also recorded eyestrain/burning, headache and neck pains as the most frequently occurring health issues. This could be caused by the poor lighting (350 lux) within the building. In the W.T.C. building, occupants said eyestrain/burning, headache and general fatigue were the frequently experienced issues probably caused by the same poor lighting issue (220 lux).

Occasionally, all the health issues showed in the diagram were experienced by occupants in both the W.T.C. and the P.T. building. Meanwhile, stiffness of limbs was neither an occasional nor a frequent happening at the H.T. building. The reason for this could be because occupants usually took intermittent breaks from their workstations mainly due to their displeased indoor conditions.

4.2.7 Summary on all buildings

i. Based on the study, the three most important parameters for occupants�' satisfaction in their office spaces were air quality, thermal comfort and fire safety. This finding introduces a new parameter which is peculiar to the Ghanaian setting (Fire safety).

Previous studies have found different sets of parameters from the above. Frontczak et al. (2012) found space available for individual work, noise level and visual privacy whiles Lai and Yik (2009, 2007) showed that thermal comfort, air quality and noise levels were the most important parameters.

ii. Occupants' of the buildings need to be trained in the accessibility and operation of their building control systems. From the study, only half of the respondents in the R.T. building could confidently operate their air-conditioners, lighting and blinds. In the other buildings, the number was less than half. By the wrong application of these control systems, energy tends to be misused too.

iii. From the study, occupants within the air-conditioned (A/C) buildings did not always want to use the A/C‘s. They sometimes (during the wet seasons with lower outdoor temperatures) wanted their windows opened for natural ventilation. This result back up the finding of Hoes et al. (2009). The authors reported that ‗occupant perception of socalled sealed, centrally air-conditioned buildings with open plan floor layouts that provide minimal adaptive opportunity, with no option for opening windows, is negative‘ (Hoes et al., 2009).

iv. Building R.T. and H.T. are not climate responsive and as such cannot fully rely on passive mode of operations. An attempt to run on passive mode increases the thermal comfort levels even with high air change rates (See Table. 4.15 and 4.18).

v. Occupants‘ within the air-conditioned buildings had their thermostat settings low (1820ºC) in order to achieve thermal comfort. With an indoor temperature of 24.3 and 24.5ºC for R.T. and P.T. respectively, the two buildings fall within the ASHRAE (2004) summer comfort temperature range of 23-26ºC.Therefore the temperature set points could have been higher to conserve energy.

vi. The relatively poor performance of the H.T. building could be attributed to the improper orientation, inoperable glazing system and the efficiency of the air-conditioning units.

vii. The use of efficient lighting systems as well as its regulation should be important to building users and managers since lighting (efficiency and its right usage) affect the level of cooling loads within the buildings (see Table 3.7 to 3.10).

The results of the survey suggest that occupants' behaviour within their indoor environment have implication on the energy performance of the building. Users' needs and behaviour could help refine and improve the design and quality of office buildings.

4.3 *Objective 2: To determine the thermal comfort conditions of the indoor environment within the selected buildings.*

The above objective was achieved by the use of three thermal comfort measuring tools: Fanger's PMV-PPD, Psychrometric and Bioclimatic charts. Results for objective two is presented below.

4.3.1 PMV-PPD results

PMV-PPD was calculated based on the initial temperature, relative humidity and air velocity values together with metabolism rate and clothing insulation rates that were derived from literature based on the kind of work and clothing the occupants were wearing.

Table 4.3: Statistical Summary of Indoor Measurements

Buildings	Air Temperature [Mean value] (min-max) [°C]	Relative Humidity [Mean value] (min-max) [%]	Air velocity [Mean value] (min-max) [m/s]	Clothing insulation [clo]	PMV Mean value (min-max)	PPD Mean value (min-max) [%]	AMV Mean value (min-max)
P.T.	24.5 (22.5 to 25.9)	54 (48 to 58.2)	0.1 (0 to 0.2)	0.8	0.3 (-0.02 to 0.6)	11 (5.5 to 18.3)	-0.5 (-3 to 2)
W.T.C.	28.4 (26.7 to 29.5)	71.6 (70 to 73.3)	0.35 (0.2 to 0.5)	0.8	1.5 (1.0 to1.8)	51.4 (27.6 to 67.3)	0.5 (-2 to 3)
H.T.	26.1 (24.8 to 27.7)	59 (54 to 68)	0.11 (0 to 0.21)	0.8	0.8 (0.4 to 1. 2)	20.24 (9 to 38.1)	-0.5 (-3 to 2)
R.T.	24.3 (23.9 to 25.1)	51.2 (50 to 52.6)	0.1 (0 to 0.2)	0.8	0.2 (0.1 to 0.4)	6.28 (5.2 to 9)	-1.5 (-3 to 0)

Where: PMV denotes Predicted Mean Votes

PPD denotes Percentage of Persons Dissatisfied

AMV denotes Actual Mean Votes

Clothing: Cotton working shirt with long sleeves/short sleeve, working trousers/ skirt and three piece suit

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From Table 4.3, mean air temperatures for R.T., P.T. and H.T. (mechanically ventilated buildings) falls within ASHRAE‘s acceptable temperature range of 23°C - 26°C (ASHRAE, 2004). Albeit, many studies have concluded that the comfort temperature is higher in tropical regions, since humans have the ability to acclimatise (Li et al., 2010). Sabarinah and Steven (2007) reported that the comfort band for Malaysia for all building types is between 23.6°C - 28.6°C. Air velocity ranges from 0.2 m/s - 0.5m/s with an average of 0.35m/s, a result which correlate well with Huang et al. (2012) studies. In their studies, mean air velocity was found to be 0.16m/s with most samples having air velocity of lower than 0.2m/s (ibid).

In the W.T.C. building, average PMV recorded was 1.5 (warm) which corresponded to 51.4% PPD. Meanwhile, the indoor temperature ranged from 26.7°C - 29.5°C. These values are in sharp contrast with Beizaee et al. (2012) studies. In their study, indoor temperature values ranged from 21.6°C - 26°C with an average of 23.9°C. PMV value of -0.25 was also found: making W.T.C warmer with PMV of 1.5.

The finding in the W.T.C. also contrasts Ealiwa et al. (2001) study in the Ghadames, Libya. In their work, the same metabolism rate and clothing values used in the current study was used to calculate the PMV values for occupants in naturally ventilated buildings. The PMV was found to be 2.7 (hot). The difference in the two values could be attributed to the climate characteristics of Libya. The climate (Ghadames) is characterized by high air temperature, high solar radiation, low rainfall, low humidity and many sandstorms.

Shape and orientation to breezes, vertical shafts to promote air flow, wing walls and overhangs in the direction of winds have to be considered for naturally ventilated buildings (Koranteng, 2010).

In addition, intelligent systems and system controllers have to be installed in buildings since they have positive effect on thermal comfort (Mohammadi, 2007). The installation of fans (with a temperature reduction capability of 2°C (Koranteng, 2010) could be installed within the offices to reduce the high temperature values as short term improvement mechanism in the freerunning building.

The H.T. building also recorded an average indoor temperature of 26.1°C with a range of 24.8°C - 27.7°C. The aforesaid could be attributed to the orientation of the building (east-west) with its unprotected glazing: confirming the assertion of a number of studies that heat gain through the exterior window accounts for 25% - 28% of the total heat gain within a space (Al-Najem, 2010 and Yu et al., 2008).

The PMV calculation for the buildings indicated that the mechanically ventilated buildings were comfortable (within the central three categories of the thermal sensation scale: -1, 0, 1). W.T.C. (naturally ventilated building) recorded a PMV of 1.5 (between slightly warm and warm). PMV and the average AMV in the W.T.C. shows wide disparities; Whiles PMV recorded is 1.5, average AMV is 0.5 (Table 4.3). Significantly, PMV has over-predicted the indoor thermal comfort in the W.T.C by 1 scale unit: A result which is in the range of the findings of Doherty and Arens (1988). They concluded in their study that there was a discrepancy between PMV and AMV by 1.3 scale units. The over-prediction nature of the PMV has also been recorded by other researchers in their studies (Brager and De Dear, 1998: Oseland, 1996). Some reasons for the over-prediction in the current study could be summarised as respondents having a couple of adaptive advantages (opening of windows, use of personal standing fans, etc.).

Again, the respondents in the office building work in the mornings when the temperature was assumed to be comfortable. During the afternoons where temperature recorded is high, 90% of the respondents are out of the office for various assignments since it‘s a financial research company.

Another rationale could also be that the respondents had acclimatised to the temperature and relative humidity values and therefore reported as such.

Additionally, there are a number of variations within the office spaces that could lead to the high value of the PMV which was not the case during the climate chamber experiment. Amongst them include the use of office equipment (laptops, photocopy machines, printers etc) and the partitions for individual personalised workstations.

4.3.2 Psychrometric Results

The maximum, minimum and mean hourly temperature and relative humidity values during the working hours were plotted on psychrometric charts to analyse the thermal comfort conditions affecting the office spaces in relation to the comfort zone. The comfort zone for Accra was derived based on the works of Auliciems (1981) as recommended by Szokolay (2004) for 90% acceptability. The outdoor temperature and relative humidity values were also plotted.

Table 4.4: Neutral temperature for 90% acceptability (Adaptive model)

	MAY	JUN	**JUL**	**AUG**	SEP	OCT	NOV	DEC	JAN	FEB	**MAR**	APR
To.av	29	27.6	**26.2**	**26.2**	27.1	28.5	29.8	29.5	29.3	30	**30.4**	30.2
Tn + 2.5	29.1	28.7	**28.2**	**28.2**	28.5	28.9	29.3	29.2	29.2	29.4	**29.5**	29.4
Tn	26.6	26.2	**25.7**	**25.7**	26	26.4	26.8	26.7	26.7	26.9	**27**	26.9
Tn – 2.5	24.1	23.7	**23.2**	**23.2**	23.5	23.9	24.3	24.2	24.2	24.4	**24.5**	24.4

Where: To.av = the mean monthly outdoor temperature (°C)
Tn = neutrality temperature (°C)

Tn +2.5 = the upper limit

Tn -2.5 = the lower limit

March is the warmest month whiles July-August are the coolest months (Table 4.4). This resulted in a shift from the upper left to the upper right (Fig.4.34). This is demonstrated with the mean hourly temperature and relative humidity values for Accra in the months of March and August. The shift is major due to the major difference in the outdoor temperatures (Tn difference of 2.7°C) during the warmest month and the coolest months.

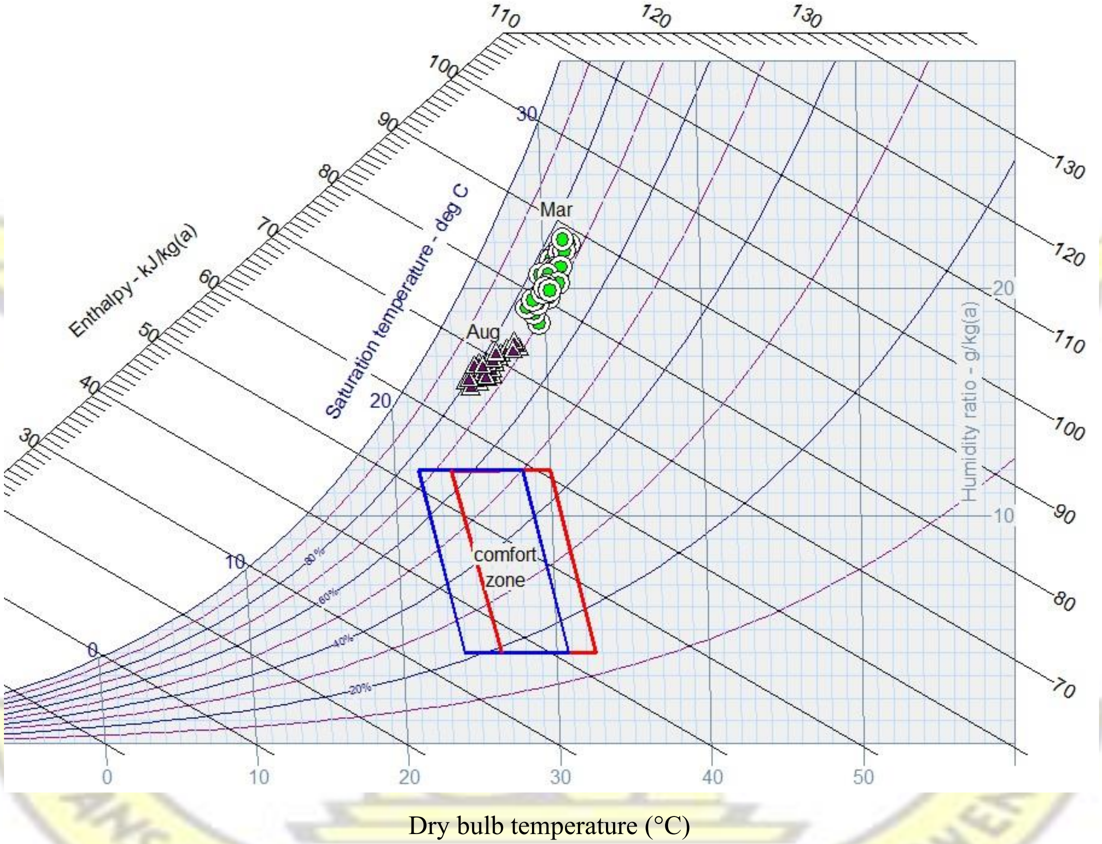

Fig.4.34: Mean hourly temperature and relative humidity values in Accra for representative days in the months of March and August

The recorded indoor temperature and relative humidity values (mean monthly hourly maximums, minimums and hourly means during the working hours) have been plotted on psychrometric charts

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to analyze the thermal comfort conditions affecting the office spaces in relation to the comfort zone.

A regression co-efficient value of 0.9 gives a good indication that both the measured outdoor temperature and that of the Accra weather station are strongly related. From Table 4.4, March is the warmest month (30.4°C) whiles July and August are the coolest (26.2°C) months. In Fig. 4.34, there is a clear shift of the outdoor mean hourly temperature and relative humidity values from the upper left to the upper right during the months of March and August. The shift is due to the difference in the environmental parameters of the coolest and warmest months in Accra (Tn difference of 2.7°C, see Table 4.4). Figure 4.34 indicates that humidity may be a problem since all the points are above the 12g/kg limit (Szokolay, 2004). During the warmest period, mean temperatures are high exceeding 30°C. Contrarily, the coolest months recorded mean temperature levels well below 28°C (June, July and August). The relative humidity values are rather high (70% - 80%), though there is no significant psychological or physiological difference in human response to such high relative humidity values for the temperature range of 20°C - 26°C (Arens et al., 2002).

The above observation was also made by Koranteng et al. (2011) who studied the climatic context of Kumasi and reported that the warmest month was February and the coolest month was August. From the study of Kumasi, there are slight differences between the Tn of the warmest month and the coolest month. In Kumasi, February recorded a Tn of 26.5°C and August: 25.4°C with relative humidity between 80% - 90%, whiles in Accra, March‘s Tn is 27°C and August 25.7°C with relative humidity between 70% - 80%. The above shows the characteristics of the warm-humid climatic zone where temperature and relative humidity values are high with intense solar radiation.

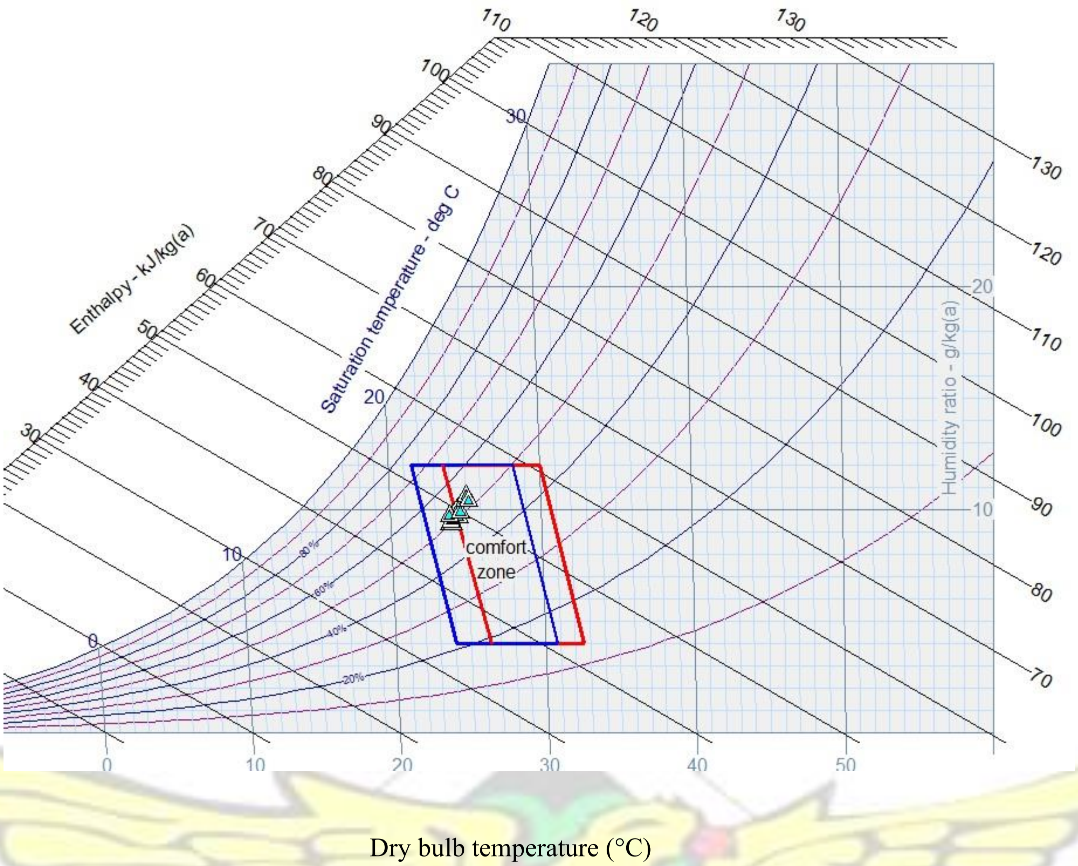

Fig.4.35: Mean monthly hourly temperature and relative humidity values in R.T. offices (measured data from 8am to 5pm)

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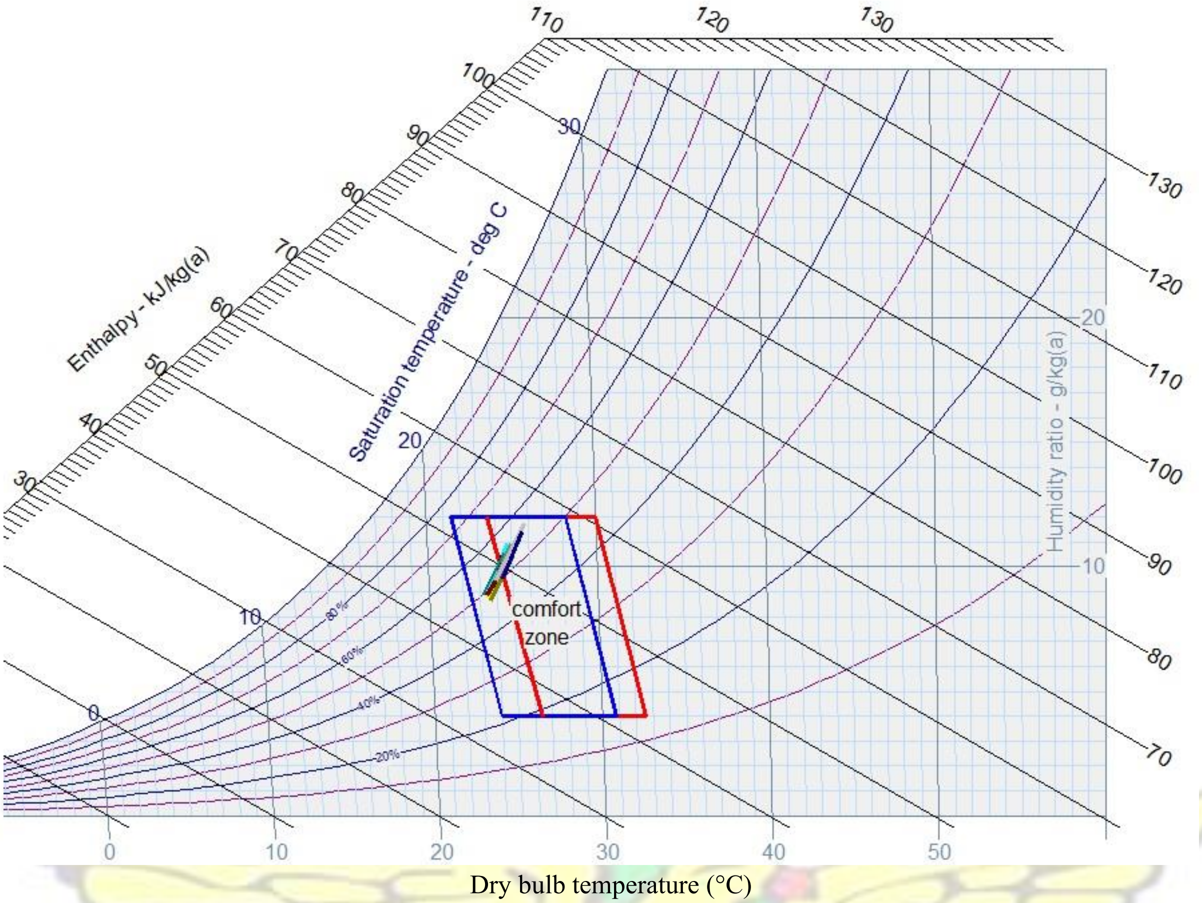

Fig.4.36: Mean monthly hourly maximum and minimum temperature and relative humidity values in R.T. offices (measured data from 8am to 5pm)

4.3.2.1 R.T. Building

The mean monthly hourly maximum and minimum temperature and relative humidity values in the R.T. offices resulted in all the months being in the comfort zone (Fig. 4.35). The R.T. has both its maximum and minimum values within the comfort zone. This gives an indication of how comfortable the office spaces are all year round. The R.T. building based on the thermal comfort scales (ASHRAE, 2004) is very comfortable. Relative humidity values ranged between 48-58%. The recorded maximum temperature value was around 25.8°C: lower than the maximum value computed for 90% acceptability based on the adaptive model (Szokolay, 2004).

In Fig. 4.36, the mean monthly hourly temperature and relative humidity values of the office spaces are presented. All the months are within the comfort zone. The average temperature recorded was 24.4°C with a corresponding relative humidity value of 51.3%. These values are well within the generally accepted design set points of 25°C temperature and 60% relative humidity (Keneally, 2002). A major elucidation for the behavior of the R.T. could be heavy reliance on air-conditioners by the occupants.

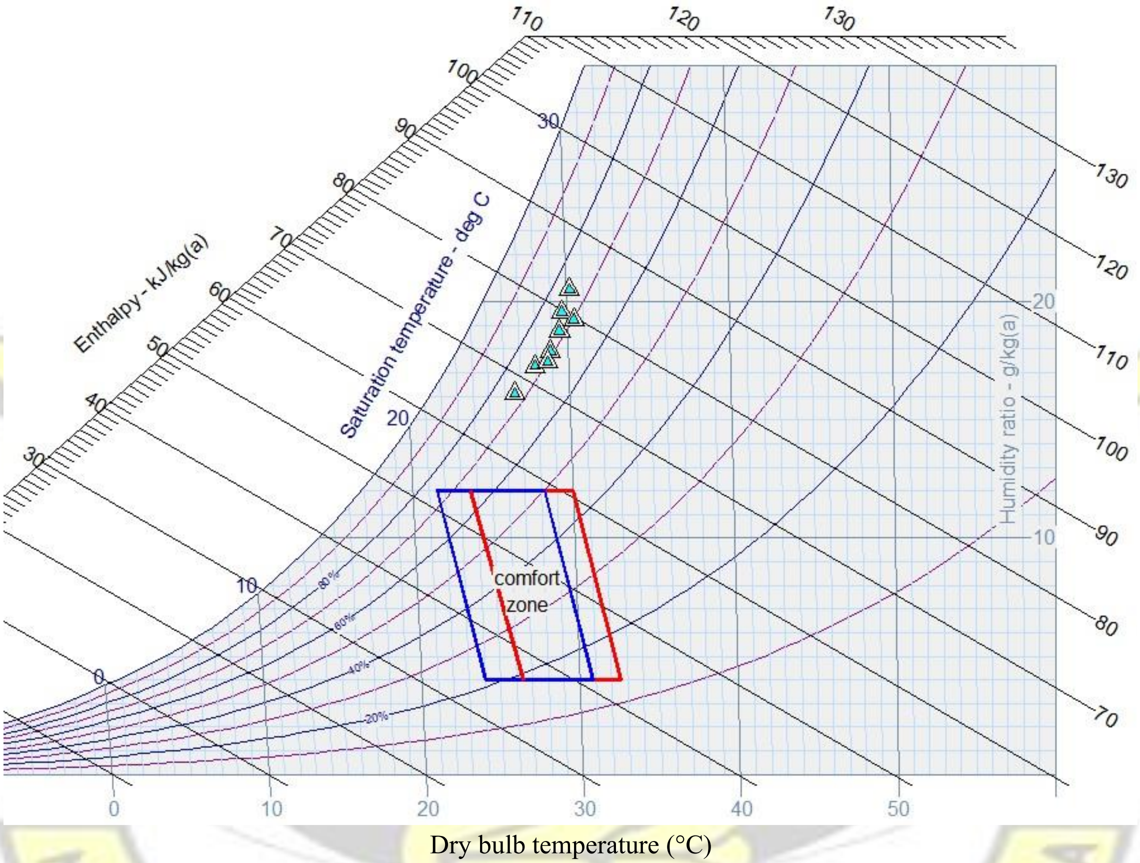

Fig.4.37: Mean monthly hourly temperature and relative humidity values of offices in the W.T.C. building (measured data from 8am to 5pm)

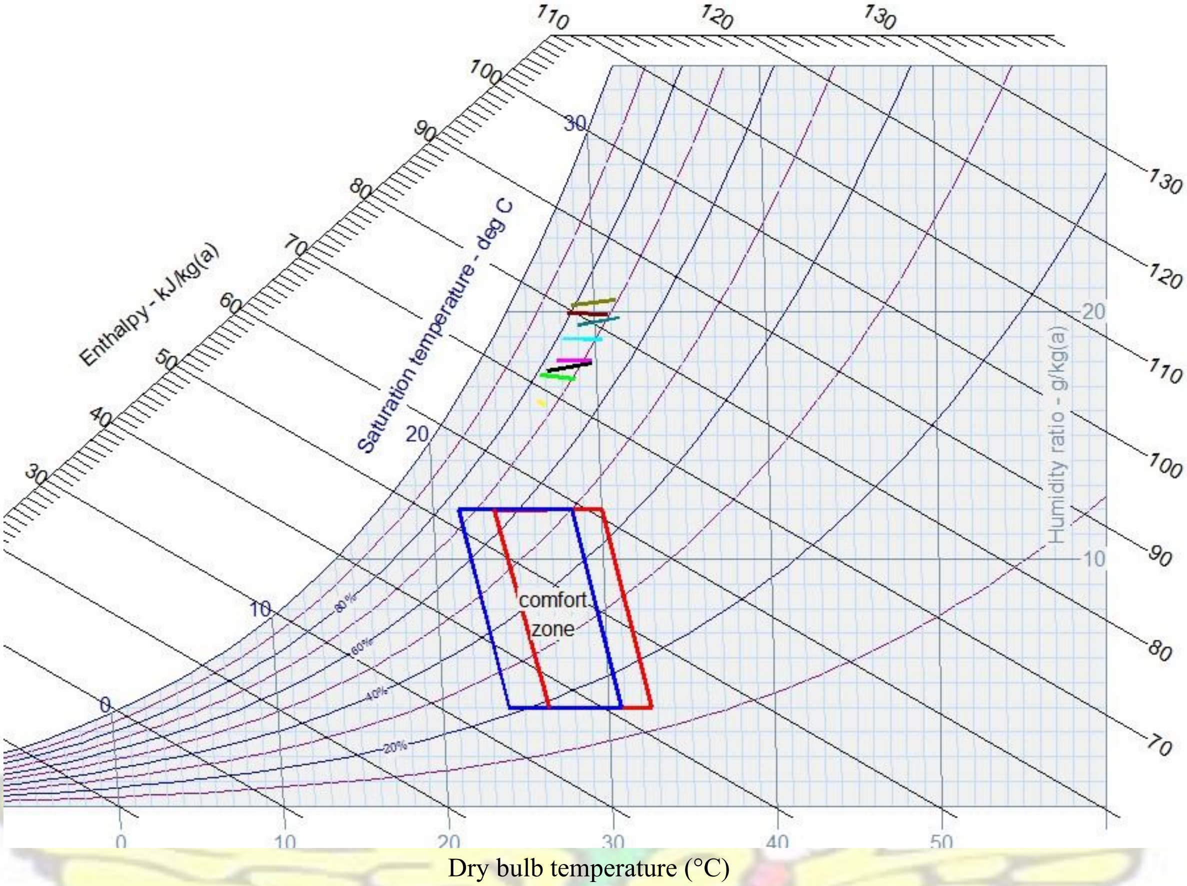

Fig. 4.38: Mean monthly minimum and maximum temperature and relative humidity values of offices in the W.T.C. building (measured data from 8am to 5pm)

4.3.2.2 W.T.C. Building

High mean indoor temperatures were recorded at the W.T.C. As a result, spaces were found to be uncomfortable. The maximum recorded temperature value was 31.4°C. Mean average temperature value was in a range of 26.6°C – 30.4°C. A result which is 0.1°C - 2.1°C divergent from findings of Beizaee et al. (2012) studies of UK naturally ventilated office buildings during summer conditions.

