

# ENERGY EFFICIENT BUILDING TECHNOLOGIES IN HOT AND HUMID CLIMATES

## Approach to Optimization of Design Parameters and Climate-Based Indoor Air Temperature Standards


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# Energy Efficient Building Technologies in Hot And Humid Climates

Approach to the Optimization of Design Parameters and Climate-based Indoor Temperature Standards

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DEDICATION:

To my beloved father

ABSTRACT:

This study explores energy efficient building technologies, specifically in hot and humid climates. The study focuses on optimization of design parameters and climate-based indoor temperature standards. Previous studies in the energy efficiency in buildings in hot and humid climates used the PMV-Fanger Model as a reference for the indoor thermal comfort but field studies have shown that it does not adequately satisfy the requirements of thermal comfort in these regions.

Field study results for the thermal comfort in hot and humid climates based on the Humphrey's equations were applied for comparison of energy efficiency and used to define the indoor thermal comfort limits for both free-running (FRB) and air-conditioned buildings (ACB). Parametric models were generated and used to investigate the influence of various design parameters in terms of the indoor thermal comfort and cooling energy demand. Comparative analysis was done with both Nicols/Humphrey's and ATG (Adaptive temperature limits) method.

The study shows that, design parameters have a potential of keeping the indoor thermal comfort of a FRB below the maximum limit of 80% acceptability for 90% of annual office working hours and reduce the annual cooling energy demand by 13% to 18%. Further analysis shows that the indoor thermal comfort of a FRB is inversely proportional to the total thermal transmittance ($\bar{U}$) of the façade construction.

From the analysis of parametric models, it can be concluded that design parameters have significant influence on the indoor thermal comfort and reduction of cooling energy demand for both FRB and ACB respectively. The use of various design parameters in buildings in a hot and humid climate is recommended as a means to regulate the indoor thermal comfort and lower the cooling energy demand.

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## 1.0 Chapter One

# 1.1 Introduction

Buildings are designed to satisfy several purposes including safety, indoor comfort, spatial requirements and social interaction. Safety has to do with protection of the occupants from outdoor hazards while indoor comfort combines the aspect of thermal, acoustic and air quality. Spatial requirements expresses the needs of occupants/owners of the building e.g. for working (office), living (house), concert hall (entertainment) and other purposes. These requirements are fulfilled by the use of different construction techniques, materials, colors and textures depending on the design. For thermal comfort, the building must act as a barrier to transform the outdoor climate from the often extreme and unbearable conditions to conditions suitable for indoor activities. Thermal comfort is one of the main focal points of this study.

The building measures taken to achieve suitable indoor thermal conditions vary according to the climate. The close relationship between climate and buildings was recognized long ago. The Roman Architect Vitruvius wrote, “It is obvious that designs for homes ought to conform to the diversities of climate”, (Flavin, 1980). Tropical climate regions are found in Africa, India, the northern part of South America, Thailand, Indonesia and Malaysia. Apart from sharing climatic conditions, countries in these regions are economically ranked as developing countries. Furthermore, the building industry in these countries is growing at an alarming rate.

However, the noticeable feature of these new buildings is the application of the technology used and developed for countries with quite different climatic conditions, specifically European countries. The ultimate result is buildings, which are not efficient in terms of energy consumption and which are a burden to the economy of these countries. The high energy consumption of buildings in these regions is mostly linked to indoor cooling. This becomes a problem for the environment and the users or owners of the buildings due to the high cost of running and maintaining such buildings. Furthermore, energy unreliability makes the situation worse as it gives the occupants little control over the comfort of the space they occupy. “This results in a combination of sensory deprivation and a lack of influence in determining individual environment”, (Jones, 1998).

The issue of energy efficiency for the buildings in hot humid climates has to be tackled by focusing on the design parameters[1], climate and its influence on the way indoor thermal comfort can be achieved. “When designing an individual building, the general outdoor climate is to be regarded as a given condition,” (Rosenlund, 2000).An understanding of the indoor thermal comfort requirements to be achieved, specifically in such climates plays a role in energy efficiency. For several years, designers have relied on ISO 7730 as a general rule to define thermal comfort in hot and humid climates. “Field studies conducted in tropical climates have found that the International standard for indoor climate, ISO7730 based on the Fanger’s predicted mean vote (PMV/PPD) equations, does not adequately describe comfortable conditions”, (Nicol, 2004).

Due to the fact that field studies in the tropics have shown that ISO7730 does not fully address the comfort requirements for these regions, there is a need to define the ranges of

[1] Design parameters: construction techniques, materials, shading, insulation and services.

comfort appropriate largely for tropical populations. Furthermore, most of the comfort studies have predominantly been centred on temperate and cool climates, where populations are accustomed to high living standards. The situation differs tremendously in terms of economy when comparisons are drawn with tropical regions. “Over most of tropics, only passive means can be employed to protect building interior from the adverse effects of climate due to economic situations” (Ahmed, 1995).

This research aims to explore energy efficient building technologies in hot and humid climates (tropical regions), on the basis of an optimal combination of design parameters and their influence on indoor thermal comfort. It is obvious that most of the design parameters have not been emphasized by present day designers due to the presence of mechanistic methods.”It is becoming increasingly obvious that energy efficiency of buildings cannot be resolved exclusively by mechanistic approach to thermal comfort” (Piechiwski, 2007). The approach to this study embraces three stages:

(a) An analysis of various construction techniques, materials and design for selected cases, in terms of thermal comfort and energy consumption.
(b) The development of parametric models for analysis of various design parameters e.g. materials, shading, insulation, construction techniques and services.
(c) The evaluation of the performance of parametric models through comparative analysis and draw conclusions.

## 1.2 Problem Statement

The current status of buildings in tropical regions does not address the issue of energy efficiency. This leads to an enormous increase in the energy demands on such buildings which are mostly dominated by air-conditioning systems. Also, the thermal comfort standards used in hot and humid climate regions does not adequately address the requirements for these regions. Fanger’s PMV model which has been used worldwide does not fully address the thermal requirements of these regions as field work research shows (Nicol, 2004). To some extent these standards necessitate high energy consumption.

Theoretically it is obvious that design parameters have an influence on the energy efficiency and thermal comfort of the buildings in which they are used. However, there is no study which has focused on the influence of these design parameters in both energy efficiency and thermal comfort, specifically in hot and humid climates. How far the optimization of various design parameters and the use of climate-based indoor air temperature standards can result in energy reduction in such climates is the regarding knowledge that needs to be filled by this research.

## 1.3 Research Objective

The main objective of this study is to explore various energy efficient building technologies in a hot and humid climate.

## 1.4 Specific Objectives

(a) To examine and analyze the performance of existing buildings in a hot humid climate in terms of energy consumption.
(b) To search for alternative construction techniques and materials to improve energy efficiency and indoor thermal comfort.
(c) To seek a better definition of thermal comfort in hot humid climate and integrate it as a means to reduce energy consumption.

(d) To provide options for designers in a hot and humid climate for applications of energy efficient building technologies.

### 1.5 Academic Objective

This research aims to study the influence of the optimization of various design parameters e.g. materials, construction techniques and services in hot humid climates in terms of the energy efficiency of the buildings based on the climate-based thermal comfort standards. How far the considerations of those design parameters have an influence in the energy efficiency in hot and a humid climate is the regarding knowledge which will benefit architects/ designers and building professionals in these regions.

### 1.6 Research Questions

(a) What is the performance of existing buildings in a hot and humid climate in terms of thermal comfort and energy consumption?
(b) In what ways and to what extent do various construction techniques, materials and design influence the energy consumption of buildings in hot humid climate?
(c) What is the proper way of expressing indoor thermal comfort in a hot humid climate region?
(d) What is the effect of optimizing various design parameters and climate-based indoor comfort temperatures in energy reduction for buildings in a hot and humid climate?

### 1.7 Scope of the Study

The scope of this study is limited to the following aspects:

(a) The climatic context is limited to tropical climate, specifically hot humid climates. Typical case studies have been taken from Dar es Salaam[2].
(b) The study is limited to office buildings which are categorized by various construction techniques.

### 1.8 Structure of the Study

This research will be executed according to the following methodology:

#### 1.8.1 A literature review

In this study a literature review will be done to address the following aspects:

(i) To establish and gain an understanding of the state of the art on the subject of energy efficient building technology in other climatic regions. Also to gain an understanding of other factors which have an influence on the energy efficiency of the buildings.
(ii) To establish a benchmark for a proper definition of thermal comfort in hot and humid climates based on the previous research into the subject of thermal comfort in hot humid climates and to analyze its influence on the energy efficiency of buildings in the region.
(i) To establish a guidance and reference on how to analyze various climatic data on the hot and humid climate, so as to retrieve reliable and proper information necessary for energy efficiency analysis.

[2] Dar es Salaam: Commercial Centre of Tanzania in East Africa Region.

### 1.8.2 Analysis of Climate Data

Climatic data on the hot and humid climates from Dar es Salaam are analyzed to fulfill the following purposes:

(i) To gain an understanding of the climatic conditions of the context of study. Also to establish options that can be analyzed for the purpose of adapting buildings to the climatic conditions.

(ii) To determine the extent of the cooling energy demanded throughout the year as well as periods of thermal stress.

(iii) To study the basic methods that can be used to properly define thermal comfort in a hot humid climate e.g. Humphrey's formulas, Mahoney Tables[3] and others.

### 1.8.3 Case Studies

At this stage, the selected case study buildings in hot and humid climates are analyzed in terms of the following parameters:

(i) Design:

- Orientation influence.
- Use of shading devices.
- Use of insulation.
- Building services.

(ii) Construction techniques and materials:

- Various wall constructions.
- Thermal mass.

(iii) Energy consumption and thermal comfort.

### 1.8.4 Parametric Models

At this stage the parametric models are developed and used to establish the analysis of energy efficiency on the basis of the various parameters mentioned in Section 1.7.3. These models are used to test the energy efficiency of various design parameters and seek innovative solutions to the problem. Finally the results are analyzed and recommendations will be made on how to use this knowledge in design.

## 1.9 Relevance

This research will form a basis for the development of better energy efficient buildings and for the improvement of the indoor thermal comfort in hot and humid climates. It also seeks to integrate the use of various design parameters so as to yield positive results. The outcome of the research can be applied in the region in several ways:

- It will develop a platform for architects/designers in hot humid regions when it comes to energy efficient building technology application in a design.
- Academic-wise it will develop a platform for the development of further research which can involve construction of experimental buildings and test the outcome. In this respect the knowledge will go beyond parametric modeling and computer simulations.

[3] Table developed by Carl Mahoney (Koenisberger, 1973)

## 2.0 Chapter Two

# 2.1 A Literature Review

This chapter cuts across a number of subjects/fields directly related to the research. It encompasses a review of knowledge from previous studies (necessary) to set the tone for this research. Various issues are discussed from general to specific ones based on the different fields and authors. A knowledge of climates from general climates to the specific-hot and humid climates is discussed in this thesis. Thermal comfort issues from Universal standards e.g. ISO 7730 and ASHRAE Standard 55 to the field studies by Humphreys and others are discussed and presented in detail. A link is made concerning a number of issues on thermal comfort standards, building design and the energy efficiency of buildings, specifically in hot and humid climates.

### 2.2 Part One: Climate

The English Concise Oxford Dictionary defines climate as the region with certain conditions of temperature, dryness, wind, light, etc. Later on this definition of climate is further modified by Givoni who defines it thus:
"The climate of a given region is determined by the pattern of several elements and their combination. The principal climatic elements when human comfort and building design is considered are solar radiation, long wave radiation to the sky, air temperature, humidity, wind and precipitation(rain ,snow, etc.)", (Givoni, 1976).
The subject of energy efficiency in the buildings is all part and parcel of a climate of the region concerned. As an architect/designer takes steps to design, he/she must be able to identify the climatic characteristics of the site in which a building is going to be erected. Therefore, an erected building must be an integral part of the climate in context. There is thus a need to have a clear understanding of the climate of the region under study as it will be emphasized in this chapter.

### 2.3 Elements of Climate

This section discusses the elements of climate.

#### 2.3.1 Air Temperature

Air temperature is the one of the most important elements of climate. The temperature of the air above the earth is mainly determined by the rate of the heating and cooling of the surface of the earth. "The air is transparent to almost all solar radiation, which therefore has an indirect effect on air temperature", (Givoni, 1976).
The DBT, dry bulb temperature (°C, °F or K), is probably the most commonly used unit to describe climate. "DBT affects the thermal response of a building and the amount of heat gain/loss through its envelope, whereas WBT dictates the amount of humidification required during dry winter days and latent cooling under humid summer conditions", (Joseph, Kevin, Tsang, & Liu, 2008).

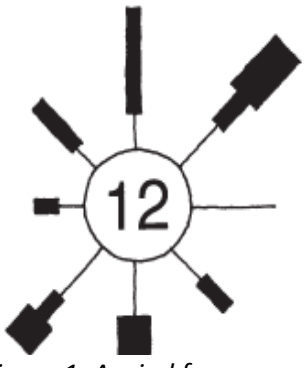


*Figure 1: A wind frequency diagram, a 'wind rose'.*

Air temperature is measured with a dry bulb thermometer protected from solar and heat radiation", (Rosenlund, 2000). This data is generally available in meteorological records in the form of monthly means, maximum and minimum values. The wet bulb temperature (WBT) is the temperature at which vapour saturation occurs.

### 2.3.2 Humidity

Air humidity refers to the water vapour content of the atmosphere. It can be specified as absolute humidity in grams per kg or $m^3$, or as partial vapour pressure (kPa). What is more common however is the expression *relative humidity* –RH (%) which describes the portion of vapour in relation to saturation. Hotter air can contain more vapour than colder air, and when cooled to the limit – the dew point – the surplus condenses. Relative humidity can be measured with electronic hygrometers or with a simple sling hygrometer including a dry bulb and a wet bulb thermometer. Meteorological data on humidity is generally available, often as maximum and minimum mean monthly values or at certain hours of the day.

### 2.3.3 Wind

Another element of the climate is wind. The common type in the tropics is monsoon winds. "At local level wind is the most irregular and varying component of the climate. It is affected by topography, vegetation and surrounding buildings; closeness to the sea may create on and offshore winds", (Rosenlund, 2000). Wind is described in terms of its speed and direction and is measured with an anemometer. Frequency diagrams and wind roses are often drawn for each month of the year or for the main seasons. Figure 1 shows wind frequency diagram, the length of the lines describes the frequencies from different directions, and the thickness describes the wind speed intervals, according to a scale and a legend. The figure in the middle is the percentage of calm. (Rosenlund, 2000)

### 2.3.4 Precipitation

Precipitation may vary considerably from season to season. Data on monthly means, extreme values and maximum precipitation during 24 hour periods are easy to find. Combinations with other elements could be interesting in relation to building design e.g. with strong winds it rains 'horizontally' (driving rain).

### 2.3.5 Solar radiation and sky conditions

Tropical regions receive large amount of solar radiation from the sun. The sun may be described as the 'engine' of the climate since it supplies a large amount of the earth's energy. The sun's path is regular and depends on the latitude and the time of the year. The season also determines the total amount of irradiation throughout the day. High altitudes give more intense solar radiation, because there is less absorption in the relatively thinner layer of atmosphere. The position of the sun may be determined with the help of solar diagrams, of the type available in most standard books on climatic design.
"Short-wave solar radiation is divided into direct (ID) and diffuse (Id) radiation and the sum of these is global radiation (IGL).These are often measured on a horizontal surface ($W/m^2$), but normal (IN) radiation, facing the sun, is commonly used. Values for vertical surfaces in

various directions may also be found. The relation between direct and diffuse radiation varies with the sky conditions", (Rosenlund, 2000).

### 2.4 Hot Humid Climate

According to Atkinson (1953), hot-humid climates were classified as Tropical climates. The general characteristic of the hot humid climate is that of very little seasonal variation throughout the year, the only difference being during the periods with little or more rain and the occurrence of thunder storms. In such climates the air temperature, i.e. dry bulb temperature, reaches a mean maximum during the day of between 27 °C and 32°C, but occasionally it may exceed the latter values. The mean minimum temperature varies between 21°C and 27°C during night periods. It can be observed from the above description that the severe problem dominating this type of climate is overheating which is aggravated by high humidity as shown in Fig. 3 and hence hinders evaporative cooling of the body.
According to the Building Science Corporation, a hot-humid climate region receives more than 20 inches of annual precipitation and either has 3,000 or more hours of 67°F temperature or 1,500 or more hours of 73°F temperature during the warmest six months of the year. In this type of climate, buildings are required to moderate the daytime heating effects of the external air (Givoni 290). In other words, it is important to design buildings whose structure and interior are best able to keep the warm air out. Living in a hot climate can quickly become uncomfortable for its inhabitants because of the extreme heat that builds up by midday. That is why it is important for the buildings' structures to have effective ventilation and an internal temperature below the outdoor level (Givoni 285). The ventilation keeps air moving through the environment and, therefore it keeps the inhabitants cooler.

### 2.5 The Dar es Salaam Climate

Climate data from a hot and humid climate has been analyzed in this study. The region used to represent this climate is Dar es Salaam, the commercial centre of Tanzania. Dar es Salaam is located along the coastal belt of the Indian Ocean (as shown in Figure 2) at a latitude of 6° 53'S and a longitude 39° 12'E. Bodoegaard (1981) classified the Dar es Salaam climate as a hot humid climate, the classification complies with the Mahoney Table of analysis.



*Figure 2: A map of Tanzania showing a position of Dar es Salaam.*

The annual mean maximum temperature varies between 28 °C and 32°C, while the annual mean minimum temperatures varies between 19 °C and 26°C. The monthly mean ranges vary between 4 °C to 9°C as illustrated in Fig.3. The highest temperatures are experienced in December to March, while the coolest period in which Mahoney table indicates relief in thermal comfort is between June and September. Relative humidity

remains high; it is about 75% most of the time, but it may vary from 55 to almost 100%. Vapour pressure is steady in the region of 2500 to 3000 N/m$^2$. The descriptions are evidenced in the chart below which has been created from data collected from Dar es Salaam harbour.

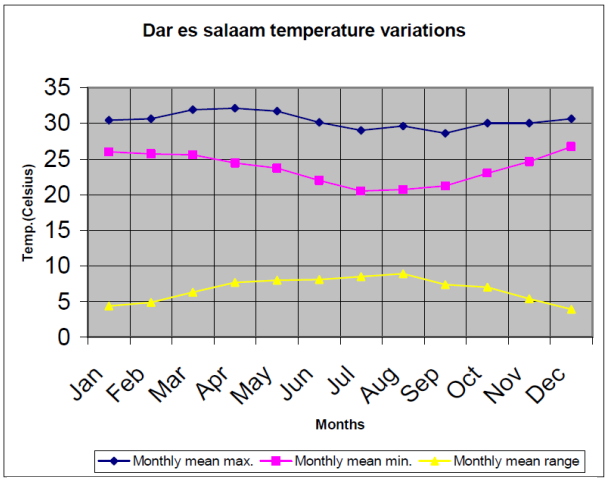



*Figure 3: Temperature variations as recorded at Dar es Salaam Harbor*

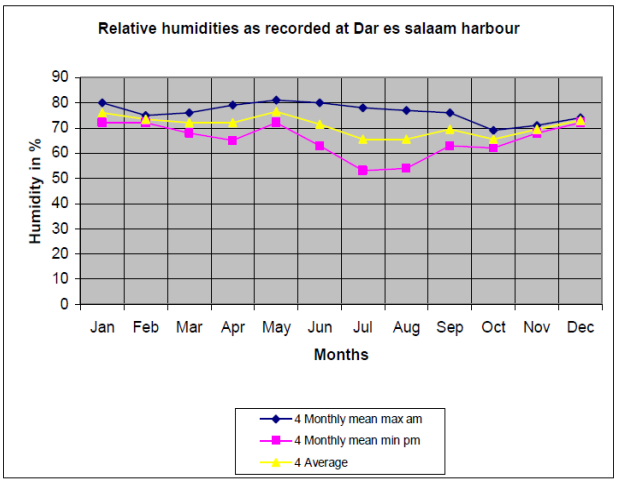



*Figure 3: Humidity variations as recorded at Dar es Salaam Harbor*

*Table 1: Average monthly climate indicators at Dar es Salaam Airport based on the 8 years of historical weather readings.*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg. Max. Temperature | 31 | 31 | 31 | 30 | 28 | 28 | 28 | 28 | 29 | 30 | 30 | 31 |
| Avg. Min. Temperature | 25 | 23 | 23 | 22 | 21 | 20 | 18 | 18 | 18 | 20 | 21 | 23 |
| Avg. Temperature | 28 | 27 | 27 | 26 | 24.5 | 24 | 23 | 23 | 23.5 | 25 | 25.5 | 27 |
| Avg. Rain Days | 2 | 2 | 4 | 7 | 9 | 3 | 1 | 1 | 1 | 2 | 3 | 2 |

Precipitation is high throughout the year, generally becoming more intense for several consecutive months. Annual rainfall can vary between 2000 and 5000mm and may exceed 500mm in one month, the wettest month.

Solar radiation is partly reflected and partly scattered by the high vapor content of the atmosphere, therefore the radiation reaching the ground is diffuse, but strong, and can cause painful sky glare, (Koenisberger, 1973). Cloud and vapour content also prevents or reduces outgoing radiation from the earth and the sea to the night sky, thus the accumulated heat is not readily dissipated.

Wind velocity is typically low, calm periods are frequent but strong winds can occur during outbursts of rain. There are usually one or two dominant wind directions.

### 2.6 Buildings and climate

The close relationship between climate and buildings was recognized long ago by old Greeks. Socrates observed, “in houses that look toward the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so

there is shade." Some centuries later, the roman architect Vitruvius wrote, "it is obvious that designs for homes ought to conform to the diversities of climate." (Flavin, 1980)
For a number of years the relationship between buildings and climate has been an intergral part of building design. Among the other factors which necessitates the existence of built environment like provision of shelter and protection from adverse parameters of physical environment, the latter still have an influence in building design. "The protection from climate was one of the initial factors that have remained a constant preoccupation and priority in the long process of the development of the built environment and the history of architecture", (Oliver, 1987).

### 2.7 Thermal Comfort in a Hot Humid Climate

'Thermal comfort is essentially a subjective response, or state of mind, where a person expresses satisfaction with the thermal environment', (Bjarne W. Olesen & Brager G.S). A person's sense of thermal comfort is primarily a result of the body's heat exchange with the environment. This is influenced by several parameters including air temperature, ambient temperature, humidity, air velocity and personal parameters like clothing and activity level. The following is a summary of the subject of thermal comfort in a hot and humid climate based on (Nicol, 2004) and other researchers.

#### 2.7.1 Key definitions

Free-running building: is the building which does not make any use of mechanical cooling or heating. They are naturally ventilated with operable windows and ceiling fans.

Free-running temperature: is temperature which represents indoor temperature of building in thermal balance with outdoor environment when neither heating nor cooling is used (Ghiaus, 2003).

Adaptive model: a linear regression model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters. Note that the range of applicable outdoor climates should be restricted to that appearing on the X-axis of the adaptive model's graph (i.e. they should not be extrapolated beyond the range of the regression models' X-variable). (de Dear, Brager, & Cooper, 1998)

Adaptive opportunity: Buildings provide their occupants with varying degrees of adaptive opportunity or scope to adjust the internal environment (and themselves) to achieve thermal comfort (de Dear, Brager, & Cooper, 1998).

PMV: Predicted Mean Vote is a thermal index derived from the heat-balance model of thermal comfort developed by Fanger (1970). PMV predicts the mean thermal *sensation* of a large group of subjects experiencing a thermal environment specified in terms of mean air and radiant temperatures, air speed, humidity, thermal insulation and metabolic rate (de Dear, Brager, & Cooper, 1998).

Temperature, air (Ta): the dry-bulb temperature of the air surrounding the occupant.

Temperature, dew point (Tdp): [or ambient water vapor pressure (Pa)], the temperature at which moist air becomes saturated (100% relative humidity) with water vapor (Psdp = Pa) when cooled at constant pressure (de Dear, Brager, & Cooper, 1998).

Temperature, mean radiant (tr): the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non uniform space (de Dear, Brager, & Cooper, 1998).

Temperature, operative (to): the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment. Operative temperature is numerically the average of the air temperature (ta) and mean radiant temperature (tr), weighted by their respective heat transfer coefficients.

### 2.7.2 (ISO7730, 1994) and (ASHRAE Standard55, 1992)

The above-mentioned matters are recognizable standards which have been used as a basis for worldwide thermal comfort determination for years. ISO7730 and ASHRAE Standard 55 describe indoor thermal comfort based on the theoretical analysis of human heat exchange with the environment calibrated using the results from experiments done in special climate-controlled laboratories or climate chambers. ISO7730 uses the (Fanger, 1970) predicted mean vote (PMV) formula which predicts a numerical value for the mean subjective response to the thermal environment on the ASHRAE scale (Table 2) from knowledge of six thermal comfort parameters mentioned above.

*Table 2: ASHRAE Comfort Scale*

| Description | Numerical Value |
|---|---|
| Hot | 3 |
| Warm | 2 |
| Slightly warm | 1 |
| Neutral | 0 |
| Slightly cool | -1 |
| Cool | -2 |
| Cold | -3 |

"Fanger was at pains to investigate the differences between groups including subjects who, though tested in Denmark, were straight from the tropics and so might have been physiologically adapted to the heat. He found no consistent difference between the 'tropical' and the 'non-tropical' subjects" (Nicol, 2004). Later field study surveys on thermal comfort have brought these results into question. Examples of these field study surveys include, (Webb, 1961), (Nicol J. , 1973), (Ellis, 1952), (Busch, 1992), (Matthews & Nicol, 1995), (Nicol, Raja, Allaudin, & Jamy, 1999) and many others who are quoted in the literature e.g. in (Humphreys, 1975) and (de Dear & Brager, 1998).

In contrast to previous studies (Fanger, 1970), the results from these surveys give the subjects' responses in situations they normally experience and not in the unfamiliar surroundings of the climate chamber. It was observed that, the conditions which they find comfortable (or vote = 0 on the ASHRAE scale) differ from the ISO7730 predictions, particularly in free-running buildings (FRB), (de Dear & Brager, 2002). The results of field study show that ISO7730 underestimates the occupant response on the ASHRAE scale at

high temperatures and overestimates it at low temperatures. As a result, it predicts discomfort at temperatures which subjects in field surveys find comfortable and it provides a narrow range of comfort when comparisons are drawn with field work studies, as indicated in Fig. 4.

De Dear & Brager, 2002 propose a new thermal comfort standard for naturally ventilated (NV) buildings, leaving PMV as the standard for AC buildings. "This approach has been well received by ASHRAE and offers some help for architects committed to low-energy solutions",(Nicol F. , 2004). Further investigation carried out by (Humphreys & Nicol, 2002) demonstrates that the errors in PMV are not confined to NV buildings; they also occur in AC buildings but are masked by the narrow range of environments.