Relative humidity values were almost in congruence with that of the H.T. building (an air-conditioning building). This could be due to the effect of ventilation and installed systems, reducing the humidity levels as opposed to the air-conditioned building (Koranteng et al., 2011). The humidity levels were high resulting in all the months being outside the comfort zone (Fig. 4.37). Furthermore, the poor performance of the W.T.C. building is also as a result of the absence of fans within the spaces. Again, the internal arrangement did not also support the positive effect of cross ventilation.

Analogous findings have been documented by Koranteng et al. (2011) where a naturally ventilated low rise office building in Kumasi was found to be uncomfortable on the psychrometric chart with comparable reasons. Similar studies of office buildings found the shading devices often installed at the southern sides and left closed or partly closed during working hours (Madhavi et al., 2007). From Fig. 4.38, both minimum and maximum values recorded all lie outside the zone of comfort. The minimum temperature found was 26.5°C with a relative humidity value of 74.9% whiles the highest temperature recorded had a relative humidity value of 67.6%. The short lines corroborate the characteristics of the humid climate with small diurnal variations (Szokolay, 2004).

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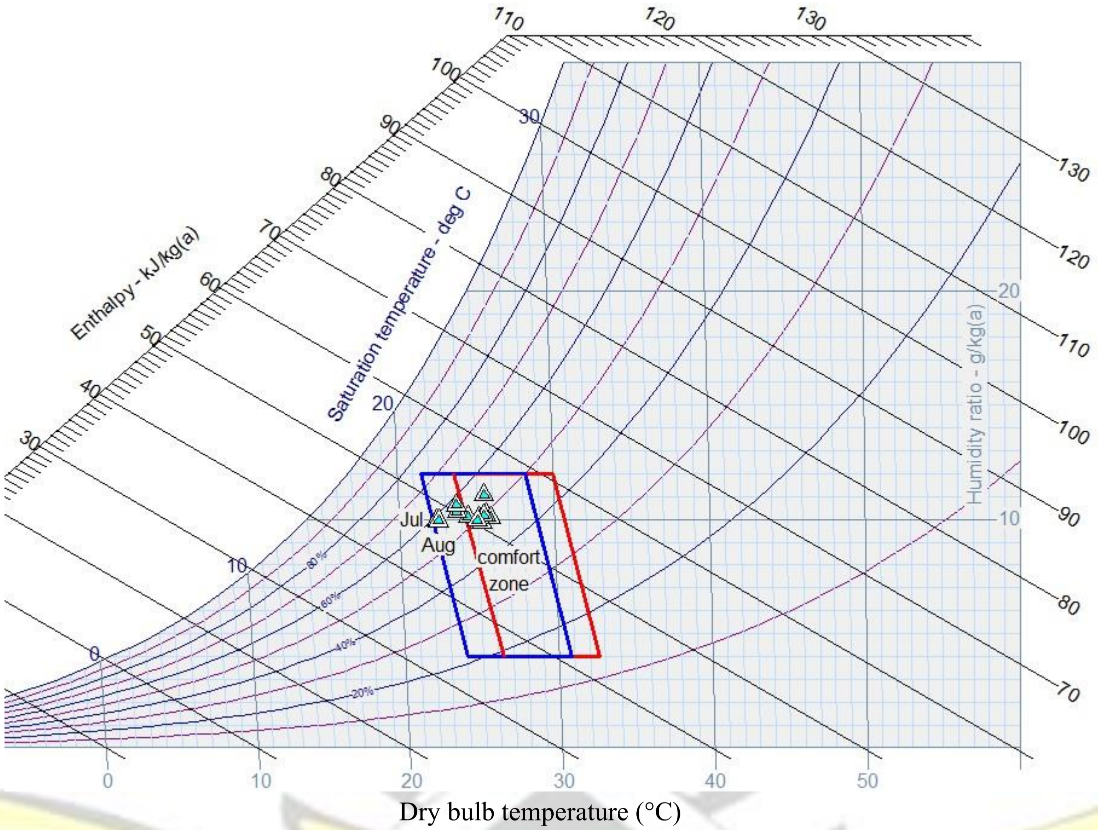


Fig. 4.39: Mean monthly hourly temperature and relative humidity values in the P.T. offices (measured data from 8am to 5pm)

4.3.2.3 P.T. Building

In Fig. 4.39, the mean monthly hourly temperature and relative humidity values resulted in all the months being comfortable with July and August falling on the comfort boundary to the left: indicating, slightly cool conditions. The mean relative humidity is around 52%. The results (Fig.4. 40) show little variation in comfort between the wet (blue box) and the dry season (red box) comfort zones and most months above the 12g/kg limit. The months of May, July and August lies outside on the left of the comfort zone signifying under-heating. September, October, November and December all have their maximum values above the comfort zone, indicating relative humidity may be the problem. Nevertheless humidity has little or no effect on thermal comfort when within 60% - 90% (Olesen and Brager, 2004: Arens et al., 2002).

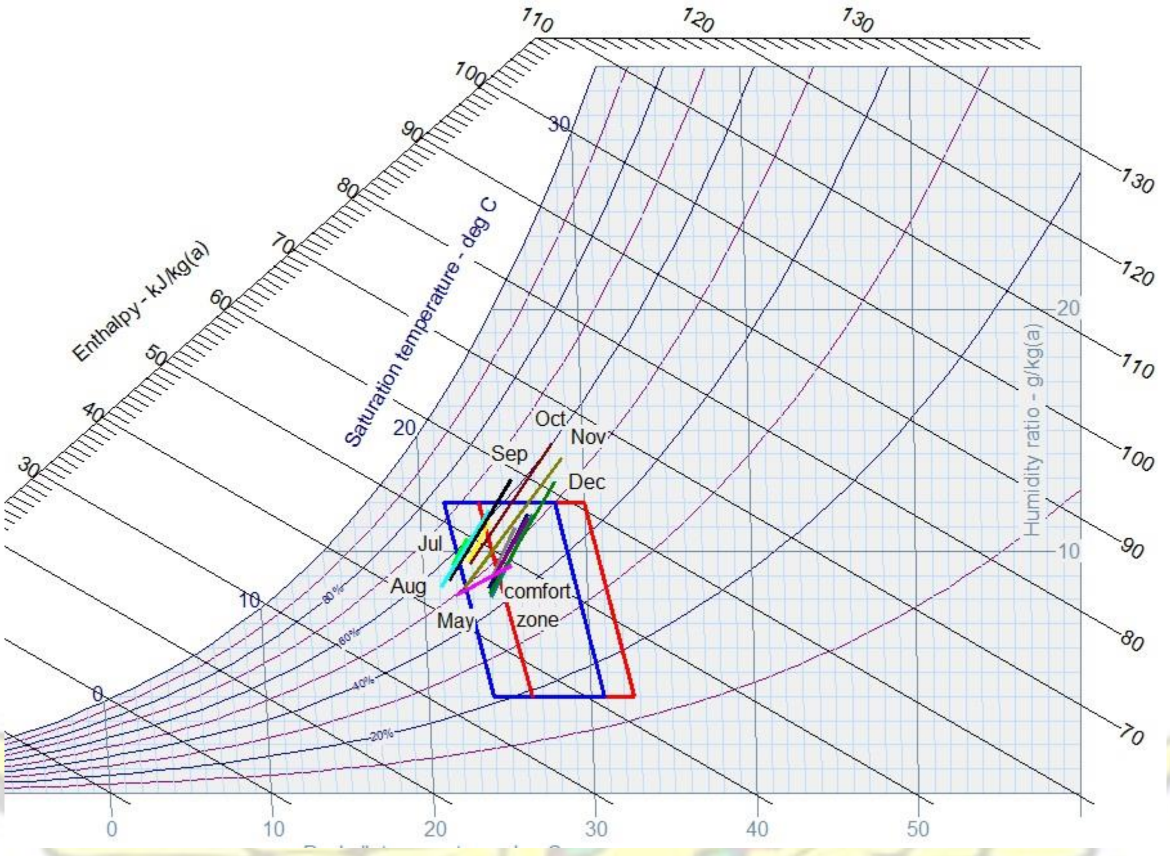


Fig. 4.40: Mean monthly hourly maximum and minimum temperature and relative humidity values in the P.T. offices (measured data from 8am to 5pm)

Based on the measured temperatures alone, the P.T building would be more comfortable. On the average, the temperature values were below 26°C given a clue that most of the occupants considered their indoor climate as comfortable. According to the comfort values recommended for tropical scales: ASHRAE (2004): Ferstl (2005) and Keneally (2002), the P.T building could be said to be comfortable. The reason for this is partly due to the fact that occupants set their airconditioning systems to much lower set points (18°C). Since P.T is an air-conditioning building, there is a better temperature control than could be obtained from opening windows (Darby and White, 2005).

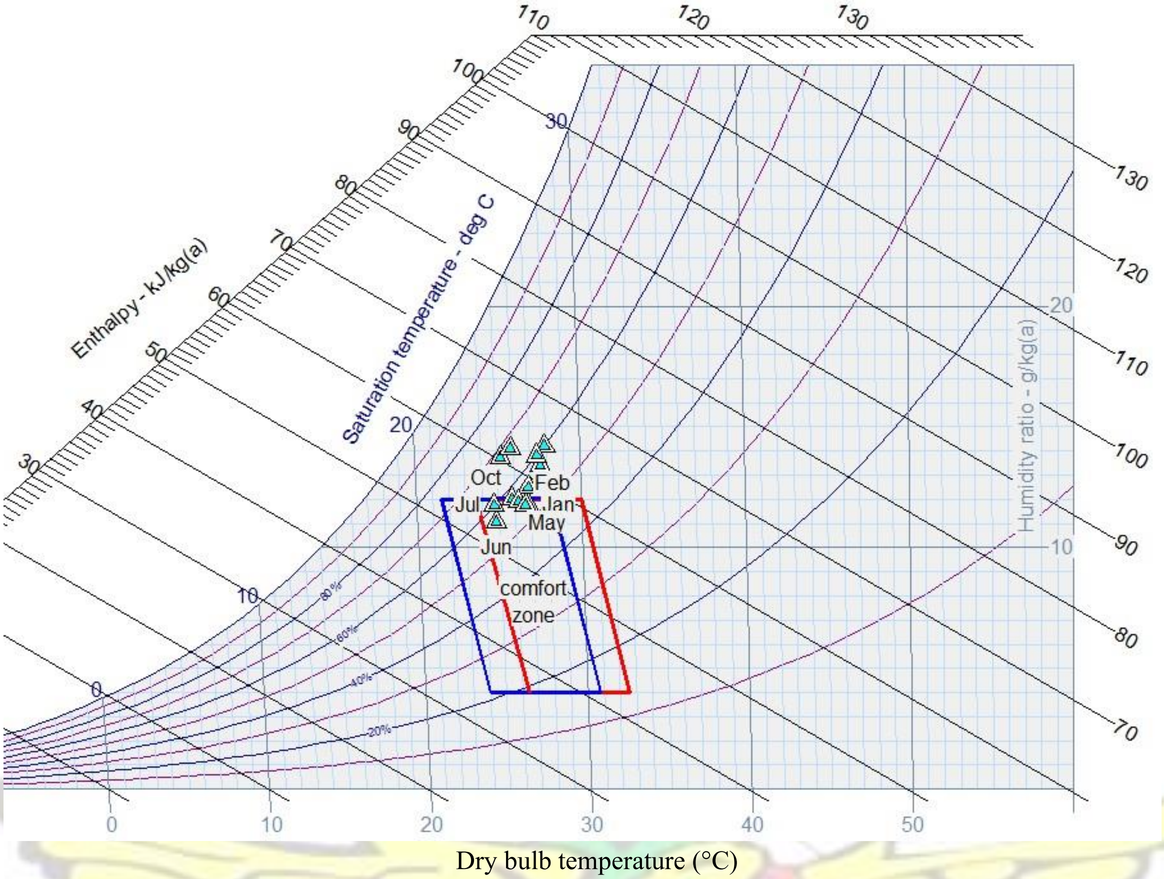
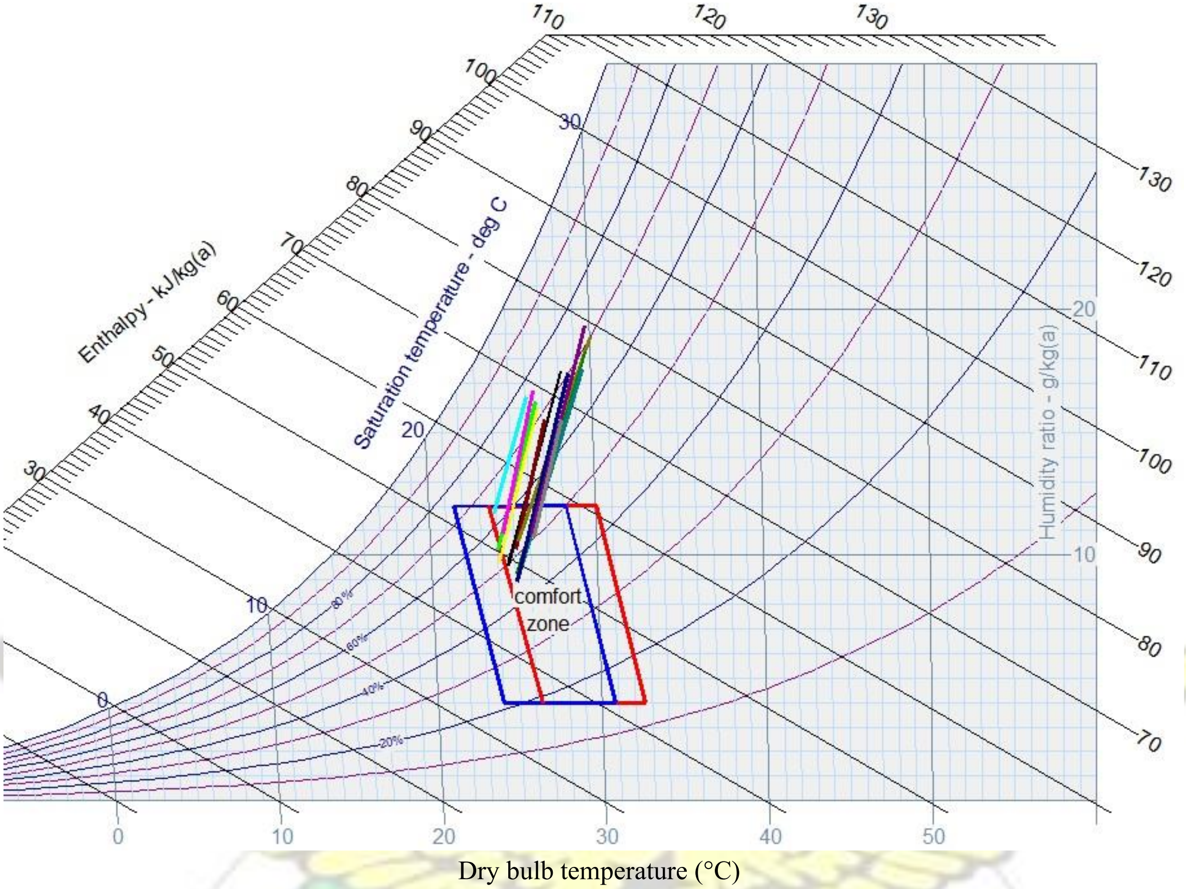


Fig. 4.41: Mean monthly hourly temperature and relative humidity values in the H.T. offices (measured data from 8am to 5pm)

4.3.2.4 H.T. Building

Temperature and relative humidity values for building H.T. offices as presented on the psychrometric chart are illustrated (Figs. 4.41 - 4.42). High mean temperature values were measured within this curtain wall building. The mean monthly hourly temperature and relative humidity values typify uncomfortable office spaces in the months of March, April, September, October, November and December. The mean average temperature value recorded was 26.3°C with relative humidity of 58.8%. Even though the mean monthly hourly temperature values were below 28°C, the high relative humidity values caused the six months to be outside the comfort zone.

Relatively, the maximum temperature and humidity values in the H.T. building are much higher than in the other air-conditioned buildings (R.T. and P.T.).



Dry bulb temperature (°C)

Fig. 4.42: Mean monthly minimum and maximum temperature and relative humidity values of offices in H.T. building (measured data from 8am to 5pm)

Whiles all the mean monthly hourly maximum values were found above the comfort zone, the minimum values were within the comfort zone. The high humidity values accounted for the discomfort nature of the maximum values. The mean maximum temperature value was about 28°C, therefore without considering the effect of relative humidity (Olesen and Brager, 2004), H.T. would still be uncomfortable (Ferstl, 2005: Keneally, 2002). Possible reasons for the behaviour of this building could be its orientation (East-West), sealed/inoperable windows, the efficiency of the air-conditioner being used and the relatively smaller office spaces.

Additionally, the occupants' activities could also have an effect on thermal comfort (Mohammadi, 2007). Other research works (Al-Najem, 2010 and Yu et al., 2008) have the assertion that heat gain through the exterior glazing accounts for 25% - 28% of the total heat gain within a space is substantiated.

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4.3.3 Bioclimatic Chart Results

Based on the Psychrometric results above, bioclimatic analysis was performed on the H.T. and the W.T.C. buildings. Both Olgyay's and Givoni's chart were used to identify the suitable cooling techniques based on the outdoor climatic condition for the two buildings. The results are shown below.

The bioclimatic chart for Accra (Figs. 4.43 – 4.44) identifies the daytime relative humidity to be above 65% throughout the year. Such high humidity values are known to restrict evaporation from the skin and in respiration (Szokolay, 2004). From the design strategy chart (Fig.4.43), comfort ventilation seems to be the option to kerb the effect of the high relative humidity. This finding corroborates Givoni (1998) and Gut (1993) who both concluded that natural ventilation should be promoted to minimize the physiological effect of the high relative humidity and to enhance convective heat loss from the body. As a result, buildings should be designed with wide openings to take advantage of air movement. Figure 4.44 also shows that whiles none of the monthly values fall within the comfort zone, an air velocity range of 0.1m/s to 0.5 m/s could be used to provide comfort. Again, from the design strategy chart, the months of February, March, May, October, November and some part of December may need air-conditioning to provide comfort within Accra.

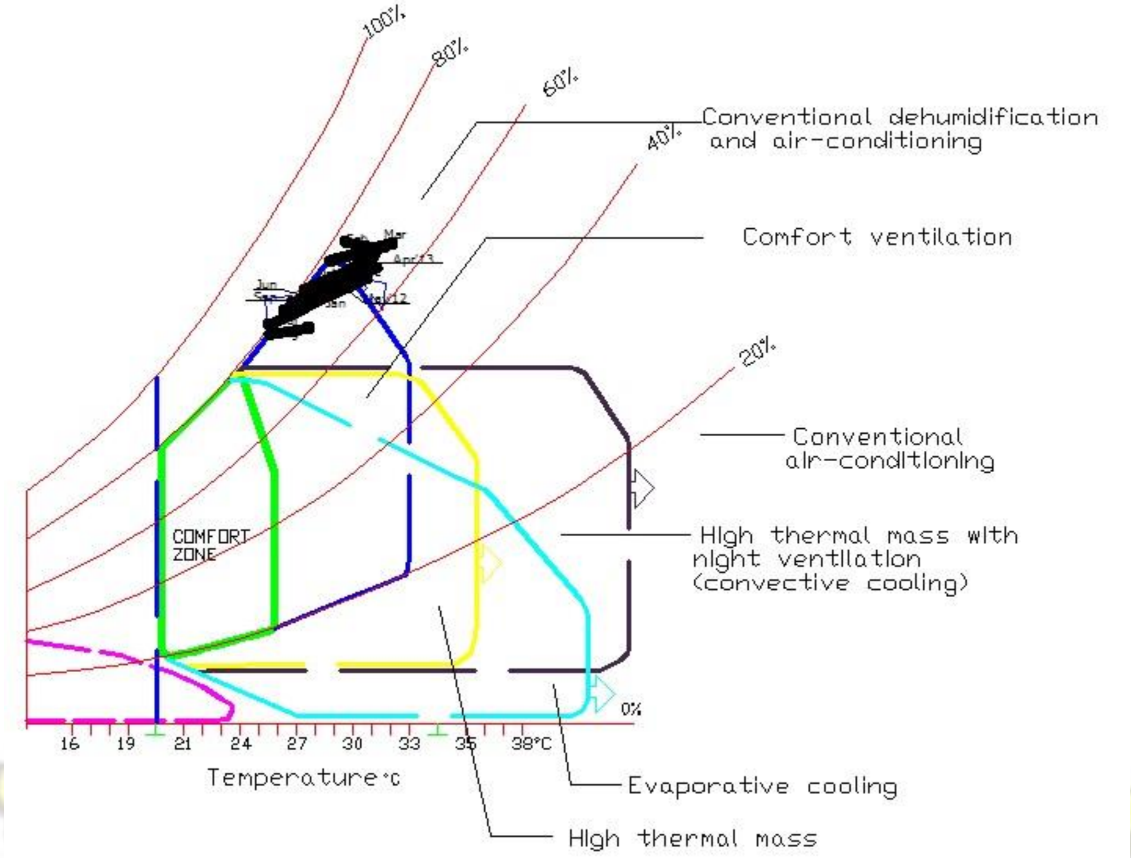

Fig. 4.43: Mean monthly outdoor temperature and relative humidity values in relation to the comfort zone and design strategies for Accra

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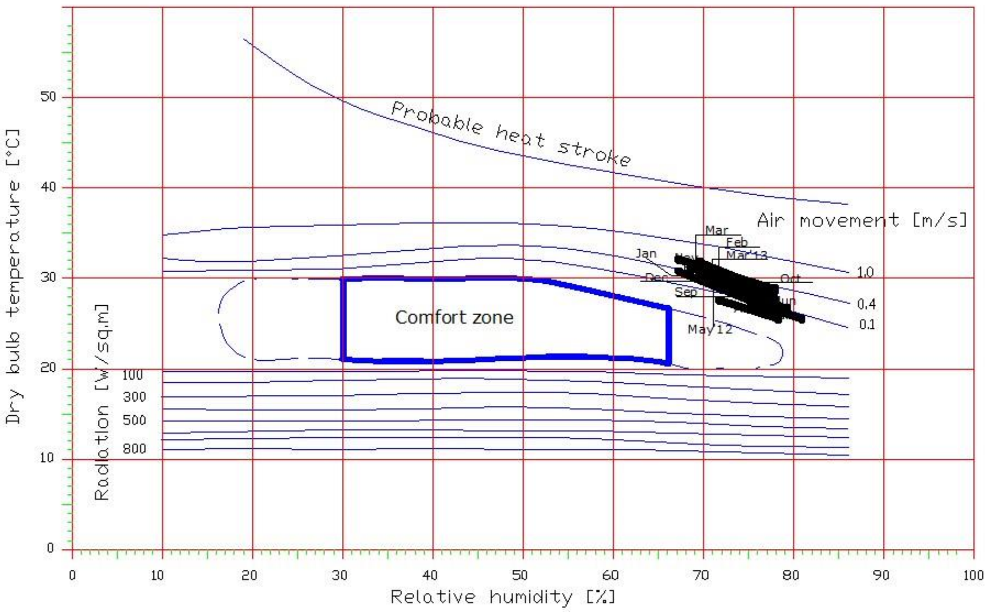