### 2.7.3 ISO7730 Prediction and Hot Humid Climate

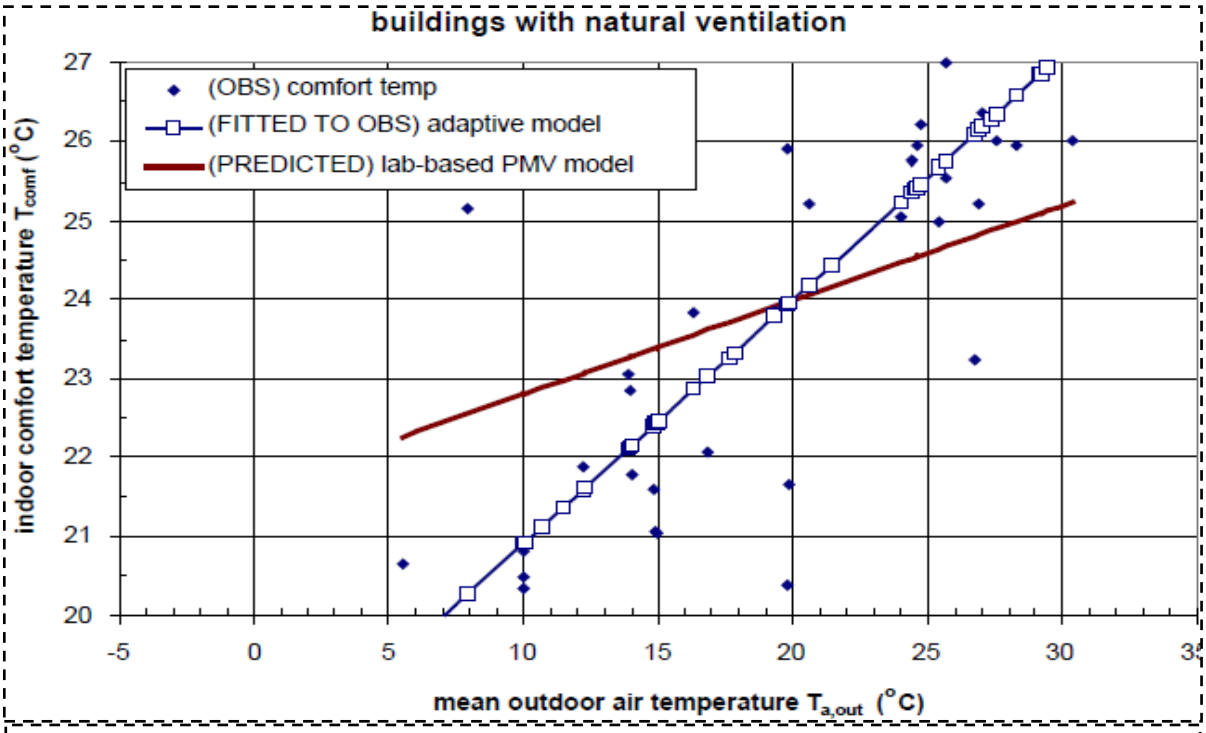



*Figure 4: Comfort temperatures in naturally ventilated buildings as predicted by the PMV model and actually measured in the field surveys (deDear & Brager, 2002)*

(Nicol F. , 2004) pointed out that one of problems when predicting comfort using ISO7730 in hot climates is the declared limitations to the applicability of the PMV, which are shown in Table 3. Furthermore, air temperatures (Ta) above 30°C and air velocities in excess of 1 m/s are not uncommon in buildings in tropical regions. From field studies, it was observed that subjects in hot climates can be comfortable at temperatures up to or even exceeding 30°C especially if they are using a fan.

(Humphreys M. &., 1996) pointed out a number of theoretical and practical reasons why the steady-state heat balance approach gives the wrong predictions of thermal sensation, particularly in the variable conditions that are found in naturally ventilated buildings in the tropics. When people find themselves uncomfortable they will take action such as by changing their clothing or, where possible, doing things like opening windows, closing blinds or switching on a fan thus changing the environment to suit themselves. "These changes will also take time to achieve and in addition the human body will take time to respond to a

change in the heat balance", (Nicol F. , 2004). Time is an important element in thermal comfort which any prediction must take into account.
There are other problems with the heat balance approach, such as the way clothes are worn—which varies from climate to climate. Most theoretical formulae see clothes as having a purely insulating function but in many climates they are used in more subtle ways to maintain an appropriate microclimate next to the skin (Berger, 1988). Furthermore, Nicol pointed that metabolic rate is usually calculated from knowledge of the activity people are engaged in. This is assumed to be independent of the temperature of the environment, yet people may well adjust their activity level to correspond to the temperature. People also adopt changes in posture to affect heat balance by changing the surface area for convective and evaporative heat loss. None of these short-term changes are adequately accounted for in heat-balance models.

*Table 3: Limitations to the range of conditions which PMV applies (ISO7730, 1994)*

| Variable | Symbol | Units | Lower limit | Upper limit |
|---|---|---|---|---|
| Metabolic rate | $M$ | $W/m^2$(met) | 46 (0.8) | 232 (4) |
| Clothing Insulation | $I_{el}$ | °C/W (clo) | 0 (0) | 0.310 (2) |
| Air temperature | $t_a$ | °C | 10 | 30 |
| Radiant temperature | $t_r$ | °C | 10 | 40 |
| Relative air velocity | $v_{ar}$ | m/s | 0 | 1.0 |
| Water vapour pressure | $p_a$ | Pa | 0 | 2700 |
| Predicted Mean Vote | *PMV* | | -2 | +2 |

Each of these effects may be a minor source of error in itself, but taken together they can create significant errors in the theoretical relationship (Nicol J. &., 1973). It is obvious that the sensation of the subjects can be the 'trigger' for subjects to change their own conditions to suit the environment, or to change the environment to suit them. Therefore, several measures may be taken by the subjects at the same time.
It is important to point out that a model which represents thermal equilibrium as a heat balance at a given point in time will not fully reflect thermal comfort in the field. "Without full allowance for the dynamic nature of the human interaction with their surroundings, such a model is likely to have limited applicability" (Nicol F. , 2004). This is especially true in the conditions found in free-running buildings in hot climates.
The inappropriateness which exists in International standards poses problems for architects and engineers in tropical countries. Nicol, 2004 discussed how architects and engineers should decide what temperatures to adhere to in their buildings in hot humid climates.

### 2.7.4 Temperatures to Provide: Survey Recommendations

Air temperature is one of the most important parameters of thermal comfort. A comfortable air temperature varies according to the time of the day, the outdoor temperature, the surroundings (walls, windows) and the activities carried out inside a building. Studies conducted by Griffiths, on user satisfaction in buildings with passive solar features, found that having the 'right temperature' was one of the things people considered most important in a building. To achieve thermal comfort the 'right temperature' needs to be recommended on the basis of the thermal environment one is dealing with.

This is not an easy task as Nicol, 2004 pointed that, “deciding what temperatures to provide in buildings is a complex problem. One way around this is to treat the process as a black box where the internal mechanisms of the relationship between comfort and the environment are less important that the outcomes”. This is the approach taken by those who use field surveys to investigate the problem. In the field all the variables are in action—people are free to change their clothes, their activity, their posture and when the building allows it, to change the temperature, air movement and even the humidity.

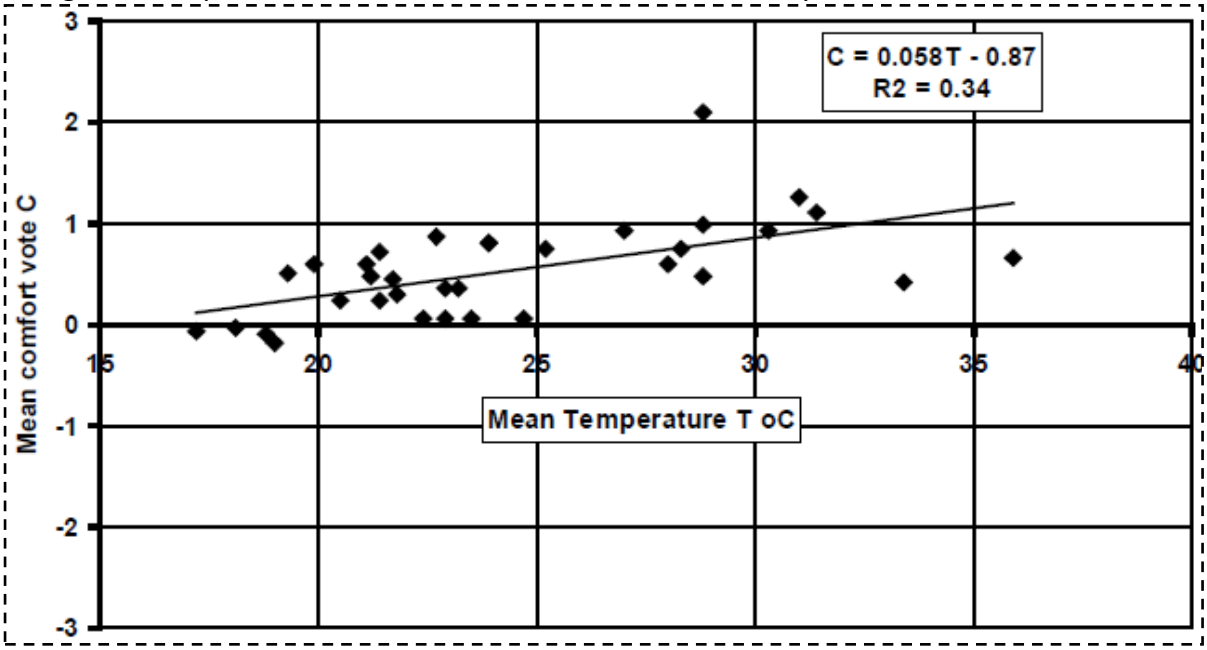



*Figure 5: Mean comfort vote on the ASHRAE comfort scale as a function of mean temperature experienced. Each point is the mean over a whole field survey*

Field studies results in UK, India, Iraq and Singapore prsented by (Nicol & Humphreys, 1973) shows that mean comfort vote changes little with the mean temperature experienced. A similar figure including the results from many more studies world-wide is shown as Fig. 6. Each point represents the mean values of comfort vote (on the scale shown in Table 1) and the mean temperature the subjects experienced over a whole survey. Note that temperatures well above 30°C are not considered uncomfortable in some cases.

Furthermore, it has been shown that the temperature which people find comfortable is closely related to the mean temperature they experience (Humphreys, 1975). This effect have been presented for a wide range of different climates including Europe, (McCartney & Nicol, 2002) as presented in Fig. 6.In other words people find ways in which to make themselves comfortable in the conditions they normally experience: they *adapt* to them behaviourally.

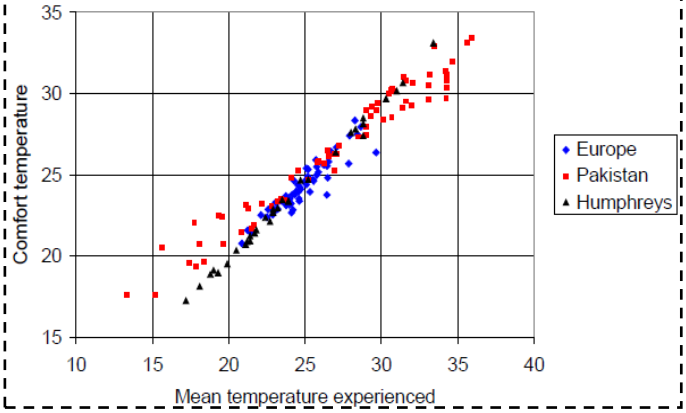



*Figure 6: The comfort temperature tends to follow outdoor temperature.*

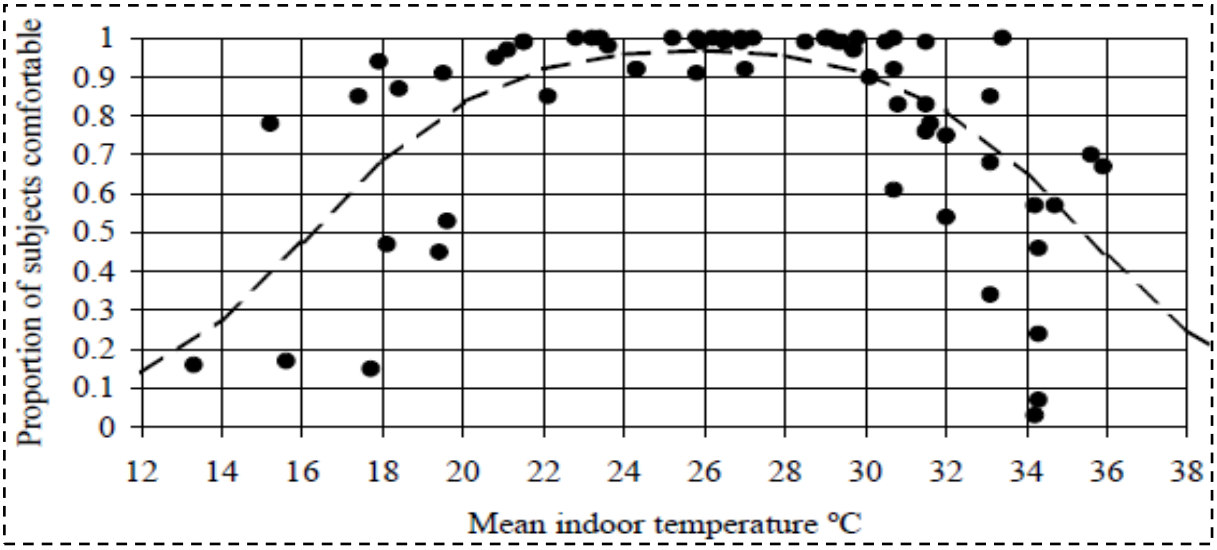



*Figure 7: The proportion of Pakistan office workers who felt uncomfortable plotted against the mean indoor temperature. Each point results from the votes of about 100 workers on the ASHRAE Scale, comfort being defined as votes 1, 0 or -1*

The effectiveness of these behavioural strategies is indicated in Fig. 7, which shows the proportion of people in Pakistani offices (Nicol, Raja, Allaudin, & Jamy, 1999), who reported themselves, comfortable at different indoor temperatures over a period of a year. Indoor temperatures between 20°C and 30°C caused little discomfort.

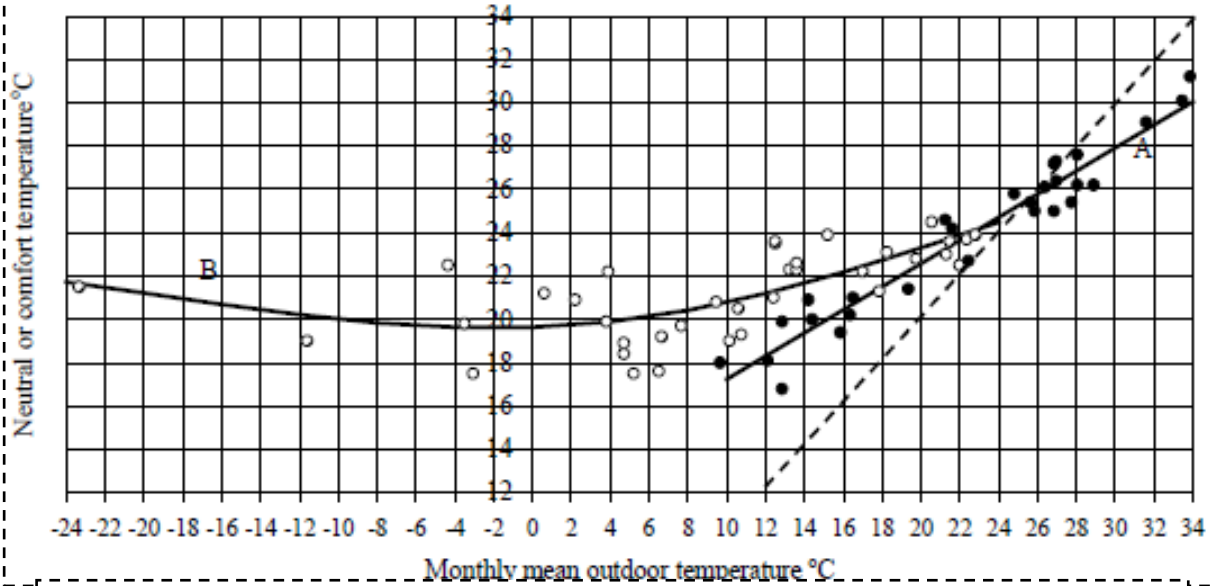



*Figure 8: The relationship between comfort temperature and monthly mean outdoor temperature. Filled points represent surveys conducted in free-running buildings and the open points those heated or cooled buildings.*

In free-running buildings[4] the mean indoor temperature tends to follow the mean outdoor temperature. Because of the strong link between the comfort temperature and the mean outdoor temperature (Fig. 6) the temperature which people find comfortable also corresponds to the outdoor temperature. In heated or cooled buildings the relationship is more complex because the indoor temperature is, to a certain extent, independent of the

[4] Free-running buildings: Neither being heated nor cooled *at the time of survey.*

outdoor temperature. Meta-analysis of the data from a large sample of comfort surveys world-wide conducted by Humphreys produced the relationships shown in Fig. 8.
The dashed line represents equality between comfort temperature and mean outdoor temperature (Humphreys M. , 1978). Humphreys derived a linear relationship between comfort temperature and mean outdoor temperature for free-running buildings (the straight line in Fig. 8) which is:

*Equation 1*
$T_c = 0.534T_o + 12.9$ (Nicol, 2004)

Where $T_c$ is the comfort temperature and $T_o$ is the mean outdoor temperature. Also recent work by (Nicol & Humphreys, 2000), using data collected by (de Dear & Brager, 1998) shows that, taking account of differences in the calculation of comfort temperatures, almost exactly matches these earlier findings. The relationship between outdoor mean temperature and comfort temperature is strong for free running buildings where occupants are able to adapt to the varying outdoor conditions but weaker, but still significant for air-conditioned buildings (ACB) which is given by the following Humphreys equation:

*Equation 2*
$T_c=0.16T_m + 18.6$ (Nicol, Humphrey, Roaf, & Sykes, 1995)

The relationship in equation one can be regarded as a basis for building professionals for determination of adaptive comfort limits. “This relationship enables building professionals to predict the temperature which will be comfortable in free-running buildings by calculation from the monthly mean outdoor temperature given by meteorological records”, (Nicol F. , 2004). Results for Islamabad, Pakistan are shown in Fig. 6. The figure shows the comfort temperature overlaid on the outdoor temperature to indicate the temperature differential which the building must achieve to remain comfortable indoors. In this case the building must be warmer than the outdoor mean in winter and cooler in summer, but by amounts which it might be possible to achieve by passive means (certainly in winter).

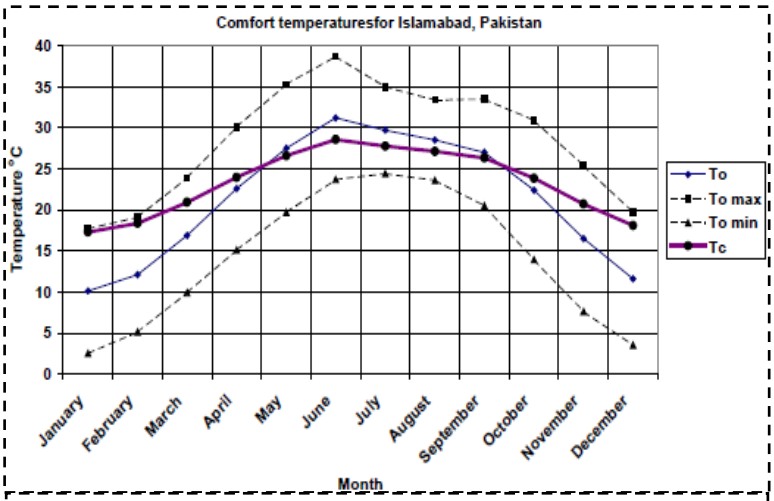


*Figure 9: Comfort temperature Tc for Islamabad Pakistan from the outdoor temperature $T_o$ using Eq. (1).*

A comfort zone within which temperatures are generally acceptable can be taken to extend some 2–3 ◦C either side of this optimum temperature.
To is calculated as the mean of the monthly mean maximum (To max) and minimum (To min).

### 2.7.5 Accounting for Air Movement and Humidity

Comfort temperature defined by Eq.1 is subjected to effects of air movements and humidity. (Nicol F. , 2004) try to show how air movement and humidity affect the comfort temperature as defined in Eq. (1) and Fig. 9 when considering comfort in hot, and in particular hot–humid (hh), climates. Since Eq. (1) is intended to give a target temperature, and not an instantaneous temperature, what we require is a simple set of rules which can be used to modify the predicted comfort temperature to account for air movement and high humidity enabling building designers to provide a comfortable environment.

The following analysis presents analytical and experimental predictions and then tests them against results from field surveys as done by Nicol (2004). In developing the relationship in Eq. (1), (Humphreys M. , 1978) attempted, where possible to give the relationship where air movement can be assumed to be small (≤0.1 m/s) and relative humidity (RH) standardised at 50%.

Several studies of the effects of temperature, humidity and air movement on the human body in hot climates have been undertaken e.g. (Kerslake & McK, 1972). Much of this work in this area was to determine the relative effects of these factors on people's subjective response to heat. The effect of air movement and humidity are particularly important in hot climates where the heat lost by evaporation predominates.

One method of investigating the relative effects of the different elements of the thermal environment was to develop an 'index' of thermal comfort, often presented as an 'equivalent' temperature. "This is defined as the temperature at a standard value of humidity and air velocity which will *feel* the same as the environment in question",(Nicol F. , 2004). One commonly used index of this sort is the effective temperature index (ET*) resulting from extensive experimental studies by (Gagge, Stolwijk, & Nishi, 1971). Such an index can also be derived from statistical analysis of a comfort survey in the field where the humidity and air movement have been measured. Two examples of empirical indices are Webb's Equatorial Comfort Index (Webb C. , 1959) developed in Singapore and Sharma and Ali's Tropical Summer Index (Sharma & Ali, 1986) from hot–dry parts of India.

### 2.7.6 Air Movements

In tropical climates air movement is an important factor in determining comfort. A theoretical analysis (Humphreys M. , 1970) suggests that where the air velocity is above 0.1 m/s and fairly constant, this allowance can be equivalent to raising the comfort temperature by:

*Equation 3*

$$7 - \frac{50}{4 + 10v^{0.5}}\,^{\circ}\mathrm{C}$$

This relationship is demonstrated in Fig. 10. (Nicol J. , 1973) showed that in the hot dry climates of Northern India and Iraq, the presence of air movement can be equivalent to a reduction in temperature of as much as 4℃, and this is more or less in line with theoretical expectation.

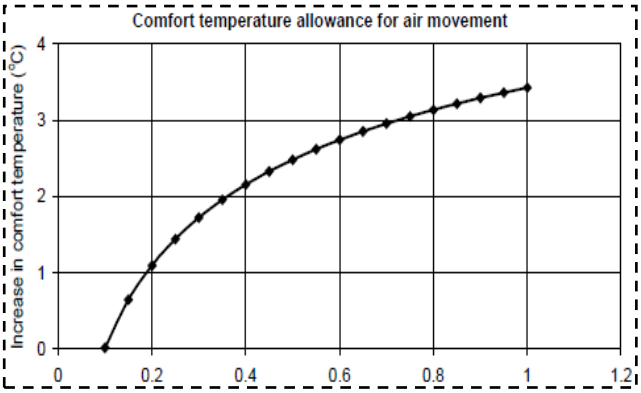



*Figure 10: The increase in comfort temperature for different air speeds.*

(Sharma & Ali, 1986) found a similar effect. At hot times of year ceiling fans are used in almost all public buildings in the tropics, and this can be assumed to allow higher comfort temperature (*T*c) than those given by Eq. (1).
"Analysis of data from Pakistan suggests that for indoor temperatures over 25 °C, mean air velocity in rooms with fans is about 0.45 m/s, as opposed to about 0.1m/s for those without fans running", (Nicol, Raja, Allaudin, & Jamy, 1999).

Using Eq. (2) and Fig. 10 this suggests in dry conditions that normal use of fans will allow building occupants to be comfortable at a about 2 ℃ above the value suggested by Eq. (1). This effect is demonstrated in Fig. 11 which shows that fan use increases the comfort temperature by about 2 ℃ over a wide range of outdoor temperatures.
The dashed line shows the dependence of comfort temperature on outdoor temperature (TOUT) when fans (F) are running (1), the solid line is for offices where fans are not running (0).

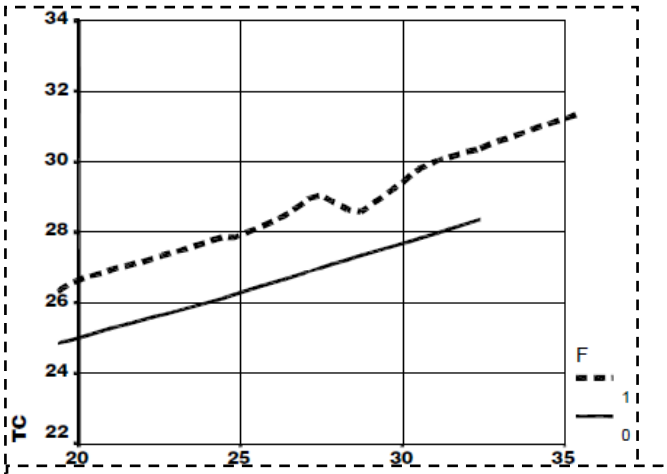


*Figure 11: Effect of fan use on comfort temperature (Tc) in offices in Pakistan*

### 2.7.7 Humidity

"It is more difficult to account for the effect of humidity. Whilst humidity has been investigated in a number of field surveys in hot climates, and found to have a significant effect on comfort temperature, the size of the effect is generally small, and further research is needed", (Nicol F. , 2004). The first problem for the analysis of the effects of humidity is to decide how humidity should be measured. The relative humidity of the air is the best known measure and has been used in most studies of thermal comfort. RH is a *relative* measure and is therefore highly dependent on air temperature, especially at high temperatures. A more robust measure is the water vapour pressure ($p_a$) in the air. The driving force for heat loss by evaporation is the difference between the saturated water vapour pressure at the skin surface and $p_a$ in the surrounding air. With the skin temperature remaining relatively constant, the saturated water vapour pressure at the skin surface is more or less constant. The $p_a$ of the air should therefore be a good predictor of the evaporative heat loss, but has not always been recorded.
"It is generally assumed that in hot conditions where loss of metabolic heat by convection and radiation decrease and the bulk of heat losses are via evaporation, increased humidity will increase discomfort", (Nicol F. , 2004). The barrier to evaporative heat loss caused by high humidity could, it is assumed, mean that people require a lower temperature for comfort.
(de Dear, Leow, & Ameen, 1991) investigated the preferred temperature for seated subjects performing light activities and dressed in standard clothing (0.6clo) and in warm conditions (25–30 °C). The RH was set at two values: 70% and 35% and no significant difference was found in the preferred temperature between the two conditions. (Ballantyne, Mhill, & Spencer, 1977) investigated the effect of water vapour pressure in thermal comfort data collected in the 60s at the Kansas State data in which Fanger's PMV was largely based. They

found that the effect of $p_a$ on the comfort votes of the subjects was small when the subjects were comfortable, but had a marked effect on the rate of change of comfort with temperature. In a moist environment people become uncomfortable with a smaller change in temperature than they do in a dry environment. The effect of activity on comfort is also more marked in a humid environment.

Reporting the results of two field studies of thermal comfort in hot dry conditions of Baghdad, Iraq and Northern India and with wvp in the region of 1.5–2.5 kPa and temperatures in the mid 30 s, (Nicol J. , 1973)found a significant but small effect of wvp on thermal sensation. (Webb C. , 1959) found that the water vapour pressure had a more marked effect on comfort in the cooler but more humid (mean wvp 3.3 kPa) conditions of Singapore. Other field studies in hot–humid climates (Busch, 1992), (de Dear, Leow, & Ameen, 1991),and (Karyono, 2000) have unfortunately combined the effects of temperature and water vapour into the equivalent temperature index (Gagge, Stolwijk, & Nishi, 1971) which 'accounts' for the effect of humidity and they are unable to shed no light in the separate effect of humidity.

### 2.7.8 Meta Analysis of Field Surveys

Nicol, F. (2004) selected three sets of data to look at the relationship between comfort and humidity:

(i) The 1998 ASHRAE database (de Dear R. , 1998);
(ii) Humphreys' 1975 database(Humphreys M. , 1975)used in development of Eq. (1);
(iii) Data from Pakistan which are not included in the ASHRAE database.

All three studies have records of mean indoor and mean outdoor temperatures and estimates of the comfort temperature. The database comprises of buildings from various locations and the rough climatic classification of the 113 comfort surveys from these databases, where there was a large proportion of results from free-running buildings. Most also include records of mean outdoor relative humidity, though there were only 22 with records of mean $p_a$. The comfort temperature has been estimated for each survey.