Fig. 4.44: Mean monthly outdoor temperature and relative humidity values in relation to the comfort zone and air-movement for Accra

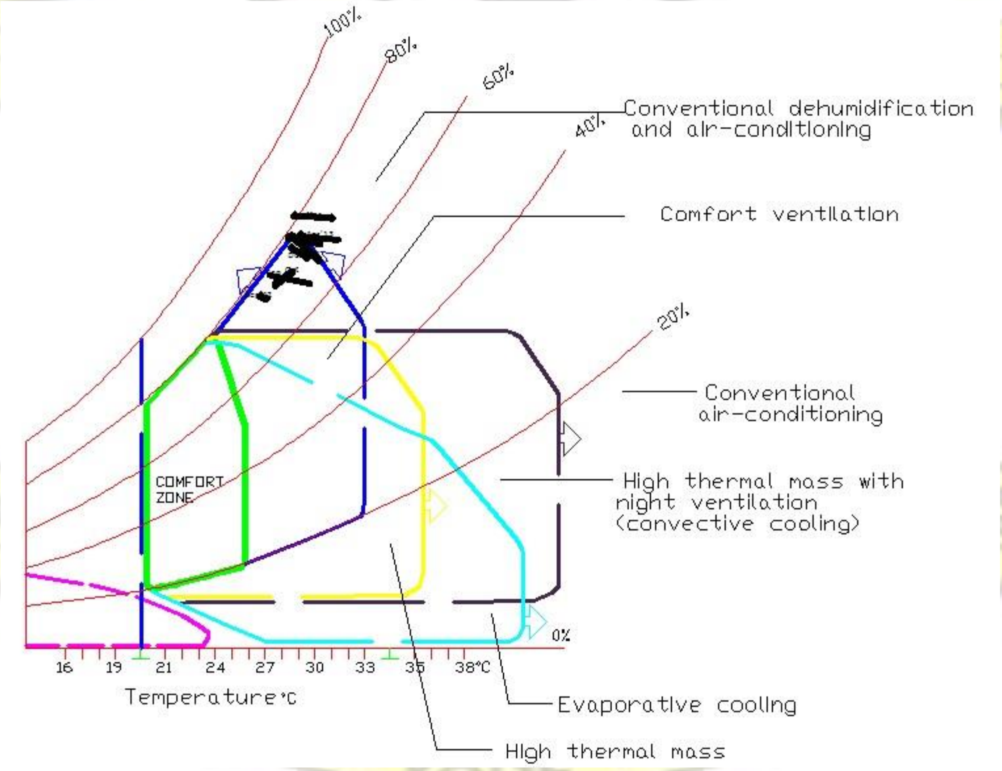

Fig. 4.45: Mean monthly indoor temperature and relative humidity values in relation to the comfort zone and design strategies on Givoni's chart (W.T.C. building)

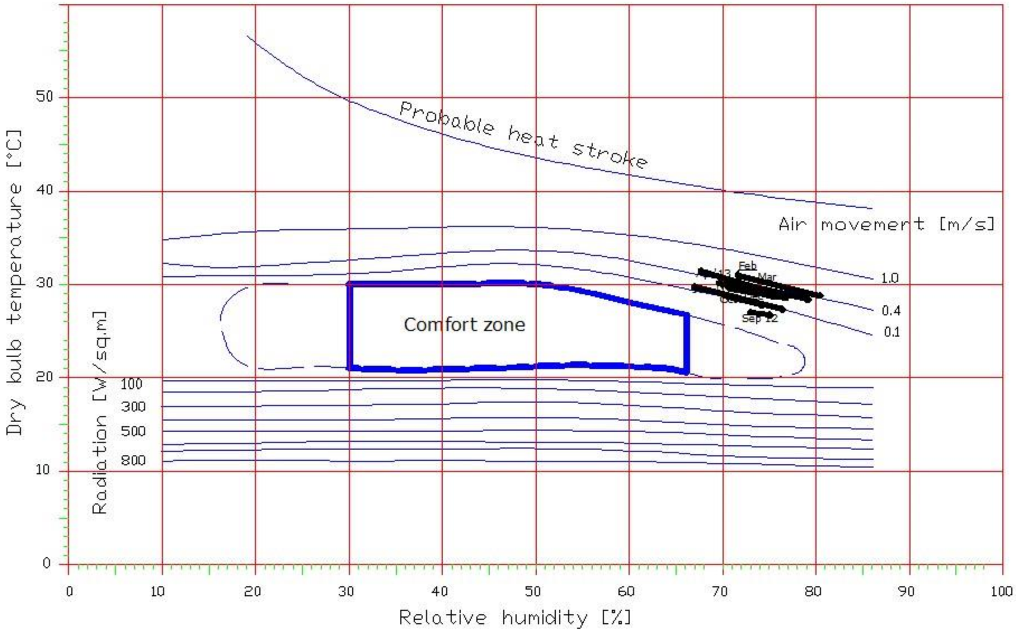

Fig.4.46: Mean monthly indoor temperature and relative humidity values in relation to the comfort zone and air-movement on Olgyay's chart (W.T.C. building)

The thermal performance of the W.T.C. follow similar trend of the outdoor data described above. Temperature and relative humidity values for six months (September, October, November, December, January, and February) fall within the comfort ventilation zone. March and April however, needs to be air-conditioned. Furthermore, an extension of the comfort zone to 0.4m/s air-movement would result in all months falling within the comfort zone. Even though W.T.C. have a balcony shading the windows, the effect of direct and reflected solar radiation could have contributed to the performance of the spaces (Lauber, 2005 and Heerwagen, 2004).

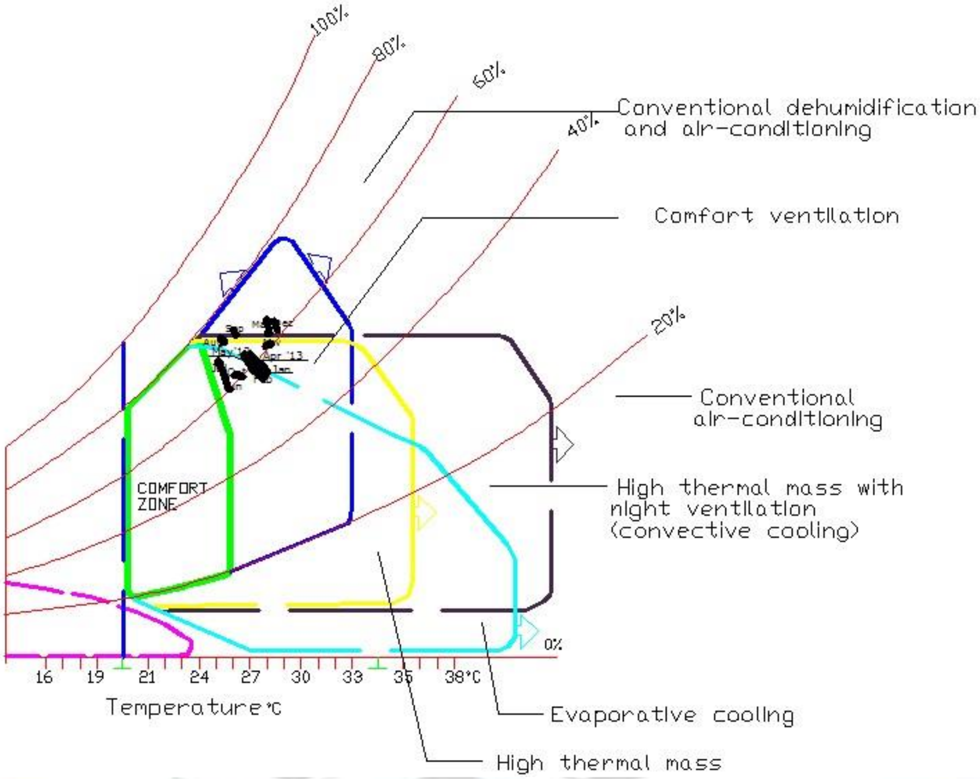

Fig. 4.47: Mean monthly indoor temperature and relative humidity values in relation to the comfort zone and design strategies on Givoni's chart (H.T. building)

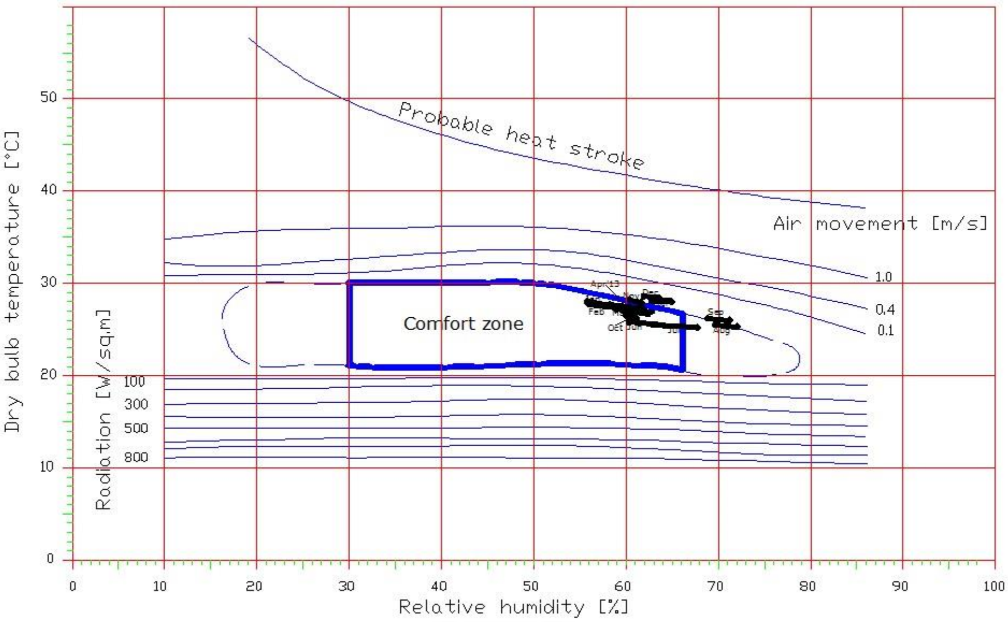

Fig.4.48: Mean monthly indoor temperature and relative humidity values in relation to the comfort zone and air-movement on Olgyay's chart (H.T. building)

Figures 4.47 and 4.48 illustrate thermal conditions within the H.T. building. The results on the Givoni chart (Fig.4.47) show an uncomfortable trend. With fixed/inoperable glazing and no option to naturally ventilate their spaces, occupants find the spaces very uncomfortable. This complaint is corroborated by the Figures illustrated above. With all the months falling outside the comfort zone, various strategies as proposed by Givoni could be used to mitigate the effect of the result. Comfort ventilation, high thermal mass, evaporative cooling, conventional airconditioning and convective cooling could all be employed to relief the discomfort within the spaces. With air-conditioning (AC) setting of between 18 to 21°C, the reasons for the above finding could be that the AC‘s are not efficient. Furthermore, the number of heat producing equipment within the offices could also be a factor. On the contrary, Olgyay‘s bioclimatic chart shows different results. From Fig. 4.48, the months of January, February, June, July, October, April and May are all within the comfort zone whilst with an air velocity of 0.1m/s, the other five months outside the comfort zone (December, March, November, August and September) could be made comfortable. In this assertion, Hyde‘s finding on the use of fans could be brought to bear: To attain comfort, the installation and use of fans (Hyde, 2000) with air velocity of 0.5 m/s would contribute to improving the performance of the spaces.

Moreover, a comfortable and clean indoor environment can be achieved by the adoption of an effective ventilation system, both in terms of providing thermal comfort and removing contaminated air (Alamdari, 1994). It is therefore clear that the inoperable windows are not the best. Occupants should have the option of opening and closing windows even if the building operates on AC‘s (Mahdavi and Orehounig 2009). Moreover, the orientation of the building (East-West) could also be a factor to the negative indoor conditions (Koranteng, 2010).

The most vital strategy would be the use of sustainable design principles of orientation, shading, ventilation, planting, insulation and efficient building materials (Dubois, 2008). In addition, buildings should be able to respond to changes in climate by rejection of solar heat, and have the thermal integrity to maintain internal comfort, despite the influence of climatic forces acting on the building envelope (Salmon, 1999).

4.4 *Objective Three: To come out with energy reduction strategies based on validated models of the selected buildings: thus a design option for multi storey office buildings that is energy efficient.*

4.4.1 Validation Results

In order to make the process of exploring possible measures that could improve the thermal performance of office buildings in Ghana more reliable, the simulated models needed to be validated. This is to make the models match the existing building in order to reduce errors. Since detailed and comprehensive outdoor weather information was not available, segments of a synthetic weather file for Accra (generated via Meteotest 2008) that matched the measurements of outdoor conditions was identified and used. Indoor air temperatures were then simulated using the above mentioned weather file segments and compared to the measured indoor air temperature values.

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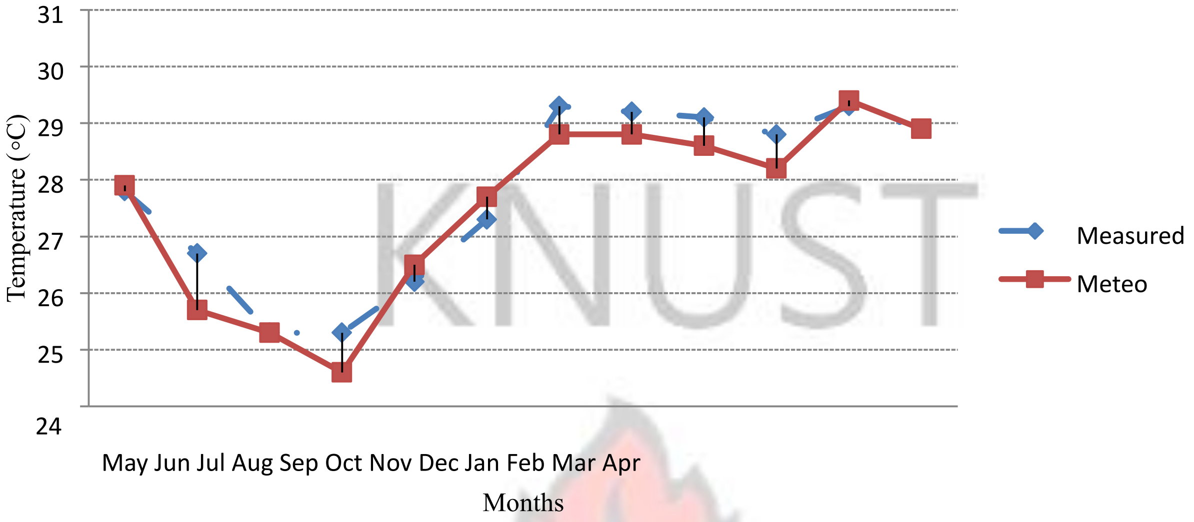

Fig. 4.49: Comparison of mean monthly outdoor temperature measurements at building locations (Measured) with Accra weather station data (Meteorological centre)

The comparison of the outdoor temperature measurements (measured) with the average temperature (Meteorological centre) obtained as the mean of maximum and minimum temperatures recorded by the Accra weather station (Fig.4.49) showed a good agreement between the measurements and those from Accra Meteorological station. The correlation coefficient was 0.92. Therefore, the basis of using the data from the loggers is justified, even though slight differences of between 1- 0.5°C (causes of urban heat island effects) were visible in the months of June, August, November, December, January and February.

4.4.1. a Comparison of Weather file and Measured Data

The simulation validation was performed using segments of a synthetic weather file with a good match to the local measurements. Fig.4.50 to 4.52 show time intervals where the weather file data (WF) and the measurements at building sites (DL) showed a relatively good agreement.

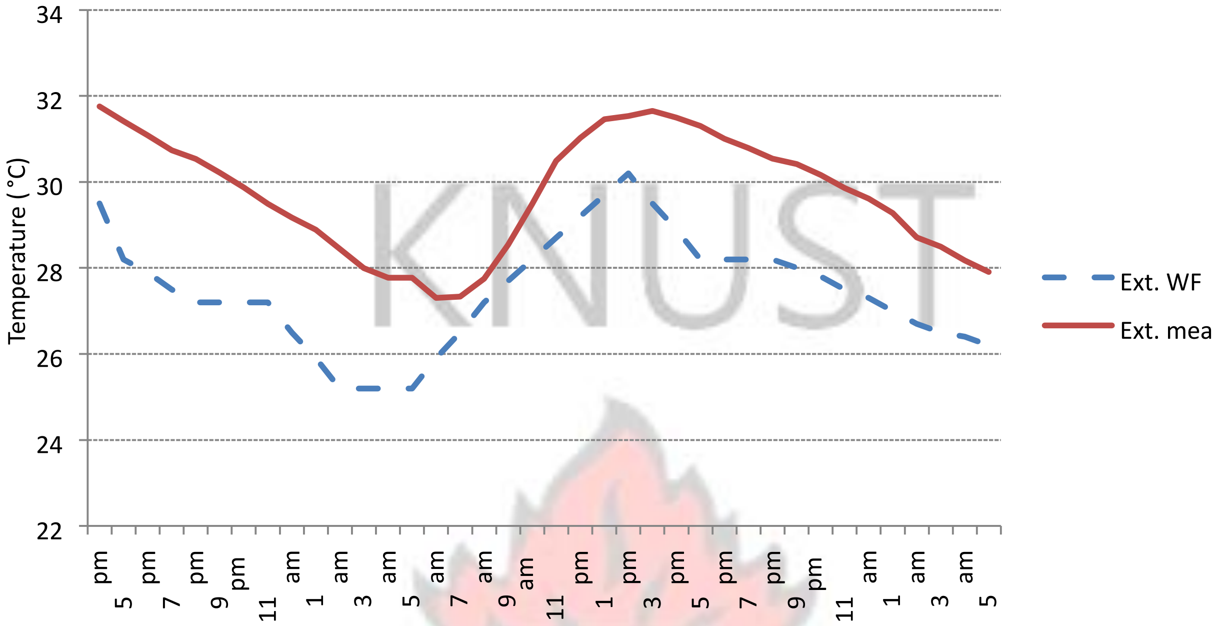

Fig. 4. 50: Outdoor air temperature value from weather file segments (WF) used for simulation validation in comparison with measurements at building location (W.T.C.) $r^2 = 0.74$

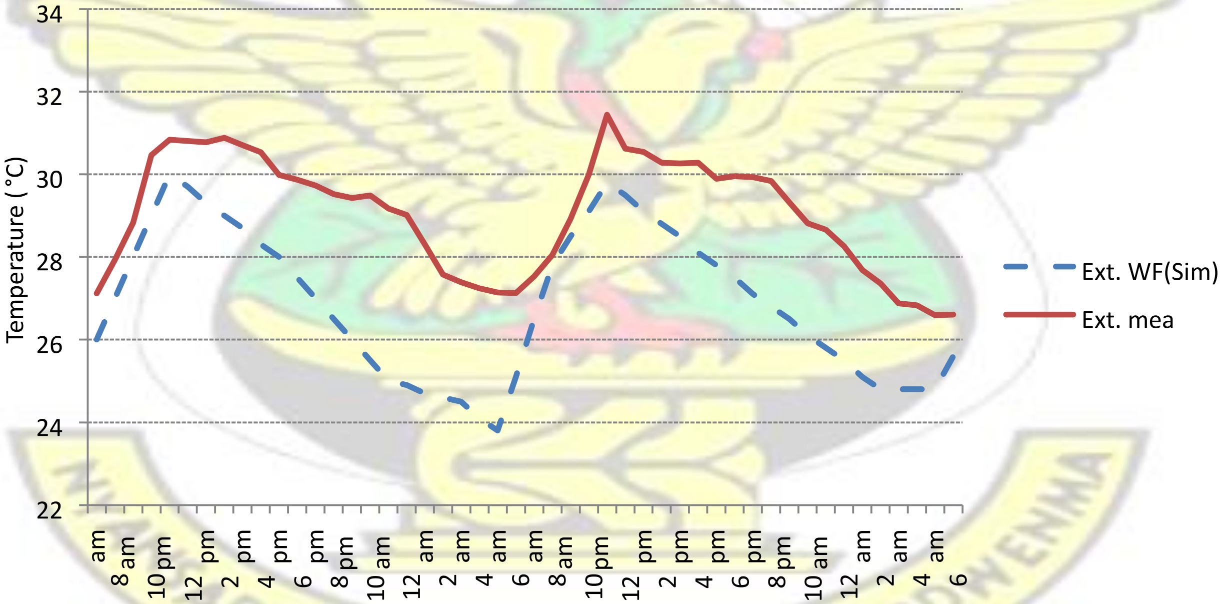

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Fig. 4.51: Outdoor air temperature value from weather file segments (WF) used for simulation validation in comparison with measurements at building location (P.T.) $r^2 = 0.70$

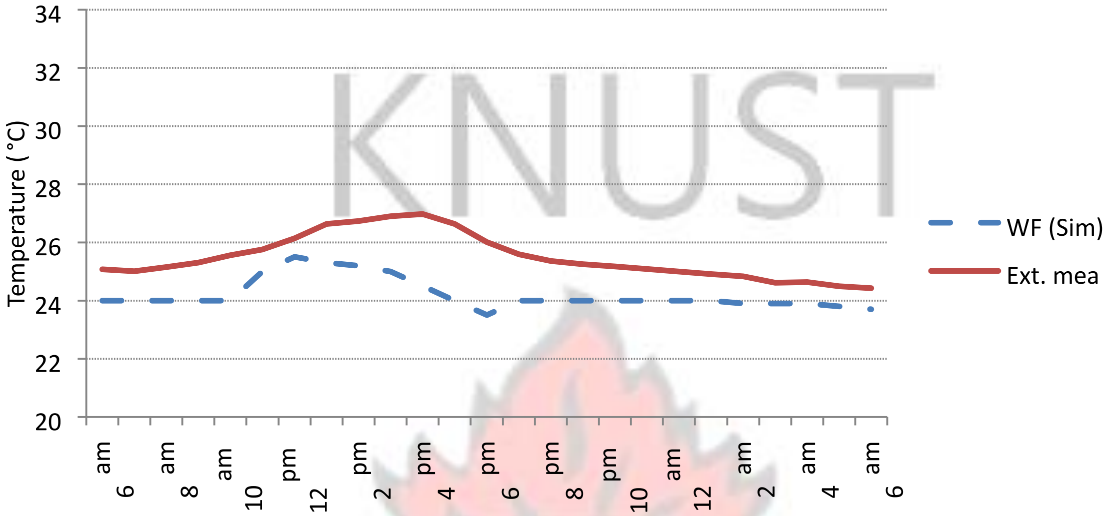

Fig. 4.52: Outdoor air temperature value from weather file segments (WF) used for simulation validation in comparison with measurements at building location (H.T.) $r^2 =0.67$

As already established, simulation model validation was performed using segments of a synthetic weather file with a good match to our local measurements. To illustrate this point, Figs. 4.50 to 4.52 show samples of time intervals where the weather file data (WF) and the measurements at building sites (Ext.mea) showed a relatively good agreement through correlation coefficient values. The _good agreement' is justified since these values were all greater than 0.5 (W.T.C. - 0.74: P.T. – 0.70: H.T. – 0.67). The coefficient of determination ranges from 0 to 1. Consequently, the generated weather file could be used to support the analysis. Though the trend shows the same direction for all the Figures, the seemingly wide difference between the temperature values could be due to the weather file (global warming and urban heat island effects).

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4.4.1. b Comparison of Measurements and Simulation results

To demonstrate the concurrence between the predictions of the validated simulation models and the measured values, Fig.4.53 to 4.55 provide measured versus simulated indoor air temperature values.