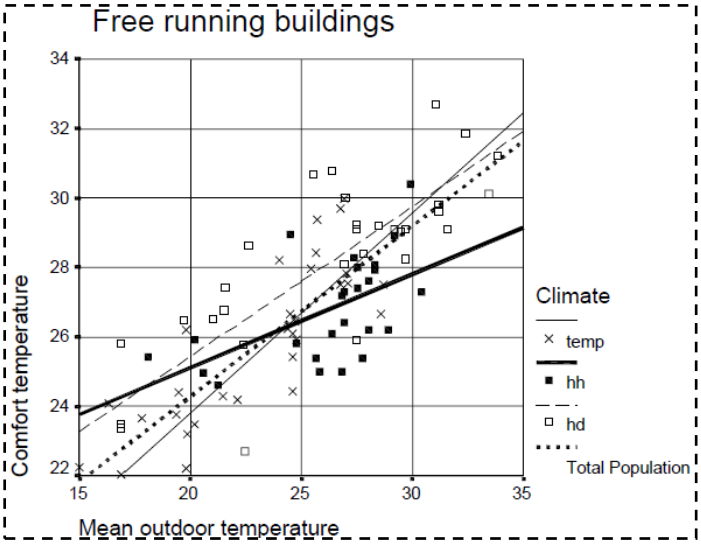



*Figure 12: The effect of climate type on comfort temperature at different values of outdoor mean temperature (TOUT)*

The surveys were all divided according to the climate at the site of the field study. These can then be classified according to climate as "hot–humid (hh)", "hot–dry (hd)", or "temperate (temp)". Fig. 12 below shows the change of comfort temperature with mean outdoor temperature for data from different sites in the ASHRAE, Humphreys and Pakistan datasets where buildings were free-running at the time of the survey. The continuous line hh shows the regression line of comfort temperature on outdoor temperature for locations with a hot–humid climate. The discontinuous line is the regression for all climates. Although the comfort line for hot–humid climates has a lower slope the actual comfort temperature for hh climates is

little different from the overall values for outdoor temperatures between about 20 and 30 °C. Subjects in free-running buildings in a hot–humid climate (hh) desire a lower comfort temperature than those with a hot dry (hd) but the difference from the overall comfort temperature line is small for a given outdoor temperature (Nicol, 2004).

In Fig. 13 a similar Figure has been produced in which the comfort lines are shown for three grouped values of mean outdoor relative humidity (RHO). The range of values contained in each group is shown in Table 3.

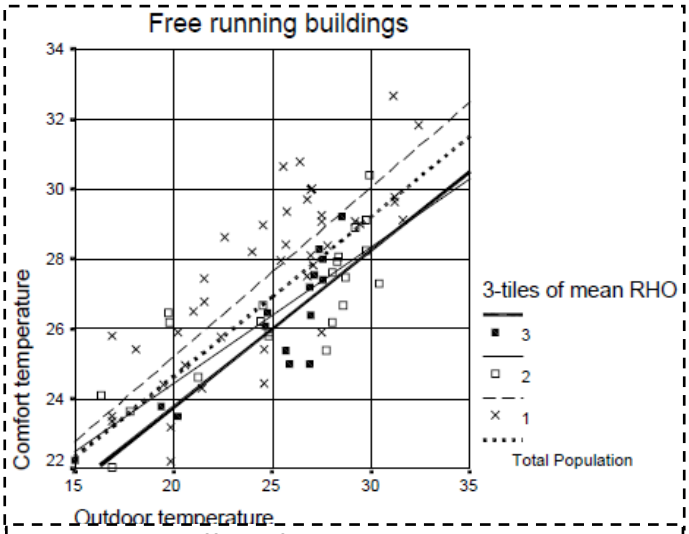



*Figure 13: The effect of mean outdoor relative humidity (RHO) on temperature at different values of outdoor mean temperature.*

Subjects in free-running buildings in a warm climate desire a lower comfort temperature if the humidity is high (3, RH > 75%) than if it is low (1, RH < 64%) but the difference from the overall comfort temperature (total population) line is only about 1 °C.

In this case the regression lines for the overall condition and for the most humid third are more-or less parallel, with the higher humidity requiring a lower air temperature for comfort than the overall line by about 1 °C over the whole range of temperatures. The difference is just significant.

In view of the discussion above regarding the relative appropriateness of using *p*a as a measure of humidity, a separate analysis was made of the results from the 22 surveys from free-running buildings where *p*a was estimated. The result is shown by Nicol, (2004) in Fig. 14 below, and suggests that there is no difference in the comfort temperature for the three groups of values of *p*a.

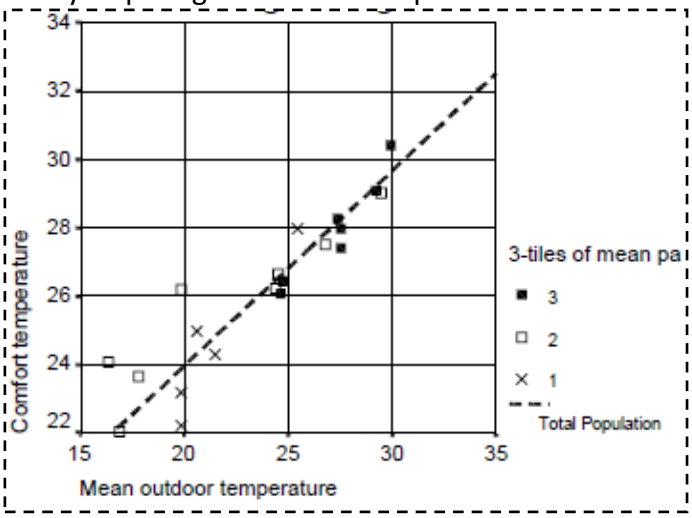



*Figure 14: The effect of mean water vapor pressure (pa) on comfort temperature at different values of mean outdoor temperature.*

*Table 3*

*Range and mean value for the 3-tiles of outdoor relative humidity (RHO) and water vapour pressure (pa)*

| N-TILE | Relative Humidity (%) | | Water vapour pressure, $p_a$ (kPa) | |
|---|---|---|---|---|
| | Range | Mean | Range | Mean |
| 1 | <63 | 53 | <1.4 | 1.1 |
| 2 | 64-75 | 71 | 1.4-2.2 | 1.9 |
| 3 | >75 | 81 | >2.2 | 2.7 |

Subjects in free-running buildings in a warm climate show little change in their comfort temperature at different values of the water vapour pressure.

### 2.7.9 Nicols' Conclusions

(i) PMV should at least predict the temperature at which people are comfortable regardless of the local conditions. This is due to the fact that the equations in which it is based take account of changes in clothing and activity and therefore it should be able to predict thermal sensation irrespective of where it is used.

(ii) In tropical conditions PMV fails to give accurate information about the temperatures which people will find comfortable. PMV predicts that people will feel hotter than they actually do and therefore tends to encourage the use of more air conditioning than necessary. In addition, because ISO7730 does not provide information about what clothing people use in any particular circumstances, there is a tendency to assume a particular clothing level and the consequent need for a constant indoor temperature, thereby encouraging the use of mechanical cooling.

(iii) International standards which take account of the evidence from field studies in the tropics are urgently needed. ASHRAE have recently approved a new version of ASHRAE comfort standard 55 incorporating the information derived from field surveys. Eventually it is to be hoped that these can be based on the theory which has been successfully tested against wide-ranging empirical results.

(iv) The cultural element and the allowance for time means that comfort surveys are needed in every area of the world, particularly in the tropics where current standards are weakest.

(v) Meanwhile, the empirical findings of field surveys can be used as a guide for informing the designers of buildings to provide comfortable conditions. For instance Eq. (1) can be taken as an international generalisation of field studies throughout the world. Wherever possible this can be improved by the conduct of local field surveys to fully reflect local climate and culture.

(vi) Fig. 9 shows the way in which the results can be used to calculate the optimum comfort temperatures at different times of year. A comfort *zone* of 2–3 °C either side of the optimum can be taken as acceptable. If fans are available to the building occupants another 2 °C can be added to the predicted comfort temperature in hot conditions.

(vii) In a humid climate or in conditions when the relative humidity is high people may require temperatures that are about 1 °C lower to remain comfortable, but the main effect of a higher humidity (or water vapour pressure) is to reduce the width of the comfort zone.

## 2.8 Thermal Comfort Standards and Building Design

It has been observed that the present guidelines ISO7730 and ASHRAE Standard hamper good thermal design of buildings in number of ways (Humphreys, 1995). These include:

### 2.8.1 Rigid Limits Lead to Needless Cooling

A rigid maximum indoor temperature for summer tends to force the provision of cooling plant when it may be in practice not necessary for thermal comfort. The designer sees that provision of cooling plant is the only way to guarantee that the temperature will not exceed the level given in the standard, so cooling equipment is specified.

Field study thermal comfort research conditions previously discussed has demonstrated that the upper limit is not rigid but flexible e.g. (Humphreys M. , 1975) and (Humphreys M. , 1978).These studies demostrate an empirical link between the outdoor temperature and the desired indoor temperature. When the outdoor temperature rises, then the indoor for comfort rises (Humphreys M. , 1995).

### 2.8.2 Rigid Limits Inhibit Traditional Design

It has been observed by Humphreys that present guidelines may prevent the construction of buildings to designs which have been found to be very comfortable by previous generations. "Sometimes Standards originating in Europe and USA are assumed to be valid for all climates and cultures", (Humphreys M., 1995). Upon that assumption, traditional designs which have performed well for centuries can be neglected since one cant guarantee that they will never 'overheat' when measured against these foreign Standards. It is necessary for the guidelines to make appropriate allowance for climate and culture where they are intended to be used. The need for local standards have been demostrated for Pakistan; field-studies which showed that people are comfortable well beyond the limits of ASHRAE comfort level (Nicol, Raja, Allaudin, & Jamy, 1999).

### 2.8.3 Present Standards and Inappropriate Design

Upon making a decision to provide air-conditioning, the need for careful climatologically and thermal design does not carry any weight. It becomes justified to build highly glazed lightweight structure in hot climates, and make them habitable by means of massive cooling, with its consequent high energy consumption.

The use of Adaptive Comfort Standards which links the indoor comfort temperature to the outdoor temperature throughout its seasonal and geographical variation can have several benefits. It can increase design flexibility without reducing user's satisfaction. It can also lead to reducing capacity of installed plant for cooling and save energy.

It is time to have a fresh look at temperature standards for thermal comfort in the buildings. "The Adaptive, people-centred way of regarding thermal comfort suggest that it would be advantageous to re-formulate temperature standards for the buildings, so that they reflect the empirical relation between climate and thermal comfort, and make due allowance for human adaptability", (Humphreys M., 1995). Advantages of the revision will be reflected not only on the ways of achieving thermal comfort but also in the energy consuption of the buildings.

## 2.9 Thermal Comfort and Energy Efficiency

"Energy efficiency in buildings refers to the ability of a building to operate and function with minimum energy consumption. If comfort is a pre-requisite for functioning effectively then comfort must not be compromised when adopting strategies to conserve energy", (Zain, Mohd, & M.S.B., 2007).

A Hot and humid climate develops a condition of thermal discomfort in the building. Mechanistic approach to air conditioning requires energy which most of the people in the developing countries have limited affordability. The challenge to the related architects/designers/researchers is to come out with effective strategies to overcome the state of discomfort with minimum energy utilization.

The link between the energy use in the building and thermal comfort is something that need to be understood and addressed so as to achieve a goal of energy efficieny. Recent studies have estimated that heating, ventilation and air conditioning (HVAC) accounted for some 65% of the energy use in the building sector(R. & Steemers, 2005).Furthermore, it has been shown that , of the total energy consumption, energy used to provide air-conditioning in commercial buildings accounts for up to 45% of the total electricity consumption in Hong Kong (Chow & Chan, 1995) .

It is envisaged that the building sector will continue to be a key energy end user in the years ahead. One way to alleviate the ever growing demand for energy is to have more energy efficient building designs. Through the knowledge of thermal comfort behavior of human and energy utilization behavior of the buildings, the best strategy can be adopted.

# 3.1 Research Approach

This chapter presents various concepts which are keys to the way the whole research is conducted. It covers the climate analysis based on the climate-based indoor air temperature standard introduced in the second chapter. It also defines the comfort limits for hot humid climates, specifically Dar es Salaam, for both free-running buildings and air-conditioned buildings. These comfort limits are going to be used as a reference for indoor thermal comfort in both FRB and ACB. It further formulates the basis for the analysis and the evaluation of the thermal comfort in case studies and parametric models.

## 3.2 Concepts

The core of this research lies in the integration of three key parameters which influence each other for a given climate; these are design parameters, energy efficiency and thermal comfort as illustrated in the Fig.15 below.

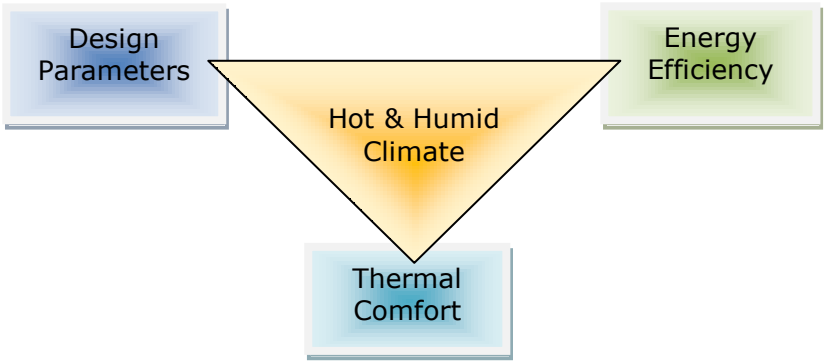



*Figure 15: A conceptual research model*

The above model is composed of several variables. As previously mentioned, for a designer/architect, the climate has to be considered as a given condition. An architect has to play with the design parameters to influence the energy efficiency and fulfill the thermal comfort requirements of the building's users.

This model outlines the key parameters with which architect/designer is confronted when starting a design. However, in most cases the issue of thermal comfort has been left to the service engineer and is looked upon as an independent entity of design. In most cases, the thermal comfort issue is addressed later after the whole design has been completed by an architect, e.g. at scheme design level in the traditional method. There are also cases where the thermal comfort issues are addressed as an afterthought; this has been the case specifically in the selected area of study, Dar es Salaam. Failure to link the issues outlined in the model above in the early design stages, have a big impact on the energy efficiency and the thermal comfort.

### 3.3 Approach to Thermal Comfort

It is important to point out that, for a number of years thermal comfort requirements have been regarded as a given condition for an architect/designer based on the standards which exists. Recent research and field surveys study has proved beyond a reasonable doubt that, this is not the case, especially for a hot and humid climate. As part of this research is to look for a proper way of defining thermal comfort in a hot and humid climate; new concepts from recent research and field survey results e.g. Nicols,2004 are going to be applied in this research.

#### 3.3.1 Comfort Temperature for Dar es Salaam

In order to determine the comfort temperatures for Dar es Salaam, Eqn. 1, $T_c = (0.534T_o + 12.9)$ °C, from section 2.7.3 is used. Data on the mean monthly temperatures for one year and 8 years were used and results compared. One year data was processed from a series of daily maximum temperature and daily minimum temperatures for the year 2007. It is important to stress the fact that this was one of the years considered to be very hot. The results are presented on Fig. 17.

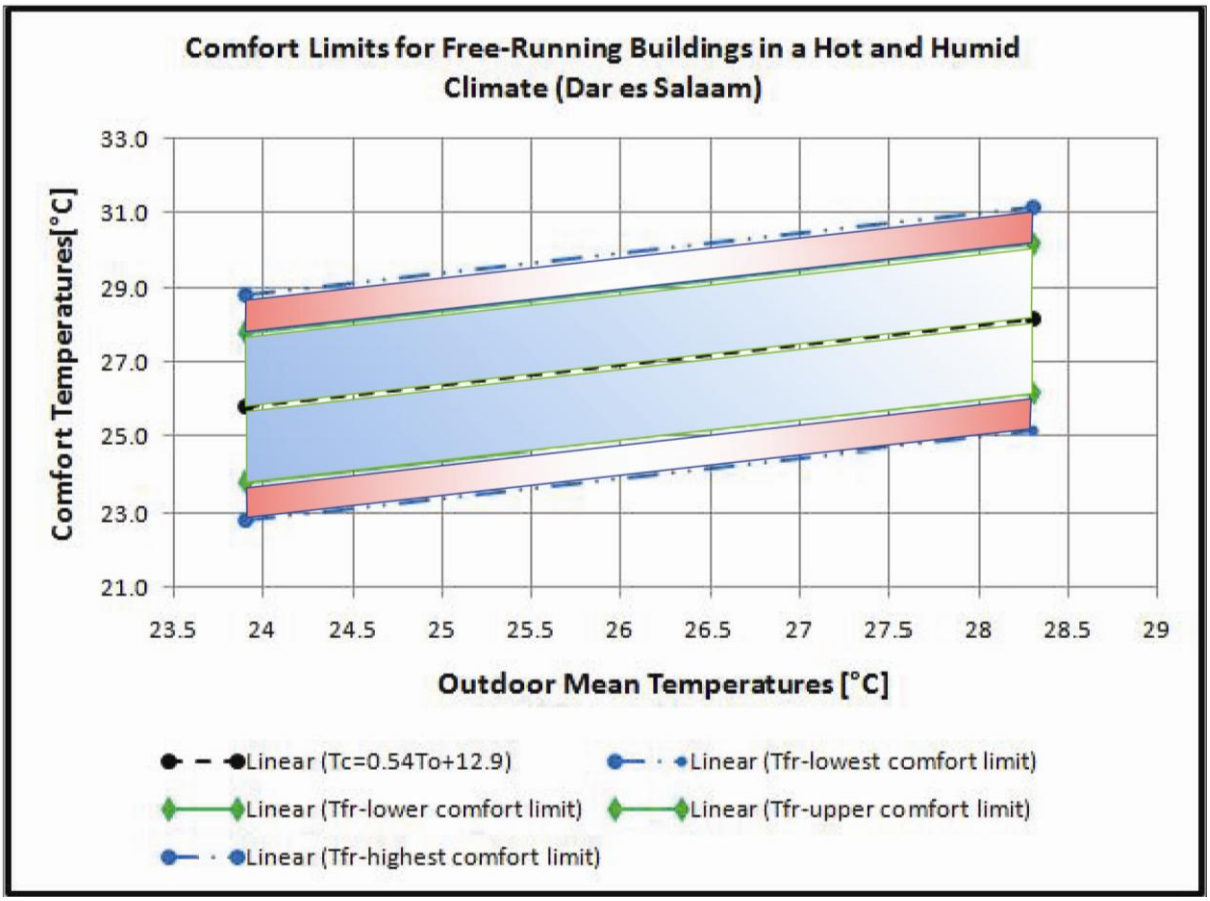



*Figure 16: Comfort temperatures for FRB in Dar es Salaam, calculated by using Eq.1.Note: RH is always above 65 percent*

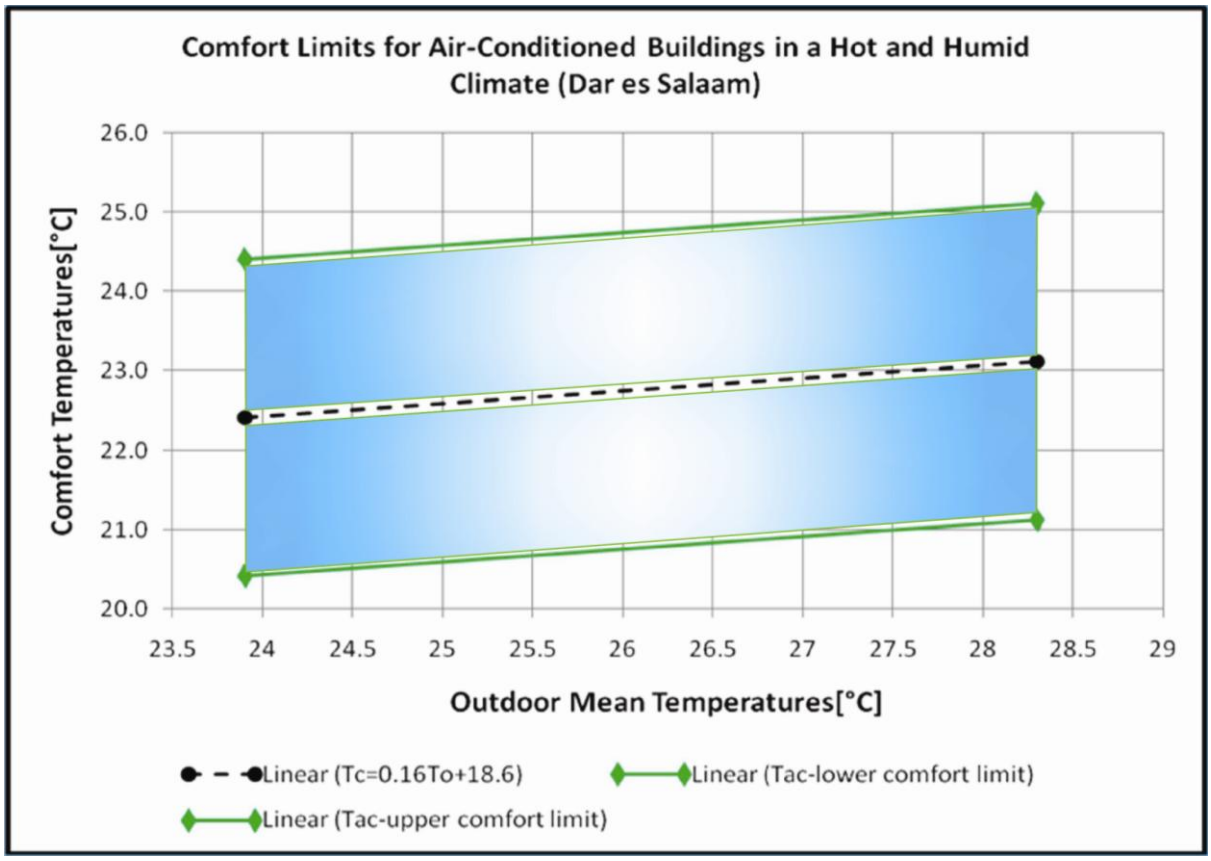



*Figure 17: Comfort temperatures for ACB in Dar es Salaam, calculated by using Eqn.2. Note: RH is always above 65 percent*

### 3.3.2 Air Movements

The comfort temperature for free-running building which is defined by Eq. 1 is subjected to effects of air movements. Since comfort temperatures in Fig. 17 is a direct result of Eq. 1, there is a practical need to oversee the influence of air movement on these temperatures, specifically for free-running buildings in tropical climates.

There is a need for a basis which can be used to account for the effect of air movements subjected in comfort temperature resulted from Eq.1. Theoretical analysis (Humphreys M., 1970) ,suggests that where the air velocity is above 0.1 m/s and fairly constant, a comfort temperature determined by Eq. 1 can be raised by a value, which is given in Eq. 2.

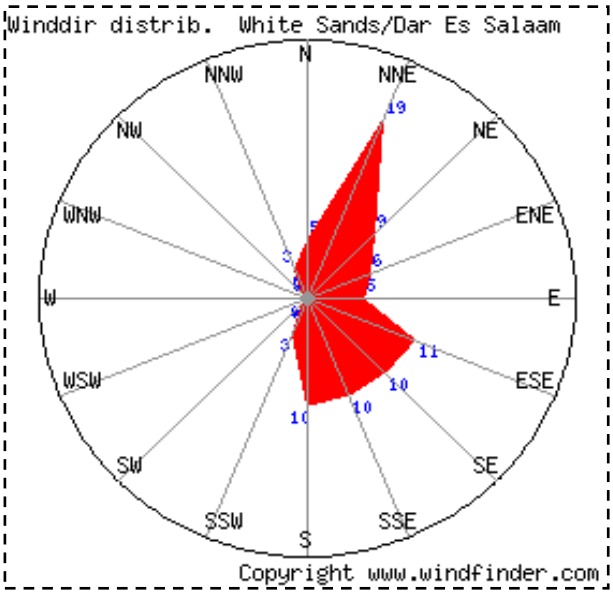



*Figure 18: Average wind speed and directions for Dar es Salaam throughout a year.*

Data on the average air speed in Dar es Salaam are presented in Table 4 and Fig.19. This average wind speed data was collected for one year period from November 2007 to November 2008 daily from 7am to 7pm local time.

It can be shown from table 6, that the minimum average wind speed (4.67 m/s) occurs in April and May. Average wind speed has a maximum of 6.17 m/s, during the period of November to January; these are the periods of maximum thermal stress too. It is important to draw a comparison between a period of maximum thermal stress and maximum wind speed to see how this advantage of wind can be utilized to improve thermal comfort in the buildings. This relationship is presented by Fig.20.

*Table 4: Average wind speed and direction in Dar es Salaam*

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dominant Wind Dir. | | | | | | | | | | | | |
| Average Wind Speed (m/s) | 6.17 | 6.17 | 5.14 | 4.67 | 4.67 | 5.66 | 5.66 | 5.14 | 5.14 | 5.14 | 5.66 | 6.17 |

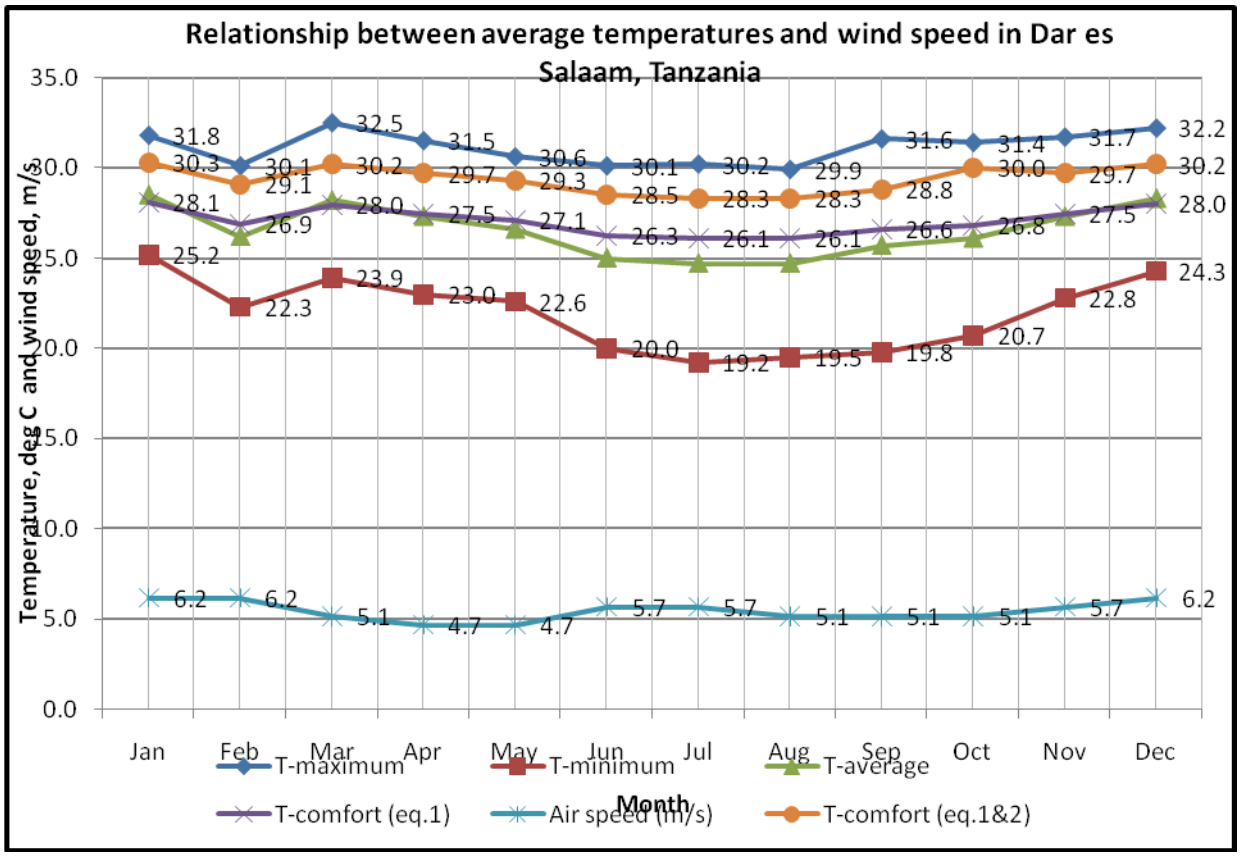



*Figure 19: Relationship between average temperatures and wind speed in Dar es Salaam. Note: RH is always above 65 percent.*

### 3.3.3 Air Humidity

Previous studies mentioned in chapter two have shown that humidity has a significant effect on the comfort temperature but the size of the effect is generally small and further research is needed. Also studies have shown that the effect of $p_a$ on thermal comfort is small when the subjects are comfortable, but has a marked effect on the rate of change of comfort with

temperature. Important aspect of all these studies so far is the fact that if subjects are in the 'right temperature', any definition of humidity has no significant influence on the thermal comfort sensation.