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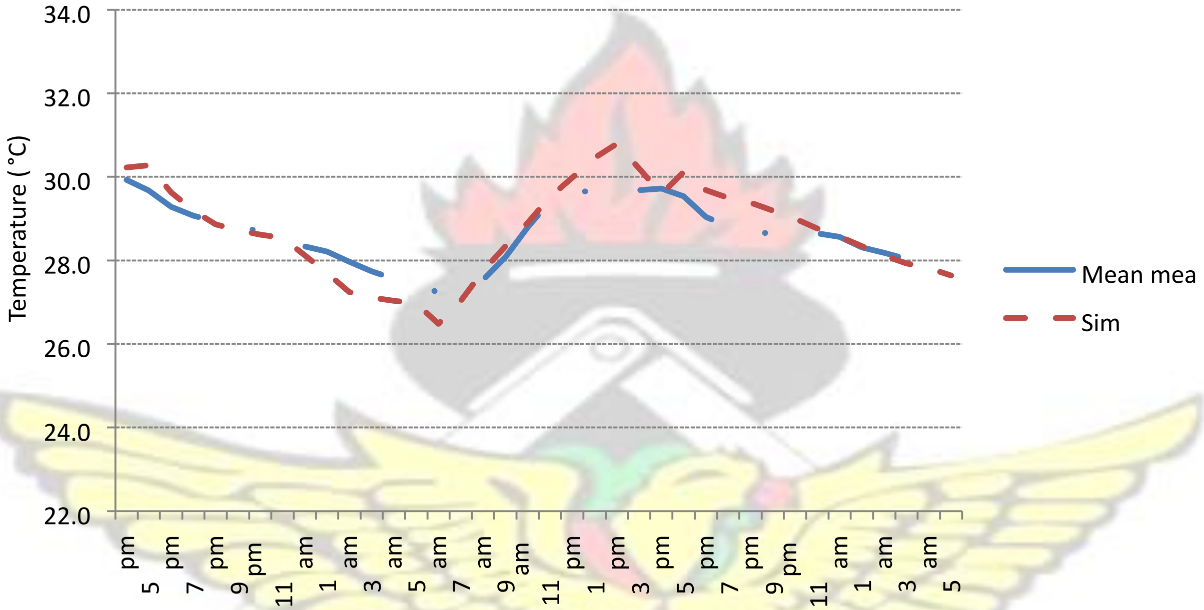

Fig.4.53: Measured versus simulated indoor air temperature values (W.T.C.) $r^2 = 0.92$

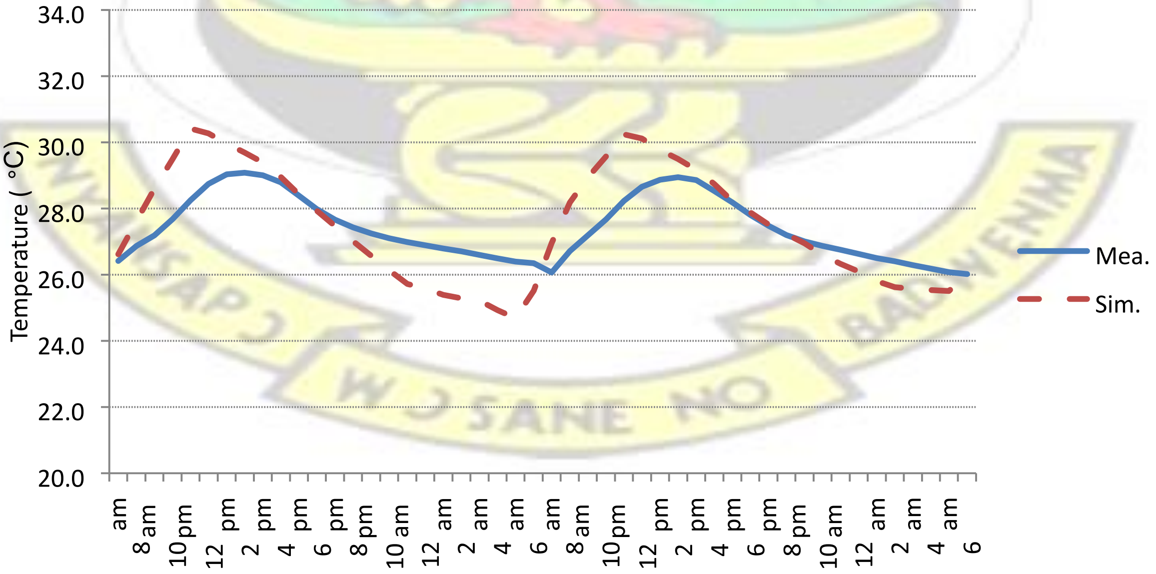

Fig.4.54: Measured versus simulated indoor air temperature values (P.T.) r^2 =0.74

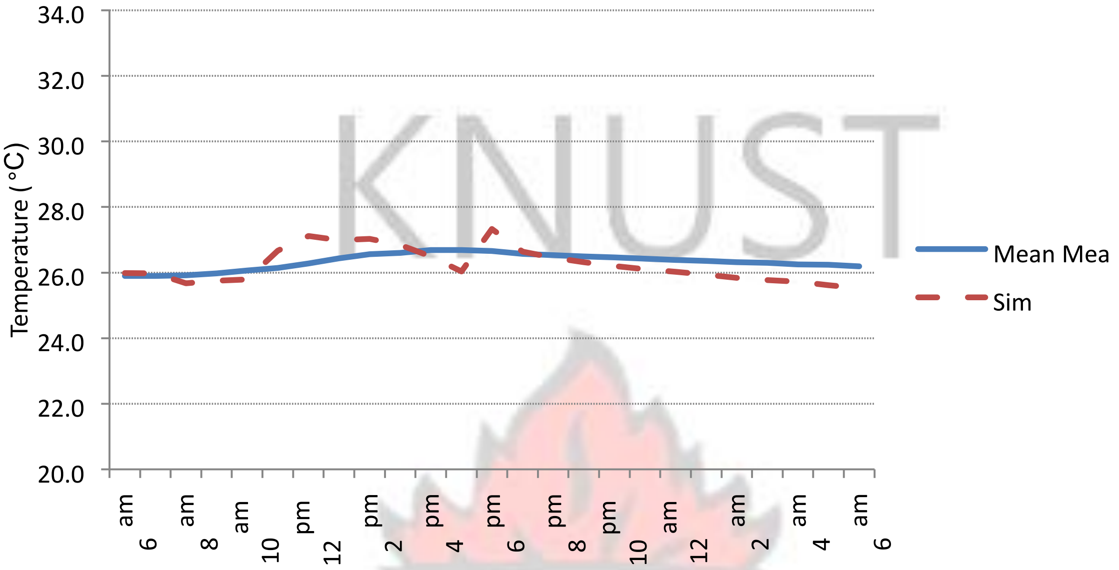

Fig. 4. 55: Measured versus simulated indoor air temperature values (H.T.) r^2 =0.74

Predictions of the validated simulation models compared well with the measured values. To illustrate this, Figs. 4.53 to 4.55 provide measured versus simulated indoor air temperatures. The correlation coefficient values (W.T.C. - 0.92: P.T. – 0.74: H.T. – 0.74) suggest a very good relationship between the measured and simulated values. The comparison of the billed and simulated electric energy for the R.T. also showed an insignificant percentage difference suggesting a good relation between simulated and measured values.

R.T. building was however validated with its monthly electricity consumption (Fig. 4.56). Comparison was made between the billed and simulated electric energy of which the percentage difference was 0.09 (Approximately negligible).

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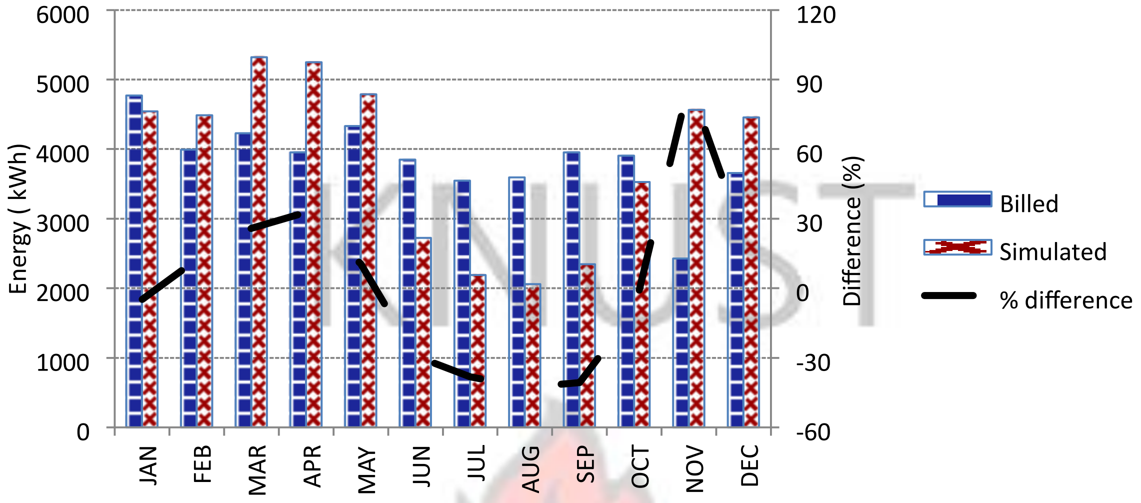

Fig. 4.56: Comparison of billed vs. simulated electric energy (R.T.)

Table 4.5: Monthly Electrical Energy Consumption in the R.T. building

MONTH	Electric Energy in kWh			
	Billed	**Simulated**	**Difference**	
Jan	4769	4542	227	-4,77%
Feb	3991	4485	-494	12,39%
Mar	4227	5319	-1092	25,85%
Apr	3952	5248	-1296	32,78%
May	4330	4786	-456	10,54%
Jun	3847	2722	1125	-29,23%
Jul	3545	2189	1356	-38,26%
Aug	3592	2058	1534	-42,71%
Sep	3952	2344	1608	-40,69%
Oct	3904	3526	378	-9,68%
Nov	2426	4562	-2136	88,05%
Dec	3655	4454	-799	21,87%
Annual	**46,190.00**	**46,235.55**	**46**	**0,09%**

4.4.2 Active scenario results

A summary of the results (annual cooling loads in kWh.m^{-2}.a^{-1}) on the parametric simulation (active case) is presented below in Tables 4.6 to 4.10. The various codes have been defined in Chapter three (page 103 – 108). For further results on the percentage reduction or increase in cooling loads of the individual parameters, see Appendix D. For the description of the codes and the combination of the various scenarios, see Table 3.6 and 3.7- 3.10.

Table 4.6: Base case Cooling Loads for all buildings

Building	R.T.	W.T.C.	P.T.	H.T.
Cooling load (kWh.m-2.a-1)	115.34	149.75	168.44	235.16

Table 4.7: Simulated Annual Cooling Loads for 40 scenarios for building R.T.

Scenario	Cooling Loads (kWh.m-2.a-1)	% Cooling loads (reduction to Base case)	Difference (kWh.m-2.a-1)	% difference
1	**80.77**	**70.0**	**34.57**	**30.0**
2	**80.72**	**70.0**	**34.62**	**30.0**
3	**82.66**	**71.7**	**32.68**	**28.3**
4	**80.9**	**70.1**	**34.44**	**29.9**
5	84.87	73.6	30.47	26.4
6	85.19	73.9	30.15	26.1
7	87.25	75.6	28.09	24.4
8	85.43	74.1	29.91	25.9
9	88.83	77.0	26.51	23.0
10	89.36	77.5	25.98	22.5
11	91.43	79.3	23.91	20.7
12	89.75	77.8	25.59	22.2
13	90.98	79	24.36	21
14	90.19	78.2	25.15	21.8
15	**80.97**	**70.2**	**34.37**	**29.8**
16	88.22	76.5	27.12	23.5

17	83.96	72.8	31.38	27.2

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Table 4. : Simulated Annual Cooling Loads for
7 40 scenarios for building R.T. Cont’d.

Scenario	Cooling Loads (kWh.m^{-2}.a^{-1})	% Cooling loads (reduction to Base case)	Difference (kWh.m^{-2}.a^{-1})	% difference
18	90.54	78.5	24.8	21.5
19	93.28	80.9	22.06	19.1
20	93.05	80.7	22.29	19.3
21	83.52	72.4	31.82	27.6
22	**79.1**	**68.6**	**36.24**	**31.4**
23	83.17	72.1	32.17	27.9
24	99.74	86.5	15.6	13.5
25	91.01	78.9	24.33	21.1
26	**79.79**	**69.2**	**35.55**	**30.8**
27	**80.15**	**69.5**	**35.19**	**30.5**
28	**80.2**	**69.5**	**35.14**	**30.5**
29	96.03	83.3	19.31	16.7
30	94.65	82.1	20.69	17.9
31	88.77	77.0	26.57	23.0
32	98.82	85.7	16.52	14.3
33	87.78	76.1	27.56	23.9
34	**81.75**	**70.9**	**33.59**	**29.1**
35	90.71	78.6	24.63	21.4
36	96.9	84.0	18.44	16.0
37	96.86	84.0	18.48	16.0
38	107.41	93.1	7.93	6.9
39	91.47	79.3	23.87	20.7
40	102	88.4	13.34	11.6

Table 4.8: Simulated Annual Cooling Loads for 40 scenarios for building W.T.C.

Scenario	Cooling Loads (kWh.m^{-2}.a^{-1})	% Cooling loads (reduction to Base case)	Difference (kWh.m^{-2}.a^{-1})	% difference
1	**79.2**	**52.9**	**70.55**	**47.1**
2	**80.75**	**53.9**	**69**	**46.1**
3	83.9	56.0	65.85	44.0

Table 4. : Simulated Annual Cooling Loads for

4	**80.22**	**53.6**	**69.53**	**46.4**
5	90.04	60.1	59.71	39.9
6	92.07	61.5	57.68	38.5

8 40 scenarios for building W.T.C. Cont'd.

Scenario	Cooling Loads (kWh.m-2.a-1)	% Cooling loads (reduction to Base case)	Difference (kWh.m-2.a-1)	% difference
7	89.35	59.7	60.4	40.3
8	92.04	61.5	57.71	38.5
9	101.34	67.7	48.41	32.3
10	96.93	64.7	52.82	35.3
11	101.32	67.7	48.43	32.3
12	104.22	69.6	45.53	30.4
13	103.04	68.8	46.71	31.2
14	94.16	62.9	55.59	37.1
15	117.53	78.5	32.22	21.5
16	98.2	65.6	51.55	34.4
17	82.69	55.2	67.06	44.8
18	105.74	70.6	44.01	29.4
19	123.28	82.3	26.47	17.7
20	**78.51**	**52.4**	**71.24**	**47.6**
21	116.34	77.7	33.41	22.3
22	**76.94**	**51.4**	**72.81**	**48.6**
23	**77.44**	**51.7**	**72.31**	**48.3**
24	88.63	59.2	61.12	40.8
25	107.45	71.8	42.3	28.2
26	88.77	59.3	60.98	40.7
27	85.52	57.1	64.23	42.9
28	107.25	71.6	42.5	28.4
29	84.52	56.4	65.23	43.6
30	**75.98**	**50.7**	**73.77**	**49.3**
31	**77.29**	**51.6**	**72.46**	**48.4**
32	124.59	83.2	25.16	16.8
33	87.56	58.5	62.19	41.5
34	**78.86**	**52.7**	**70.89**	**47.3**
35	81.08	54.1	68.67	45.9

Table 4. : Simulated Annual Cooling Loads for

36	104.07	69.5	45.68	30.5
37	126.25	84.3	23.5	15.7
38	81.05	54.1	68.7	45.9
39	**80.72**	**53.9**	**69.03**	**46.1**
40	86.4	57.7	63.35	42.3

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9 40 scenarios for building P.T.

Scenario	Cooling Loads (kWh.m-2.a-1)	% Cooling loads (reduction to Base case	Difference (kWh.m-2.a-1)	% difference
1	**115.36**	**68.5**	**53.08**	**31.5**
2	116.71	69.3	51.73	30.7
3	**113.45**	**67.4**	**54.99**	**32.6**
4	**113.37**	**67.3**	**55.07**	**32.7**
5	121.17	71.9	47.27	28.1
6	122.7	72.8	45.74	27.2
7	119.11	70.7	49.33	29.3
8	117.94	70.0	50.5	30.0
9	**115.62**	**68.6**	**52.82**	**31.4**
10	115.69	68.7	52.75	31.3
11	129.43	76.8	39.01	23.2
12	131.12	77.8	37.32	22.2
13	127.32	75.6	41.12	24.4
14	**113.45**	**67.4**	**54.99**	**32.6**
15	121.65	72.2	46.79	27.8
16	133.04	79.0	35.4	21.0
17	119.84	71.1	48.6	28.9
18	127.37	75.6	41.07	24.4
19	**115.63**	**68.6**	**52.81**	**31.4**
20	127.97	76.0	40.47	24.0
21	125.19	74.3	43.25	25.7
22	129.09	76.6	39.35	23.4
23	**113.66**	**67.5**	**54.78**	**32.5**
24	122.1	72.5	46.34	27.5
25	127.39	75.6	41.05	24.4
26	117.23	69.6	51.21	30.4

Table 4. : Simulated Annual Cooling Loads for

27	127.38	75.6	41.06	24.4
28	**115.92**	**68.8**	**52.52**	**31.2**
29	123.93	73.6	44.51	26.4
30	121.95	72.4	46.49	27.6
31	**115.63**	**68.6**	**52.81**	**31.4**
32	116.79	69.3	51.65	30.7
33	117.13	69.5	51.31	30.5
34	119.33	70.8	49.11	29.2

9 40 scenarios for building P.T. Cont'd

Scenario	Cooling Loads (kWh.m$_{-2}$.a$_{-1}$)	% Cooling loads (reduction to Base case	Difference (kWh.m$_{-2}$.a$_{-1}$)	% difference
35	139.17	82.6	29.27	17.4
36	**115.63**	**68.6**	**52.81**	**31.4**
37	121.47	72.1	46.97	27.9
38	122.66	72.8	45.78	27.2
39	122.77	72.9	45.67	27.1
40	121.73	72.3	46.71	27.7

Table 4.10: Simulated Annual Cooling Loads for 40 scenarios for building H.T.

Scenario	Cooling Loads (kWh.m$_{-2}$.a$_{-1}$)	% Cooling loads (reduction to Base case)	Difference (kWh.m$_{-2}$.a$_{-1}$)	% difference
1	161.85	68.8	73.31	31.2
2	**155.21**	**66.0**	**79.95**	**34.0**
3	**155.87**	**66.3**	**79.29**	**33.7**
4	168.07	71.5	67.09	28.5
5	160.83	68.4	74.33	31.6
6	161.77	68.8	73.39	31.2
7	173.14	73.6	62.02	26.4
8	166.8	70.9	68.36	29.1
9	167.68	71.3	67.48	28.7
10	**155.75**	**66.2**	**79.41**	**33.8**
11	161.03	68.5	74.13	31.5
12	156.56	66.6	78.6	33.4

Table 4. : Simulated Annual Cooling Loads for

13	167.39	71.2	67.77	28.8
14	160.29	68.2	74.87	31.8
15	161.5	68.7	73.66	31.3
16	**155.71**	**66.2**	**79.45**	**33.8**
17	**155.46**	**66.1**	**79.7**	**33.9**
18	161.08	68.5	74.08	31.5
19	**156.2**	**66.4**	**78.96**	**33.6**
20	**155.93**	**66.3**	**79.23**	**33.7**
21	**155.58**	**66.2**	**79.58**	**33.8**

Table 4.

10: Simulated Annual Cooling Loads for 40 scenarios for building H.T. Cont'd.

Scenario	Cooling Loads (kWh.m$_{-2}$.a$_{-1}$)	% Cooling loads (reduction to Base case)	Difference (kWh.m$_{-2}$.a$_{-1}$)	% difference
22	166.87	71.0	68.29	29.0
23	161.6	68.7	73.56	31.3
24	161	68.5	74.16	31.5
25	167.43	71.2	67.73	28.8
26	171.72	73.0	63.44	27.0
27	167.05	71.0	68.11	29.0
28	162.47	69.1	72.69	30.9
29	160.54	68.3	74.62	31.7
30	165.65	70.4	69.51	29.6
31	**154.2**	**65.6**	**80.96**	**34.4**
32	160.15	68.1	75.01	31.9
33	156.2	66.4	78.96	33.6
34	172.03	73.2	63.13	26.8
35	163.95	69.7	71.21	30.3
36	162.78	69.2	72.38	30.8
37	156.56	66.6	78.6	33.4
38	162.33	69.0	72.83	31.0
39	159.68	67.9	75.48	32.1
40	**155.7**	**66.2**	**79.46**	**33.8**

Figures 57-60 show the ten scenarios for each building that best reduce the base case cooling loads with their associated percentage reductions.

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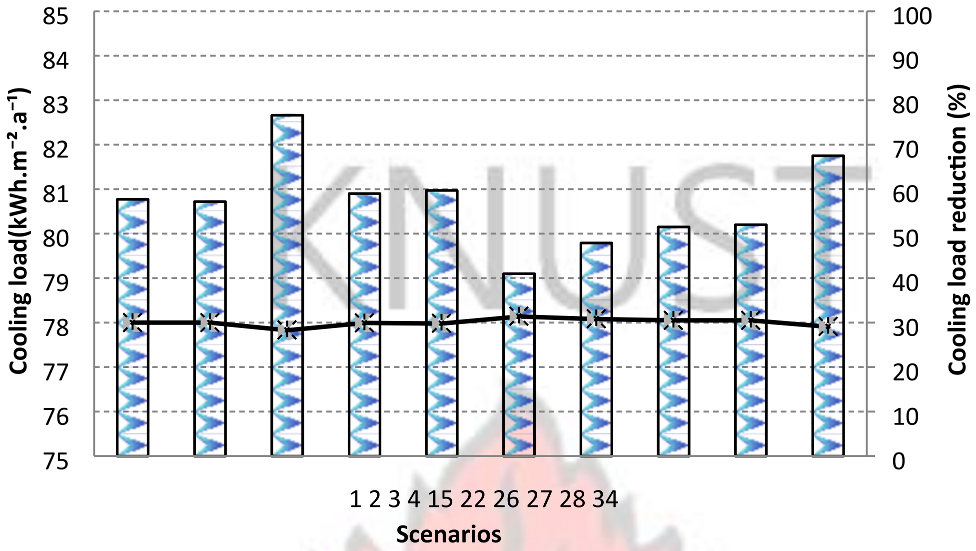

Fig. 4.57: R.T.'s simulated annual cooling loads (kWh.m^{-2}.a^{-1}) for the ten best scenarios and their percentage reduction

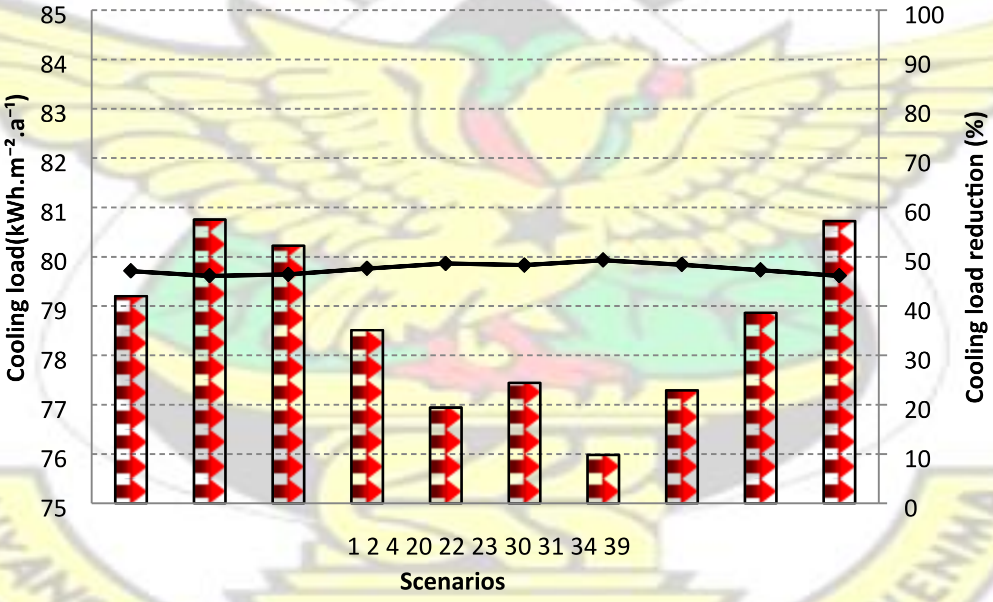

Fig. 4.58: W.T.C.'s simulated annual cooling loads (kWh.m^{-2}.a^{-1}) for the ten best scenarios and their percentage reduction

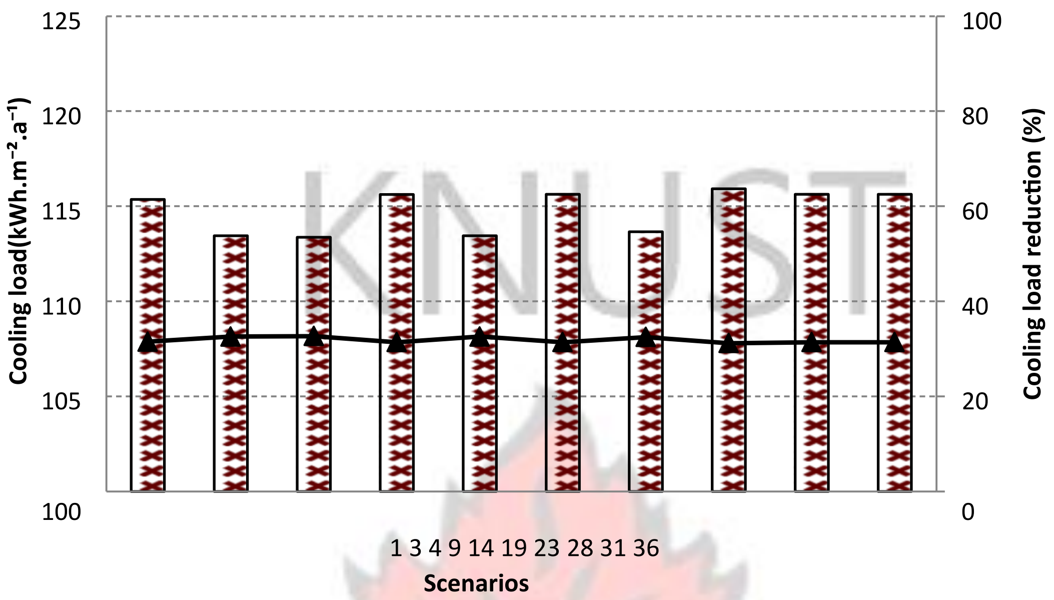

Fig. 4.59: P.T.'s simulated annual cooling loads (kWh.m^{-2}.a^{-1}) for the ten best scenarios and their percentage reduction

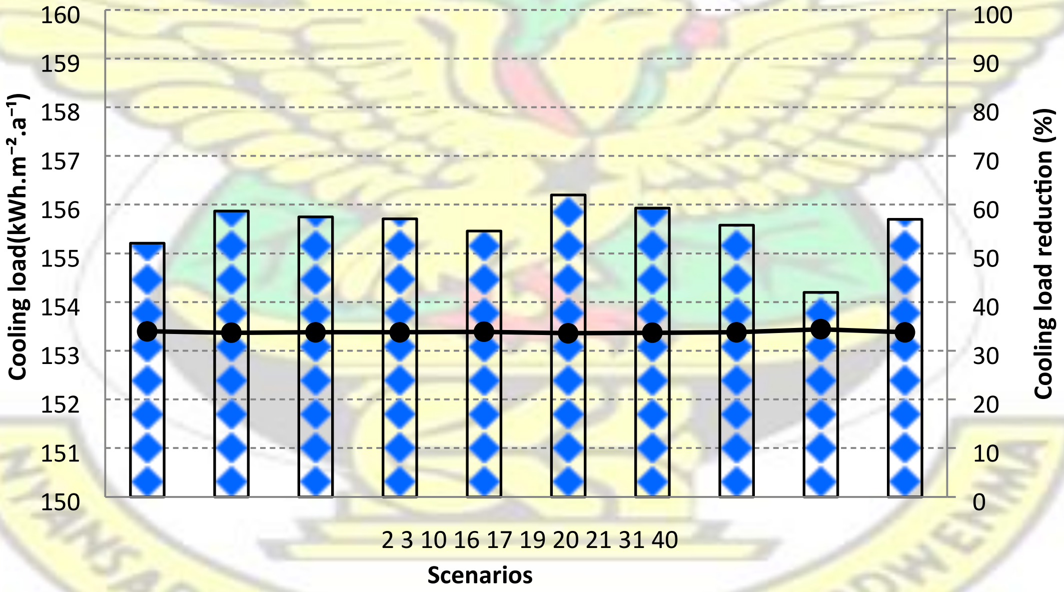

Fig. 4.60: H.T.'s simulated annual cooling loads (kWh.m^{-2}.a^{-1}) for the ten best scenarios and their percentage reduction

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4.4.3 Active case discussion

The results above describe the parametric simulation study (case the active scenario). They contain the base case simulation results and tested improvement scenarios towards the reduction of cooling loads (Tables 3.7 to 3.10). These are discussed from building to building.