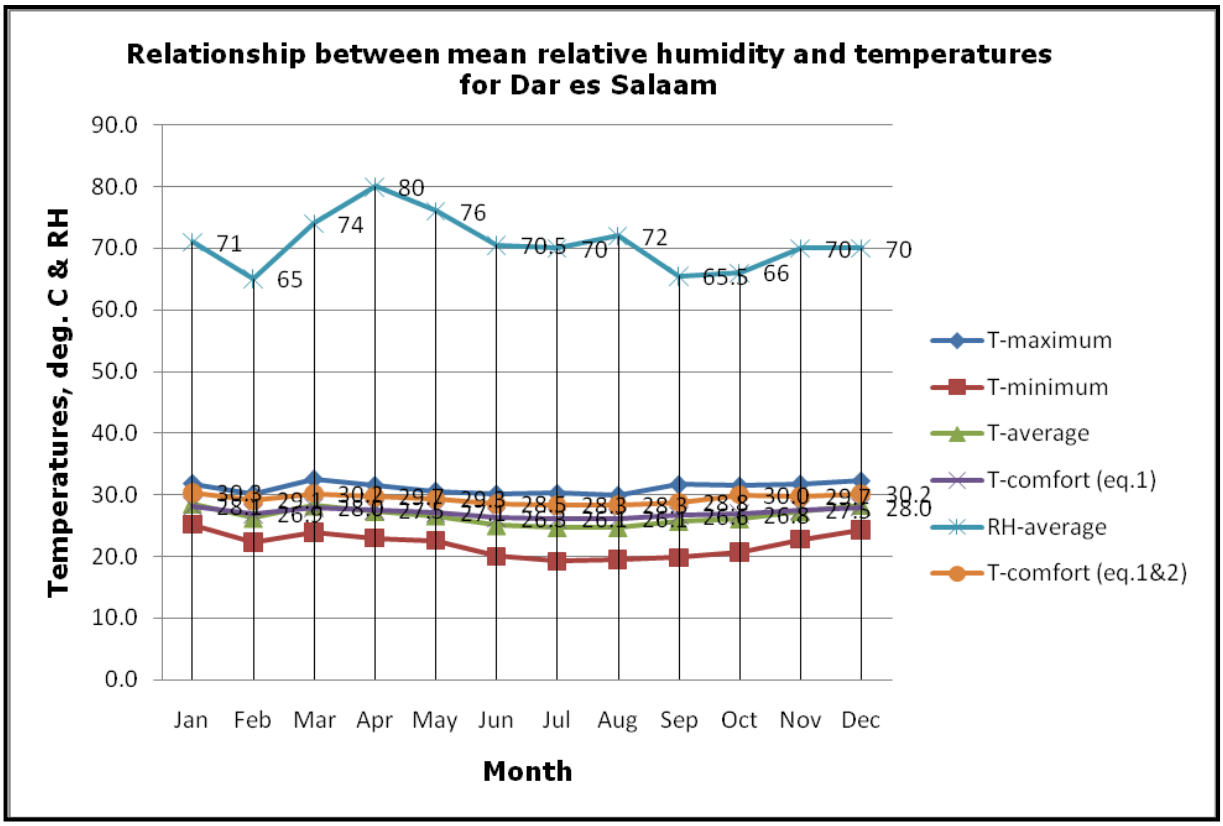



*Figure 20: Relationship between mean outdoor relative humidity and mean temperatures for Dar es Salaam, Tanzania.*

### 3.4 Comfort Based on the Fanger's Model

From the climate data used to determine comfort temperature, it is obvious that humidity is high throughout a year. The mean monthly humidity is above 65 percent. To check for its influence on the thermal comfort based on the Fanger's Model, the following Table 5 of calculation is presented. Two months with lowest and highest humidity which are February and April respectively, were considered. The influence of humidity here is tested against the previously determined comfort temperatures.

*Table 5: The influence of relative humidity on thermal comfort based on the Fanger's Model*

| Variable | Symbol | Units | Case I-February | Case II- April |
|---|---|---|---|---|
| Metabolic rate | *M* | W/m$^2$(met) | 70 (1.2) | 70 (1.2) |
| Clothing Insulation | $I_{el}$ | °C/W (clo) | 0.7 | 0.7 |
| Air temperature | $t_a$ | °C | 26 | 28 |
| Radiant temperature | $t_r$ | °C | 26 | 28 |
| Relative air velocity | $v_{ar}$ | m/s | 0.1 | 0.1 |
| Relative humidity | *r.h* | % | 65 | 80 |
| Predicted Mean Vote | *PMV* | | 0.68 | 1.34 |
| Percentage Dissatisfied | *PPD* | % | 14.7 | 42.3 |

Results shows that the percentage dissatisfied increased tremendously from 15 to 42 percent when the relative humidity changes from 65 to 80 percent respectively. These results are just an indication of the effect of relative humidity on thermal comfort in air conditioned buildings, but they do not reflect what the effect would be in free running buildings.

### 3.5 Degree Days Concept

Degree-days (heating or cooling) are a means of evaluating the energy demand in order to maintain the indoor environment of a building within the thermal comfort requirements. Since this research is focused on a hot and humid climate, the discussion will focus on cooling degree days. Cooling degree-days (CDD) are defined as the positive deviation of the mean daily temperature $T_m$ from a base temperature $T_b$, practically the outdoor ambient temperature above which cooling is activated to sustain the indoor temperature to a comfortable level. The base temperature is an arbitrary but generally accepted temperature and depends on the personal preferences of the people, which live or work in the building. "Base temperatures between 10 and 28 $^{o}$C are usually considered but traditionally, cooling degree-days are determined at the base temperature of 25 $^{o}$C", (Santamouris, 1997). Annual cooling degree- day values are computed from daily CDD values which are summed over a year period. Annual CDD, however, tend to accrue primarily during the warm summer months.

Cooling degree-days are the most common practical method for assessing the effect of air temperature on the energy performance of the building and they are used as a reasonable approximation of the cooling energy demands of a city with respect to it. Knowledge of the spatial distribution of CDD in a city allows for the description and mapping of the temperature conditions within the urban web. This can be a useful tool for architects and service engineers at preliminary stages of design as a rule of thumb evaluation of local environment. "This information may e of high interest to architects, urban planners and climatologists, as the application of such knowledge can lead to the improvement of the urban environment and the decrease of energy consumption in cities, since location-specific standards for thermal insulation can be determined to ensure satisfactory energy performance of the buildings", (Stathopoulou, 2006). In addition, knowledge of the spatial variations in CDD in a particular region can be utilized by civil engineers and architects as a rule of thumb evaluation of the local environment during early design stages of a building.

According to their definition, cooling degree-days (CDD) are calculated as:

*Equation 4*

$$CDD = (1\ day) \sum_{days} (T_m - T_b)^{+}$$

Where $T_b$ = the base temperature and $T_m$ = the mean daily outdoor temperature.

The plus sign (+) of the equation indicates that only positive values are to be counted, meaning that if Tm < Tb then CDD = 0. For example, using a base temperature of 25℃ and considering a day with a mean temperature of 30℃, then a value of 5-degree cooling days is obtained from Eqn. (4) for the given day. Daily values of CDD are summed to calculate the total number of cooling degree-days over a period in question.

### 3.5.1 Limitations of CDD Method

A main limitation of the CDD methods discussed above is the fact that there is lack of ground data, both in terms of spatial and temporal coverage. “Even in the most developed countries, it is rare the average separation of the stations to be less than 1 km”, (Stathopoulou, 2006). Data from only two or three ground stations which are usually several kilometres apart from each other, fail to describe the spatial heterogeneity over urban areas as there are strong micro-scale variations in the main climatic variables such as air temperature, solar radiation, moisture (humidity and precipitation) and winds (Santamouris, 1997). However, the present data can form the basis of qualitative and quantitative approximation of the cooling energy demand, specifically where there is no access to Satellite remote sensing. It is worth to point out that satellite remote sensing provides better spatial coverage than do surface meteorological data, in view of the fact that satellite data are more spatially contiguous and available over much of the earth on a regular basis.

### 3.5.2 Cooling Degree Days for Dar es Salaam

To establish CDD for Dar es Salaam, climate data with mean maximum and minimum daily temperature were used. The only challenge was to determine the appropriate base temperature which can be used for calculation. The building Science Corporation define hot humid climate with the use of CDD calculated with a base temperature of 18 or 22 °C. On the other hand (Santamouris, 1997) recommends 25 °C as a base temperature for CDD calculations. However, we have to acknowledge the fact that base temperature is arbitrary. For the purpose of this study a base temperature of 25 °C was a logical choice. To draw a comparison calculation was done for both 22 and 25 °C as base temperatures as indicated in the Figures 21.

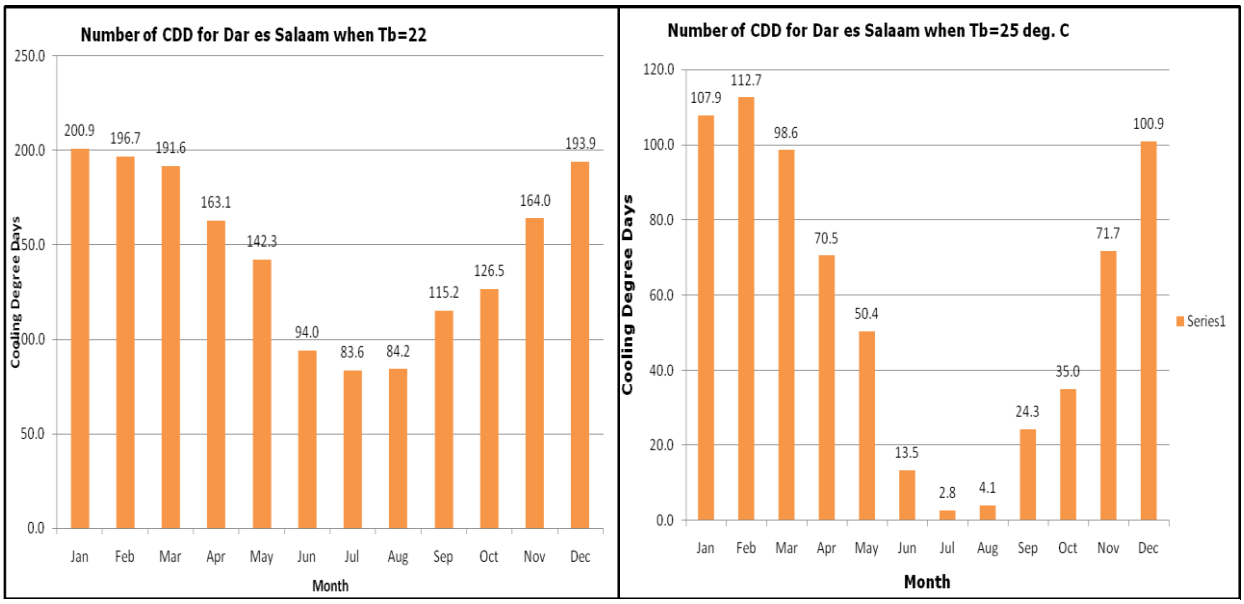



*Figure 21: Number of cooling degree days for Dar es Salaam*

### 3.5.3 Conclusions

Determination of CDD for Dar es Salaam has shown tremendous difference in terms of cooling energy demand. This difference is reflected on how we define thermal comfort in this region as in other hot humid climates cities. When a base temperature of 22 °C is used, the number of CDD ranges from 85 to 200 marking the lowest and the highest months respectively. When a base temperature of 25 °C is used, the number of CDD ranges from 3 to 107 marking the lowest and the highest months respectively.

So far base temperature selection is referred as arbitrary choice, but a base temperature of 25 °C to determine the CDD in a hot and humid climate seems not only logical but also concur with the field work survey findings of comfort temperatures in the region. If subjects can be thermally comfortable up to a temperatures of 28 °C in a free-running buildings, this has an implications also in what we refer as base temperature and finally what we conclude as CDD in these regions. It is an obvious fact that this has a big implication on the cooling energy demand in the region. Theoretically, the further we make reference to the field work findings of thermal comfort, the more savings can be gained in the cooling energy demand.

# 4.1 Case Studies

A case study method has been adopted as one of the research method by a researcher. The necessity of the use of this method is based on the fact that it enables a researcher to gain an understanding of the energy consumption of existing buildings as well as to draw comparisons between these buildings. All buildings selected are office buildings from Dar es Salaam, Tanzania in which some have been represented in Figure 22 below. Since Dar es Salaam is a typical hot and humid climate city, it can be a representative of the climate and a general idea of the influence of this climate in the energy consumption of buildings can be drawn.

Through a thorough study and analysis of these existing buildings, the knowledge of their energy consumption can be gained. It was not possible to get field data in the energy consumption of such buildings. However, based on the design parameters of these buildings and climatic information of the area, simulation results are able to give energy consumption trends of such buildings.




*Figure 22: Aerial view of parts of Dar es Salaam with some of the Case Study buildings.*

## 4.2 Justification

Selection of the case studies is based on the primary objective of the study which is to understand how various materials, construction techniques, services and other design parameters influence energy consumption of the building. Different case study buildings with different materials have been selected. The choice was also based on the easy access of necessary data from such buildings. Apart from design parameters, another category was they way buildings are serviced. To learn more about these buildings both categories of air-conditioned buildings and those intentionally designed to run as free-running buildings are included.

### 4.3 Analysis Method

The method used to analyse the energy performance and the indoor thermal comfort in both case studies and parametric models is simulation. This is the process of developing a simplified model of a complex system and uses that model to analyses and predicts behaviour of the original system.
The main reasons which justify the use of simulations in this kind of analysis are based on the fact that real-life systems are often difficult or impossible to analyse in all their complexity. By careful taking from the real system the elements necessary for the stated requirements and ignore relatively insignificant ones, it is possible to develop a model, which can be used to predict the behaviour of a real system accurately.

### 4.4 Software Used

CAPSOL is the computer simulation program which can be used to calculate multi-zonal steady-state and dynamic heat transfer. A calculation includes one dimensional heat conduction, convection, view factor based on the infra-red radiation, multi-zonal ventilation and solar radiation. A system of energy balance equations is built and solved each calculation step by using a finite difference method. The steady state calculation can be used to determine the required heating and cooling loads.
CAPSOL consists of four modules: input module, calculation module, function editor module and wall type editor module. All these modules work seamlessly together during the problem definition, making the calculation and reporting the results. Reports can consist of several user defined charts and alpha-numeric results in an MS-Word compatible format (RTF) (CAPSOL, 2002).

### 4.5 Case Study One

#### 4.5.1 Building Description

The first case study to be analyzed is Bank of Tanzania (B.O.T) headquarters building. This is one of the recently finished multi-storey office buildings located in Dar es Salaam. It is a high-rise building in which the external façade is made of a double glazed curtain wall system coupled with Namibian pearl cladding as shown in Fig. 23 on the right hand side.
The main structural system is made of reinforced concrete. It is an air-conditioned building with a central cooling system. For the purpose of the study a typical room from this building is analyzed.



*Figure 23: Bank of Tanzania Headquarter in Dar es Salaam. View from Indian Ocean.*

#### 4.5.2 Room Description

The investigated room is an office for two people. The size of the room is 25.3 $m^2$ and the ceiling height is 2.85 m. The depth of the room is 6.2 m. The general presentation of the room is as

shown in Figure 24.

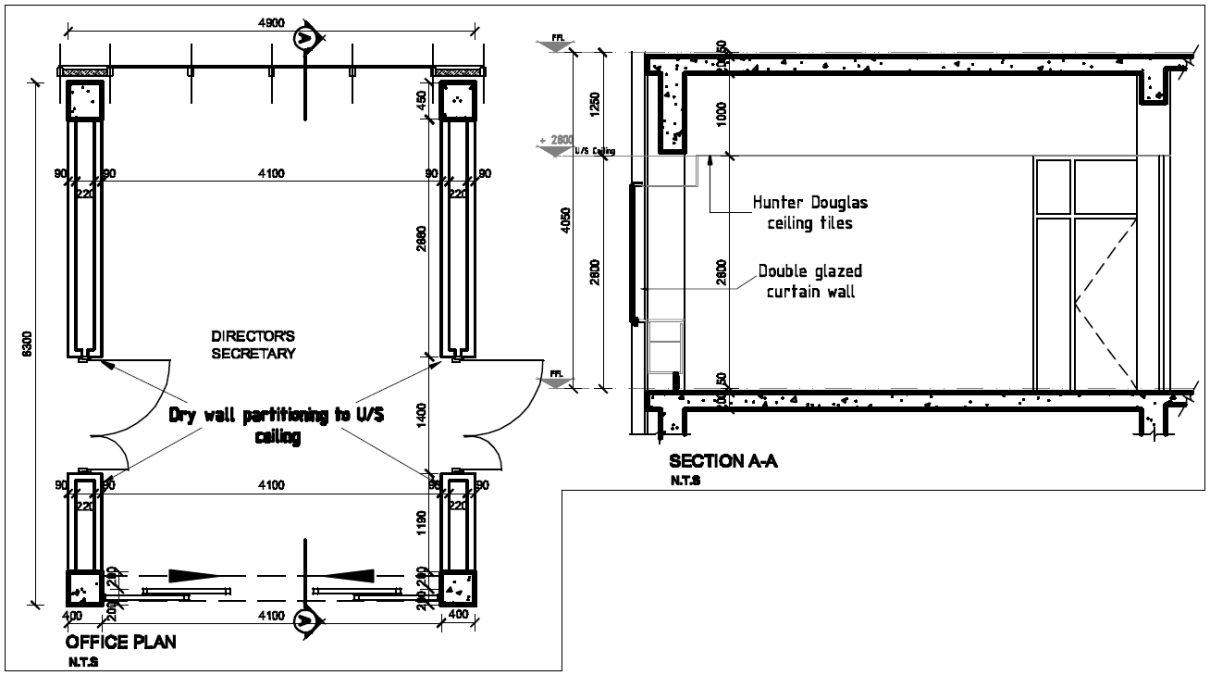



*Figure 24: Plan and section for the selected office used for case study one.*

### 4.5.3 Materials and Construction

A detailed description of materials and construction is presented in the Table 7 below. Only a double glazed façade is exposed to the outside and facing east direction. Necessary information on material properties as used in the thermal simulation software are been presented.

*Table 6: Materials used for various parts of a modeled room*

| Location | Description | Material used | Thickness (mm) | Resultant U-Value ($Wm^2/K$) | Area ($m^2$) |
|---|---|---|---|---|---|
| Floor | | Granite floor tiles | 20 | 0.02 | 27 |
| | | Reinforced concrete | 200 | | |
| | | Air Gap | 1000 | | |
| | | Al. Acoustic Ceiling tiles | 2 | | |
| Walls | Outside wall | Double glazed | 6:12:6 | 3 | 13.9 |
| | Partition wall | Dry-wall partitions | 90:230:90 | 0.1 | 17.7 |
| Note: the resultant U-Value is the one calculate by the software | | | | | |
| Window System | | Infrared emission factor | Solar reflection factor | Solar absorption factor | |
| Double glazed | | 0.90 | 0.45 | 0.55 | |
| Shading Employed | | No shading employed | | | |

### 4.5.4 Simulation Results

Simulation results for case study one which has double glazed façade shows comfort temperature to be within the comfort limits as indicated in Fig.26. The total annual cooling energy demand is 4034.7 kW [*h]. For this building the only means of controlling the indoor comfort is through central cooling system, there is no possibility of opening the windows.

However, the use of double glazed improves the indoor comfort by reducing the amount of solar radiation penetrating through the façade. The monthly energy consumption presented in the Figure 25 shows periods of maximum and minimum thermal stress. This correlates to the degree days for the Dar es Salaam.

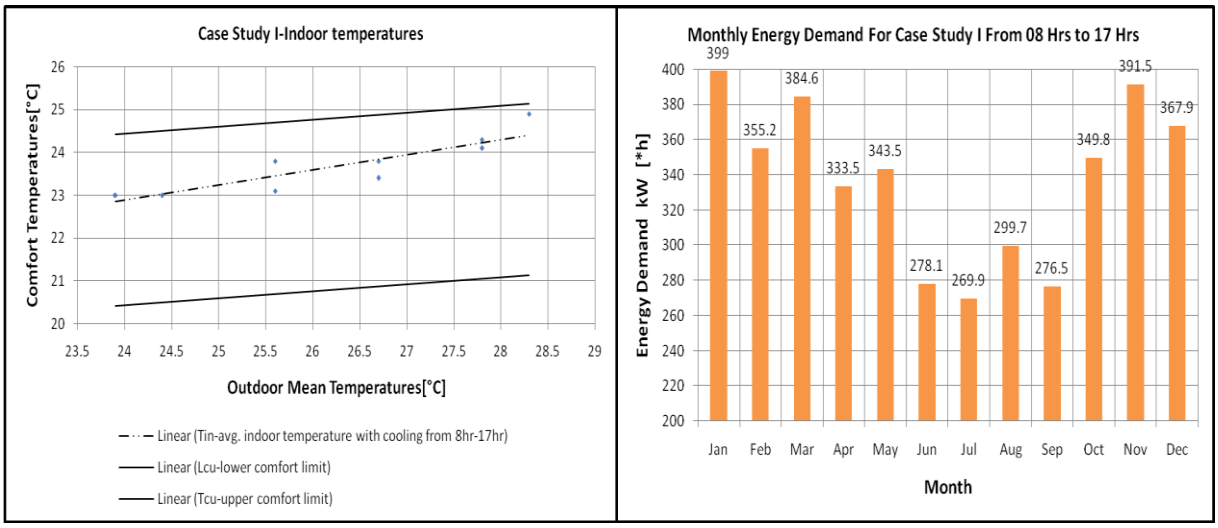



*Figure 25: Indoor temperatures and energy demand for Case Study I*

## 4.6 Case Study Two

### 4.6.1 Building Description

The National Investment Corporation (N.I.C) building is one of the buildings built in early sixties. As shown in Figure 26, N.I.C is a multi-storey building situated in the city centre of Dar es Salaam.

The main structural system of the building is reinforced concrete. It is designed as a free-running building and takes into account the influences of external conditions by carefully designed external shading devices. These shading devices are made of prefabricated concrete panels and they are fixed to the floor on each level.



*Figure 26: N.I.C Building. View from Samora Avenue.*

### 4.6.2 Room Description

The investigated room is an office for two people. The size of the room is 25 $m^2$ and the ceiling height is 2.45m. The depth of the room is 5.2 m. The general presentation of the room is as presented in figure 27.

### 4.6.3 Materials and Construction

A detailed description of the materials and the construction is presented in the Table 10. In this case a concrete wall with a single glazed window coupled with prefabricated concrete

static shading devices is exposed to the outside facing east. Necessary information on material properties as used in the simulation software has also been presented on table 8.

*Table 7: Materials used for various parts of modeled office*

| Location | Description | Material used | Thickness (mm) | U-Value ($Wm^2/K$) | Area ($m^2$) |
|---|---|---|---|---|---|
| Floor | | Terrazzo floor finish | 50 | 0.05 | 25 |
| | | Reinforced conc. slab | 200 | | |
| | | Air space | 450 | | |
| | | Gypsum boards | 20 | | |
| Walls | Outside wall | Smooth Cement rendering | 10 | 3.9 | 13 |
| | | Concrete wall | 150 | | |
| | Partition walls | Chipboard partitions | 12.5 | 4.16 | 17.7 |
| | | Single glazed | 6 | 5.64 | 13 |
| Note: the resultant U-Value is the one calculated by the software | | | | | |
| Window System | | Transmission | Reflectance | | Emmittance (e) |
| Single glazed | | 83% | 7% | | 7% |
| Shading Employed | | Material | Type | | G-Value |
| | | Prefab conc. panels | Static | | 0.35 |

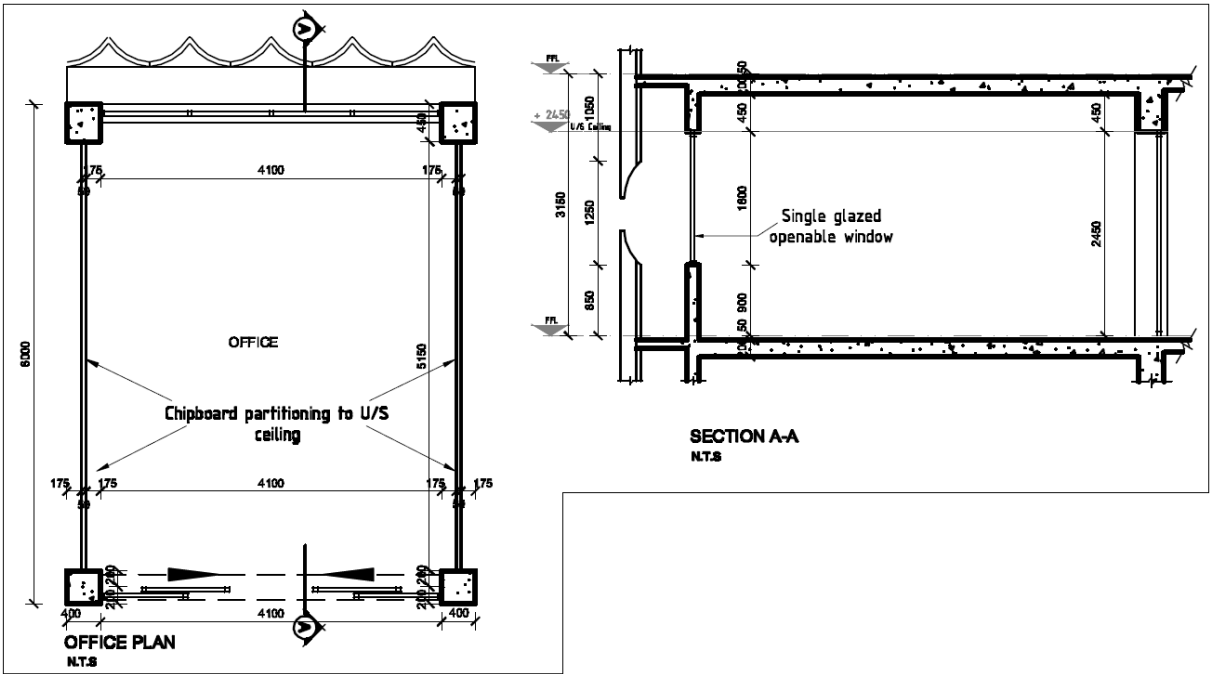



*Figure 27: Plan and section for selected office used in analysis of case study two.*

### 4.6.4 Simulation Results

Simulation results for Case study II which is free-running building indicate that there is big influence of ventilation on the indoor comfort. As indicated in the Figure 28, on the l.h.s air changes per hour was 5 which shows almost half of the free-running temperature line is beyond the comfort range. Upon doubling the number of air changes per hour, the free-running temperature line is almost within the comfort limit. However, there is the region beyond which mechanical cooling is necessary; theoretically this is when both the free-

running temperature and outdoor temperature are beyond the comfort limit (Ghiaus, 2003). Based on that requirement, mechanical cooling is not needed for this building.

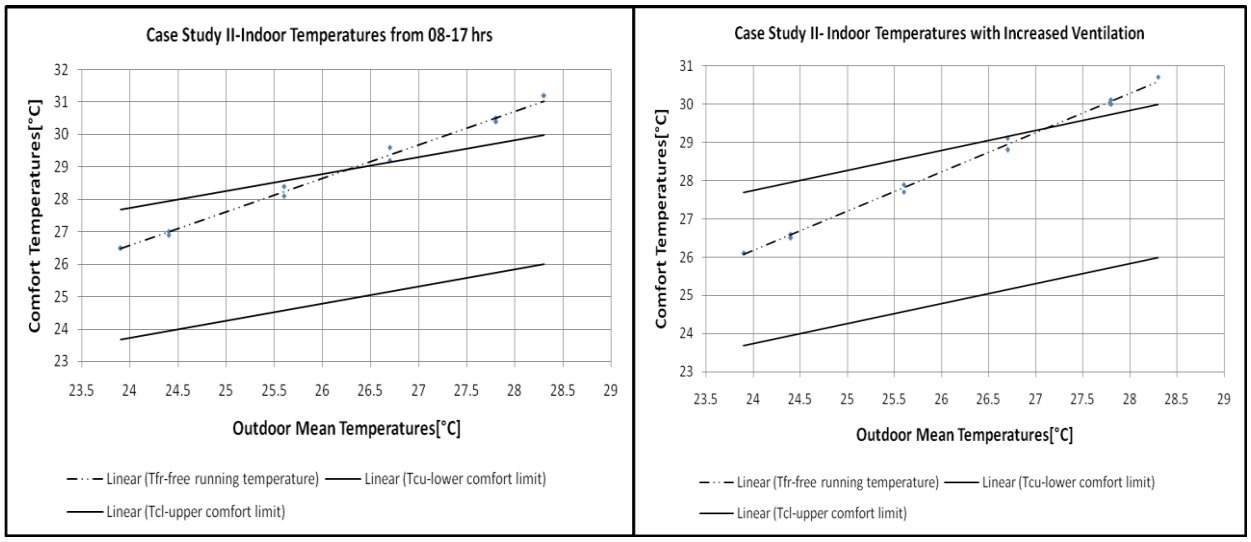



*Figure 28: Indoor temperatures and comfort zone for Case Study II*

## 4.7 Case Study Three

### 4.7.1 Building Description

The Parastatal Pension Fund (P.P.F) Tower is the third case study to be analysed. This is multi-storey office block situated in Dar es Salaam. As the first case study, the building's external facades are made of curtain walls as shown in the Figure 29 on the right hand side. It is an air-conditioned building and as the former building, the main structural system is reinforced concrete.

A typical room from this building is analysed for study purposes, a room description is presented in the following section. A major difference when comparisons are drawn with case one is the fact that while the former is double glazed, the latter is single glazed.



*Figure 29: P.P.F Tower. Favored view from Garden Avenue.*

### 4.7.2 Room Description

The room for investigation is an office for two people. The size of the room is 26.8 $m^2$ and the ceiling height is 2.8 m, the depth of the room is 6 m. The general room description is shown in figure 30.

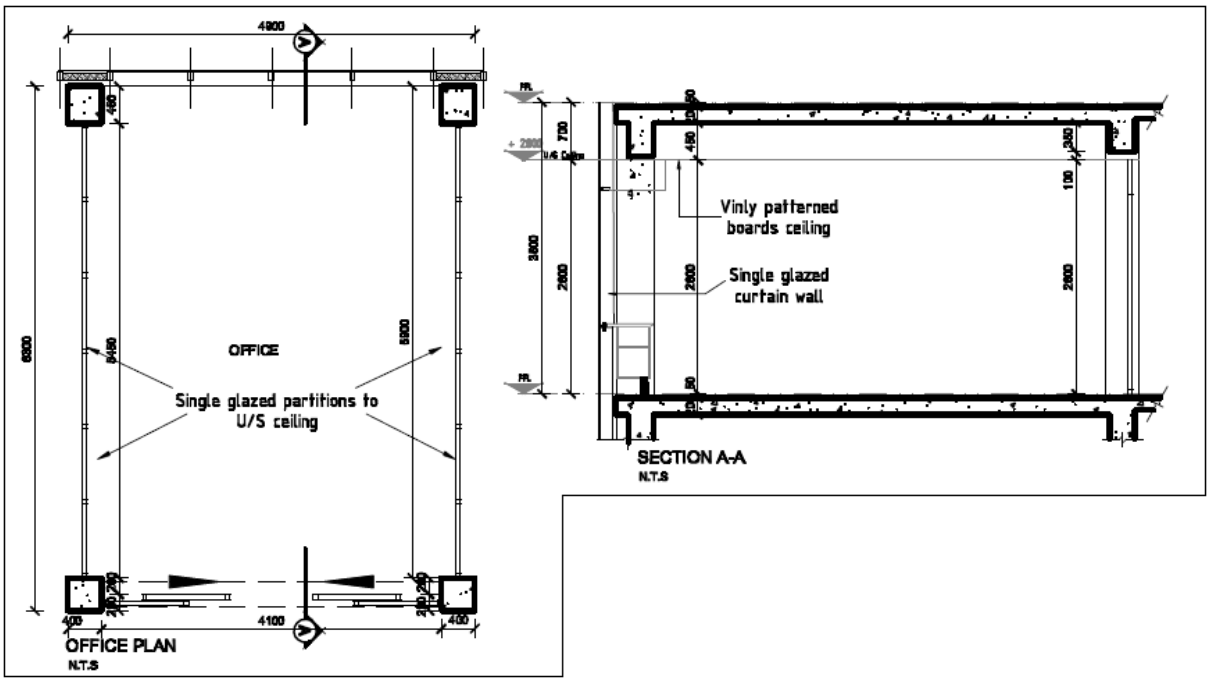



*Figure 30: Plans and sections for selected room for analysis of case study three.*

### 4.7.3 Materials and Construction

A detailed description of the materials and the construction is presented in the table 10. In this case a concrete wall with a single glazed window coupled with prefabricated concrete static shading devices exposed to the outside facing east. Necessary information on material properties as used in the simulation software has also been presented in the table.

*Table 8: Materials used for various parts of modeled room*

| Location | Description | Material used | Thickness (mm) | U-Value ($Wm^2/K$) | Area ($m^2$) |
|---|---|---|---|---|---|
| Floor | | Grey marble floor tiles | 30 | 0.05 | 27 |
| | | Reinforced conc. Slab | 200 | | |
| | | Air gap | 500 | | |
| | | PVC vinyl ceiling boards | 20 | | |
| Walls | Outside wall | Glass curtains | 6 | 5.6 | 13 |
| | Partition walls | Glass partitions/Al. frames | 6 | 5.6 | 17.7 |
| Note: the resultant U-Value is the one calculated by the software | | | | | |
| Window System | | Transmission | Reflectance | Emmittance (e) | |
| Single glazed | | 83% | 7% | 7% | |
| Shading Employed | | No shading device employed | | | |

### 4.7.4 Simulation Results

Case study III which is single-glazed with openable windows shows that there is a certain period in which temperature can be beyond the comfort limits as presented in the Fig. 31. The annual cooling energy demand for this case is 4164 kW [*h]. It is worth to note that the cooling load applied is the same to case study I (double glazed). Due to distinct characters and differences between case I&II, it is not proper to make a conclusion but results indicates that single glazed uses more energy and results to comfort temperatures beyond comfort limit. This necessitates excessive cooling to maintain the indoor temperatures within the comfort limits.

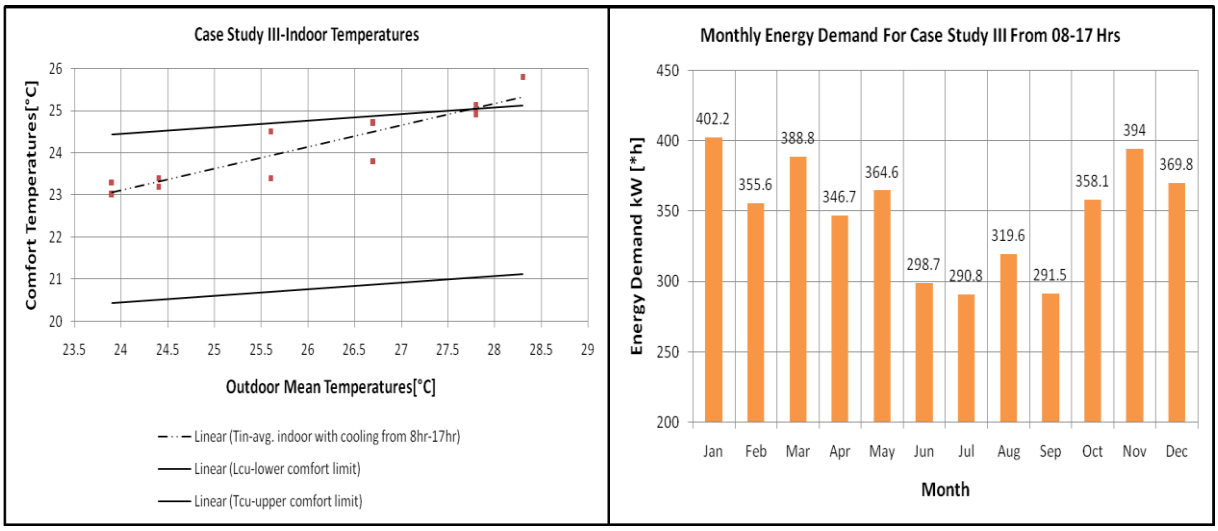



*Figure 31: Indoor temperatures and energy demand for Case Study III*

## 4.8 Case Study Four

### 4.8.1 Building Description

Bank of Tanzania (B.O.T) first headquarter building was built in built in early sixties. As shown in Figure 32. N.I.C is a multi-storey building situated in the city centre of Dar es Salaam.

The main structural system of the building is made of reinforced concrete. It is designed as a free-running building and takes into account the influences of external conditions by carefully designed external shading devices. These shading devices are made of prefabricated concrete panels and they are fixed to the floor at each level.



*Figure 32: First Headquarter Building for Bank of Tanzania.*

### 4.8.2 Room Description

The room for investigation is an office for two people. The size of the room is 25 $m^2$ and the ceiling height is 2.45m. The depth of the room is 5.5m as shown in the Figure 33 below.

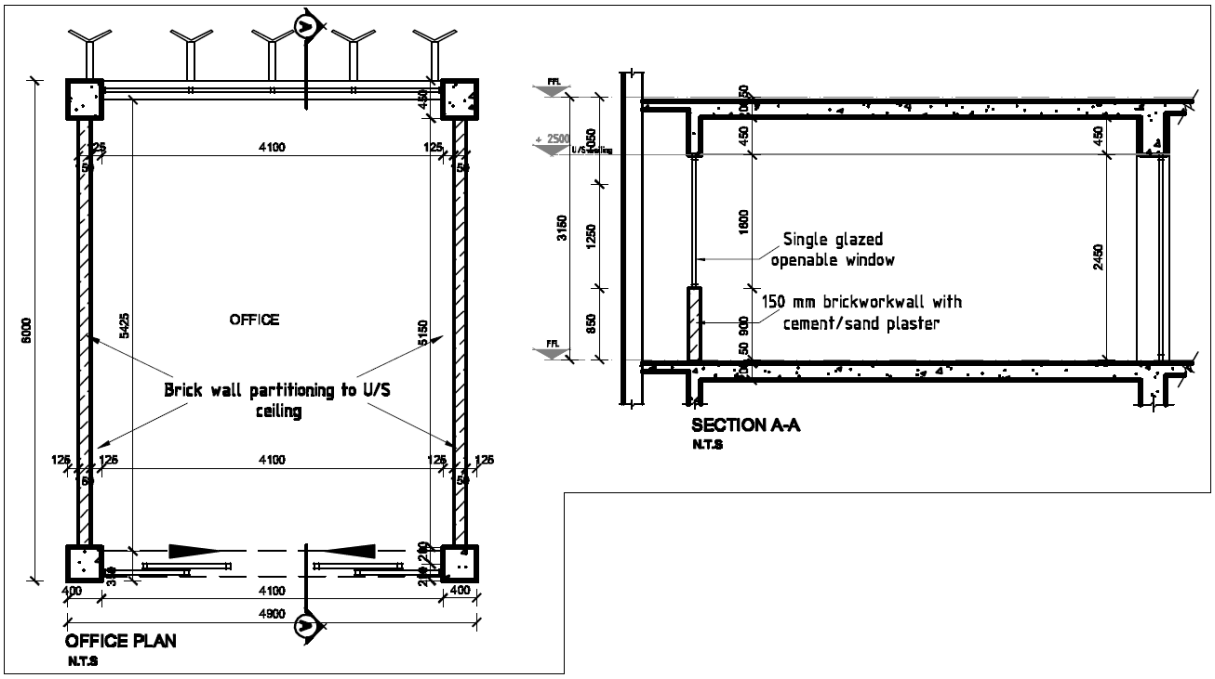



*Figure 33: Plan and section of a selected office for analysis of case study four.*

### 4.8.3 Materials and Construction

*Table 9: Materials specified for a modeled room.*

| Location | Description | Material used | Thickness (mm) | U-Value ($Wm^2/K$) | Area ($m^2$) |
|---|---|---|---|---|---|
| Floor | | Marble floor tiles | 20 | 0.05 | 25 |
| | | Reinforced conc. slab | 200 | | |
| | | Air gap | 450 | | |
| | | Gypsum boards | 20 | | |
| Walls | Outside walls | Smooth Cement rendering | 10 | 3.9 | 13 |
| | | Concrete wall | 150 | | |
| | Partition walls | Brickwork partitions | 150 | 2.37 | 17.7 |
| | | Single glazed | 6 | 5.64 | 13 |
| Note: the resultant U-Value is the one calculated by the software | | | | | |
| Window System | | Transmission | Reflectance | Emmittance (e) | |
| Single glazed | | 83% | 7% | 7% | |
| Shading Employed | | Material | Type | G-Value | |
| | | Prefab conc. panels | Static | 0.35 | |

### 4.8.4 Simulation Results

Results of Case Study IV are slightly similar to Case study II since they are all free-running buildings with similar nature in terms of construction. Figure 34 on the l.h.s shows the free-

running temperature in relation to adaptive comfort limit. Figure 34 shows the influence of ventilation increase on the indoor comfort .On the r.h.s the free-running temperature of the buildings aligns more within the adaptive comfort limits after an increase of ventilation.

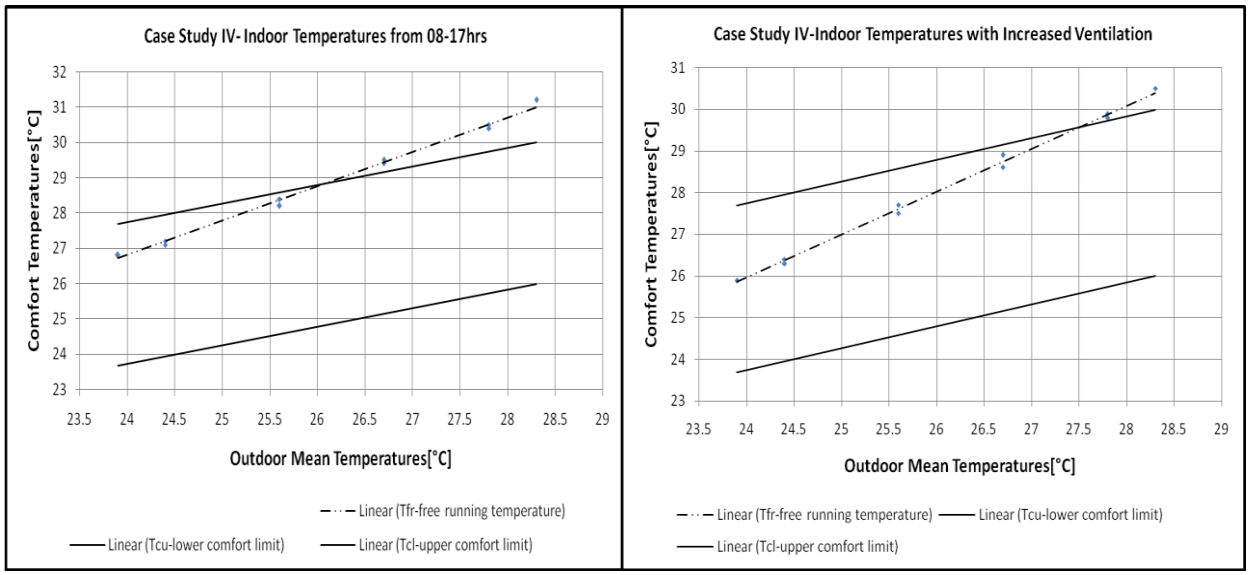



*Figure 34: Indoor temperature and comfort zone-Case Study IV*

### 4.9 Conclusions

With respect to all the case studies, the following conclusions can be reached:

(a) Double glazed façade results in an indoor condition with slightly lower indoor temperatures when comparisons are drawn with single glazed façade in a hot and humid climate as presented in the Figure 35.

(b) Double glazed façade saves a certain amount of energy when compared to single glazed façade as shown in Figure 35.

(c) It is possible to keep the free-running temperature within free-running buildings with an increase of air velocity as shown in Figure 28&34.

(d) An increase of ventilation has significant influence on the indoor comfort in free-running buildings as shown in Fig. 28&34.

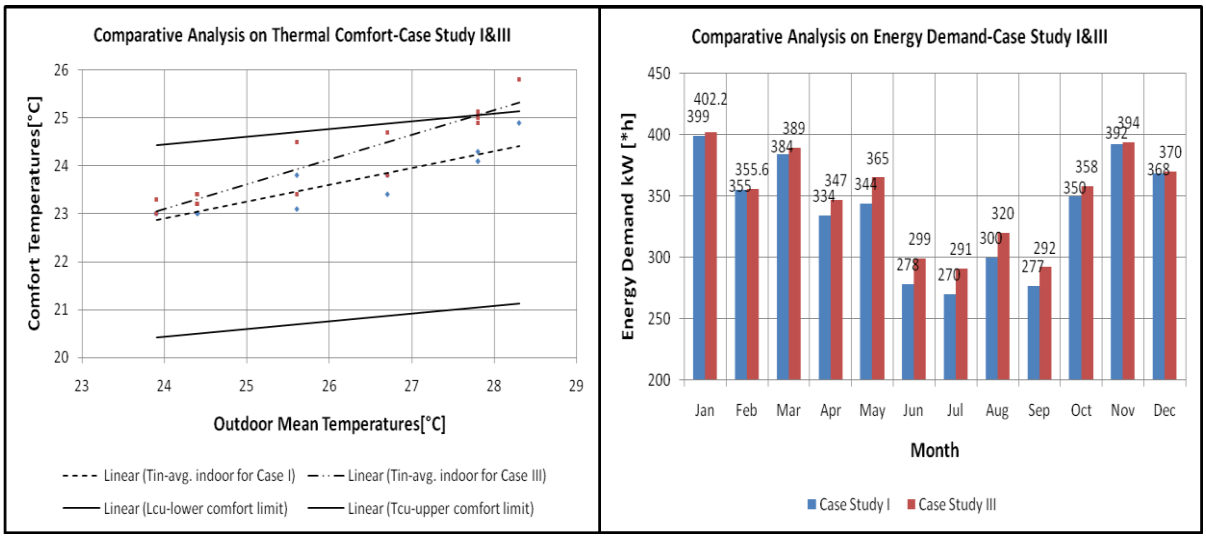



*Figure 35: Comparative analysis for the case studies*

### 4.10 Assumptions

For each room analysed on the case studies and parametric models, the following assumptions are taken into consideration for the purpose of systemizing the analysis of the results. These assumptions are presented in Table 10. It is important to point out that despite the fact that assumptions are generalized for all case studies, for most of the cases they reflect the real situation.

*Table 10: Assumptions made for each case study room.*

| Heat Sources in the room | |
|---|---|
| Two people occupy the room @ 80 Watts | 160 Watts |
| Two computers @ 100 Watts | 200 Watts |
| Printer | 150 Watts |
| Fax Machine | 38 Watts |
| Occupancy time | 8 hours per day, 5 days per week |
| One fluorescent tube 35 Watts | 35 Watts |
| Ventilation fold (@person 50$m^3$/s) | 2 |
| Infiltration | 0.15 |

Figure 36 below shows the power schedule for each office room as represented on the Table 10. It indicates the trend of the use of various office equipments throughout a working day.

The room used for parametric models has the following comfigaration ;room size is 6.5m deep x 4.3m wide x 3.0 metres high. Window size is 7 $m^2$ for both air-conditioned and free-running room. Glazing type is single.

The climate files used for Dar es Salaam is from Physibel who are manufacturers and distributors of Capsol simulation software Heirweg21B-9990, Maldegem, Belgium. Telephone+32-50-711432, email: mail@physibel.be, website www.physibel.be

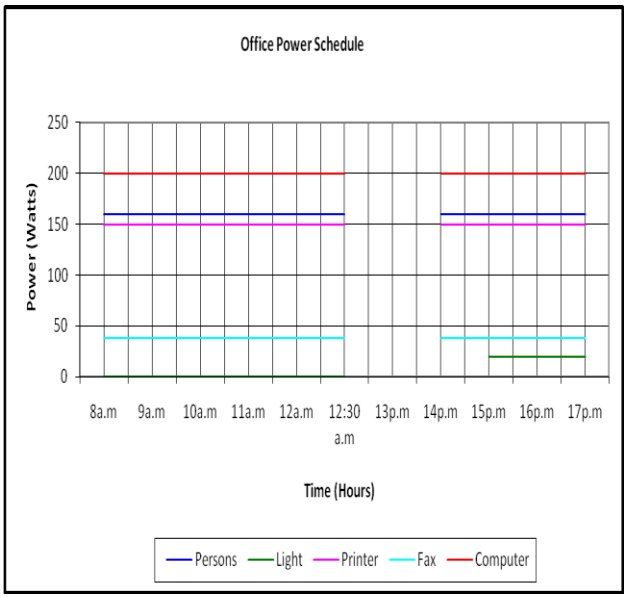



*Figure 36: Power schedule for the office*

# 5.1 Parametric Models

Parametric models are used to study the effect of various design parameters on the performance of the whole simplified system, which represents the real system. Design parameters which are selected to be studied are based on the objectives of the study set by the researcher. Depending on the kind of the study there can be many parameters and a job to analyse and present results can be exhorting one. In this study, the author seeks to investigate parameters with a focus on the following:

(a) To adequately address the research objectives
(b) To simplify and use an architect-friendly way to present the analysis

The build up of each parametric model will focus on the parameters to be analysed. The size of each model as well as internal loads is among the factors which remains constant for each model. Parameters for the analysis include materials, construction techniques, shading devices, variation of window size and the use of insulation for both free-running and air-conditioned buildings.

Presentation of the results is the key for conveying the information to the intended users of the findings, in these regard architects/designers, researchers and building industry in tropical regions. There are so many ways of presenting results; in this study the author has selected charts, tables and drawings due to the fact that they fit a particular conception of the study. Furthermore, charts, table and drawings are able to provide as much information as needed. It is author's expectation that this method is architects friendly.

### 5.1.1 Models and Parameters

This study involves 13 parametric models for the analysis of various design parameters. The key description of each model will be material and construction technique used to identify it as presented in Table 11. Based on various materials which are used in the building industry for the facades, six main groups of materials are identified.

After having the parametric models, an analysis of the models to study their influence in terms of the indoor thermal comfort and energy demand are performed. A method for analysis of the parametric models is presented in Table 11. This method is developed in order to have a systematic way of analysing these models, comparing their results and come up with reliable conclusions. All models are tested as free-running building (FRB) and air-conditioned building (ACB) as illustrated in Table 11.

*Table 11: Parametric Models*

| Parametric Models | | | | | | | |
|---|---|---|---|---|---|---|---|
| **General Identification** | | | **Design Parameters** | | | | |
| Group | Specific Material | | **Material Influence** | **Shading influence** | **Size of openings** | **Insulation Influence** | **As FRB&ACB** |
| Clay | 1 | Earth Blocks | + | + | + | + | + |
| | 2 | Brickwork | + | + | + | + | + |
| Concrete | 3 | Concrete Hollow Blocks | + | + | + | + | + |
| | 4 | Concrete Blocks | + | + | + | + | + |
| Timber | 5 | Timber Panels | + | + | + | + | + |
| Stone | 6 | Granite | + | + | + | + | + |
| Plastic | 7 | Polycarbonate | + | + | + | + | + |
| | 8 | ETFE Foils | + | + | + | + | + |
| Glass | 9 | Single Glazed | + | + | - | - | + |
| | 10 | Double Glazed | + | + | - | - | + |
| | 11 | Glass Blocks | + | + | - | - | + |
| Other | 12 | Water Facade | + | + | + | + | + |
| | 13 | PCM | + | + | + | + | + |
| | | | | | | | |
| **General Identification** | | | **Design Parameters** | | | | |
| Group | Specific Material | | Orientation Influence | | Load factor 0.5 | Internal walls | **As FRB&ACB** |
| Clay | 14 | Earth Blocks | + | + | + | + | + |
| Concrete | 15 | Concrete Blocks | + | + | + | + | + |
| Timber | 16 | Timber Panels | + | + | + | + | + |

### 5.1.2 Fixed Parameters

In each parametric model, the dimensions of the room and the schedule of internal loads used is the same so as to try as much as possible to systemize the results. This is the schedule used in the case studies as presented in Table 10 section 4.10. Also the dimensions of the model will remain the same, so as to systemize the results, only other parameters will be changed. Furthermore, the construction of floor, ceiling and indoor partitions is similar for all models with exception of model 14 and 15 in which internal partitions are changed to study the influence of thermal mass for internal walls. The construction of floors and ceiling for all models are as presented in the parametric model I.

## 5.2 Parametric Model I- Clay

This parametric model illustrated in Fig. 37 is made of compressed earth blocks (CEBs) façade. Compressed earth blocks are a modern variation of traditional materials. The blocks are typically composed of 65% clay, 30% sand and 5% lime/cement as a stabilizer to create water resistant block. The percentage of each ingredient may vary from region to region depending on the soil composition.
A typical example of a clay building is Trade fair ground administration tower in Hannover by Herzog + Partners Architects. This building uses ventilated clay brick curtain wall system on aluminium supporting construction.



*Figure 37: Parametric Model I*

### 5.2.1 Material and Construction

Table 12 shows materials and construction as used on the simulation of parametric model V-brickwork. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 12: Materials for parametric model I*

| Location | Description | Material used | Thickness (mm) | λ (W/m K) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Floor | | Marble floor tiles | 20 | 2.9 | 2600 | 840 | 0.05 | 28.1 |
| | | Reinforced conc. slab | 200 | 2.6 | 2300 | 930 | | |
| | | Air gap | 500 | 0.025 | 1.23 | 1008 | | |
| | | Gypsum boards | 20 | 0.25 | 900 | 1000 | | |
| Walls | Outside wall | Smooth Cement rendering | 10 | 0.7 | 1600 | 850 | 2.5 | 7.56 |
| | | Compressed Earth Blocks | 150 | 0.8 | 1700 | 864 | | |
| | Window | Single glazed | 6 | 0.8 | 2500 | 840 | 5.64 | 7.14 |
| | Partition walls | Dry wall partitions (wood panels) | 90 | 0.12 | 550 | 2260 | 2.37 | 23.5 |
| Note: the resultant U-Value is the one calculated by the software | | | | | | | | |

### 5.2.2 Simulation Results and Discussion

Simulation results for parametric model I-clay building are as presented in the Fig. 38 below. On this model the following parameters were tested to determine their influence on the indoor comfort and energy demand of the building, shading, window size variation and insulation. First the model was tested without shading and later on shading was applied to check the influence.