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4.4.3.1 R.T. Building

The R.T. building is relatively juxtaposition of squares, oriented towards the north-south with north-west glazing positions. The total simulated annual cooling load for the base case (BC, Table 4.6) was 115.34kWh.$m^{-2}.a^{-1}$. The probed alternative of a more efficient glazing type with a better shading coefficient (0.3) resulted in a significant reduction of the base case cooling loads by 14.1% (See Appendix A). The effect was that only 30% of radiation could be transmitted through the glass as compared to the 50% at the base case scenario (Table 3.5).

By using more efficient lighting systems, cooling loads could be reduced by 4%. This corroborates studies which have concluded that lighting gains has a positive effect on cooling loads (Yufan and Hassim, 2011: Galasiu and Veitch, 2006)

Night ventilation could reduce the base case cooling loads by as much as 11% - 13% (Appendix D, Table 1) depending on the time of the night. Though $NV_{m.1}$ (6pm to 6am) reduced cooling loads considerably (12.9%), $NV_{m.2}$ (9pm to 6am) was found to be effective since the percentage reduction between the two was 0.7%.

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An increase in the building's thermal mass as simulated via the virtual removal of the floor carpeting and ceiling panels however led to a 3.2% increase in the base case cooling loads. This outcome could be related to the cooling effects being used up rapidly in the building.

Different external blind deployment times also led to the reduction of cooling loads by 2.3 to 5.2%. The position of the glazing was also considered for the blind deployments.

The introduction of an insulation material of both 5cm and 10cm to the building's external façade, all resulted in an increase in cooling loads (0.2 to 1% increase).

All the various improvements combined to form scenarios did reduce the base case cooling loads extensively (Table 4.7) as compared to literature (Koranteng, 2010). The best ten scenarios did reduce cooling loads by 28.3 to 31.4% with scenario 22 reducing cooling loads by the highest percentage. This result is significant and has been achieved through improved and efficient building elements, as well as sustainable design principles.

4.4.3.2 W.T.C. Building

The base case cooling load of the rectangular block was 149.75 $kWh.m^{-2}.a^{-1}$. The building is oriented towards the north-west and south-east with a veranda shading the north-west part of the elongated sides. It's naturally ventilated on the 15th floor.

As much as 7.1% reduction was simulated when efficient lighting was used (See Appendix D: Table 2). Different time modes for night ventilation recorded percentage reductions from 6.6 % (12am -6am) to as much as 9.2% (6pm- 6am). Thermal mass reduced cooling loads by 4.6%, a

1.4% higher than that of the R.T. building. A combination of thermal mass and night ventilation led to a significant decrease in cooling loads of 13.5%.

Various glazing options were simulated to find one that considerably reduced the base case loads. This led to cooling load reductions from 9% to 26.6%. Such high percentage could be due to the shading that is provided by the verandah. According to Al-Tamimi et al. (2011), reducing the glazing to wall ratio helps reduce the cooling loads. A proper selection for the optimal area of the glass and applying natural ventilation system can reduce the negative effect of solar radiation in increasing the indoor air temperature (Al-Tamimi and Fazil, 2010).

The use of external blinds at the south-east area from 1pm to 5pm did reduce cooling loads by 7.6% whiles from 2pm to 5pm also reduced the loads by 6.5%. In terms of form and orientation (Rilling, 2007) the W.T.C. performs better than the R.T. Adding insulation to the façade (5cm/10cm) reduced the cooling loads by 4.3%. This result could be due to the orientation of the building and also the tightness of the envelope (Koranteng, 2010). The result also agrees with Lauber‘s (2005) recommendation of using façade insulation to reduce cooling loads. This assertion however does not work for all buildings.

The total reduction in cooling loads by the combination of the various parameters led to ten scenarios reducing cooling loads by as much as 46.1% to 49.3%. With the provision of shading by the verandah, and the right orientation and aspect ratio, the W.T.C. with efficient lighting, better glazing, night ventilation, façade insulation and thermal mass the cooling loads could be reduced by as much as 49.3%. W.T.C. could perform better if all the various parameters are adhered to. Designers are advised to make use of the positive effects of the natural environment, transform the environmental burden and use the building as the basis of its defense before the implementation of active control devices (Heerwagen 2004).

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4.4.3.3 H.T. Building

The rectangular block oriented towards north-east and south-west had an original cooling load of 235.16 kWh.m^2.a^1.

Different glazing types were explored. Single glazed window with a solar heat gain coefficient of 0.18 and a u-value of 5.7 recorded a 25.4% reduction in cooling loads. This means that only 18% of radiation could be transmitted through the glass. In comparison with the use of efficient lighting which could reduce the cooling loads by 7.5%, it is recommended that the single glazing could be used (for medium height buildings, for very tall buildings, the high wind pressure may need double glazing) and the effect of it (in terms of not so much sunlight into the space) could be complemented by artificial light (energy efficient fixtures).

Building H.T. had the highest base case cooling loads amongst all the case study buildings. It‘s sealed inoperable windows, orientation, high window to wall ratio and no external shading, etc. could account for the high initial cooling loads. Possibly, the loads could have reduced if there was external shading. Other glazing alternatives investigated into resulted in the reduction of the cooling loads by 8.1% to 23.8%. Designing buildings with sealed windows and without reference to solar orientation, with high standards of comfort but without reference to operating costs, with the newest technology but without much sense of what tomorrow might bring must be reconsidered, as the non-sustainable use of resources poses a danger to humanity (Koranteng, 2010). Various night ventilation times also led to a reduction in the base case cooling loads. As much as 6.3% was reduced by the night ventilation time of 12am to 6am. Thermal mass reduced cooling loads by 0.3%. The effect of thermal mass in a hot humid climate as documented by Cheng and Givoni (2008) has not worked so well here. Perhaps, this observation is so because the case study buildings lack the heavy massing that is important for heat transfer in thermal mass (Amos- Abanyie, 2012) and a high diurnal temperature difference (Szokolay, 2004).

Façade insulation applied to the building led to an increase in cooling loads by 6.2% (when the insulation was applied to just one side of the façade) and 7.4% (when the insulation was applied to both sides of the façade). The effect of uncontrolled ventilation or leakage through cracks in the building envelope also leads to increased cooling loads (Carmody 2007).

The total results from the positive combination of the parameters led to major reductions to the base case cooling loads. Percentage reductions of 33.6% to 34.4% was recorded which is equivalent to 156.2 $kWh.m^2.a^1$ to 154.2$kWh.m^2.a^1$ reduction.

4.4.3.4 P.T. Building

The curtain wall building had an initial cooling load of 126.2 $KWh.m^{-2}.a^{-1}$. The alternative improvement of using an efficient glazing reduced the cooling loads by 17.7%. Other glazing types were also explored with different shading coefficient values. Cooling loads were reduced by 4.6% to 15.8%. An efficient lighting gain of $2W/m^2$ led to a decrease in the initial cooling loads by 10.2%. Night ventilation options did reduce cooling loads but inconsequentially (See appendix A). External shading at 11am to 4pm did reduce cooling loads by 5.8%. Whiles façade insulation reduce cooling loads by 1.8% and 1.2% respectively for the 5cm and 10cm insulation material, a combination of façade insulation, night ventilation and thermal mass increase the cooling loads by 1.3%.

The cooling potential of improvement of many of the scenarios considered was significant. Through a combination of building features, cooling loads reductions of 31.2 to 32.7% was simulated and recorded.

4.4.3.5 Summary for all buildings

From the discussion of all the case study buildings, certain interpretations were clear. These are as follows:

i. The installation of more efficient electrical lighting system has a positive effect in reducing the buildings‘ total cooling loads. From the above, cooling loads were reduced in all the buildings by the use of an efficient lighting gains (2W/m^2).

ii. The study revealed that thermal mass, façade insulation, night ventilation (various times) depending on the orientation, form and building elements, have varied effect in reducing the total cooling loads. Through the combination of the building features, the total base case cooling loads for all the buildings were reduced significantly. As compared to the base case, cooling load reductions could reach 31.4% to 49.3%.

iii. The existence and deployment of external shade with proper opening schedules is a major factor of all the better performing scenarios. The top ten performing scenarios amongst the 40 scenarios considered, included external blinds (see Table 3.7 to 3.10).

iv. There was a clear improvement in the initial cooling loads for all the buildings when glazing with higher shading effectiveness (specified via g-value) was considered. From the study, it‘s clear that the u-value does not play a decisive role in reducing the cooling loads. Glazing type $G_{0.3}$, which has a low g-value but a high u-value was the glazing used in the top performing scenarios (R.T, W.T.C. and P.T.). As in this case, the visual transmittance is not too low (0.3) and therefore daylight usage potential (reduction in electric energy for lighting) is not compromised.

v. From the study, it was also observed that the double glazing performs better than the single glazing. A single glazed window of $G_{0.18}$ led to a reduction in cooling loads by 25.4% whiles a double glazing of $G_{0.3}$ reduced cooling loads by 26.6%. This could be due to the insulation gas between the panes (aside their u-values).

vi. Increased night time ventilation also led to a reduction in the initial cooling loads for all the buildings though the decreases were all below 10% except for the R.T. building. This could be due to the rather small diurnal temperature range in Ghana: the night temperature does not drop low enough to effectively cool the building mass.

vii. Previous studies conducted with low-rise office buildings in Kumasi (Koranteng, 2010) led to summary cooling load reduction of 20% to 35%. The difference in glazing, location, building typology, orientation, internal conditions, etc. could have accounted for the difference.

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viii. Insulating the façade of a building does not always lead to a decrease in the cooling loads of the building. From the study, it was observed that only W.T.C. and P.T. had their initial cooling loads reduced by insulating the façade albeit these reductions were modest. This condition can occur in buildings that are cooling load dominated and are related to the heat retaining effect of better-insulated walls.

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4.4.4 Energy Calculations

The energy used for each base case scenario was calculated as well as the best reduction scenario. The calculation was based on the current unit cost of electricity which was multiplied by the total cooling loads each building consumed.

Table 4.11: Estimated Annual Energy use for all buildings

Buildings	Floor area (m^2) [A]	Cooling load (BC), ($kWh.m^{-2}.a^{-1}$) [B]	Cooling load (BS), ($kWh.m^{-2}.a^{-1}$) [B^1]	Efficiency of cooling systems [C]	Annual energy use (BC), (kWh) [A x B x C] [F]	Annual energy use (BS), (kWh) [A x B^1 x C] [G]
R.T.	204	115.34	79.10	2.60	61,176.34	41,954.60
W.T.C.	280	149.75	75.98	2.60	109,018.00	55,313.44
P.T.	300	168.44	113.37	2.60	131,383.20	88,428.60
H.T.	210	235.16	154.20	2.60	128,397.36	84,193.20
Total	**-**	**668.69**	**422.65**	**-**	**429,974.90**	**269,889.84**

Table 4.12: Estimated Annual Energy Savings for all buildings (GHC)

Buildings	Unit energy cost [GHC] (E)	Annual energy cost (BC) [GHC] (E x F) [H]	Annual energy cost (BS) [GHC] (E x G) [J]	Annual energy savings [GHC] (H – J)	Annual energy savings [kWh] (F – G)
R.T.	9.84	601,975.19	412,833.26	189,141.93	19,221.74
W.T.C.	9.84	1,072,737.12	544,284.25	528,452.87	53,704.56
P.T.	9.84	1,292,810.69	870,137.42	422,673.27	42,954.60

H.T.	9.84	1,263,430.02	828,461.09	434,968.93	44,204.16
Total	**-**	**4,230,953.02**	**2,655,716.03**	**1,575,236.99**	**160,085.06**

Table 4.13: Estimated Annual Energy Savings for all buildings (USD)

Buildings	**Unit energy cost (BS) savings [Dollars] (F – G) [H]**	**Annual energy cost savings [kWh] (E) [J]**	**Annual energy [Dollars]* (E x F)**	**Annual energy energy [Dollars] (E x G)**	**Annual cost of (BC) [Dollars] (H – J)**
R.T.	3.1	189,646.65	130,059.26	59,587.39	19,221.74
W.T.C.	3.1	337,955.80	171,471.66	166,484.14	53,704.56
P.T.	3.1	407,287.92	274,128.66	133,159.26	42,954.60
H.T.	3.1	398,031.82	260,998.92	137,032.90	44,204.16
Total	**-**	**1,332,922.19**	**836,658.50**	**496,263.69**	**160,085.06**

Where: BC denotes Base case

BS denotes Best Scenario

*the cedi to dollar conversion as at 17/09/14. Bank of Ghana rate: GHC 3.2 = USD 1

The estimated energy use of the case study buildings have been calculated and presented (see Table 4.11 and 4.12). These calculations have been done for both the base case (BC) and the best improvement scenarios (BS). The efficiency of the split unit air-condition systems (LGE 2008) were factored into the calculation of the annual energy use.This was multiplied by the cooling loads per kilo Watt hour and the total area of the floor studied. It is estimated that in a year, 429,974.90kWh of energy is used by all four buildings. Through the application of various improvement scenarios, there is a reduction of the aforementioned value to 269,889.84kWh representing a 37.2% decrease in energy used annually.

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For calculating of the annual energy cost, the unit price of electricity for 2014 GHC 9.84 which is equivalent to USD3.1 (current BOG rate for the Cedi to the Dollar is GHC 3.2 to USD 1) was used. The annual energy cost of the buildings could be reduced by USD 496,263.69 (Table 4.13).

4.4.5 Carbon dioxide (CO_2) Emissions

For determining the CO_2 emissions, the energy mix in Ghana was referenced and percentages calculated. From the Table, the largest source of Ghana‘s energy is by hydro (67.12%). With a final consumption of 8552kWh of electricity, 17.17% is used by the commercial and public services sector including office buildings.

Table 4.14: Energy production sources in Ghana as at 2012

Items	Amount [kWh]	Percentage [%]
Oil	2505	20.83
Gas	1448	12.04
Hydro	8071	67.12
Total 1	**12024**	
Import	128	
Export	-667	
Domestic Supply	**11485**	
Statistical difference	-216	
Energy industry own use	-71	
Losses	-2646	23.04

Table 4.14: Energy production sources in Ghana as at 2012 Cont’d.

Items	Amount [kWh]	Percentage [%]
Final Consumption	**8552**	**100**
Industry	4153	48.56
Residential	2931	34.27
Commercial/Public services	1468	**17.17**

(Source: IEA, 2012)

Further, the average CO_2 emission per kWh of electricity for Ghana (0.259) according to the International Energy Agency (IEA, 2012) was used to calculate the annual CO_2 savings for all the buildings.

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Table 4.15: Estimated Annual Savings of CO_2 for all buildings

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Building	Annual Annual	$KgCO_2$.	Total CO_2	Total Annual %	energy use	energy use	kWh BC (

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kg) CO_2 savings savings BC, (BS), BS (kg) ($kgCO_2$) (kWh) (kWh)

R.T.	61,176.34	41,954.60	0.259	15,844.67	10,866.24	4,978.43	12.00
W.T.C.	109,018.00	55,313.44	0.259	28,235.66	14,326.18	13,909.48	33.55
P.T.	131,383.20	88,428.60	0.259	34,028.25	22,903.00	11,125.25	26.83
H.T.	128,397.36	84,193.20	0.259	33,254.92	21,806.04	11,448.88	27.61
Total	**429,974.90**	**269,889.84**		**111,363.50**	**69,901.46**	**41,462.04**	**100**

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The large amount of electricity consumed from thermal generating plants releases large quantities of carbon dioxide (CO_2) and carbon emissions into the atmosphere. The release of carbon dioxide and carbon emissions into the atmosphere are associated with global warming (Beggs, 2002). The lesser energy needed for indoor comfort, the more reductions in greenhouse gas emissions and a filtering potential on pollutants (Salmon, 1999 and Wagner et al. 1980 as cited in Koranteng, 2010).

From the current study, the difference in emissions resulting from the base case and the best scenario was 41,462.04$kgCO_2$ which is equivalent to 41.46 tons valued at 1,658.48 USD. This figure is calculated by multiplying the difference in emissions (per ton) by the unit cost per ton of carbon dioxide which is 40 USD (Wagner, 2014). Based on the study, the largest amount of carbon dioxide is saved in the W.T.C. building whiles the least is within the R.T. building; a result synonymous to the annual energy savings. The synergistic effect of less energy used, more reduction in CO_2 emitted is brought to bear.

4.5 *Objective Four: To identify overheating reduction strategies (passive case-no air conditioners) of the selected buildings.*

4.5.1 Passive scenario results

For the passive scenario (free-running building operation assumption), various air change rates (ACH) were explored with the best scenario from the active case (active building operation assumption). The design alternatives simulated were based on thermal mass, improved glazing, efficient lighting, and façade insulation. Refer to Table 3.12 for the two sets of assumptions pertaining to the applicable value for the reference overheating temperature.

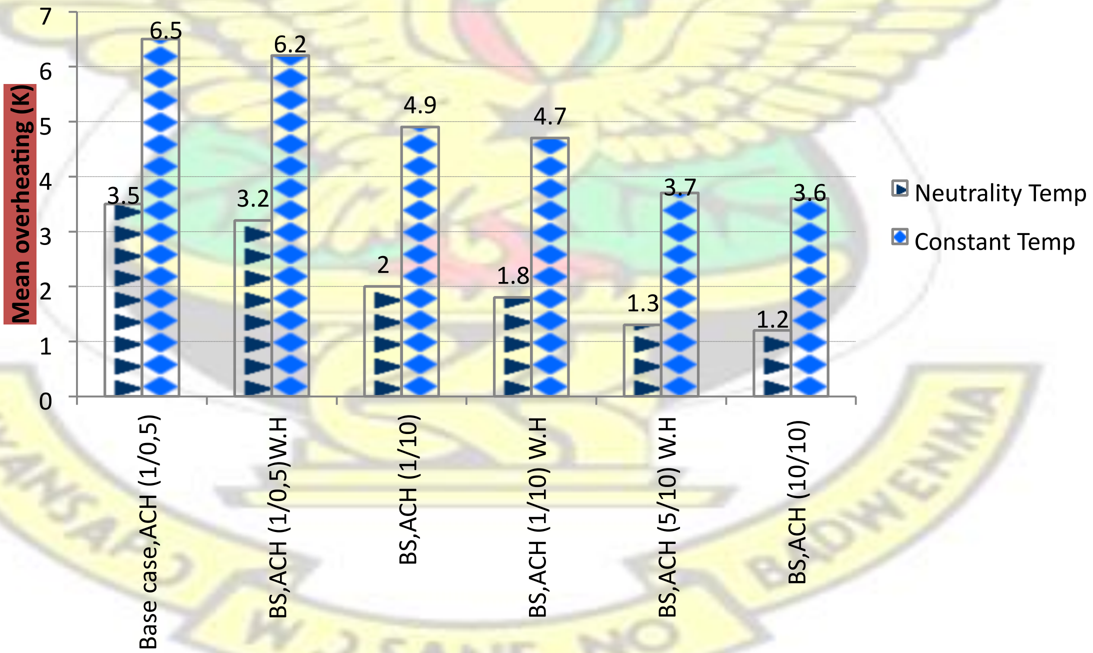

Fig. 4. 61: Mean - overheating for different ACH scenarios (R.T.)

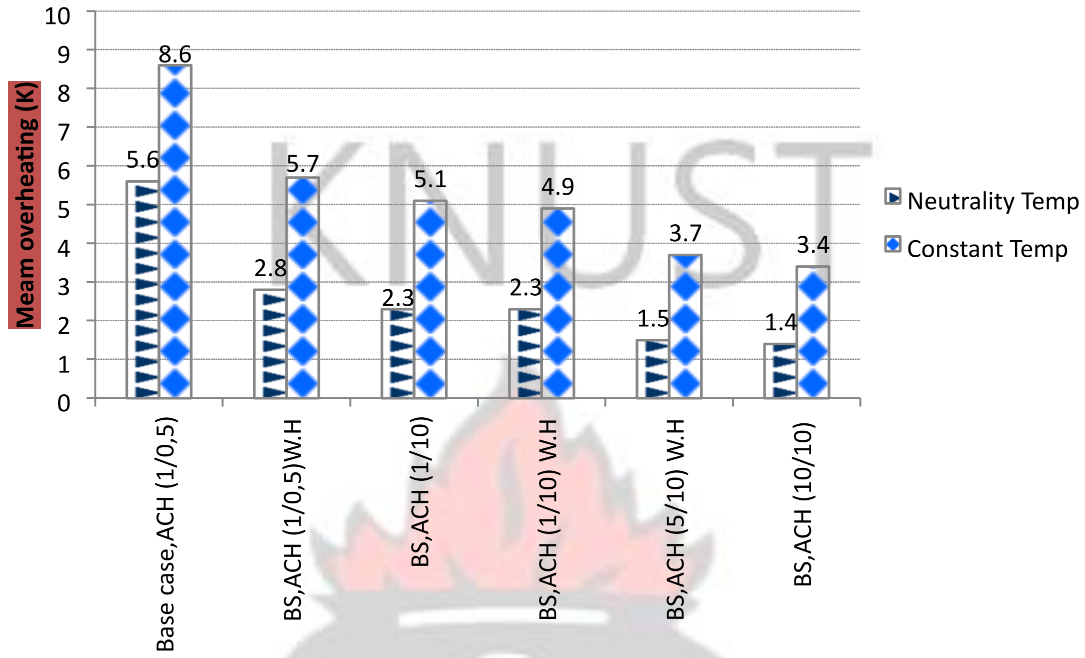

Fig. 4.62: Mean - overheating for different ACH scenarios (W.T.C.) Simulated mean indoor air temperature values were all lower than the reference neutrality temperatures for the P.T. building and therefore, no overheating occurred at the neutrality temperatures.

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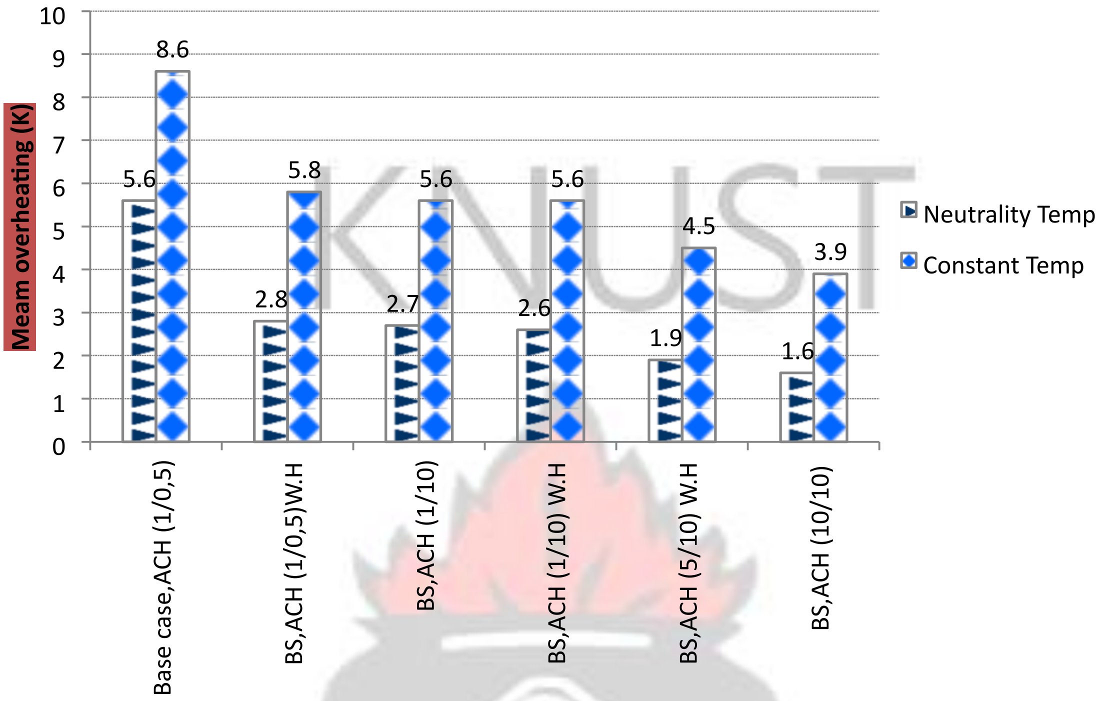

Fig. 4.63: Mean - overheating for different ACH scenarios (H.T.)

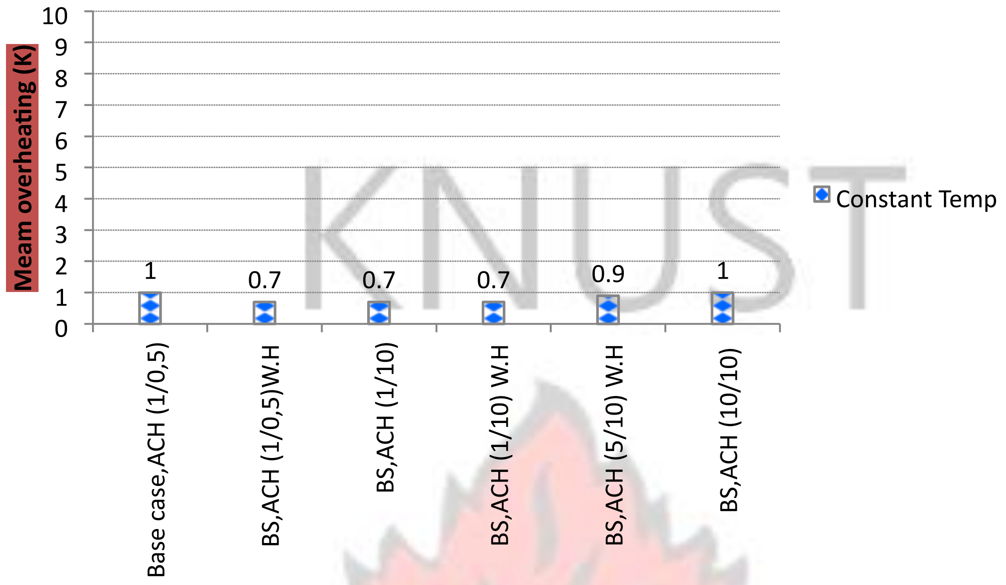

Fig. 4.64: Mean overheating for different ACH scenarios (P.T.)