Results shows that among all the parameters tested, shading has significant influence on indoor comfort and energy demand for both free-running and air-conditioned building as shown in Fig 38. In both buildings categories (FRB & ACB), shading was the only design parameter which maintains the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand. Upon ranking these design parameters based on

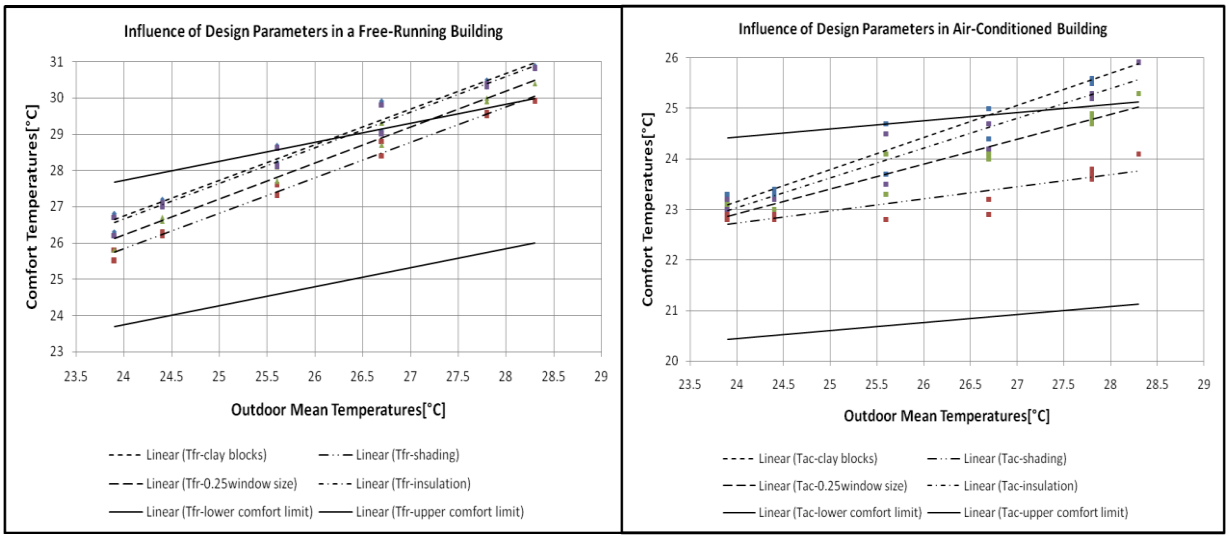



*Figure 38: Influence of design parameters for FRB and ACB on a Clay Model*

their performance; shading has higher influence followed by window size variation and insulation shows insignificant influence.

Application of shading device as a design parameter for parametric model I reduces energy consumption for 13%, from 4214 kW [*h] to 3721 kW [*h] for this parametric as Fig. 39 shows.

Variation of the window size from 50% to 25% of the façade area has an influence in both indoor comfort and energy consumption for both FRB and ACB respectively. Window size variation reduces annual cooling energy demand by 4.3 %. This is indicated in Fig. 40.

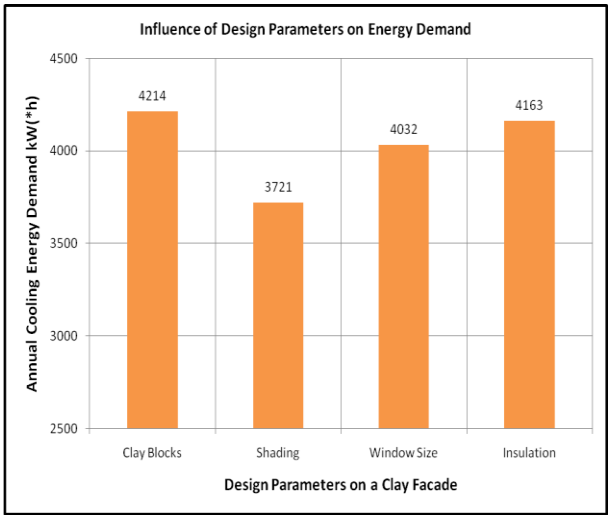



*Figure 39: Influence of design parameters in the energy demand for clay model*

### 5.3 Parametric Model II- Concrete

This model as presented in Fig. 40 is designed with the use of hollow concrete blocks for external walls. These blocks are manufactured as both load and non-load bearing façade component. The size can vary depending on the requirement of the design but usually 150 mm thick for external wall is preferable.

For further analysis concrete blocks were also investigated to determine their influence on the indoor thermal comfort and cooling energy demand. Results are included in the comparative analysis of the parametric models for the reference.



*Figure 40: Parametric Model II*

#### 5.3.1 Material and Construction

Table 13 shows materials and construction as used on the simulation of parametric model V-brickwork. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 13: Materials for parametric model II*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside wall | Hollow Concrete Blocks | 150 | 2.6 | 2300 | 930 | 0.39 | 7.56 |
| | Window | Single glazed | 6 | 0.8 | 2500 | 840 | 5.64 | 7.14 |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 (Table 12) | | | | | | | | |
| Note: the resultant U-Value is the one calculated by the software | | | | | | | | |

### 5.3.2 Simulation Results and Discussion

Simulation results for parametric model II-concrete hollow blocks building are as presented in the Fig. 41. On this model parameters which were tested to determine their influence on the indoor comfort and energy demand of the building are shading and window size variation. First the model was tested without shading and later on shading was applied to check the influence. Since concrete hollow blocks construction has high insulation value, there was no need to add insulation as a design parameter in this model. Results shows that among all the parameters tested, shading has significant influence on indoor comfort and energy demand for both free-running and air-conditioned building as shown in Fig 41.

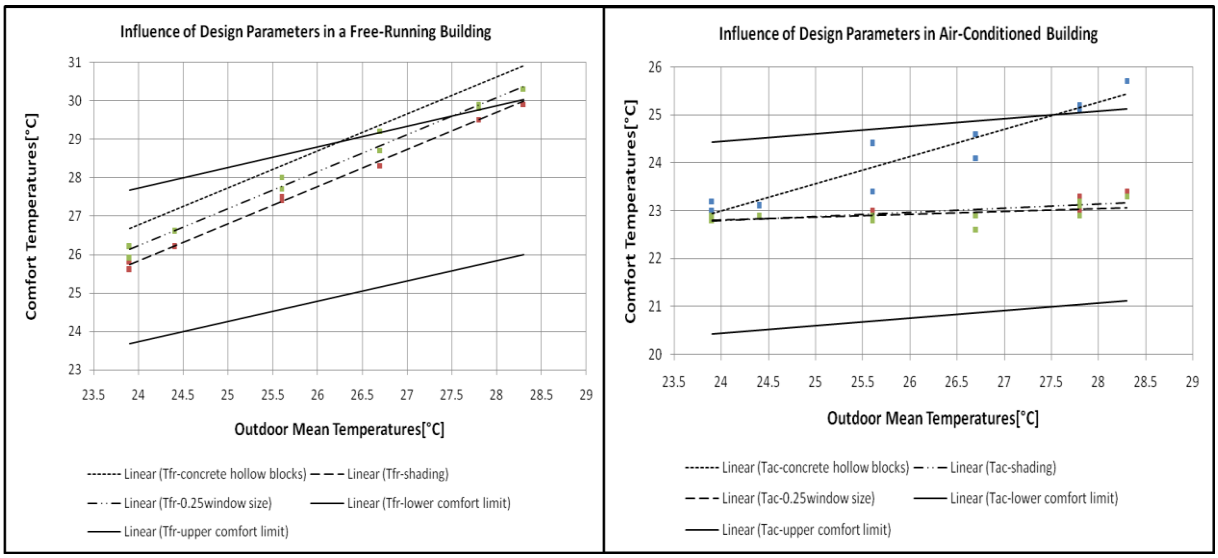



*Figure 41: Influence of design parameters for FRB and ACB in a concrete hollow blocks model*

In both categories of buildings (FRB & ACB), the use of shading maintains the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand of the building. The use of shading as a design parameter reduces the annual cooling energy demand by only 4.6 percent as Fig. 42 shows. The influence of insulation on this model is insignificant as shown in the Fig.43.

Contrary to other parametric models, the pattern of the shading and window size parameters in an air-conditioned building in this model has a slightly straight line. This is due to the influence of the high insulation nature of the façade material which negates the external air temperature influence.

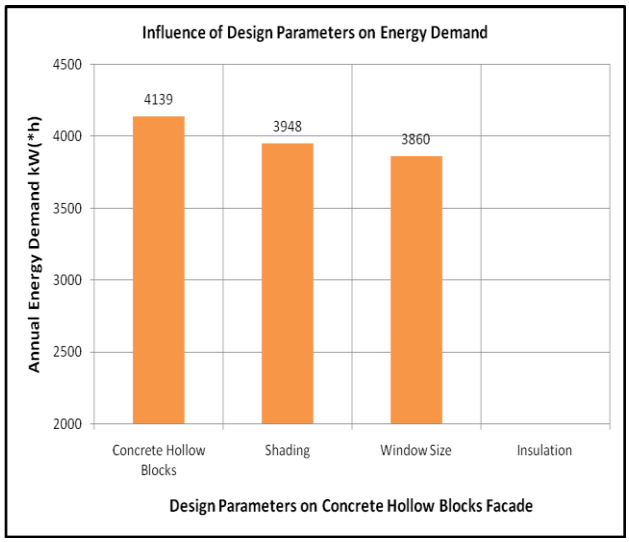



*Figure 42: Influence of design parameters in the energy demand*

Variation of the window size in this parametric model reduces the annual cooling energy demand by 6.7% as indicated in Fig. 42.

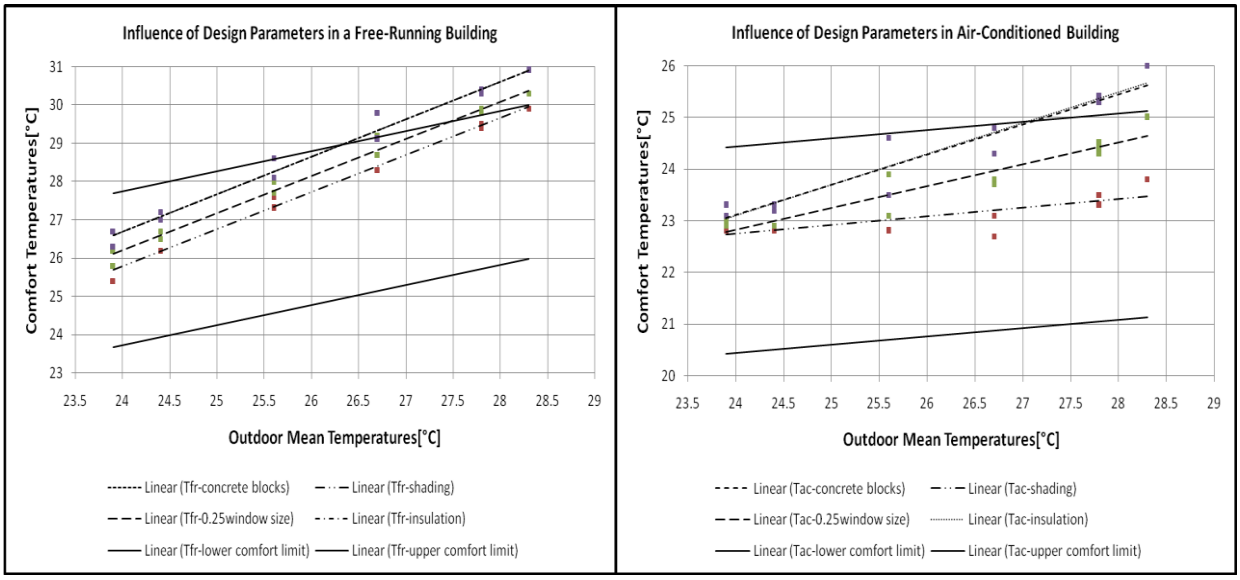



*Figure 44: Influence of design parameters in FRB and ACB for concrete blocks model*

For curiosity reasons another simulation which involves concrete blocks was done. The results for this model are presented in the Fig. 44. On this model parameter includes material, shading, window size variation and insulation. As in all other previous models, shading shows greater influence in terms of indoor comfort and energy demand for both FRB and ACB as shown in Fig. 44.

### 5.4 Parametric Model III- Timber

As the building material, wood can be employed universally. This model seeks to explore the thermal performance of wood as a façade material. In most cases wood has been used as partition walls inside of the building.

However, the use of wood as façade material enjoys technical properties which can be offered by the wood like high strength with low weight, good working options and advanced techniques, high thermal resistance. There are several forms in which wood can be used as a façade material, these include as cladding and as infill façade component e.g. profiled panels as Figure 43 shows.



*Figure 43: Parametric Model III*

#### 5.4.1 Material and Construction

Table 14 shows materials and construction as used on the simulation of parametric model V-brickwork. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 14: Materials for parametric model III*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside walls | Timber Panels | 40 | 0.24 | 1000 | 1600 | 2.64 | 7.56 |
| | | Single glazed | 6 | 0.8 | 2500 | 840 | 5.64 | 7.14 |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 | | | | | | | | |
| Note: the resultant U-Value is the one calculated by the software | | | | | | | | |

### 5.4.2 Simulation Results and Discussion

Simulation results for parametric model III-timber panels building are as presented in the Fig. 45. Parameters which were tested on this model are shading, window size variation and insulation. First the model was tested without shading and later on shading was applied to check the influence. As for previous models results shows that among all the parameters tested, shading has significant influence on indoor comfort and energy demand for both free-running and air-conditioned building as shown in Fig 45.

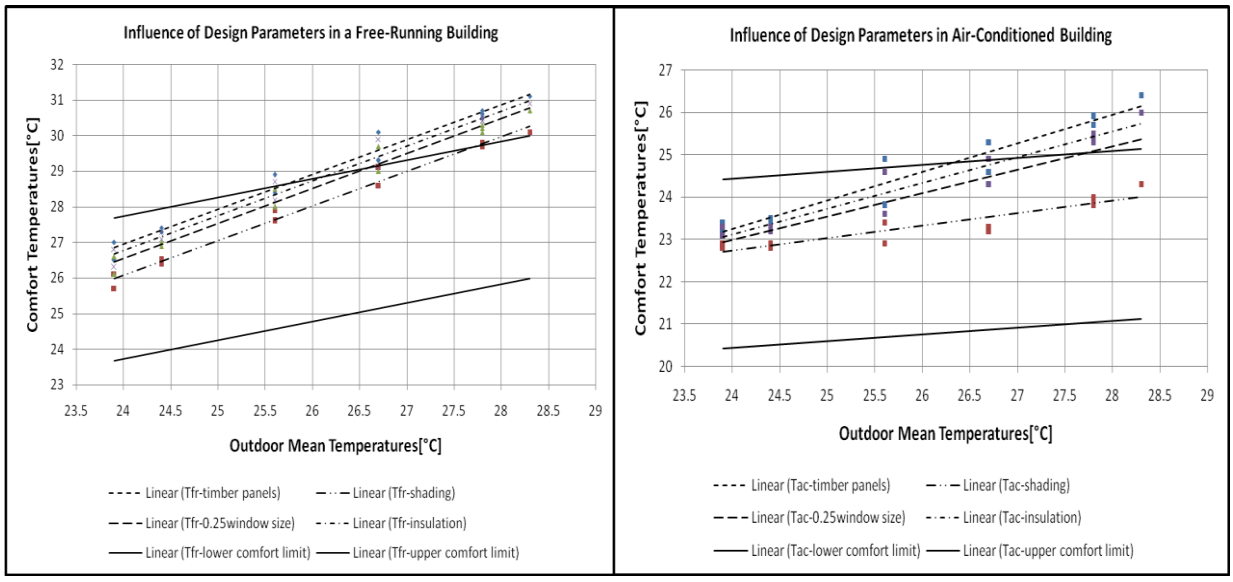



*Figure 45: Influence of design parameters for FRB and ACB on a timber model*

The use of shading as design parameter reduces the cooling energy demand of the building by 10.8% as shown in Fig 47. Shading reduces the annual energy demand from 4259kW [*h] to 3799kW [*h].

Contrary to previous models, the use of insulation shows an influence on the indoor thermal comfort although not significant one. This is due to the fact that timber as a façade material has lower thermal mass and the use of insulation increases the thermal inertia of the façade material and influence indoor comfort in both FRB & ACB as shown in Fig. 46.

The variation of the window size from 50% to 25% reduces annual energy consumption

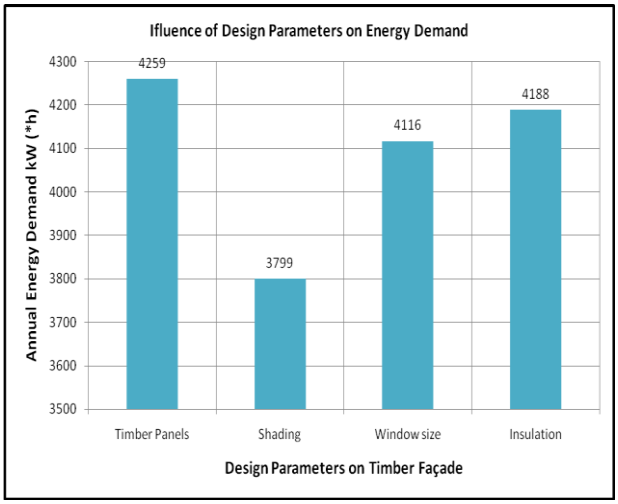



*Figure 46: Influence of design parameters on the energy demand*

by 3% as indicated from Figure 46. It also influences the indoor comfort temperature especially for FRB as indicated in Fig. 45.

### 5.5 Parametric Model IV- Polycarbonate

"Architecture is plastic," was a statement by Theo van Deosburg. The core meaning of the name plastic is "capable of being shaped". In 1924, the above-mentioned Dutch architect gave the statement implying that architecture is all about shaping and molding. By that time, plastic was not a common construction material.
Today's architects are making an extensive use of various plastic products and turning van Deosburg's vision of architecture into a reality. This model is designed with the purpose of analyzing the thermal and energy performance of plastic as a façade material. A typical example of the building employed plastic as a façade material is Instutional building in Grenoble, France by Anne Lacaton & Jean Philippe Vassal Architects. In this study parametric model IV is presented in Fig. 47.



*Figure 47: Parametric Model IV*

#### 5.5.1 Material and Construction

Table 15 shows materials and construction as used on the simulation of parametric model V-brickwork. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 15: Materials for parametric model IV*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside walls | Polycarbonate panels | 40 | 0.1 | 1200 | 1200 | 1.75 | 7.56 |
| | | Single glazed | 6 | 0.8 | 2500 | 840 | 5.64 | 7.14 |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 | | | | | | | | |
| Note: the resultant U-Value is the one calculated by the software | | | | | | | | |

#### 5.5.2 Simulation Results and Discussion

Simulation results for parametric model IV-polycarbonate building are as presented in Fig.48. Parameters which were tested on this model are shading and window size variation. Insulation was not used as a design parameter for the tests. First the model was tested without shading and later on shading was applied to check the influence. Results shows that shading has significant influence on indoor comfort and energy demand for as shown in Figure 49.

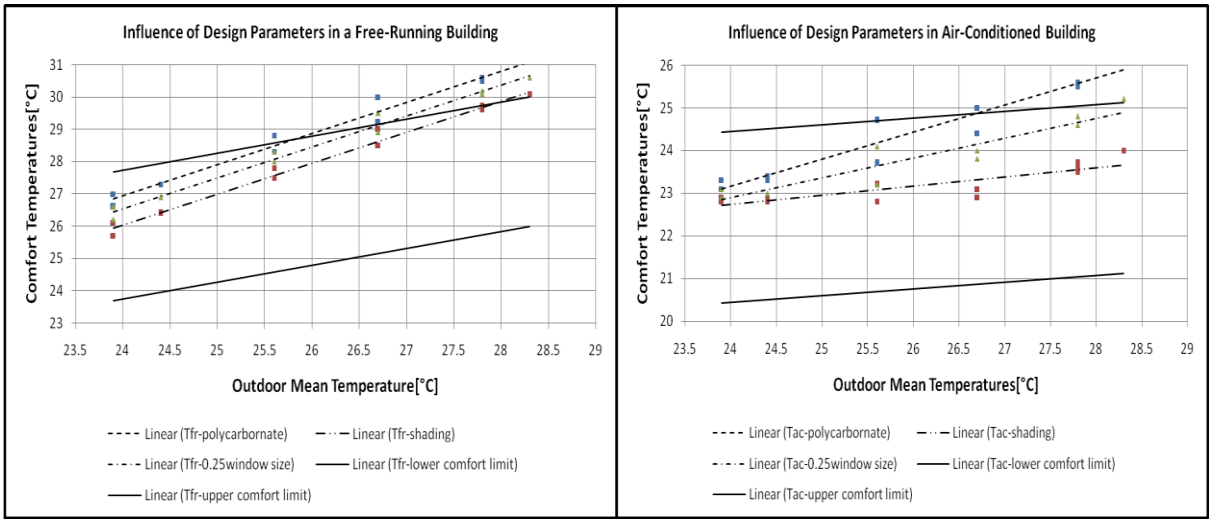



*Figure 48: Influence of design parameters for FRB and ACB on a polycarbonate model*

The use of shading reduces annual cooling energy demand by 12.5% from 4219 kW (*h) to 3691 kW (*h) as shown in the Fig.49. Furthermore, shading is the only design parameter which entirely maintains indoor temperatures within the comfort limits for both FRB and ACB.

Variation of the window size also contributes to the reduction of the annual cooling energy demand by 4.4% as shown in Fig. 50. It also has an influence on the indoor comfort in both categories of buildings as shown in Fig. 49.

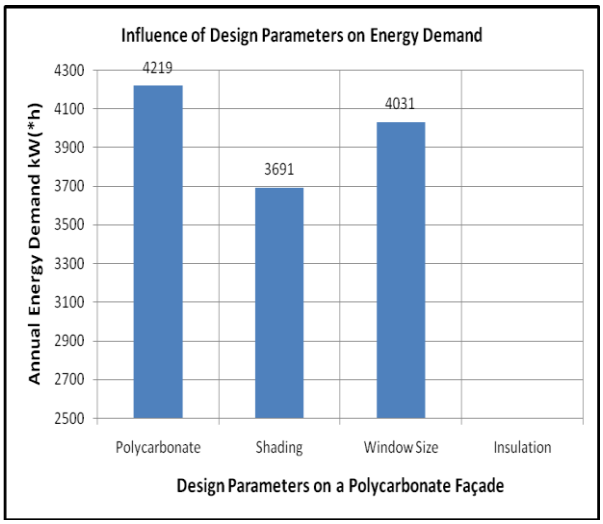



*Figure 49: Influence of design parameters in the energy demand*

### 5.6 Parametric Model V-Brickwork

Bricks are among the common traditional building materials for many societies. Bricks are used to produce brickwork masonry by the use of bricks and mortar to produce facades and other structures. There are several types of brickwork; these are solid, hollow or architectural terra cotta. They can be used as structural or decoration and they differ in formation and composition depending on the function intended for. Parametric Model V in the Fig. 50 is designed to test the influence of brickwork constructions on the indoor thermal comfort.



*Figure 50: Parametric Model V*

### 5.6.1 Materials and Construction

Table 16 shows materials and construction as used on the simulation of parametric model V-brickwork. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 16: Materials for parametric model V*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside walls | Brickwork | 150 | 0.45 | 1200 | 850 | 1.91 | 7.56 |
| | | Sand and cement plaster | 15 | 0.7 | 1600 | 850 | | |
| | | Single glazed | 6 | 0.8 | 2500 | 840 | 5.64 | 7.14 |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 | | | | | | | | |
| Note: the resultant U-Value is the one calculated by the software | | | | | | | | |

### 5.6.2 Simulation Results and Discussion

Simulation results for parametric model V-brickwork masonry building are as presented in the Fig. 51. Parameters were tested are shading, window size variation and insulation. First the model was tested without shading and later on shading was applied to check the influence. Results shows that the use of shading as a design parameter has a profound influence on indoor comfort and energy demand for both free-running and air-conditioned building as shown in Fig 52. In both buildings categories (FRB & ACB), shading shows high performance on maintaining the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand.

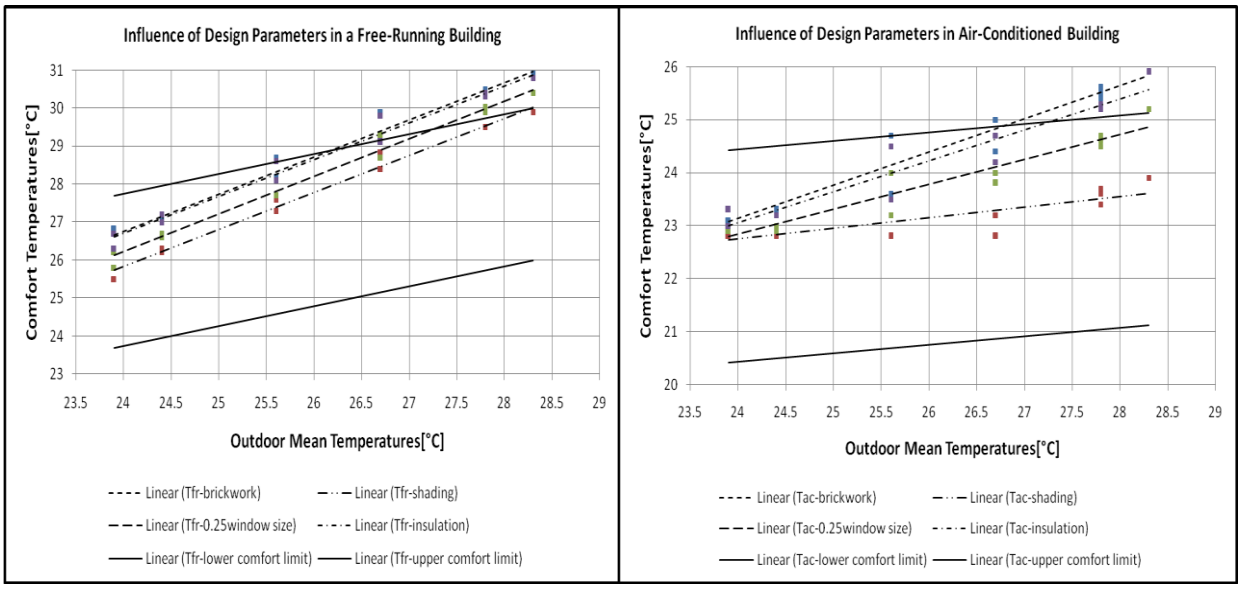



*Figure 51: Influence of design parameters for FRB&ACB on brickwork model*

The use of shading as a design parameter in this model reduces annual cooling energy demand by 12.5% from 4202 kW (*h) to 3677 kW (*h) as shown in the Fig.52. It also shows greater influence in maintaining indoor temperatures within the comfort limits for both FRB and ACB.

For parametric model V-brickwork, the variation of the window size results to the reduction of the annual cooling energy demand by 4.6% as shown in Fig. 53.
From the point of view of indoor comfort, the variation of the window size from 50% to 25% helps to keep the indoor temperature within the thermal comfort limit for longer time as Figure 52 shows.

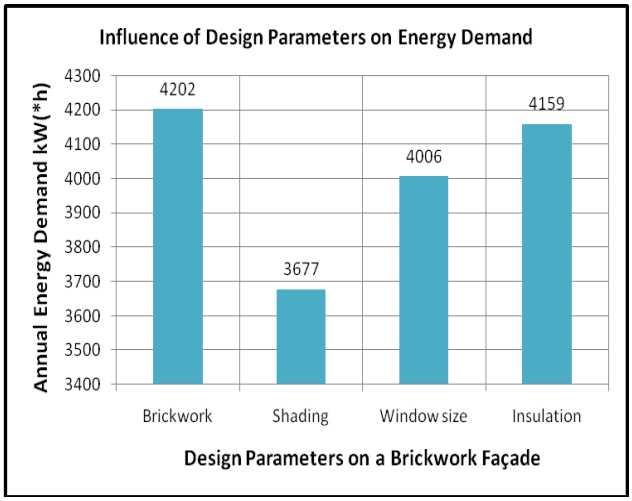



*Figure 52: Influence of design parameters in the energy demand*

## 5.7 Parametric Model VI- Granite Stone

Stone has been used as a building material in different ways. For a long period of time, stones have been used as a façade material but the construction techniques varies. In recent years most of the buildings have used stones as a cladding material due to their appealing nature.
A typical example of the building which has used stone as a façade cladding material is office of the Federal President in Berlin by Gruber+Kleine-Kranebug Architects. Figure 53 represents parametric model VI designed to investigate the influence of stone façade construction on the inddoor thermal comfort and energy demand.