The above results were further analysed using the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) method after Fanger (1973). The parameters used were the four environmental factors (air temperature, relative humidity, air velocity and mean radiant temperature) and two personal factors (metabolic rate and clothing) according to Szokolay (2004). With a metabolism rate of 1.2 Mets, clothing value of 0.7 and various air velocity rates (see Szokolay, pp 17), the mean monthly PMV-PPD for all the buildings were calculated. **Table 4.16: Fanger's PMV Scale**

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Table 4.17: Mean Annual hourly PMV and PPD of building R.T. (Based on simulated data from 8 am to 5 pm)

Air velocity (m/s)	Base case (1/0.5)		Best scenario with ACH (1/0.5)		Best scenario with ACH (1/10)		Best scenario with ACH (5/10)		**Best scenario with ACH (10/10)**	
	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD	**PMV**	**PPD**
0.1	2.6	92	2.5	91.8	2.1	80.6	2.1	80.6	**1.8**	**65.9**
0.5	2.5	89.9	2.4	89.4	2	74.2	2	74.2	**1.6**	**55.8**

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1	2.5	89.9	2.4	89.4	1.9	70.7	1.9	70.7	**1.5**	**51.7**
1.5	2.5	88	2.4	87.9	1.9	69.2	1.9	69.2	**1.4**	**49.3**

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Table 4.18: Mean Annual hourly PMV and PPD of building W.T. C. (Based on simulated data from 8 am to 5 pm)

Air velocity (m/s)	Base case (1/0.5)		Best scenario with ACH (1/0.5)		Best scenario with ACH (1/10)		Best scenario with ACH (5/10)		**Best scenario with ACH (10/10)**	
	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD	**PMV**	**PPD**
0.1	3.1	95.9	2.3	85.2	2.1	70.6	1.7	61.5	**1.6**	**57**
0.5	3.1	94.7	2.2	79.5	1.9	70.7	1.5	50.5	**1.3**	**44.9**
1	3.2	94	2.1	76.3	1.8	65.8	1.3	45	**1.2**	**39.8**
1.5	3.2	93.6	2.1	75.5	1.8	64	1.2	40.8	**1.1**	**37.5**

Table 4.19: Mean Annual hourly PMV and PPD of building H.T. (Based on simulated data from 8 am to 5 pm)

Air velocity (m/s)	Base case (1/0.5)		Best scenario with ACH (1/0.5)		Best scenario with ACH (1/10)		Best scenario with ACH (5/10)		**Best scenario with ACH (10/10)**	
	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD	**PMV**	**PPD**
0.1	3.1	99.5	2.4	90.4	2.4	88.9	2.1	79.2	**2**	**73.6**
0.5	3.1	99.5	2.3	87.2	2.3	87.2	1.9	72	**1.8**	**64**
1	3.1	99.5	2.3	86.8	2.2	83.3	1.9	69	**1.7**	**61.9**
1.5	3.1	99.5	2.2	84.3	2.2	82.5	1.8	67.7	**1.6**	**57.6**

Table 4.20: Mean Annual hourly PMV and PPD of building P.T. (Based on simulated data from 8 am to 5 pm)

Air velocity (m/s)	Base case (1/0.5)		**Best scenario with ACH (1/0.5)**		Best scenario with ACH (1/10)		Best scenario with ACH (5/10)		Best scenario with ACH (10/10)	
	PMV	PPD	**PMV**	**PPD**	PMV	PPD	PMV	PPD	PMV	PPD
0.1	1.3	40.3	**1.2**	**35.2**	1.2	35.2	1.2	35.2	1.2	40.3

0.5	0.9	22.1	**0.9**	**22.1**	0.9	22.1	0.9	22.1	0.9	22.1
1	0.8	18.5	**0.7**	**15.3**	0.7	15.3	0.8	18.5	0.8	18.5
1.5	0.7	15.3	**0.6**	**12.5**	0.6	12.5	0.7	15.3	0.7	15.3

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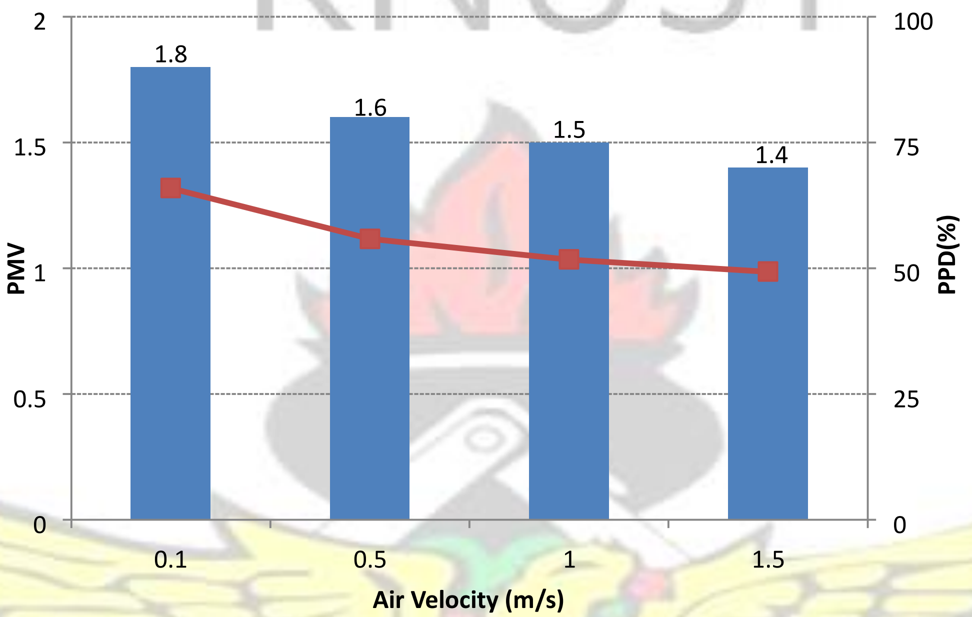

Fig. 4.65: PMV and PPD representation of the best ACH (10/10) for R.T. building

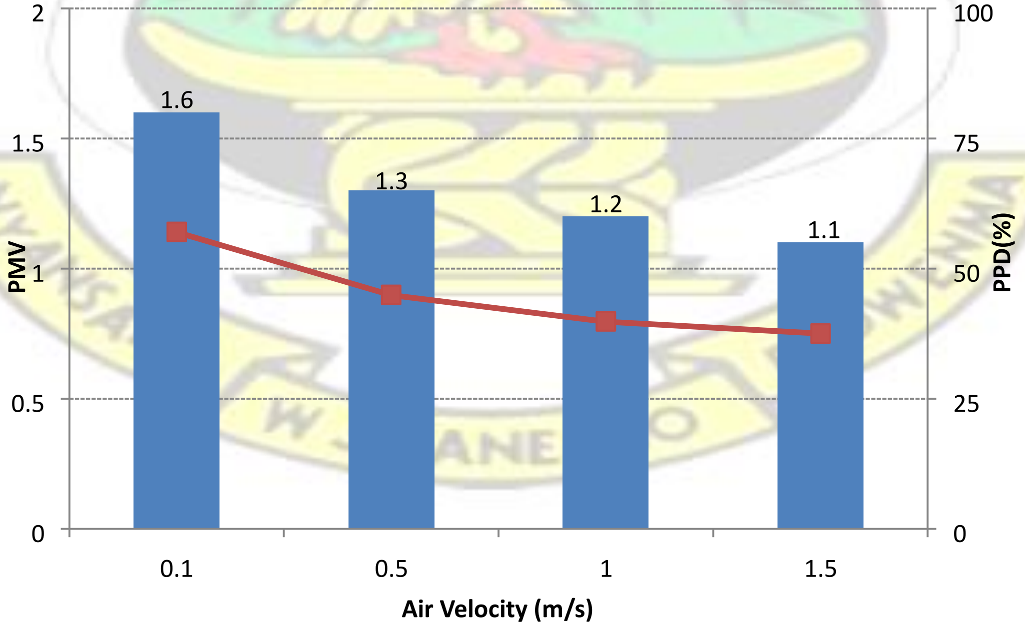

Fig. 4.66: PMV and PPD representation of the best ACH (10/10) for W.T.C. building

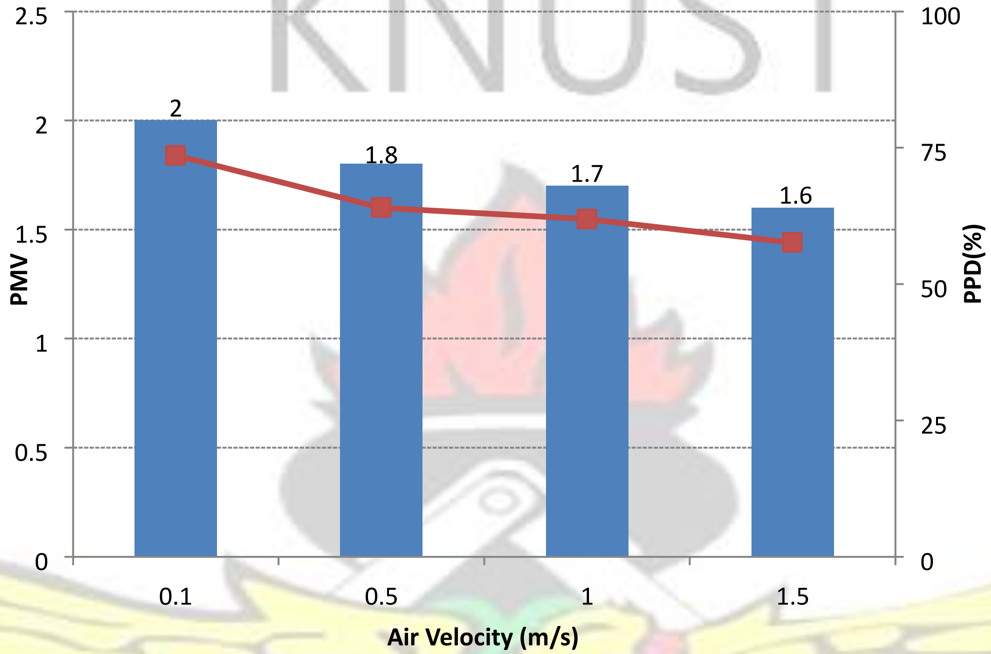

Fig. 4.67: PMV and PPD representation of the best ACH (10/10) for H.T. building

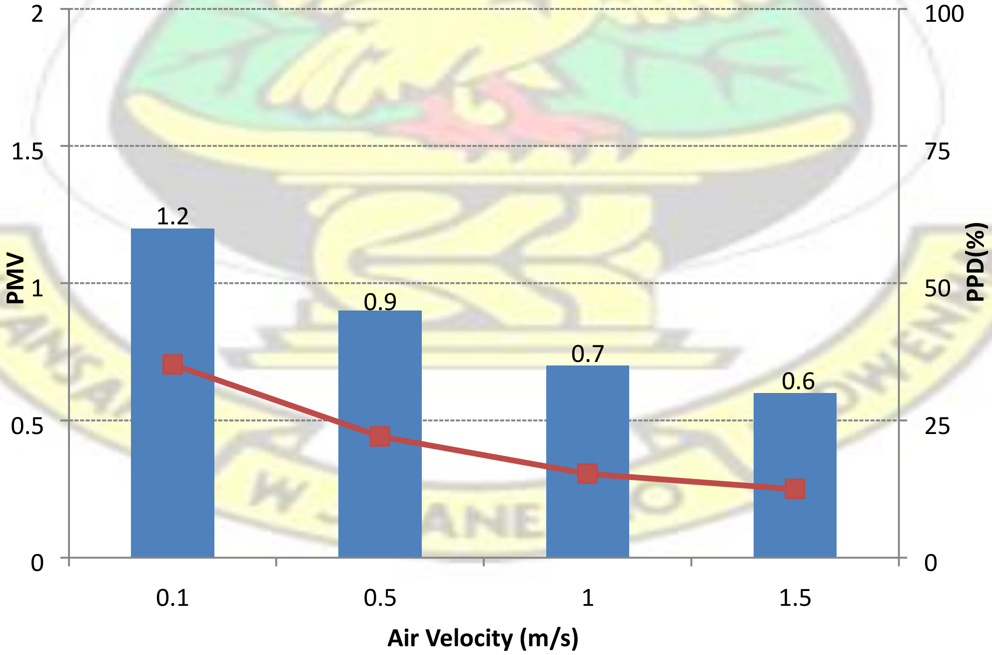

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Fig. 4.68: PMV and PPD representation of the best ACH (1/0.5 & 1/10) for P.T. building

4.5.2 Passive Scenarios discussion

The case study buildings were assumed to operate in the passive state thus, functioning without air- conditioners. The aim was to investigate alternatives leading to the reduction in indoor temperature (thermal comfort). With this calculation, the main indicator was mean-overheating (See Eq. 9). Only cases where the indoor air temperature was higher than the reference temperature was considered. Further, the predicted mean votes (PMV) after Fanger was used to determine the thermal sensations within the various buildings as well as the percentage of persons dissatisfied (PPD).

4.5.2.1 R.T. Building

The results of the parametric study on the above building are presented in Fig. 4. 61. The base case scenario had a mean-overheating temperature of 3.5K when the neutrality temperature (Tn) was considered. The constant temperature (CT) of 26ºC (ASHRAE, 2004) when considered recorded a higher mean-overheating: 3K more than that of the NT. The effect of the best scenario (efficient glazing, efficient lighting, night ventilation, external shading, façade insulation and 1/0.5 ACH) decreased the overheating level for both the Tn and CT by 0.3K. Additional increase in the ventilation rates (in terms of the air-change-rate per hour [ACH]) reduced the temperature values. An increase in the day/night ventilation to 1/10 ACH further reduced the meanoverheating to 2 and 4.9K for Tn and CT respectively.

Since the effect of natural ventilation during the day proved to be positive, the air change rate was further improved to 10ACH, thus 10/10 ACH, and the effect was a final decline of the mean overheating to 1.2 and 3.6K for Tn and CT correspondingly. Through the positive factors with regard to sustainability, a more comfortable working environment could be created. The effective use of natural ventilation can ensure internal comfort conditions for about 73% of the time (Amos-Abanyie et al. 2009). Since the R.T. building is square form with a north-west and southeast orientation, the prevailing winds is able to ventilate those offices with windows to south west. Szokolay (2004) recommends an aspect ratio of 1: 1.3 to 2.0 for elongated buildings, depending on the climate, and walls with major openings (on the elongated side) to face within 45° of the prevailing wind direction.

PMV and PPD values which were computed for the various passive scenarios are also presented in Table 4.15. A PMV of 1.8 was recorded with 65.9 % of the occupants' dissatisfied (Fig. 4.65) Thermal comfort could be increased by using air motion (fan- induced ventilation) to effect physiological cooling. Though air velocity of 1.5m/s reduced the PMV to 1.4 (more comfortable) with a PPD of 49.3%, the subjective reaction of this air movement according to Szokolay (2004) suggests draughty conditions and therefore not highly recommended. Air velocity of 1m/s will reduce PMV to 1.5 (warm) and PPD to 51.7% and is recommended. Through the various PMV's calculated, it is clear that the R.T. building is not comfortable since the ASHRAE (2004) recommended comfort zone is within -1 to +1 (slightly cool, neutral and slightly warm) hence, the use of air-conditioners. The above finding corroborates the findings of Amos-Abanyie et al, (2009).The authors concluded that outdoor conditions can ensure internal comfort for only about 21% of the year with cooling being required for 79%.

4.5.2.2 W.T.C. Building

The base case simulated scenario for building W.T.C. led to a mean-overheating temperature of 5.6K when Tn was used and 8.6K when CT was used. Here again, CT is 3K more than Tn. This is one of the highest over-heating values and the effect of efficient glazing, night ventilation, external shading, façade insulation and night ventilation (best scenario) could reduce it (Fig. 4. 62). The alternative increase in the day/night ventilation could decrease the mean over-heating to 1.6K for Tn and 3.6K for CT (when air-change-rate per hour is 10/10ACH). The comparatively good orientation of the rectangular block (north- west and south- east) with windows on the longer sides did help reduced the temperature when ventilation was increased along with the other parameters (Table 3.10).

The veranda along the studied offices also acted as protective shield against the intense solar radiation. These findings agree with (Lechner 2001), who states that attention should be given to a good orientation, wind direction and a high window to wall ratio in order to reduce the indoor air temperature within a space. The arrangement of the offices did support cross ventilation. There were fewer partitions which were not too deep. The thermal sensation levels of the occupants when the ACH was increased to 10/10 was 1.6 (warm conditions) and the percentage of occupants who were dissatisfied was 57% (PPD). The aforementioned values were recorded when the air-velocity within the spaces was 0.1m/s. A further increase in the air velocity (fan induced) to 0.5, 1 and 1.5m/s will gradually reduce the discomfort level within the spaces to 1.3, 1.2 and 1.1 (all slightly warm conditions) with PPD also reducing to 44.9, 39.8 and 37.5% respectively (Fig. 4. 66). Though at an air velocity of 1.5m/s the PMV reduces and the occupants are comfortable (fairly), the subjective

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reaction to this air movement results in draughty situations where papers begin to fly and it becomes uncomfortable [(Szokolay, 2004). see Table 3.13].

4.5.2.3 H.T. Building

The curtain wall office building with inoperable windows also had the highest base case mean overheating of 5.6K when Tn was operating and 8.6K when CT was working. This was due to the effect of solar radiation (improper orientation), since there was no shading on all sides of the building. The increase in radiation led to the higher conductive gains in the office spaces, which resulted in uncomfortable indoors (Heerwagen 2004). Nonetheless, the improved parameters combined (scenario) led to the attenuation of the mean-over heating by 2.8K (Fig. 4.63) for both situations (Tn and CT). The positive effect of natural ventilation (ACH) finally reduced the mean overheating to 1.6K for Tn and 3.9K for CT. The enhanced result in comparison to the base case scenario was also due to the shading protection provided by the quality glazing. The thermal mass (no carpeted floor) supported storage of cool air, leading to temperature drops. The orientation of the building had a negative effect on thermal gains (Koranteng, 2010). Among other factors, the thermal gains problems were due to the fact that a large area at the eastern and western sides of the building fabric was exposed to intense solar radiation. The effect of orientation, shading and thermal mass on indoor climate has been emphasized by Lauber (2005), Szokolay (2004), and Givoni (1981).

The PMV and PPD values recorded in the H.T. building suggest warm (ACH of 10/10) interior spaces with high percentage of dissatisfied occupants (Table 4.19). At 0.1 m/s air velocity, PMV is 2 (warm) with PPD of 73.6%. As the air velocity is increased by means of fans, the PMV also reduces. At air velocity 1.5 m/s, PMV was still warm (1.6) but the degree of warmness is low (Fig.

4.67). Occupants who were dissatisfied were more than half of the tenants (57.6%). Heat gained from the façade due to the orientation, contributed to the poor performance and the problem was worsened by the inoperable nature of the glazing system used.

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4.5.2.4 P.T. Building

At P.T., the base case mean-over heating value recorded was 1K for CT (Fig. 4. 64). The P.T. building shows better results for passive mode than the rest of the buildings. It does not record any overheating value for neutrality temperature. This indicates that the indoor temperatures simulated were all below the Tn but higher than the CT. Comparatively, conditions in the P.T. are comfortable. Through the improvement scenario, the mean-overheating dropped to 0.7K.

The form, orientation (north-south), could have led to the temperature reduction in P.T. This was enhanced by the almost open floor plan arrangement of the office spaces that allowed natural and cross ventilation through the spaces.

With a base case ACH of 1/0.5 and air velocity of 0.1m/s, the thermal sensation level was 1.3 (slightly warm) with 40.3% of occupants dissatisfied. As air velocity is increased to 0.5 and 1m/s, PMV also reduces marginally to 0.9 and 0.8, likewise the PPD (Table 4.20). The introduction of the improvement scenario with the same ACH and when ACH was increased to 1/10, all led to various degrees of PMV and PPD reductions (Fig. 4.68).

4.5.2.5 Summary for all buildings

The above passive scenario results generate significant principles that is worth noting for future passive building designs:

i. Overheating tendencies are more pronounced in offices with west orientations (R.T., W.T.C. and H.T.). Form and orientation principles in the sitting and arrangement of office spaces must be informatively carried out to provide thermal comfort within the interior spaces.

ii. The alternative improvement scenarios considerably reduced the mean overheating in the offices (up to about 2.9K, depending on the reference overheating temperature assumption). Though not exactly identical, there is a clear correspondence between the ranking of the scenarios in view of lower cooling demands (active building mode) and lower overheating tendency (passive operation mode).

iii. Within the climatic context of the study (Accra), the R.T., W.T.C. and H.T. buildings cannot operate under passive conditions throughout the year since indoor conditions are warm/hot.

iv. Natural ventilation is the key issue in passive design, though efficient building elements also lead to temperature reductions. From the study, increase in the air-change-rate (ACH) did reduce the thermal sensation levels within the spaces. For instance, at a day/night ventilation rate of 10/10 air-change-rate per hour, predicted mean votes in all the buildings reduces. This finding substantiates that of studies conducted using measurements and simulations in schools and offices. The results showed air change rates between 5 and 22 per hour for cross ventilation and 1 and 4 for single-sided ventilation to greatly reduce indoor temperature (Fisch and Zargari, 2009; Breesch,2006 and Eicker et al.,2006).

v. None of the passive scenarios examined truly eliminates overheating risks. In the probing, it was discovered that mean-overheating could be increased to 8.6.K and reduced to 0.7K (depending on the overheating reference temperature assumption considered).

vi. From Table 3.11 (neutrality temperature), the highest value of 29.5ºC was calculated. The highest recorded temperature level in the office buildings was in the region of 35°C. This temperature is high (less and inoperable windows in some of the cases) and could lead to thermal discomfort in the spaces. However, the use of fans has been found to positively support evaporative cooling by providing a physiological cooling sensation of up to 3°C (Ferstl 2003 and Hyde 2000). Therefore, it is recommended to always use fans for the purpose of physiological cooling in all indoor spaces. Conversely, the increase in the velocity of the fan to 1.5m/s involves considerable draft discomfort outcome.

vii. To effectively minimize overheating tendencies under the neutrality temperature assumption, climate responsive designs (geometry, layout, construction elements, materials and orientation) must be explored.

viii. The study shows that the ASHRAE (2004) maximum summer comfort temperature of 26ºC is not achievable in most multi-storey office buildings operating under passive assumptions (R.T., W.T.C. and H.T.).

ix. The most vital strategy would be the use of sustainable design principles of orientation, shading, ventilation, planting, insulation and efficient building materials (Dubois, 2008)

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The current research studied the thermal performance of multi-storey office buildings in Ghana. The research objectives presented in sub section 1. 5 were developed in order to achieve the aim of the research which was to assess thermal comfort conditions and to explore design options towards the reduction of energy use in multi-storey office buildings. A methodology was developed exploring thermal comfort models, subjective votes and simulation through the case study of 4 existing buildings. To accomplish the aim to the research, a model questionnaire which sought to find out how occupants felt in their offices, their knowledge concerning building control systems, energy-consciousness in offices among others was designed and administered to the building tenants. Further, three thermal comfort models based on thermal comfort theories (heat-balance approach: PMV-PPD [after Fanger, 1973], adaptive approach: Psychrometric and Bioclimatic charts) were used to determine the comfort zones within the study area and further find out if the buildings were comfortable. Design-based approaches were also given as to how the uncomfortable spaces could be made comfortable.

Moreover, a Tas simulation programme was used to determine the cooling loads (active mode) and mean- overheating tendencies (passive mode) for the case study buildings. Base models were developed for the building and by validation; the base case cooling loads were simulated. Further, parameters considered for the simulation process were internal loads (lighting loads, occupancy latent and sensible heat, and equipment sensible heat), infiltration, and glazing types. Different parameters (efficient glazing, low lighting gains, thermal mass, etc.) were individually simulated and their effects on the base case cooling loads were analysed. These parameters were further combined to form scenarios which when simulated, reduced the initial cooling loads by various percentages. In all, 160 scenarios (40 for each building) were simulated for all the buildings. Graphical and statistical analyses were employed in the validation to achieve a satisfactory agreement between simulated results and measured data.

This chapter presents the conclusions of the study and recommendations. The chapter discusses the achievements of the research objectives, implications of the research, and highlights the contributions of the research. The recommendations are alienated into two sub-sections; one aimed at policy formulation in the design, built environment, selection of materials for buildings, and the other in respect of further research.

5.2 Research findings

The major research findings for the current study are presented in sections under the main research objectives. These findings provide the major highlights of the study and provide the basis for policy and future research.

5.2.1 Objective One

To assess occupants‘ views of their indoor thermal comfort conditions within the selected building.

From the study, occupants‘ behaviour (leaving the lights on when day lighting is enough, usage of equipment, thermostat set points, etc.) is known to have implications on the energy use within the offices. A significant percentage of occupants (52%) did not switch off their air- conditioners when they were out of their offices even for as long as between 30 to 45 minutes because the AC‘s were centralized and as such there was no way to switch off just one out of the lot.

Further, air quality, thermal comfort and fire safety are the most important parameters the tenants consider within their spaces. Open floor plan concept enhances cross ventilation within the offices when the air-conditioners are not in use.

Whiles about 96% of the occupants in the air-conditioned buildings found their indoor thermal sensation levels to be from cold (-3) to slightly warm (2), they actually would prefer slightly cool (-2) to slightly warm (2) conditions. Due to the orientation and lack of shading, the H.T. building which is an air-conditioned building resulted or showed uncomfortable conditions internally.

Even though occupants in the W.T.C. building were always willing to leave their offices in the afternoons because of the negative indoor conditions, their wish is for an air-conditioned or mixed mode office environment. Although building R.T. appears to be over cooled, occupants would not want any condition otherwise, stressing that they would rather feel cold than to feel warm. The desire for better air quality and thermal comfort were considered essential for high performance and productivity.

In addition, it was found that most occupants‘ were not well informed regarding the available control systems as well as how they functioned. Forty-one percent of the occupants‘ in the H.T. building felt that they were insufficiently informed on how their lighting and internal shading systems operated and will be willing to attend workshops on the subject matter. Frequent workshops need to be organized by facility managers in conjunction with the maintenance department of each building to educate occupants on the effect of their actions on building control systems and energy usage in the office buildings.

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5.2.2 Objective Two

To determine the thermal comfort conditions within the indoor environment of the selected buildings.

From the analysis on the thermal comfort conditions, the PMV-PPD, Psychrometric and Bioclimatic charts were used. The PMV indicated comfortable conditions within the mechanically ventilated offices (MVO) and over predicted the thermal conditions within the W.T.C. Whiles the actual mean vote (AMV) was found to be 0.5 (slightly warm), PMV was 1.5 (warm) Thus, thermal comfort levels found within the MVO compared well with the ASHRAE and ISO standards. The mean temperature of 25˚C for the MVO falls within ASHRAE's acceptable temperature range of 23°C - 26˚C (summer comfort). Meanwhile the average subject satisfaction for the MVO of 87.5% is also within ISO 7730's range of 75% and close to ASHRAE's 90% of total subject satisfaction which is not the case for the naturally ventilated building (W.T.C.).

From the Psychrometric charts, the existing indoor conditions within the MVO show comfortable conditions with the exception of building H.T. where the months of May- July and January all fall on the upper part of the comfort zone.

In the naturally ventilated building, all the months fell outside the zone of comfort. High relative humidity values as well as temperature values measured (31.4°C) accounted for this. For the airconditioned buildings, the temperature values were below 29°C. It was realized that the occupants had become accustomed to the high humidity levels due to their assertion of comfort: comfort is a personal achievement.

Guidelines for sustainable design principles (form, orientation, shading, high room height, low energy consuming fans etc) should be followed in order to produce positive indoor thermal conditions. For the reason that most of the temperature values were within the proposed values for tropical countries, the effect of relative humidity on thermal comfort in the climatic context of Accra needs to be studied further for adjustments. Subsequently, the relative humidity limits for the determination of the comfort zone (12 and 4 k/kg) must also be amended for tropical climates.

On the bioclimatic charts, the temperature and relative humidity values plotted on comfort and design strategies graphs showed conditions of discomfort in the buildings. The study also revealed that the adoption of a single strategy cannot ensure comfort conditions for the entire year, thus a hybrid strategy will have to be employed. The most effective design strategy to attain thermal satisfaction was found to be comfort ventilation. Furthermore, an air velocity of between 0.1m/s to 0.5m/s was capable of achieving comfort in the buildings. The use of sustainable design principles of orientation, shading, and efficient building elements can contribute to thermal comfort sensation in offices and as such, these measures have to be employed by designers.

5.2.3 Objective Three

To come out with energy reduction strategies based on validated models of the selected buildings.

From the study, measured indoor air temperature compared well with the weather file used in the simulation application. Co-efficient values (r^2) of between 0.67 and 0.92 were calculated when the measured and weather file data was compared. This shows a good relationship. The results compared favourably with validation exercise in earlier studies performed with the Tas simulation program.

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From the analysis on the simulation of cooling loads (active building operation), it could be demonstrated that through a combination of design features (glazing, lighting, facade insulation, thermal mass, night ventilation, external shading and shading schedule), a significant reduction of the cooling loads can be achieved. Even in exclusive mood, sustainable design principles of orientation, shading, and efficient building elements could contribute to low thermal comfort sensation in the offices. The W.T.C. building with a better form and orientation as compared to the other buildings had a relatively higher percentage reduction in cooling loads of 49.3%.
Additionally, efficient glazing and lighting have been noted to reduce cooling loads significantly.

5.2.4 Objective Four

To identify overheating reduction strategies (passive case: no air conditioners) of the selected buildings.

As far as the potential of a passive operation mode is concerned, given the current building typology and practices, provision of thermally comfortable indoor environment represents a challenge. A number of requirements must be met in order to make such a passive option practically feasible. These include sufficient thermal mass, external shading, effective day-time and night-time ventilation, cross ventilation possibilities and cautious use of air movement inducing fans. An increase in the ventilation rate, leads to reduction in the PMV (better indoor thermal conditions) and a subsequent decrease in the PPD. A combination of air-change rates with fan induced air velocity provides a better indoor thermal comfort. For instance a ventilation rate of 10/10ACH with air velocity of 0.5 or 1m/s leads to various degrees of PMV's ranging from 0.8 to 1.8 (slightly warm and warm conditions).

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The percentage of people dissatisfied (PPD) also reduces from 64% to 18.5%. Though 1.5m/s air velocity could further reduce PMV, the draughty (papers begin to fly) nature makes it unattractive to occupants except in very uncomfortable situations. Further increases in ACH rate could reduce the thermal sensation levels within the spaces more and thereby lessening PPD as well. Flexible thermal comfort requirements (consistent with the implications of the adaptive thermal comfort theory) and a fitting dress code (involving climatically adapted clothing with low clo-values) would have to be considered. From the study, sealed inoperable glazed windows do not offer opportunity for the building to operate in the passive mode. Though the passive mode reduces the use of cooling energy to the barest minimum, it does not provide indoor comfort for all buildings. Only 2 of the four buildings studied could apply the passive techniques for effective results (W.T.C and P.T.) with fan induced air velocities of 0.5m/s or 1m/s.

Additionally, given the number of severe globally pertinent developments (energy supply and demand dynamics, energy price increase, environmental emissions due to operation of buildings and climate change, etc), attention must be paid to the applicability of strict indoor environment standards (constant low indoor temperatures) . Instead, climate responsive designs with creative approaches in architecture accompanied with appropriate organisational and cultural (working hours, clothing practices etc) behaviour, needs to be part of the solution schemes for sustainable and habitable built environments.

5.3 Research Implication

The conclusion for this study have implications for improving thermal performance of buildings and the amount of energy consumed in space cooling. There are implications for theories on energy efficient building design, implications for building design, and architectural practice in Ghana.

5.3.1 Theory

The findings of this study have some implications on the theory of thermal comfort. As shown from the literature review, the heat-balance approach (PMV-PPD) does over predict the thermal sensation levels within free-running buildings. The findings of the current research corroborate the above-mentioned assertion as the actual mean votes (AMV) recorded at W.T.C. was 0.5 (slightly warm, the PMV recorded was 1.5 (warm).

Another implication on the thermal comfort theory is that literature mentions glazing types, shading, orientation, natural ventilation, thermal mass as factors that affect the energy (cooling loads) within a building. The study provides empirical data to support the afore-mentioned assertion with efficient glazing and lighting significantly reducing cooling loads.

Again, it is established that the u-value of glazing does not have a pronounced, effect on the cooling loads; rather the g-value plays a decisive role towards the reduction of cooling loads. Further, without the use of fan-induced air velocity; ACH alone could not provide thermal comfort within the indoor environment.

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5.3.2 Practice

The study_s repercussions for building design and architectural practice in Ghana are as follows: Choosing the appropriate glazing type with a low solar heat gain co-efficient value will significantly reduce the cooling loads within buildings. Efficient lighting of $2W/m^2$ also leads to an appreciable decrease in cooling loads.

Through the combined effect of building features and a good responds to our localized climate, the total base case cooling loads for buildings will reduce significantly.

Thermal comfort, air quality and fire safety are the three top most parameters that developers and building managers should look at in satisfying for occupants in order to increase productivity.

Sealed inoperable glazed windows with inappropriate orientation do not work in the warm humid climate of Ghana and should be avoided.

The application of passive cooling techniques (thermal mass, natural ventilation [day/night], external shading, façade insulation) together with a fan induced air velocity, can reduce the PMV within the indoor spaces by various degrees, likewise the PPD.

5.4 Research Contribution to Knowledge

i. A significant contribution of this research to the body of knowledge is the provision of empirical evidence with respect to the improvement of thermal performance in multi-storey office buildings in Ghana. Until the current research, this assertion had not been supported by any empirical study from research findings within the localized climate of Ghana.

ii. The simulation results suggest that certain measures regarding building fabric and controls can improve the buildings' energy performance. Specifically, certain combinations of improvement measures (such as better windows, external shading, thermal mass, façade insulation and efficient electrical lighting) have a synergistic effect of reducing the cooling loads of the buildings' in the climatic context of Accra.

iii. Based on the study, the three most important parameters for occupants' satisfaction in their office spaces were air quality, thermal comfort and fire safety. This finding introduces a new parameter (Fire safety) which is peculiar to the Ghanaian setting.

iv. Passive cooling techniques have been established to reduce energy use in buildings. This research contributes further to the body of knowledge by providing sufficient evidence to support earlier studies that concluded that the cooling effect of air movement (0.5m/s to1.5m/s), resulting in physiological cooling, could provide comfort conditions and thereby reducing the percentage of occupants dissatisfied.

v. Validated simulation models are used in retrofit analysis for improvement in the thermal performance of buildings. Therefore another significant contribution of this research is the achievement of validated simulation models for energy assessment in multi-storey office buildings in Ghana. This provides a reference point for future validated simulation studies in Ghana.

vi. Another significant contribution of this research to the body of knowledge is the provision of sufficient evidence to confirm that the procedure for the determination of the comfort zone on the psychrometric chart could be adjusted for tropical climate where higher relative humidity and moderate temperatures are recorded.

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5.5 Recommendations

This section proposes recommendations arising from this research. Two sets of proposals are have been outlined. The first is relevant to professionals in the building industry, policy makers and also facility managers (stakeholders) to develop parameters that would lead to energy use reductions whiles creating thermal comfort. The second is for further research work into the thermal performance of buildings in Ghana.

5.5.1 Recommendation to Stakeholders

The following recommendations for stakeholders on developing parameters that would lead to energy use reductions whiles creating thermal comfort in building design in Ghana are made on the basis of this research work:

i. Specialized research units with focus on building thermal performance should be established in research institutions and the energy ministry in Ghana.

ii. There should be initiatives by policy makers, energy ministry, building professional bodies etc to enhance awareness on energy efficient designs.

iii. Architects should make a conscious effort to provide external shading for buildings as this is seen to perform better than internal blinds.

iv. Best practices and climate responsive designs are the way forward.

v. Building user‘s and facility managers are informed to use energy efficient equipment and lighting systems. This has a great potential of reducing total annual cooling loads.

vi. Facility managers can employ the use of a comprehensive energy management system (EMS) towards achieving low energy consumption for their buildings. This is through a continuous monitoring of the energy consumption with a software programme. Action can thus be taken where unusual high energy consumptions are registered.

vii. Occupants and workers in the multi-storey office buildings should frequently be trained in the proper use of their environmental control systems, especially the air-conditioners and lighting systems to ensure efficient use and cooling load reductions.

5.5.2 Recommendation for Future Research

The following recommendations, based on the limitations of the scope of this study are made for further research into passive and low energy cooling techniques in Ghana:

i. The climatic conditions of the various regions of Ghana have varying diurnal temperature range. However, this study was limited to the climatic conditions of the Greater Accra Region. Further research is required to investigate the thermal performance and energy reduction strategies for the Northern part of Ghana where the variations are wide.

ii. Future research should aim at the varying sizes of window to wall ratio towards the reduction of cooling loads.

iii. Building performance simulation employs detailed and reliable micro-climatic data of which there is limited monitoring equipment in Ghana. Research projects should be developed to encourage the acquisition and setting up of equipment to create banks of detailed and reliable climatic data in Ghana.

iv. The current research studied four multi-storey office buildings. It is recommended that future research should consider other types of buildings (residential, industrial etc) where annual cooling loads are also considered to be high.

v. The effect of high relative humidity (above 70%) with moderate temperatures should be studied in detail. The aim should be towards a possible adjustment of the comfort zone on the psychrometric chart for the humid climatic Regions of Ghana.

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APPENDICES

APPENDIX A: Information on Data loggers

For detailed information on the data loggers (specifications, accuracy, resolution, battery life, operation, etc) please refer to the Website of Onset Computer Corporation – www.onsetcomp.com

Fig. 1: Image of Data logger

NYANSAPO WO SANE NO BADWENMA

APPENDIX B: System Settings

System settings in the Control Panel:

Regional and Language Options:

Regional Options:

Standard format "English (UK)"

Location "Austria" Customize:

Numbers:

Decimal Symbol "," [Comma]

No. of digits after decimal "2"

Digit grouping symbol "."

Digit grouping "123.456.789"

Negative sign symbol "-" [Minus]
Negative number format "-1,1"

Display leading zeros "0,7"

List separator ";" [Semicolon]

Measurement system "Metric" Currency:

Currency symbol "$"

Positive currency format "$1,1"

Negative currency format "-$1,1"

Decimal symbol "," [Comma]

No. of digits after decimal "2"

Digit grouping symbol "."

Digit grouping "123.456.789" Time:

Time sample "13:03:08"

Time format "HH: mm: ss"

Time separator ":" [Column]

AM symbol [left empty]

PM symbol [left empty]

Date

Calendar "2029"

Short date sample "28.04.2005"

Short date format "dd. mm. yyyy"

Date separator "." [Point]

Long date sample "Thursday, 28.04.2005"

Long date format "dddd, dd. mm. yyyy" **APPENDIX C: Questionnaires**

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The table below summarises the results from the sets of questions distributed to the building occupants. The first section represents results on general questions and the remaining sections shows the response on specific topics.

Table 1: Summary of questionnaire response expressed in percentage of occupants

General Questions						
1.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
1.1	Gender	Male	85.7	69.2	50	41.7
		Female	14.3	30.8	50	58.3
1.2	Age	<25	7.1	-	-	8.3
		25-35	64.3	84.6	66.7	58.3
		36-45	14.3	15.4	22.2	8.3
		46-55	7.1	-	5.6	17.7
		>56	7.1	-	5.6	8.3
1.3	Education	Elementary	7.1	-	11.1	-
		Junior High	-	-	-	-
		Senior High	-	7.7	11.1	-
		O level	7.1	7.7	5.6	-
		A level	-	-	-	-
		Undergraduate	42.9	38.5	38.9	50
		Post graduate	42.9	46.2	33.3	50
1.4	How long have you been working in your current office	Under 1year	21.4	30.8	33.3	33.3
		1-5 years	57.1	69.2	61.1	66.6
		6-10 years	21.4	-	5.6	-
		>10 years	-	-	-	-
1.5	What percentage of your work do you perform on your computer	0-10	21.4	15.4	-	-
		11-20	-	-	5.6	-

		21-30	-	-	-	-
		31-40	-	-	5.6	-
		41-50	7.1	15.4	-	-
		51-60	28.6	-	11.1	8.3
		>60	42.9	69.2	77.7	91.7

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Table 1: Summary of questionnaire response expressed in percentage of occupants Cont'd.

General Questions						
1.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
1.6	How many hours in average do you work per week	0-30hrs	14.3	23.1	27.8	33.3
		30-40hrs	21.4	46.2	61.1	33.3
		41-50hrs	21.4	15.4	11.1	16.7
		51-60hrs	21.4	-	-	8.3
		>60hrs	21.4	15.4	-	8.3
1.7	Of these, how many hours do you spend at your workstation	0-30hrs	57.1	53.8	50	58.3
		30-40hrs	27.4	30.8	50	25
		41-50hrs	14.3	-	-	8.3
		51-60hrs	7.1	7.7	-	-
		>60hrs	-	7.7	-	8.4

Table 2: Summary of questionnaire response expressed in percentage of occupants

Indoor Environment (thermal ,visual etc)						
2.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
2.1	What is your general feeling concerning the under listed parameter in your office?					
	Temperature	Warm	4.8	54	13	50
		Neutral	21.4	46	3.7	38.3
		Cool	73.8	-	83	11.7
	Relative Humidity	Very poor	-	-	7.4	8.3
		Poor	7.1	15.5	3.7	-
		Neutral	14.3	48.7	11.1	33.3
		Good	50	17.9	48.1	58.4
		Excellent	14.3	17.9	13	-
		Don‘t Know	14.3	-	16.7	-

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Table 2: Summary of questionnaire response percentage of occupants Cont'd.

Indoor Environment (thermal ,visual etc)						
2.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
2.1	What is your general feeling concerning the under listed parameter in your office?					
	Odours	Very poor	-	-	5.6	-
		Poor	-	20.5	1.9	30
		Neutral	14.3	64	20.4	33.3
		Good	64.3	13	38.7	36.7
		Excellent	11.9	2.5	16.7	-
		Don't Know	9.5	-	16.7	-
	Ventilation	Very poor	2.4	23	9.3	8.3
		Poor	14.3	28.2	-	25
		Neutral	26.2	33.3	22.2	21.7
		Good	35.7	13	40.7	45
		Excellent	14.3	2.5	11.1	-
		Don't Know	7.1	-	16.7	-
	Lighting quality	Very poor	-	-	5.6	-
		Poor	-	5.1	-	13.4
		Neutral	7.1	17.9	11.1	28.3
		Good	69.1	66.7	44.4	58.3
		Excellent	16.7	10.3	22.2	-
		Don't Know	7.1	-	16.7	-
	Air quality	Very poor	2.4	-	5.6	8.3
		Poor	14.3	15.5	1.9	5
		Neutral	11.9	35.9	20.4	50
		Good	42.8	30.7	40.6	36.7
		Excellent	14.3	17.9	11.1	-
		Don't Know	14.3	-	16.7	-
2.2		Not good at all	-	38.5	5.6	16.7

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Table 2: Summary of questionnaire response expressed in percentage of occupants Cont'd.

	Do you feel that the environment in which you work is agreeable/satisfying?	Somewhat	28.6	30.8	16.7	50
		Agreeable	28.6	23.1	55.6	33.3
		Very agreeable	42.8	7.7	22.1	-

expressed in

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Indoor Environment (thermal ,visual etc)

2.0	Question	Category	R.T.	W.T.C.	P.T.	H.T.
2.3	How is the average temperature in your office during the Dry Season or (Harmattan)?	Cold	22	-	3	-
		Cool	30	4	12	4
		Slightly cool	24	8	10	8
		Neutral	24	12	35	12
		Slightly warm	-	14	19	12
		Warm	-	36	21	26
		Hot	-	26	-	38
2.4	How would you prefer to feel during the Dry Season?	Cold	-	-	-	-
		Cool	54	36	47	30
		Slightly cool	18	30	19	30
		Neutral	22	22	28	20
		Slightly warm	6	12	6	20
		Warm	-	-	-	-
		Hot	-	-	-	-
2.5	How is the average temperature in your office during the Rainy Season?	Cold	16	-	38	20
		Cool	54	16	28	30
		Slightly cool	12	50	-	25
		Neutral	18	14	34	25
		Slightly warm	-	10	-	-
		Warm	-	10	-	-
		Hot	-	-	-	-
2.6	How would you prefer to feel during the Rainy Season?	Cold	6	6	-	-
		Cool	42	18	30	20
		Slightly cool	6	24	24	25

Table 2: Summary of questionnaire response percentage of occupants Cont’d.

		Neutral	24	28	46	35
		Slightly warm	6	24	-	20
		Warm	-	-	-	-
		Hot	-	-	-	-

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Indoor Environment (thermal ,visual etc)						
2.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
2.7	What do you do when you feel cold in the office?	Leave the office	7.1	25	-	-
		Put on added clothes	21.4	45	38.9	-
		Move from my workstation	7.1	30	-	8.3
		Turn off the A/C	57.1	-	61.1	91.7
		other, please state	7.1	-	-	-
2.8	What do you do when you feel warm in your office?	Remove some clothing	7.1	15	-	8.3
		Turn on the A/C	64.3	-	77.8	91.7
		Get a chilled drink	21.4	10	11.1	-
		Other, please state	7.1	-	11.1	-
2.9	How satisfied are you with the Airconditioning?	Very satisfied	7.1	75	22.2	-
		Satisfied	35.7	-	16.7	8.3
		It‘s ok	50	-	55.6	75
		Less satisfied	7.1	-	-	16.7
		Not satisfied at all	-	-	5.6	-
		No air-conditioning	-	100	-	-
2.10	Do you have control over air temperature?	Yes	71.4	61.5	50	41.7

Table 2: Summary of questionnaire response expressed in percentage of occupants Cont’d.

		No	28.6	38.5	50	58.3

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expressed in

Indoor Environment (thermal ,visual etc)						
2.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
2.11	Do you have control over air speed?	Yes	50	38.5	22.2	16.7
		No	50	61.5	77.8	83.3
2.12	Evaluate air speed in your office:	Calm	50	61.5	44.4	8.3
		Light air	35.7	38.5	33.3	25
		Stagnant	14.3	-	22.3	66.7
2.13	Do you have sufficient daylight in your office?	A bit too much	-	-	-	16.7
		It‘s ok	100	61.5	72.2	25
		Could be more	-	38.5	28.7	58.3
2.14	Are you annoyed by direct sunlight at your workstation?	Yes, frequently	21.4	-	11.1	-
		Occasionally	14.3	30.8	11.1	25
		Rarely	28.6	38.5	11.1	25
		Never	35.7	30.8	66.7	50
2.15	Are you annoyed by reflections or too bright surfaces on your computer screen?	Yes, frequently	14.3	-	11.1	-
		Occasionally	21.4	46.1	27.8	16.6
		Rarely	21.4	7.8	22.2	41.7
		Never	42.9	46.1	38.9	41.7
2.16	Do you have sufficient artificial light in your office?					
		A bit too much	-	7.7	-	8.3
		It‘s ok	78.6	69.2	77.8	91.7
		Could be more	21.4	23.1	22.2	-

Table 2: Summary of questionnaire response percentage of occupants Cont'd.

2.17	During the day, do you have to turn on the lights in your office before you can work?	Yes	78.6	61.5	83.3	91.7
		No	21.4	38.5	16.7	8.3

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Indoor Environment (thermal ,visual etc)

2.0	Question	Category	R.T.	W.T.C.	P.T.	H.T.
2.18	What is your perception of the lighting levels in your office?	Bright	28.9	38.5	38.9	25
		Slightly bright	7.1	-	11.1	-
		Ok	64.3	53.8	38.9	66.7
		Slightly dim	-	-	11.1	-
		Dim	-	7.7	-	8.3
2.19	How would you prefer the lighting levels in your office?	A bit brighter	50	53.8	27.8	66.7
		No change	50	46.2	72.2	33.3
		A bit dimmer	-	-	-	-
2.20	Are you annoyed by noise in your office?	Yes, frequently	14.3	23.1	-	16.7
		Occasionally	21.4	23.1	16.7	16.7
		Rarely	50	46.1	33.3	50
		Never	14.3	7.7	50	16.6
2.21	Evaluate the distance of your workstation from the window?	Too close	-	7.7	11.1	16.7
		It‘s ok	85.7	61.1	88.9	75
		Too far	14.3	30.8	-	8.3
2.22	Do you have enough privacy in your office to work undisturbed?	Yes	35.7	15.4	27.8	33.3
		It‘s ok	50	61.5	44.4	66.7
		No	14.3	23.1	27.8	-

Table 2: Summary of questionnaire response expressed in percentage of occupants Cont’d.

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Table 3: Summary of questionnaire response expressed in percentage of occupants

Operation and Accessibility of the systems and system controls						
3.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
3.1	Can you open the windows of your office if required?	Very easily	14.3	16.2	-	-
		Easily	21.4	56.8	11.1	-
		It‘s ok	7.1	15	16.7	-
		complicated	21.4	-	-	-
		Not at all	35.7	12	72.2	-
3.2	How important is it for you to have the possibility to open the windows?	Important	71.4	53.9	54.4	50
		Don‘t know	14.3	7.1	16.7	8.3
		Not so important	14.3	38.5	28.9	41.7
3.3	Can you decide independently when to open/close the windows in your office or do you have to negotiate with other people?	Myself	50	15.4	44.4	-
		With others	50	84.6	55.6	-
3.4	Are you satisfied with the possibility to ventilate your office?	Very satisfied	35.7	53.7	27.8	25
		It‘s ok	50	30.7	44.4	58.4
		Less satisfied	14.3	15.6	27.8	16.6
3.5	Do you in the morning ventilate your office before switching on the air-conditioner?	Yes, frequently	-	-	-	-
		Occasionally	8	-	10	6
		Rarely	-	-	1	-
		Never	92	-	89	94
3.6	Can you open/close the curtains/blinds easily?	Very easily	14.3	7.7	33.3	16.7
		Easily	28.6	30.8	22.2	25
		It‘s ok	50	30.8	27.8	41.7
		Complicated	-	30.8	11.1	16.7
		Not at all	7.1	-	5.6	-

Table 3: Summary of questionnaire response expressed in percentage of occupants Cont'd.

Operation and Accessibility of the systems and system controls						
3.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
3.7	How important is it for you to have the possibility to operate the curtains/blinds?	Very important	7.1	23.1	27.8	58.5
		Important	50	23.1	33.3	41.5
		Don't know	7.1	15.4	-	-
		Not so Important	35.7	30.8	33.3	-
		Unimportant	-	7.7	5.6	-
3.8	Can you decide independently when to operate the curtains/blinds in your office or do you have to negotiate with other people?	Myself	50	23.1	33.3	41.7
		With others	35.7	53.8	38.9	41.7
		Not applicable	14.3	23.1	27.8	16.7
3.9	Is the thermostat (air-conditioning regulator) easily accessible to you?	Very easily	7.1	-	27.8	63.3
		Easily	57.1	-	22.2	16.7
		It's ok	21.4	-	16.7	-
		Not at all	14.3	-	33.3	20
		Not applicable	-	-	-	-
3.10	Can you regulate the temperature on your own or do you have to negotiate with other people?	Myself	28.6	-	22.2	33.3
		With others	57.1	-	55.5	58.3
		Not applicable	14.3	-	22.2	8.3
3.11	How satisfied are you with the position of the air conditioner to your workspace?	Very satisfied	7.1	-	22.2	-
		Satisfied	-	-	22.2	25
		It's ok	64.3	-	38.9	50
		Less satisfied	28.6	-	16.7	25
		Not satisfied at all	-	-	-	-
		Not applicable	-	-		-
3.12	Are there fans in your office?	yes	-	-	-	-
		no	100	100	100	100

Table 3: Summary of questionnaire response expressed in percentage of occupants Cont'd.