*Figure 53: Parametric Model VI*

### 5.7.1 Materials and Construction

Table 17 shows materials and construction as used on the simulation of parametric model VI-granite stone. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 17: Materials for parametric model VI*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside walls | Granite Stone Panels | 30 | 3.5 | 2500 | 840 | 0.42 | 7.56 |
| | | Air gap | 50 | 0.025 | 1.23 | 1008 | | |
| | | Wood Panels | 30 | 0.17 | 700 | 2070 | | |
| | | Single glazed | 6 | 0.8 | 2500 | 840 | 5.64 | 7.14 |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 | | | | | | | | |

### 5.7.2 Simulation Results and Discussion

Results of parametric model VI-granite stone building are as presented in the Fig. 54. Parameters which were tested on this model are shading and window size variation. First the model was tested without shading and later on shading was applied to check the influence. Results shows that both shading and variation of window size as design parameters have significant influence on indoor comfort and energy demand for both free-running and air-conditioned building as shown in Fig 54. In buildings categories (FRB & ACB), shading and window size variation maintains the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand.

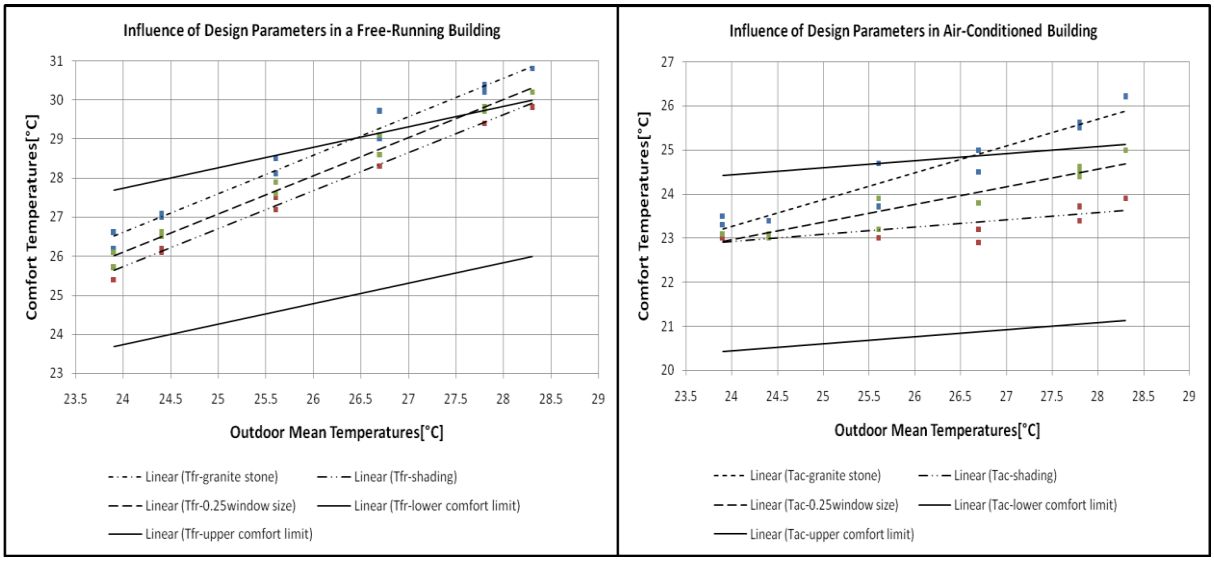



*Figure 54: Influence of design parameters on FRB&ACB on a granite model*

Application of shading device as a design parameter in this model reduces annual cooling energy demand by 15% from 3707 kW (*h) to 3148 kW (*h) as shown in the Fig.55. It also shows greater influence in maintaining indoor temperatures within the comfort limits for both FRB and ACB.

For parametric model VI-granite stone, the variation of the window size results to the reduction of the annual cooling energy demand by 11.2% as shown in Fig. 55. From the point of view of indoor comfort, the variation of the window size from 50% to 25% maintains to keep the indoor temperature within the comfort limit for longer time as illustrated in the Figure 54.

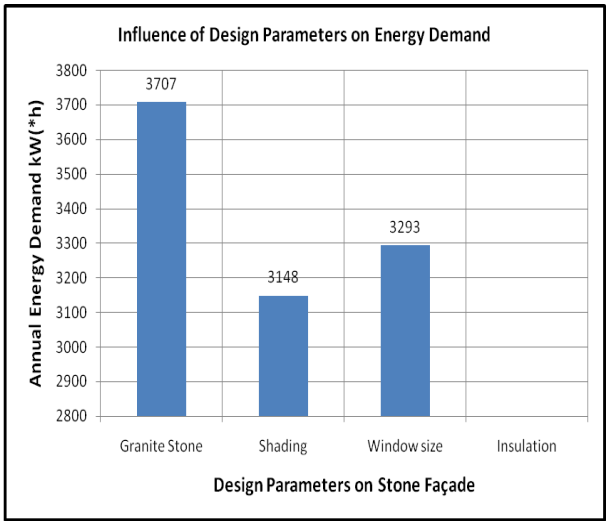



*Figure 55: Influence of design parameters in the energy demand*

## 5.8 Parametric Model VII-Single Glazed

Glass as a façade material has been in use for so many years. Architect's interests on the use of glassed are based on the ability of the material to provide visual continuity (transparency) as well as spacious feeling associated with it.
Parametric model VII in Figure 56 is designed to study the influence of single glazed on the indoor comfort and cooling energy demand in this study.



*Figure 56: Parametric Model VII*

### 5.8.1 Materials and Constructions

Table 16 shows materials and construction as used on the simulation of parametric model VII-single glazed. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 18: Materials for parametric model VII*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Floor | | Marble floor tiles | 20 | 2.9 | 2600 | 840 | 0.05 | 28.1 |
| | | Reinforced conc. slab | 200 | 2.6 | 2300 | 930 | | |
| | | Air gap | 500 | 0.025 | 1.23 | 1008 | | |
| | | Gypsum boards | 20 | 0.25 | 900 | 1000 | | |
| Walls | Outside wall | Soda lime (float glass) | 6 | 0.8 | 2500 | 840 | 3.85 | 14.7 |
| | Partitions | Dry wall partitions | 90 | 0.12 | 550 | 2260 | 2.37 | 23.5 |
| The solar shading coefficient of the glass is 0.39 | | | | | | | | |

### 5.8.2 Simulation Results and Discussion

Simulation results for parametric model VII-single glazed building are as presented in the Fig. 58. Parameters which were tested are material and shading. First the model was tested without shading and later on shading was applied to check the influence. Results show that shading have a significant influence on the indoor comfort as shown in Fig. 58. In both buildings categories (FRB & ACB), shading maintains the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand.

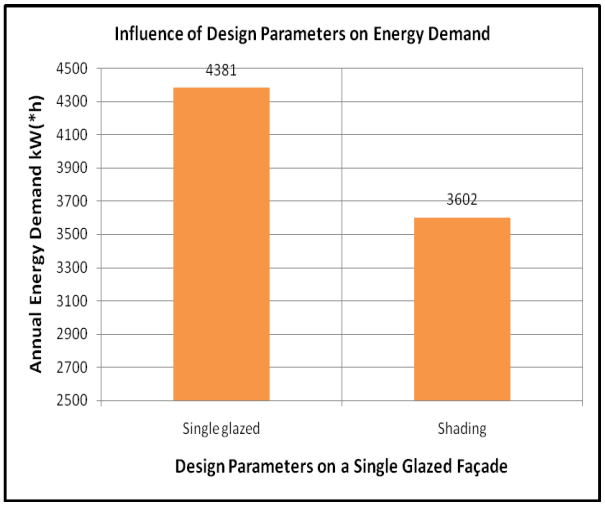



*Figure 57: Influence of design parameters in the energy demand*

Also the result shows that material (single-glazed) causes the temperature to be beyond the comfort limit throughout the year as indicated in Fig. 58. However, the use of shading maintains the indoor temperature

within the comfort limit almost throughout the year as shown in Fig 59. Furthermore, application of shading as a design parameter reduces annual cooling energy demand by 17.7% as shown in Fig. 57. The annual cooling energy demand falls from 4381 kW (*h) to 3602 kW (*h) as indicated.

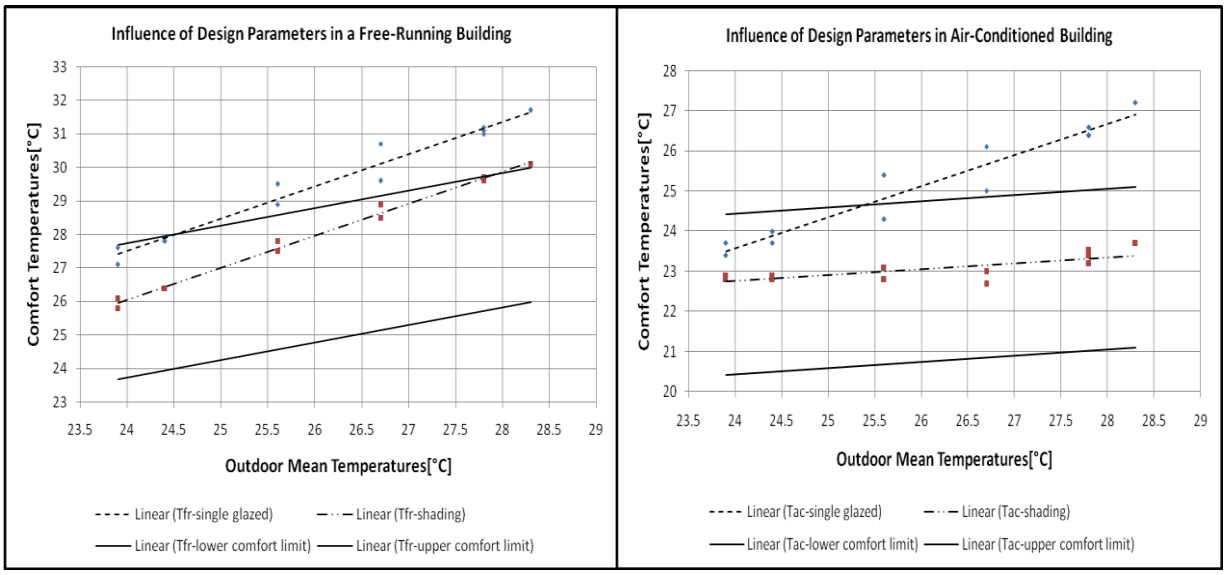



*Figure 58: Influence of design parameter on FRB&ACB on a single glazed model*

### 5.9 Parametric Model VIII-Double Glazed

Double glazed facades are popular for their ability to reduce the amount of heat gain into the building from both the sun's direct short-wave radiation and the transfer of energy from the exterior environment (diffuse component). There are several types of double glazed façade depending on their performance and properties.

The degree of solar control of these glasses is determined by their ability to resist heat flow from the sun's direct radiation, including short-wave infrared energy that lies near visible light in the spectrum. This can be measured by solar heat gain coefficient which is the ratio of the solar heat gain through the glass to the solar radiation falling onto the glass. Parametric model VIII-Figure 59 is designed to study the influence of double glazed as façade material on the indoor thermal comfort and energy demand.



*Figure 59: Parametric Model VIII*

#### 5.9.1 Materials and Constructions

Table 16 shows materials and construction as used on the simulation of parametric model VIII-double glazed. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 19: Materials for parametric model VIII*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside wall | Soda lime (float glass) | 6 | 1 | 2500 | 750 | 1.71 | 14.7 |
| | | Air gap | 12.7 | 0.025 | 1.23 | 1008 | | |
| | | Soda lime (float glass) | 6 | 1 | 2500 | 750 | | |
| Note: the resultant U-Value is the one calculated by the software<br>The shading coefficient of the façade is 0.22 | | | | | | | | |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 | | | | | | | | |

### 5.9.2 Simulation Results and Discussion

Simulation results for parametric model VIII-double glazed building are as presented in the Fig. 60. Parameters which were tested are material and shading. Results show that shading have a significant influence on the indoor comfort as shown in Fig. 60. In both buildings categories (FRB & ACB), shading maintains the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand.

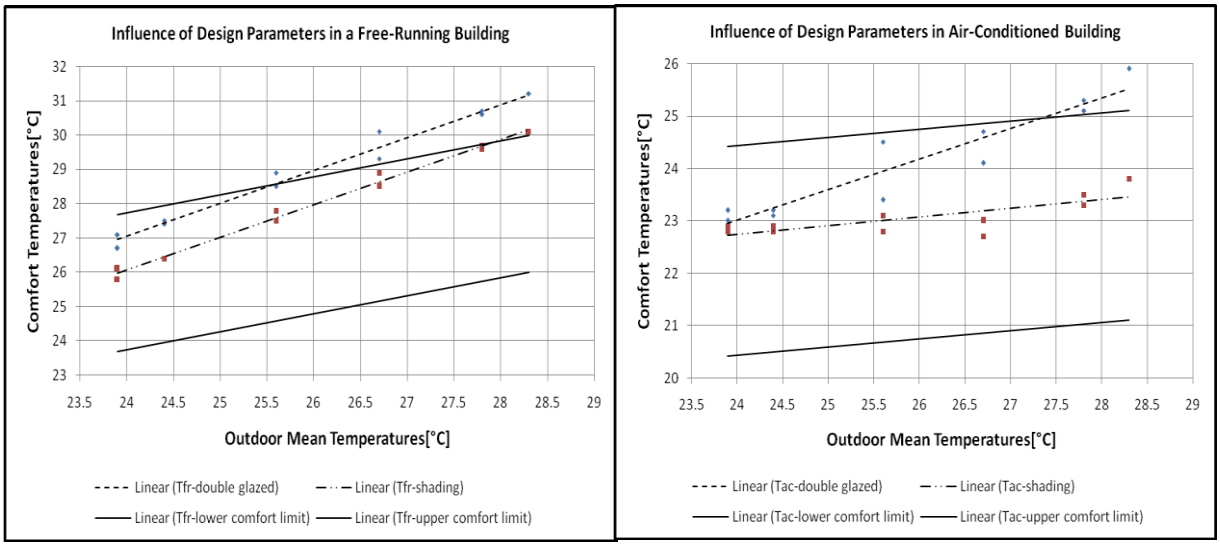



*Figure 61: Influence of design parameters on FRB&ACB on a double glazed model*

Furthermore, the result shows that material (double-glazed) causes the temperature to be beyond the comfort limit for a longer period of the year as indicated in Fig. 60 above.

The use of shading maintains the indoor temperature within the comfort limit almost throughout the year. Also application of shading as a design parameter reduces annual cooling energy demand by 13.5% as shown in Fig. 61. The annual cooling energy demand falls from 4192 kW (*h) to 3627 kW (*h) as indicated.

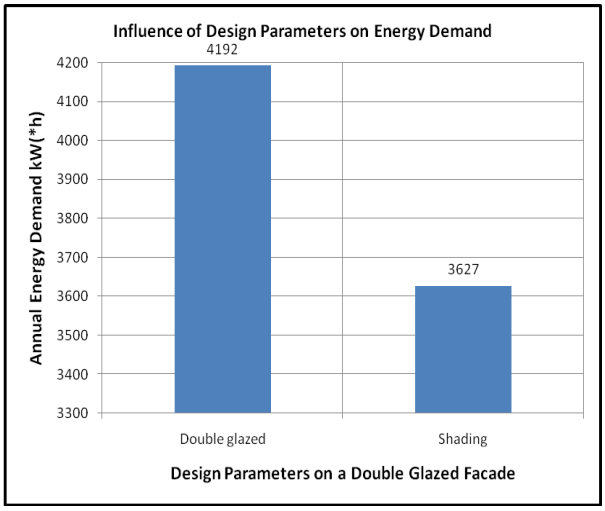



*Figure 60: Influence of design parameters in the energy demand*

### 5.10 Parametric Model IX- Glass Blocks

Glass blocks are not frequently used construction material for facades in a hot and humid region. Tests on this parametric model are based on the aim of investigating their performance in terms of thermal comfort and energy demand. Figure 62 represents parametric model IX made of the glass blocks and designed to investigate the influence of the glass blocks on the indoor thermal comfort and energy demand for the building.



*Figure 62: Parametric Model IX*

#### 5.10.1 Materials and Constructions

Table 20 shows materials and construction as used on the simulation of parametric model IX-glass block building. Materials and construction for the floors and internal partitions are as presented in the parametric model I.

*Table 20: Materials for parametric model IX*

| Location | Description | Material used | Thickness (mm) | λ (W/mK) | ρ (kg/m$^3$) | C (J/kgK) | U-Value (Wm$^2$/K) | Area (m$^2$) |
|---|---|---|---|---|---|---|---|---|
| Walls | Outside wall | Soda lime (float glass) | 10 | 1 | 2500 | 750 | 0.71 | 14.7 |
| | | Air gap | 80 | 0.025 | 1.23 | 1008 | | |
| | | Soda lime (float glass) | 10 | 1 | 2500 | 750 | | |
| Note: the resultant U-Value is the one calculated by the software<br>The shading coefficient of the façade is 0.33 | | | | | | | | |
| Note: Floors and internal partitions are as in Model 1-Section 5.2.1 | | | | | | | | |

#### 5.10.2 Simulation Results and Discussion

Simulation results for parametric model IX-glass block building are as illustrated in the Fig. 63. Parameters which were tested are material and shading. Results presented by Fig. 64 show that shading have a significant influence on the indoor thermal comfort and reduction of annual cooling energy demand. In both buildings categories (FRB & ACB), shading maintains the indoor temperature within the comfort limit as well as minimizes the total cooling energy demand.

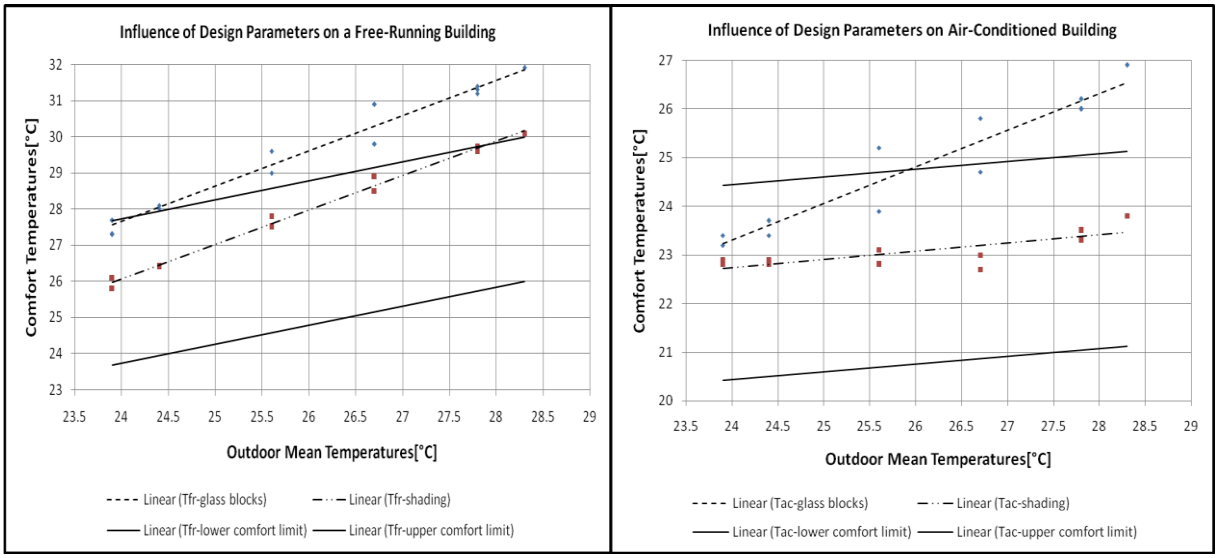



*Figure 64: Influence of design parameters on FRB&ACB on a glass block model*

Furthermore, the result shows that material (glass blocks) causes the temperature to be higher beyond the comfort limit for almost throughout the year as indicated in Fig. 63.

The use of shading maintains the indoor temperature within the comfort limit almost throughout the year. Also application of shading as a design parameter reduces annual cooling energy demand by 17% as shown in Fig. 64. The annual cooling energy demand falls from 4383 kW (*h) to 3627 kW (*h) as indicated.

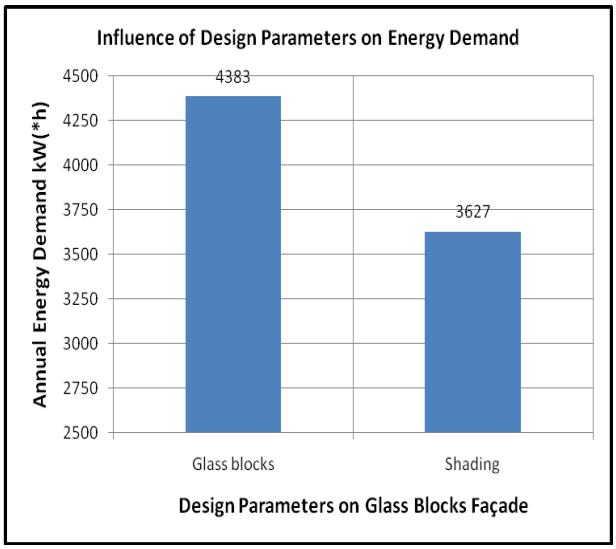



*Figure 63: Influence of design parameters in the energy demand*

### 5.11 Parametric Model X- Orientation Influence

Parametric model X is created for the purpose of determining the influence of orientation in thermal comfort as well as energy demand for the building. The building model used for this test is Clay model. The tests are done for both FRB and ACB. Since all models are affected in similar way when it comes to orientation, one model can be used to both represent others and draw conclusions.

### 5.11.1 Simulation Results and Discussion

The simulation results for parametric model X (orientation influence) are as illustrated in the Fig. 65. Design parameters which are tested in this model are material, shading and variation of window size. The influence of each parameter is determined in respect to different orientation.

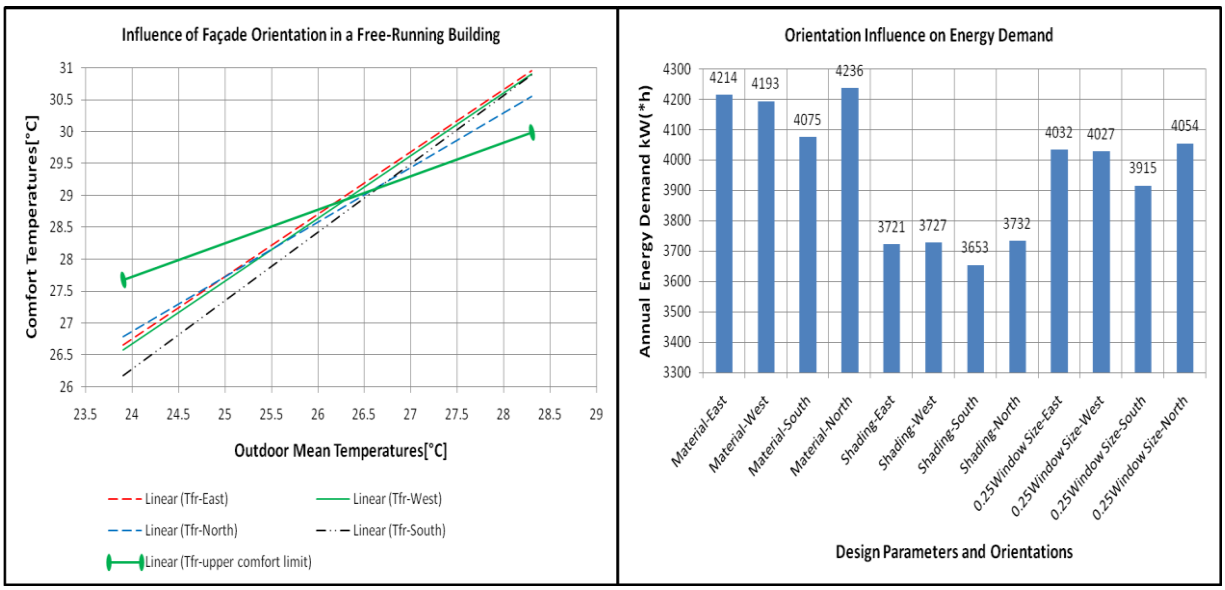



*Figure 65: Influence of orientation on indoor comfort and energy demand*

Results show that there is no significant influence of orientation on the indoor thermal comfort in FRB as shown in Fig. 65. A closer look on all orientations shows that north and south orientations have a better condition in terms of the thermal comfort than east and west orientations. However, the overall performance in terms of the indoor thermal comfort shows a small difference.

Analysis of the influence of orientation in energy demand for ACB is as presented in Fig. 65 above. Result shows that south orientation has minimum energy consumption when compared to all other orientations. Also north, east and west orientation exhibits the same trend of energy consumption. There is no significant difference in terms of cooling energy demand when north, east and west orientations are compared.

Other design parameters like shading and variation of window size show an influence on cooling energy demand. This influence is independent of the orientation. However, on each parameter (shading and window size variation), south orientation shows significant decrease in cooling energy demand as mentioned previously. The use of shading regardless of orientation reduces the amount of energy consumption by an average of 10-11% as shown in the Fig. 65.

## 5.12 Parametric Model XI- Internal Load

Parametric model XI- (internal load) is created for the purpose of determining the influence of variations in internal load on the thermal comfort as well as energy demand for the building for both FRB and ACB. In all parametric models the schedule of internal load used is as presented in Table 10. Since there is no reliable information on the number of hours in which people spend in the office in this region, it was assumed that an average of

70% of the internal load is active throughout a year. In this parametric model the internal load is further reduced by 50% to determine its influence.

### 5.12.1 Simulation Results and Discussion

A simulation result indicates that the reduction of internal load has a small influence on the indoor thermal comfort, specifically in a free-running building as illustrated in the Fig. 66 below. This is attributed by fact that outdoor conditions which influence indoor conditions in a free-running have very small seasonal variations. Without application of other design parameters, the influence of reduction of internal load can merely be noticed in a free-running building.

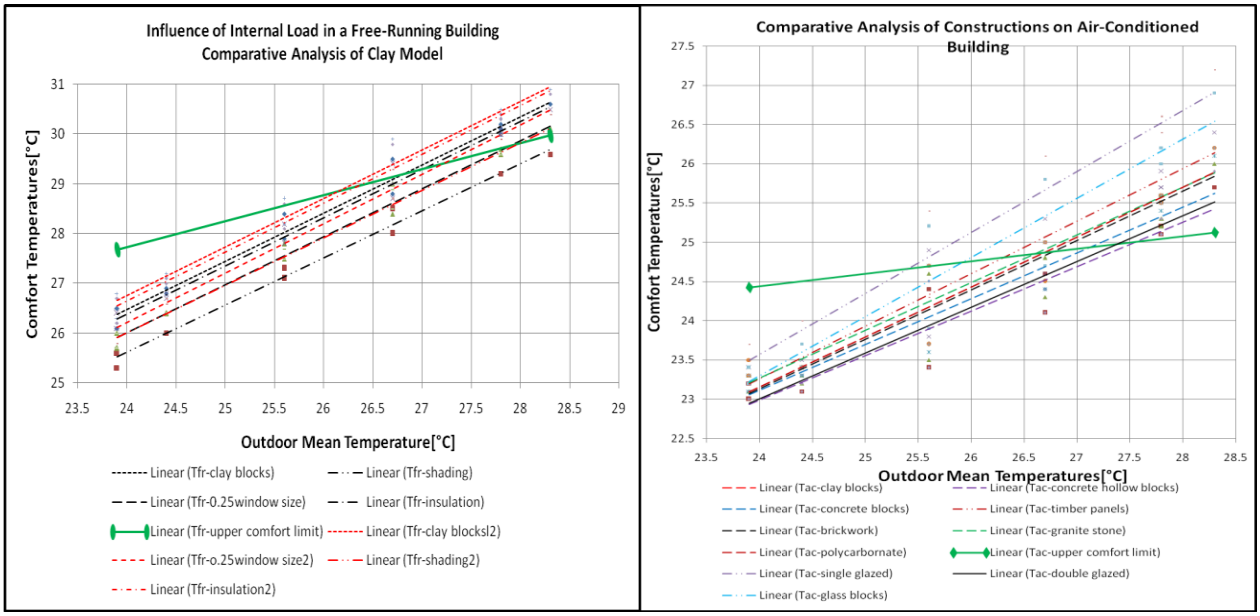



*Figure 66: Influence of variation of internal load on FRB& ACB for clay model, black color represents 50% reduction of the internal load*

When it comes to air-conditioned buildings reduction of internal load also shows a little difference in terms of both thermal comfort and energy demand. Taking an example of the Clay model, results shows that 50% reduction of internal load yield only 3% savings on cooling energy demand. However, the application of other design parameters e.g. shading, window size variation and insulation results in the energy demand savings of 8%, 4.7% and 4.1% respectively as illustrated in the Fig. 67.