Operation and Accessibility of the systems and system controls						
3.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
3.13	Do you wish there were fans installed in your office?	yes	55.5	60	56.7	57
		No	44.5	40	43.3	43
3.14	Is the light switch easily accessible to you?	Very easily	7.1	30.8	44.4	25
		Easily	35.7	15.4	27.8	33.3
		It's ok	50	46.1	22.2	41.7
		Complicated	-	-	-	-
		Not at all	7.1	7.7	5.6	-
3.15	Can you decide independently when to switch on/off the light in your office or do you have to negotiate with other people?	Myself	42.9	38.5	50	33.3
		With others	57.1	68.5	50	66.7

Table 4: Summary of questionnaire response expressed in percentage of occupants

Awareness of the Functionality of the Building Control Systems						
4.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
4.1	How satisfied are you with the fan in your office?	NO fans				
4.2	How satisfied are you with the air-conditioners in your office?	Very satisfied	22.1	-	16.7	-
		Satisfied	28.6	-	38.9	15.7
		It's ok	35	-	22.2	34.3
		Less satisfied	7.1	-	16.7	50
		Not satisfied at all	7.1	-	5.6	-
		Not applicable	-	-	-	-
4.3	Are you sufficiently informed about how the following systems work in your office?					

Table 3: Summary of questionnaire response expressed in percentage of

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: Summary of questionnaire response expressed in percentage of occupants Cont'd.
Table 4

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Awareness of the Functionality of the Building Control Systems						
4.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
4.3a	Ventilation?	Very well informed	35.7	15.4	27.8	10
		It's ok	42.9	46.1	44.4	16.7
		Insufficiently informed	21.4	38.5	27.8	73.3
4.3b	Air – conditioning?	Very well informed	50	-	33.3	-
		It's ok	42.9	-	33.3	58.3
		Insufficiently informed	7.1	-	33.4	41.7
4.3c	Lighting	Very well informed	50	30.8	33.3	8.3
		It's ok	42.9	46.1	44.4	50
		Insufficiently informed	7.1	23.1	22.2	41.7
4.3d	Blind protection?	Very well informed	28.6	7.7	33.3	8.3
		It's ok	57.1	61.5	33.4	50
		Insufficiently informed	21.4	30.8	33.3	41.7
4.4	Have you ever had a training concerning the systems in your office?	yes	21.4	46.2	38.9	41.7
		no	78.6	53.8	61.1	58.3
4.4a	If ―yes‖, how do you evaluate this training?	Very good	48	-	-	-
		ok	52	100	100	100
		Not so good	-	-	-	-
4.4b		Yes	35.7	58.5	42.8	72

: Summary of questionnaire response expressed in percentage of occupants Cont'd.

	If ―no‖, would you be interested in such training?	Don‘t know	21.4	15.4	42.8	25
		No	42.9	26.1	14.4	3

Table 4

Awareness of the Functionality of the Building Control Systems

4.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
4.5	To whom do you refer in case of a problem with the building systems (Cooling, Lighting, etc.)?	Building managers	100	100	100	100
		Maintenance Dept	-	-	-	-
		Other, please state	-	-	-	-
4.6	Are you satisfied with the system services and support in your office?	Yes	28.6	23.1	33.3	16.7
		It‘s ok	57.1	53.8	50	66.7
		No	14.3	23.1	16.7	16.7

Table 5: Summary of questionnaire response expressed in percentage of occupants

Energy Implications of user Control Actions

5.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
5.1	Do you think that you can influence building energy consumption in the way you operate building systems?	yes	50	46.1	22.2	41.7
		Don‘t know	28.6	53.8	61.1	25
		no	21.4	-	16.7	33.3
5.2	Do you think about energy conservation, when you operate building systems?	yes	64.3	92.3	66.7	58.3
		Don‘t know	21.4	7.7	11.1	25
		no	14.3	-	22.2	16.7
5.3	What temperature range do you normally set your air-conditioner?	18-20ºC	87.1	-	75.5	68.3
		21-23ºC	12.9	-	25.5	31.7
		24-26ºC	-	-	-	
		27-29ºC	-	-	-	

: Summary of questionnaire response expressed in percentage of occupants Cont'd.

5.4	Do you switch off your air-conditioner during short absence from the office?	yes	42.9	-	44.4	41.7
		no	57.1	-	55.6	58.3

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Table 5

Energy Implications of user Control Actions

5.0	Question	Category	R.T.	W.T.C.	P.T.	H.T.
5.5	If yes, choose the range of time that you would normally switch off the AC when you have to leave the office.	Under 20 mins	-	-	-	-
		21-40 mins	-	-	8.3	-
		41-60 mins	76.4	-	19.7	-
		1-2 hours	23.6	-	42	64
		2-3 hours	-	-	30	25
		Above 3 hours	-	-	-	11
5.6	Which office environment would you prefer to work in?	Naturally ventilated	-	15.4	16.7	16.7
		Air-conditioned	42.9	15.5	38.9	25
		A bit of both	57.1	69.2	44.4	58.3
5.7	How do you operate the air-conditioning system in your office?	Constant temperature	28.6	-	44.4	74.6
		Regulate with the thermostat	57.1	-	22.2	10
		Both a different times	14.3	-	33.3	15.4
5.8	How often do you use the lifts in this building?	All the time	94.1	86.9	86.7	83.3
		sometimes	1.6	7.4	13.3	16.7
		rarely	4.3	5.7	-	-
		Other, please state	-	-	-	-

: Summary of questionnaire response expressed in percentage of occupants Cont’d.

Table 6: Summary of questionnaire response expressed in percentage of occupants

Personal Preferences of organising the current/Ideal working space; Health complaints						
6.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
6.1	How important are the effects of plants on indoor climate to you?	Very important	35.7	53.8	27.8	25
		important	7.1	30.8	27.8	8.3
		Don‘t know	28.6	7.7	33.3	50
		Not so important	14.3	7.7	11.1	8.3
		unimportant	14.3	-		8.3

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Table 6: Summary of questionnaire response expressed in percentage of occupants Cont'd.

Personal Preferences of organising the current/Ideal working space; Health complaints

6.0	Question	Category	R.T.	W.T.C.	P.T.	H.T.
6.2	Are you satisfied with the available possibilities to personalize your working place (Furniture, Plants, Photos…)?	Very satisfied	-	23.1	16.7	16.7
		Satisfied	28.6	30.8	16.7	41.7
		It‘s ok	71.4	46.1	50	25
		Less satisfied	-	-	11.1	-
		Not satisfied at all	-	-	5.6	16.7
6.3	Generally, how do you find your office climate?	Very good	7.7	7.7	16.7	-
		Good	42.9	30.8	22.2	58.3
		It‘s ok	42.9	61.5	44.4	41.7
		Not so good	7.1	-	16.7	-
		Poor	-	-	-	-
6.4	Are you satisfied about your office layout?	yes	85.7	69.2	72.2	83.3
		no	14.3	30.8	27.8	16.7
6.5	What are the most important features of ideal working place from your point of view? Classify (from 1 to 10), in order of importance in a work environment, the items indicated (with the least mean vote as the most important).	Thermal comfort	3.29	3.23	3.29	2.73
		Air quality	2.79	3.38	3.18	4.27
		Visual comfort	4.50	3.62	4.88	3.91
		Acoustic comfort	6.07	3.85	4.88	5.73
		Acoustic and visual privacy	6.14	3.85	4.35	4.45
		Comfort of furnishings and dimensions of workstation	3.86	2.85	6.35	4.82
		Fire safety	3.43	2.15	5.12	1.64
		Security against theft	5.07	2.31	6.35	4.55
		Liberty to control your own work environment	6.43	3.85	7.61	4.73

Table 6: Summary of questionnaire response expressed in percentage of occupants Cont'd.

		Beauty/Aesthetics of the building	7.64	4.85	9.24	5.55
		Other, please state	-	-	-	-

Personal Preferences of organising the current/Ideal working space; Health complaints

6.0	Question	Category	R.T.	W.T.C.	P.T.	H.T.
6.6	Which improvement measures in your office would you consider as most urgent? Classify (from 1 to 10), in order of importance in a work environment, the items indicated (with the least mean as the most important).	Thermal comfort	2.50	1.92	2.33	2.50
		Air quality	1.86	1.92	2.39	3.92
		Visual comfort	3.57	2.77	2.50	4.17
		Acoustic comfort	5.79	3.92	4.00	5.08
		Acoustic and visual privacy	4.46	4.00	4.22	4.33
		Comfort of furnishings and dimensions of workstation	5.21	3.23	5.83	4.50
		Fire safety	5.64	1.62	5.67	4.08
		Security against theft	6.57	2.31	6.83	6.50
		Liberty to control your own work environment	7.57	4.15	6.72	5.67
		Beauty/Aesthetics of the building	8.43	5.54	8.17	6.92
		Other, please state	-	-	-	-
6.7	Do you have any health complaints?					
	Backache	Frequently	21.4	15.4	33.3	-
		Occasionally	50	61.5	27.8	41.7
		Rarely	28.6	7.7	16.7	41.7
		Never	-	15.4	22.2	16.7

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Table 6: Summary of questionnaire response expressed in percentage of occupants Cont'd.

	Eyestrain/ burning	Frequently	64.3	46.2	27.8	16.6
		Occasionally	-	30.8	38.9	50
		Rarely	35.7	15.4	-	16.7
		Never	-	7.7	33.3	16.7

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Personal Preferences of organising the current/Ideal working space; Health complaints

6.0	Question	Category	R.T.	W.T.C.	P.T.	H.T.
	Headache	Frequently	57.1	15.4	-	16.6
		Occasionally	-	38.5	44.4	50
		Rarely	42.9	38.5	22.2	33.3
		Never	-	7.7	33.3	-
	General Fatigue	Frequently	42.9	15.4	16.7	-
		Occasionally	35.7	69.2	44.4	41.7
		Rarely	21.4	7.7	22.2	58.3
		Never		7.7	16.7	-
	Respiratory problems	Frequently	-	-	-	-
		Occasionally	-	15.4	22.2	8.3
		Rarely	57.1	23.1	33.3	41.7
		Never	42.8	61.5	44.4	50
	Sore throat	Frequently	-	-	-	-
		Occasionally	35.7	23.1	27.8	25
		Rarely	42.9	28.5	27.8	16.7
		Never	21.4	38.5	44.4	58.3

Table 6: Summary of questionnaire response expressed in percentage of occupants Cont'd.

Personal Preferences of organising the current/Ideal working space; Health complaints						
6.0	**Question**	**Category**	**R.T.**	**W.T.C.**	**P.T.**	**H.T.**
	Stiffness of limbs	Frequently	21.4	15.4	-	-
		Occasionally	-	7.7	27.8	-
		Rarely	42.9	23.1	27.8	33.3
		Never	35.7	53.8	44.4	66.7
	Nasal irritation	Frequently	-	-	-	-
		Occasionally	28.5	23.1	33.3	16.7
		Rarely	50	38.5	27.8	25
		Never	21.4	38.5	38.9	58.3
	Other , please state	Frequently	-	-	-	-
		Occasionally	-	-	-	-
		Rarely	-	-	-	-
		Never	-	-	-	-
	Neck Pain	Frequently	28.6	-	-	8.3
		Occasionally	14.2	38.5	33.3	25
		Rarely	28.6	23.1	38.9	41.7
		Never	28.5	38.5	27.8	25
	Rheumatic Pains	Frequently	21.4	-	-	-
		Occasionally	-	-	27.8	25
		Rarely	35.7	38.5	27.8	16.7
		Never	42.8	61.5	44.4	58.3

APPENDIX D: Individual reductions of parameters' to initial cooling loads

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Table 6: Summary of questionnaire response expressed in percentage of occupants Cont'd.

The following Table shows results of the base case and the individual parameter cooling loads of each building with the percentage increase or reduction to the base case.

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Table 1: Simulated annual cooling loads for the base case and individual parameters and their percentage difference to the base case (R.T. building)

Parameters	Total cooling loads (kWh.m^{-2}.a^{-1})	% increase/ decrease
Base case	115.34	100
$G_{0.5}$	110.51	-4.2
$G_{0.4}$	106.30	-7.8
$G_{0.3}$	99.07	-14.1
L_e	110.72	-4.0
$DV_{m.1}$	211.62	+83.5

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Table 1: Simulated annual cooling loads for the base case and individual parameters and their percentage difference to the base case (R.T. building) Cont'd.

Parameters	Total cooling loads (kWh.m^{-2}.a^{-1})	% increase/ decrease
$DV_{m.2}$	201.82	+75
$NV_{m.1}$	100.42	-12.9
$NV_{m.2}$	101.25	-12.2
$NV_{m.3}$	101.68	-11.8
$NV_{m.4}$	102.84	-10.8
SOe	109.32	-5.2
BS_{12}	109.32	-5.2
BS_{1}	111.02	-3.7
BS_{2}	112.74	-2.3
BS_{F}	104.67	-9.3
TM_{a}	119.04	+3.2
I_{51}	116.35	+1.0
I_{101}	115.91	+0.5
I_{52}	115.58	+0.2
I_{102}	115.31	0

Table 2: Simulated annual cooling loads for the base case and individual parameters and their percentage difference to the base case (W.T. C building)

Parameters	Total cooling loads (kWh.m^{-2}.a^{-1})	% increase/ decrease
Base case	149.75	100
$G_{0.5}$	136.22	-9
$G_{0.4}$	123.95	-17.2
$G_{0.3}$	109.87	-26.6
L_{e}	139.18	-7.1
$DV_{m.1}$	267.35	+78.5
$DV_{m.2}$	255.92	+70.9
$NV_{m.1}$	135.94	-9.2
$NV_{m.2}$	137.63	-8.1
$NV_{m.3}$	138.30	-7.6
$NV_{m.4}$	139.91	-6.6

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Table 2: Simulated annual cooling loads for the base case and individual parameters and their percentage difference to the base case (W.T. C building) Cont'd.

SOe	109.32	-5.2
BS_{12}	139.49	-6.9
BS_{1}	138.44	-7.6
BS_{2}	140.05	-6.5

Parameters	Total cooling loads (kWh.m^{-2}.a^{-1})	% increase/ decrease
BS_{F}	128.30	-14.3
TM_{a}	142.92	-4.6
I_{51}	143.33	-4.3
I_{101}	143.32	-4.3
I_{52}	145.10	-3.1
I_{102}	145.21	-3.0

Table 3: Simulated annual cooling loads for the base case and individual parameters and their percentage difference to the base case (P.T. building)

Parameters	Total cooling loads (kWh.m^{-2}.a^{-1})	% increase/ decrease
Base case	168.44	100
$G_{0.5}$	154.23	-8.4
$G_{0.4}$	146	-13.3
$G_{PT0.4}$	141.79	-15.8
$G_{0.3}$	138.65	-17.7
L_{e}	151.24	-10.2
$DV_{m.1}$	281.57	+67.2
$DV_{m.2}$	281.09	+66.9
$NV_{m.1}$	167.62	-0.5
$NV_{m.4}$	167.34	-0.7
$NV_{m.5}$	167.39	-0.6
SOe	161.56	-4.1
BS_{11}	158.72	-5.8
BS_{12}	161.56	-4.1
BS_{F}	150.2	-10.8
TM_{a}	174.52	+3.6

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Table

I_{51}	165.45	-1.8
I_{101}	165.39	-1.8
I_{52}	166.42	-1.2
I_{102}	166.37	-1.2

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4: Simulated annual cooling loads for the base case and individual parameters and their percentage difference to the base case (H.T. building)

Parameters	Total cooling loads (kWh.m^{-2}.a^{-1})	% increase/ decrease
Base case	235.16	100
$G_{0.18}$	175.44	-25.4
$G_{0.24}$	182.06	-22.6
$G_{0.3}$	189.37	-19.5
$G_{0.2}$	179.29	-23.8
L_e	217.60	-7.5
$DV_{m.1}$	332.75	+41.5
$DV_{m.2}$	318.90	+35.6
$NV_{m.1}$	222.05	-5.6
$NV_{m.4}$	220.26	-6.3
$NV_{m.5}$	221.33	-5.9
$NV_{m.6}$	222.58	-5.3
SOe	226.87	-3.5
BS_{11}	223.80	-4.8
BS_{HT11}	221.56	-5.8
BS_{12}	226.87	-3.5
BS_F	207.04	-12
TM_a	234.55	-0.3
I_{51}	250.06	+6.2
I_{101}	249.78	+6.2
I_{52}	252.51	+7.4
I_{102}	252.51	+7.4

NYANSAPɔ WɔSANE NO BADWENMA

Table

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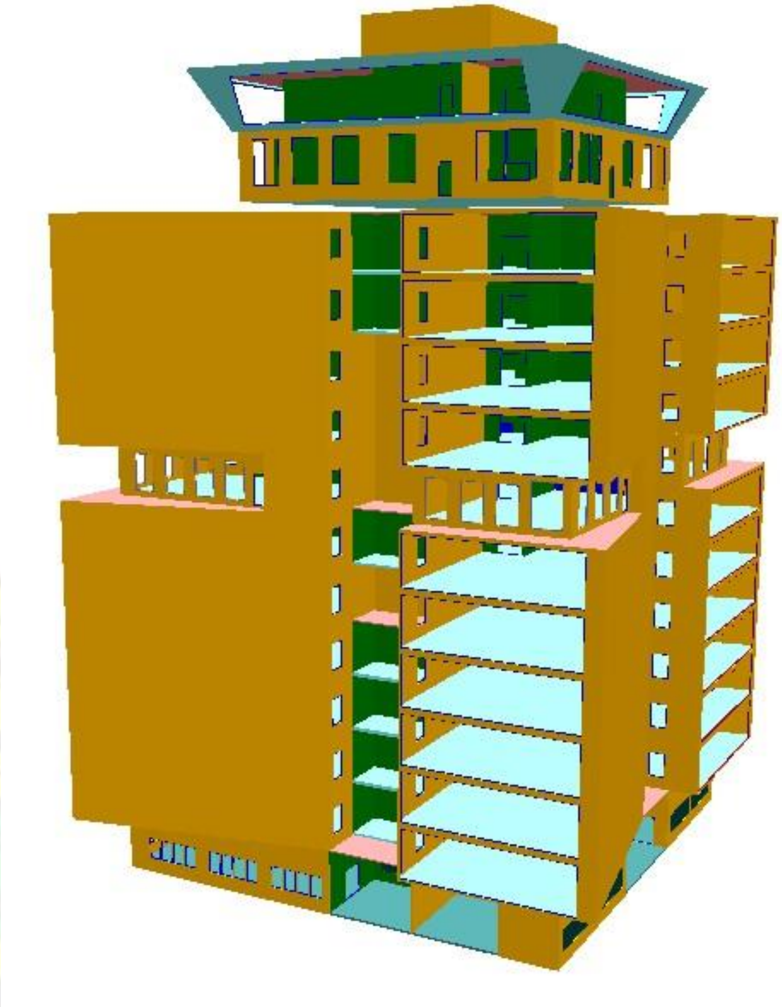
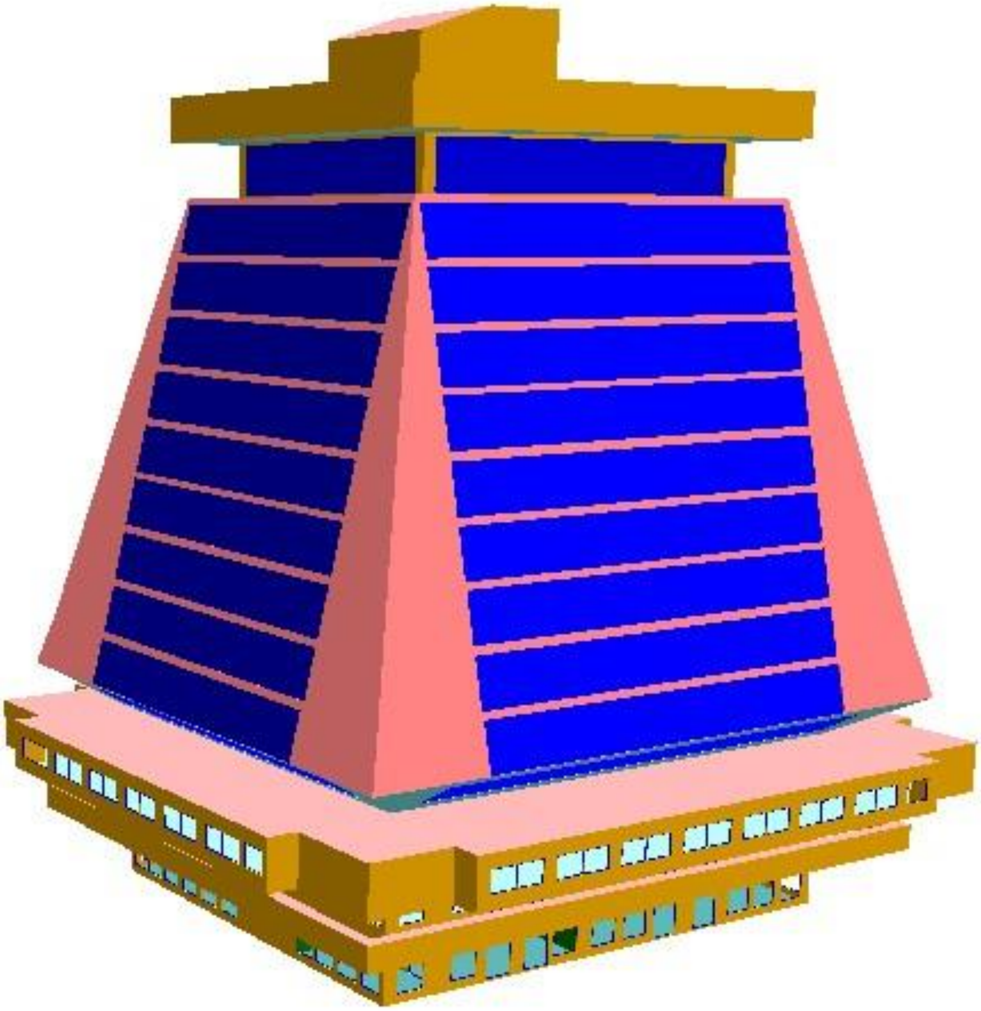
APPENDIX E: Tas Model of Case Study Buildings



RIDGE TOWER BUILDING

WORLD TRADE CENTRE BUILDING

NYANSAPƆ WƆSANE NO BADWENMA



PREMIER TOWER BUILDING

NYANSAPƆ WƆSANE NO BADWENMA

HERITAGE TOWER BUILDING

NYANSAPƆ WƆSANE NO BADWENMA

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APPENDIX F: Construction Tables

RIDGE TOWER

Building Element	Material Layer	Width (mm)	Conductivity (W/m^2)	Density (kg/m^3)	Solar Absorptance Exterior	Solar Absorptance Interior	U-value (W/m$^{2\cdot o}$C)
Wall	Plaster	10	1.73	1890	0.40	0.40	2.10
	Block	150	0.85	400			
	Plaster	10	1.73	1890			
Floor	Carpet	10	0.06	186	0.40	0.70	1.40
	Tile/13	15	1.75	2400			
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
Upper floor/ Ceiling	Tile/13	15	1.75	2400	0.65	0.50	1.40
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
	Soffit Plaster	20	1.73	1890			
Door Pane	Glass door	25	1	-	0.05	0.05	5.8
Door & Window Frames	Aluminium frame	50	204	2700	0.50	0.50	4.9
	Opt-clear/4	12	1	-	0.29	0.19	2.8

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Window Pane	Cavity/1	10	-	-			
	Opt-clear/4	12	1	-			

WORLD TRADE CENTRE

Building Element	**Material Layer**	**Width (mm)**	**Conductivity (W/m^2)**	**Density (kg/m^3)**	**Solar Absorptance Exterior**	**Solar Absorptance Interior**	**U-value (W/m$^{2\cdot o}$C)**
Wall	Plaster	10	1.73	1890	0.40	0.40	2.10
	Block	150	0.85	400			
	Plaster	10	1.73	1890			
Floor	Tile/12	15	2	2700	0.40	0.79	2.8
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
Upper floor/ Ceiling	Tile/12	15	1.75	2700	0.79	0.50	0.40
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
	Soffit Plaster	20	1.73	1890			
Door Pane	Glass door	25	1	-	0.05	0.05	5.8
Door & Window	Aluminium frame	50	204	2700	0.50	0.50	4.9

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Frames							
Window Pane	Opt-clear/3	10	1	-	0.23	0.16	2.9
	Cavity/1	10	-	-			
	Opt-clear/3	10	1	-			

PREMIER TOWER

Building Element	**Material Layer**	**Width (mm)**	**Conductivity (W/m^2)**	**Density (kg/m^3)**	**Solar Absorptance Exterior**	**Solar Absorptance Interior**	**U-value (W/m$^{2.o}$C)**
Wall	Plaster	10	1.73	1890	0.40	0.40	2.10
	Block	150	0.85	400			
	Plaster	10	1.73	1890			
Floor	Carpet	10	0.06	186	0.40	0.70	1.40
	Tile/13	15	1.75	2400			
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
Upper floor/ Ceiling	Tile/13	15	1.75	2400	0.79	0.50	1.40
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
	Soffit Plaster	20	1.73	1890			

NYANSAPO WO SANE NO BADWEMMA

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Door Pane	Glass door	25	1	-	0.05	0.05	5.8
Door & Window Frames	Aluminium frame	50	204	2700	0.50	0.50	4.9
Window Pane	Opt-clear/3	12	1	-	0.24	0.16	2.9
	Cavity/1	10	-	-			
	Opt-clear/3	12	1	-			

HERITAGE TOWER

Building Element	Material Layer	Width (mm)	Conductivity (W/m^2)	Density (kg/m^3)	Solar Absorptance Exterior	Solar Absorptance Interior	U-value (W/m$^{2\cdot o}$C)
Wall	Plaster	10	1.73	1890	0.40	0.40	2.10
	Block	150	0.85	400			
	Plaster	10	1.73	1890			
Floor	Timber/27	20	0.29	770	0.40	0.60	2.4
	Concrete screed	25	1.83	2400			
	Concrete	150	1.4	2360			
Upper floor/ Ceiling	Tile/13	15	1.75	2400	0.4	0.65	2.8
	Concrete screed	25	1.83	2400			

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	Concrete Soffit Plaster	150 20	1.4 1.73	2360 1890			
Door Pane	Glass door	25	1	-	0.05	0.05	5.8
Door & Window Frames	Aluminium frame	50	204	2700	0.50	0.50	4.9
Window Pane	Opt-clear/3	10	1	-	0.12	0.12	5.6

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