To make a comparison of the influence of variation of internal load on the thermal comfort and cooling energy demand, another model (timber panels) was tested and simulation results are presented in Fig. 67. A simulation result shows coherence in percentages of the cooling energy demand savings regarding both models. An application of design parameters e.g. shading, window size variation and insulation on a timber model yield cooling energy savings of 7.6%, 4.3% and 4% respectively as indicated in the Fig. 67&68.

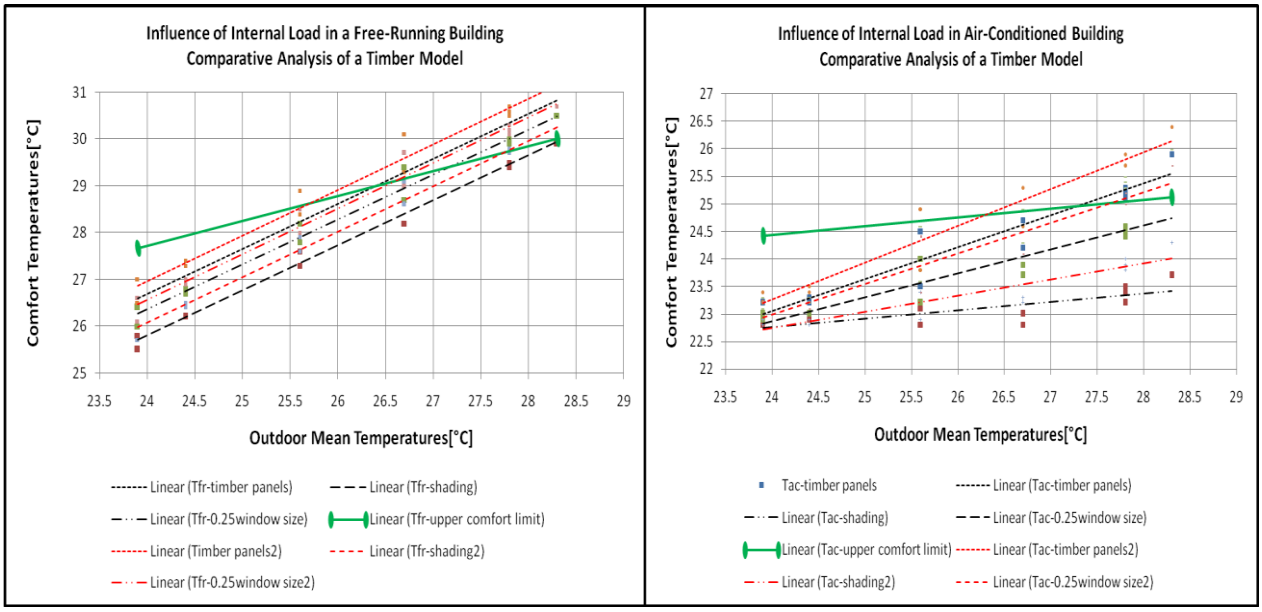



*Figure 67: Influence of variation of internal load for FRB&ÂCB for a timber model, black color represent 50% reduction of the internal load*

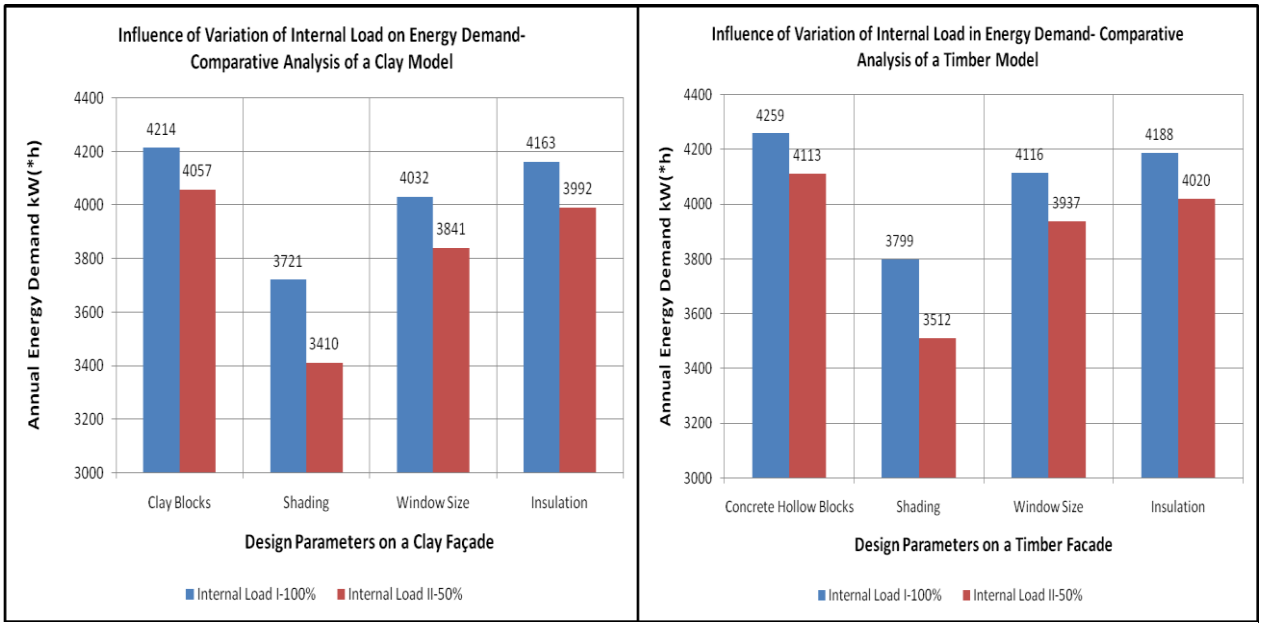



*Figure 68: Influence of variation of internal load in the energy demand for clay and timber models*

### 5.13 Parametric Model XII- Internal Thermal Mass

Parametric model XII- (internal thermal mass) is created for the purpose of determining the influence of variations in internal thermal mass on the thermal comfort as well as energy demand for the building for both FRB and ACB. In all previous parametric models, the inner walls used were timber board's partitions. In this parametric model, 150mm thick brickwork partition walls are used. Tests are done with both timber panels and clay blocks as external façades.

### 5.13.1 Simulation Results and Discussion

A simulation result indicates that changes of internal thermal mass from low to medium has a negative influence on the indoor thermal comfort and cooling energy demand. When timber panels (low thermal mass) are used as external facades, result shows that the changes of internal walls from timber panels partitions to brickwork does not improve the indoor thermal comfort of the building for both FRB&ACB. A change to a medium thermal mass internal wall (brickwork) with low thermal mass external wall (timber panels) results to a slight increase of the indoor comfort temperatures as shown in the Fig. 69.

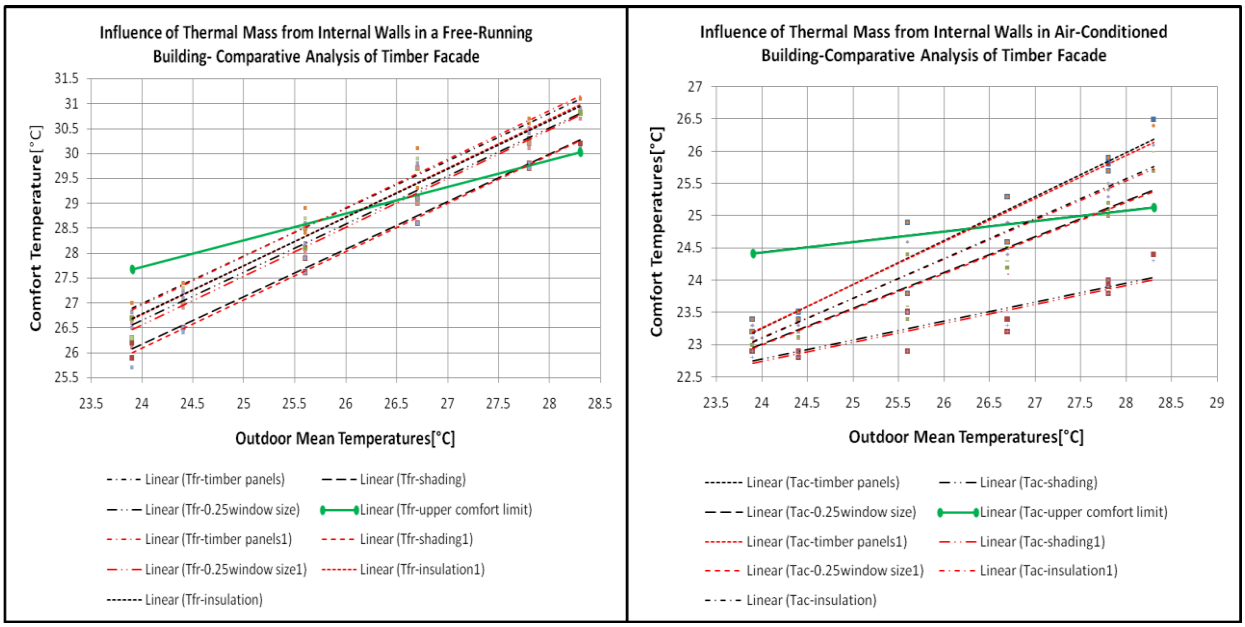



*Figure 69 : Influence of variation of internal thermal mass in FRB&ACB on timber façade, black and red colors show brickwork and timber panels respectively*

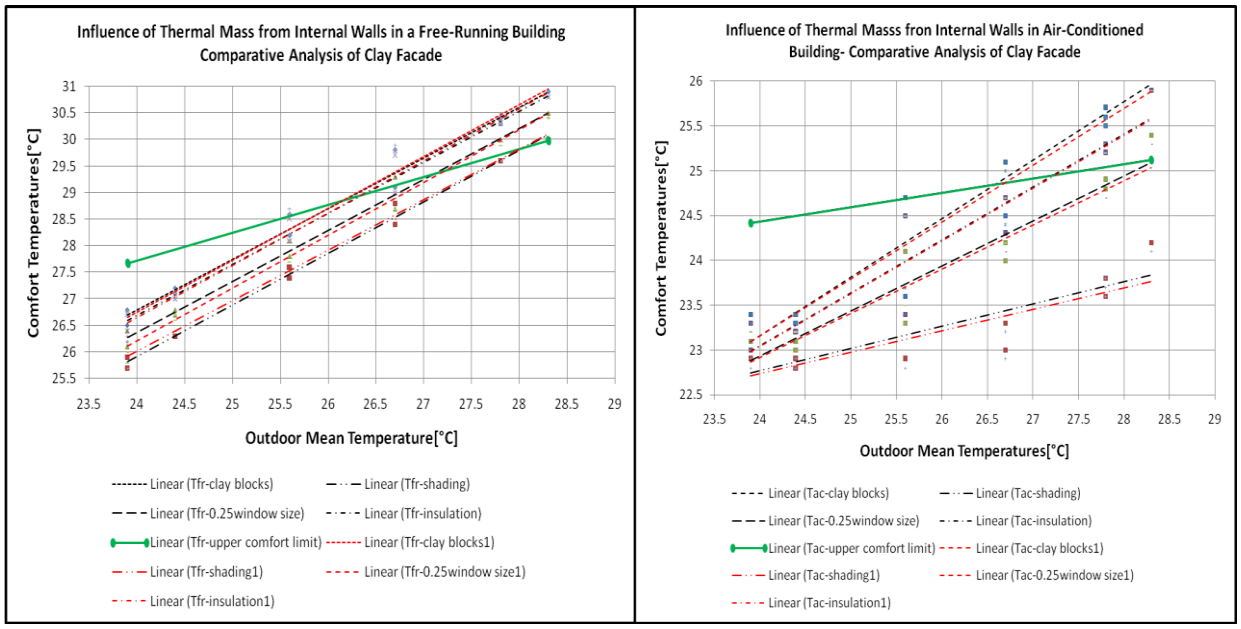



*Figure 70: Influence of variation of internal thermal mass in FRB&ACB on clay façade, black and red colors show brickwork and timber panels respectively*

Similar pattern of results are observed when clay blocks (medium thermal mass) are used as external facades. Result shows that the change of internal walls from timber panels'

partitions to brickwork does not improve the indoor thermal comfort of the building for both FRB&ACB. This change results to a slight increase of the indoor comfort temperatures as shown in the Fig. 70.

Furthermore, the influence of thermal mass from internal walls on the cooling energy demand shows varying results when clay and timber facades are compared. On a timber façade, a change of internal walls from timber board panels to brickwork has no significant impact on the cooling energy demand of the model as illustrated on the Fig. 71. The amount of cooling energy demand remains the same for both type of inner walls when timber façade is used.

For a clay façade, a change of internal walls from timber board panels to brickwork has a noticiable impact on the cooling energy demand of the model as illustrated on the Fig. 71. A simulation result indicates that a change from low thermal mass partitions walls to medium thermal mass partitions walls (brickwork) reduces cooling energy demand of the clay model as illustrated in the Fig. 71.

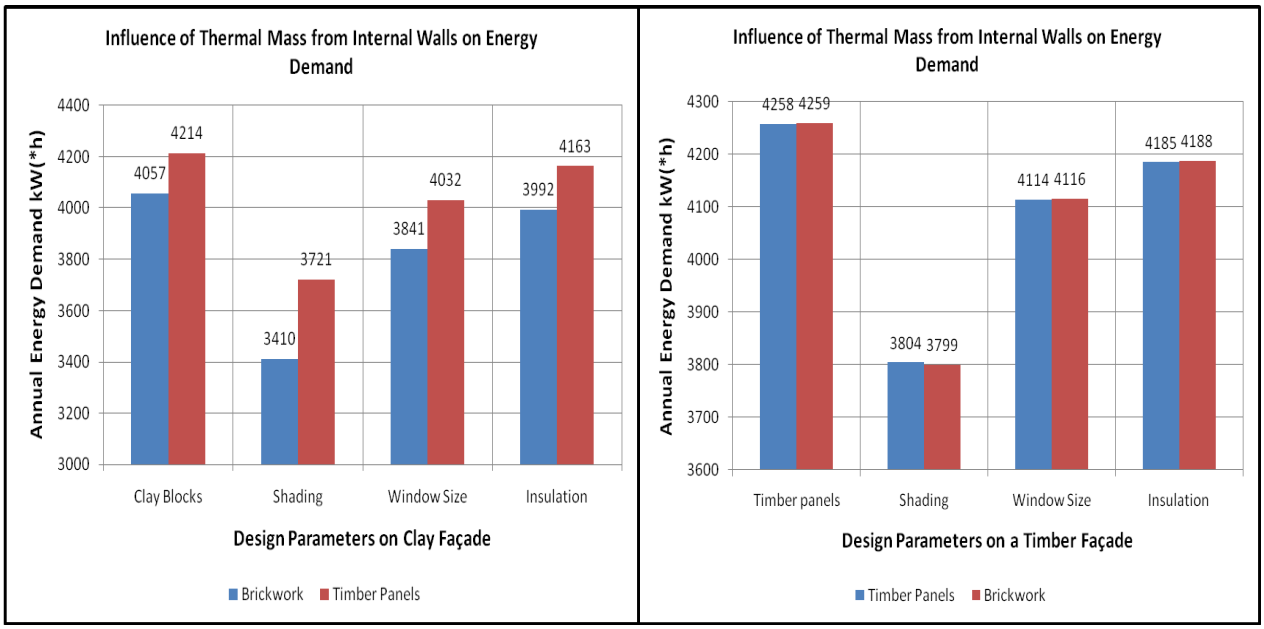



*Figure 71: Influence of variation of internal thermal mass in the energy demand for clay & timber models*

A further decrease of cooling energy demand is attained with the application of other design parameters like shading and variation of window size for both models with varying results when models are compared. While for clay model reduction of cooling energy demand when brickwork is used as internal partition is experienced in each design parameters, for timber models the situation is different. For timber model the reduction of cooling energy demand is merely due to design parameters and not a change of internal walls as indicated in the Figure 71. A change of internal walls for timber model has no impact on the amount cooling energy demand.

# 6.1 Analysis

This chapter focuses in analysis of the results obtained from studies of parametric models. It encompasses the analysis of previous methods used for studying and comparing the influence of various design parameters in both FRB and ACB. It goes beyond the general method of analysis and introduces a detailed method of analysis (ATG Method) as a tool for not only studying the indoor thermal comfort but also the performance of the building materials and constructions. Comparative analysis of various design parameters previously studied are done so as to prepare a benchmark for drawing conclusions.

## 6.2 Nicols /Humphrey's Approach

Based on the Humphrey's equations previously used to determine the thermal comfort ranges for free-running and air-conditioned buildings in chapter five (parametric models), different constructions are compared. The aim of this comparative analysis is to determine the performance of each materials and constructions as previously used in parametric models for both FRB and ACB.

### 6.2.1 Free-Running Buildings

As previously mentioned, Humphreys equations introduced in chapter two have been used to form the basis for analysis of the indoor thermal comfort in free-running buildings. Also analysis of how materials/constructions perform in relation to the indoor thermal comfort in free-running building is done based on the same method as illustrated in Fig. 73. Later on materials performance are analyzed and ranked with respect to their thermal properties (total thermal transmittance of façade).

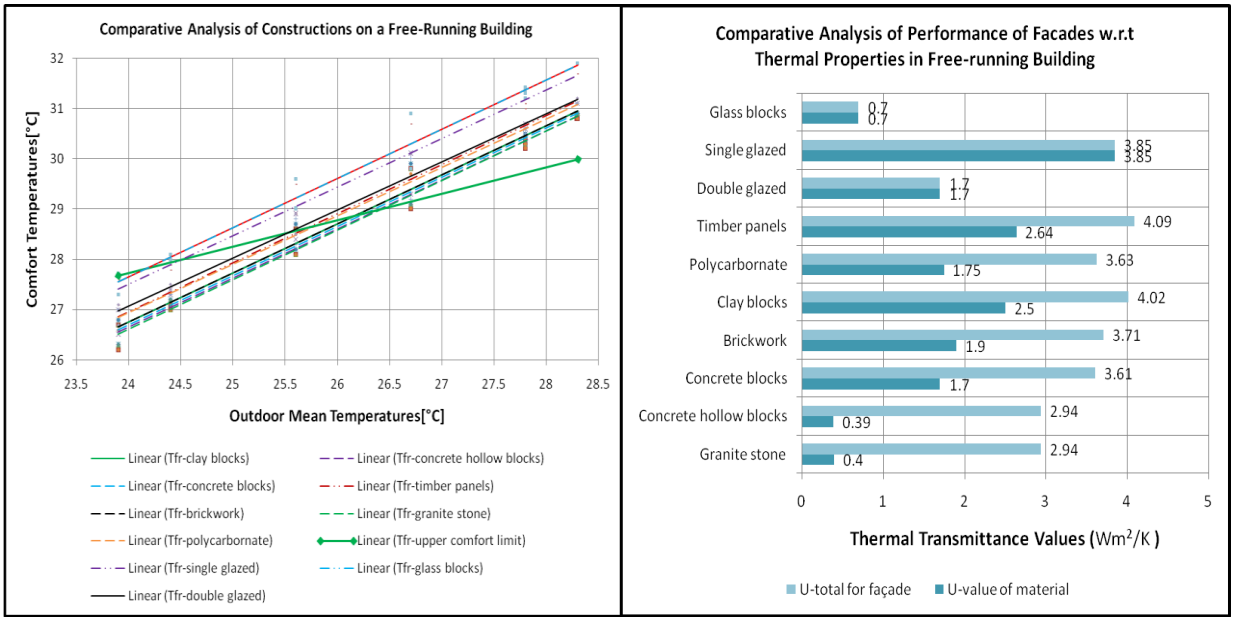



*Figure 72: Performance of constructions in a FRB; the performance decreases in upward*

Comparative analysis of various constructions previously used in parametric models 1-10 shows that material performs differently when it comes to the indoor thermal comfort as shown in Table 21. In Table 21 all materials/constructions which were used in parametric

models are ranked according to their indoor thermal performance. This ranking is also presented in the Fig. 72. The analysis shows that materials/constructions like concrete hollow blocks, granite stone, concrete blocks performs better than others. Analysis by Nicols/Humphrey approach shows that for free-running building the lower the total thermal transmittance of the façade construction the better the indoor thermal comfort as illustrated in Table. 21. Hence the following relationship can be deduced;

*The indoor thermal comfort in a free-running building is inversely proportional to the total thermal transmittance of construction (for masonry construction).*

Façade construction with lower total thermal transmittance has higher performance on the indoor thermal comfort in a free-running building. Analysis shows that the individual properties of material like thermal capacity, density and thermal conductivity are not enough to deduce the way the material will perform. Analysis of the total construction (façade) is necessary to determine the influence of the material on the thermal comfort.

*Table 21: A rank of construction in relation to the performance in a free-running building*

| Rank | Façade Construction Material | Façade Area | Material Transmittance ($Wm^2/K$) | Window Total Transmittance ($A_w.U_w$) | Total Transmittance [$\bar{U}= (A_g.U_g+A_w.U_w)/A_t$] |
|---|---|---|---|---|---|
| 1 | Concrete hollow blocks | 7.56 | 0.4 | 40.2 | 2.95 |
| 2 | Granite stone | 7.56 | 0.42 | 40.2 | 2.95 |
| 3 | Concrete blocks | 7.56 | 1.7 | 40.2 | 3.61 |
| 4 | Brickwork | 7.56 | 1.9 | 40.2 | 3.71 |
| 5 | Clay blocks | 7.56 | 2.5 | 40.2 | 4.02 |
| 6 | Polycarbonate | 7.56 | 1.75 | 40.2 | 3.63 |
| 7 | Timber panels | 7.56 | 2.64 | 40.2 | 4.09 |
| 8 | Double glazed | 14.8 | 1.71 | - | 1.71 |
| 9 | Single glazed | 14.8 | 3.85 | - | 3.85 |
| 10 | Glass blocks | 14.8 | 0.71 | - | 0.71 |

### 6.2.2 Air-conditioned Buildings

Analysis of the performance of various parametric models in air-conditioned buildings is as presented in the Fig. 73. In this analysis material/constructions are ranked in the order of their performance with respect to the indoor thermal comfort as illustrated in the Fig.73. Comparative analysis of parametric models which defines the constructions presented in the Table 22 shows that concrete hollow blocks, double glazed, concrete blocks and brickwork performs better than other constructions.

The rank of parametric models in relation to their performance on the indoor thermal comfort aspect in air-conditioned building is as presented in Table 22. Comparative analysis shows that various constructions perform differently in air-conditioned building and free-running buildings. Contrary to the free-running buildings which entirely depend on the total thermal transmittance of the façade, air-conditioned buildings shows different pattern which is independent of total transmittance.

This pattern is shown by the performance of parametric model which uses double glazed as a façade material. On the free-running building condition, double glazed model ranks number 9 which is last but one but in air-conditioned building it ranks number 2 on the

indoor thermal comfort performance as illustrated in Fig. 74 and presented in the Table 22. This performance of double glazed parametric models shows that air-conditioned buildings depends on both the total transmittance (for opaque materials) and nature of the material (for transparent materials).

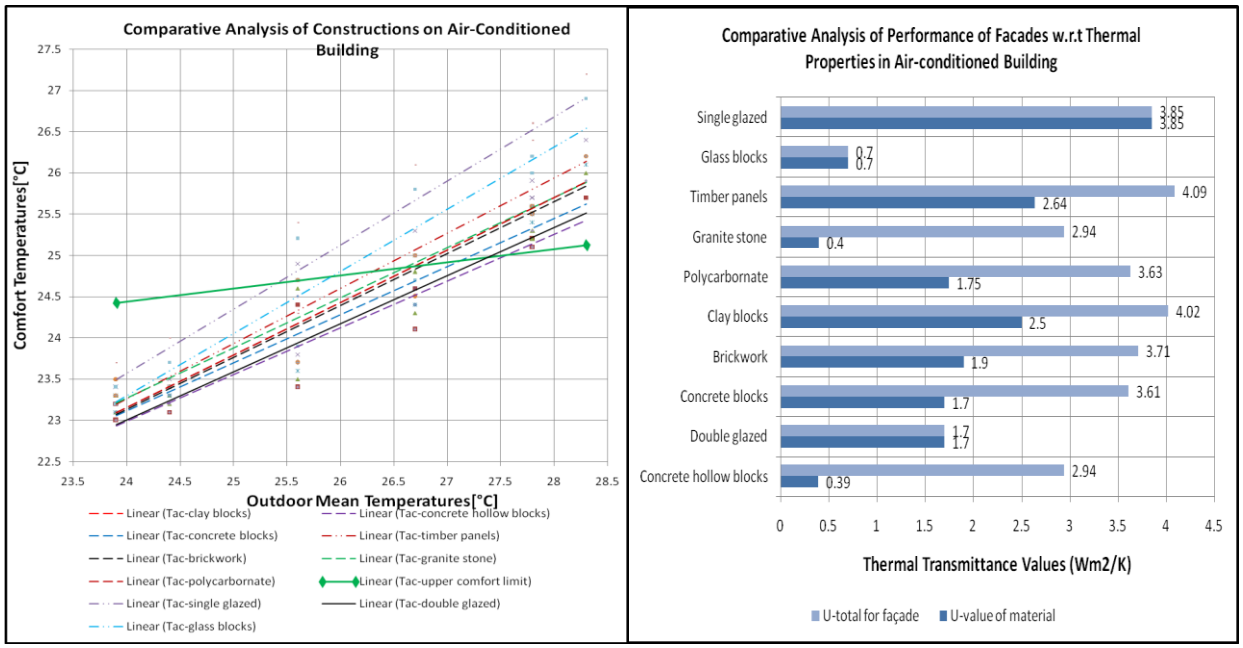



*Figure 73: Performance of constructions in air-conditioned building; the performance decreases in upward direction*

*Table 22: A rank of constructions in relation to the performance in air-conditioned buildings*

| Rank | Façade Construction Material | Façade Area | Material Transmittance ($Wm^2/K$) | Window Total Transmittance ($A_w .U_w$) | Total Transmittance [$\bar{U}= (A_g.U_g +A_w.U_w)/A_t$] |
|---|---|---|---|---|---|
| 1 | Concrete hollow blocks | 7.56 | 0.39 | 40.2 | 2.94 |
| 2 | Double glazed | 14.8 | 1.71 | - | 1.71 |
| 3 | Concrete blocks | 7.56 | 1.7 | 40.2 | 3.61 |
| 4 | Brickwork | 7.56 | 1.9 | 40.2 | 3.71 |
| 5 | Clay blocks | 7.56 | 2.5 | 40.2 | 4.02 |
| 6 | Polycarbonate | 7.56 | 1.75 | 40.2 | 3.63 |
| 7 | Granite stone | 7.56 | 0.42 | 40.2 | 2.95 |
| 8 | Timber panels | 7.56 | 2.64 | 40.2 | 4.09 |
| 9 | Glass blocks | 14.8 | 0.71 | - | 0.71 |
| 10 | Single glazed | 14.8 | 3.85 | - | 3.85 |

The nature of the materials previously pointed out in respect to transparent materials also contributes on the indoor thermal performance of the construction, specifically in air-conditioned buildings.

### 6.3 Design Parameters

This study comprises an analysis of the influence of six design parameters; these are materials/construction, use of shading, variation of window size and insulation for both air conditioned and free-running buildings. The influence of these design parameters were

analysed based on the indoor thermal comfort and cooling energy demand. As previously pointed out, Humphrey's equations are used to derive the method of comparative analysis of all these design parameters.

### 6.3.1 Air-conditioned buildings

Comparative analysis of design parameters in air-conditioned building is as presented in the Fig. 74. In this analysis design parameters are presented with respect to both energy consumption and the percentage of the energy saved by each design parameters. The percentage of the energy saved is determined from the total energy consumed by the material/construction prior to the use of any design parameter. This implies that the amount of energy used after applying a design parameter e.g. shading is divided by amount of energy before application of any design parameter to get the percentage of the energy reduced. It is worthwhile to point out that in this study each design parameter is investigated independently.

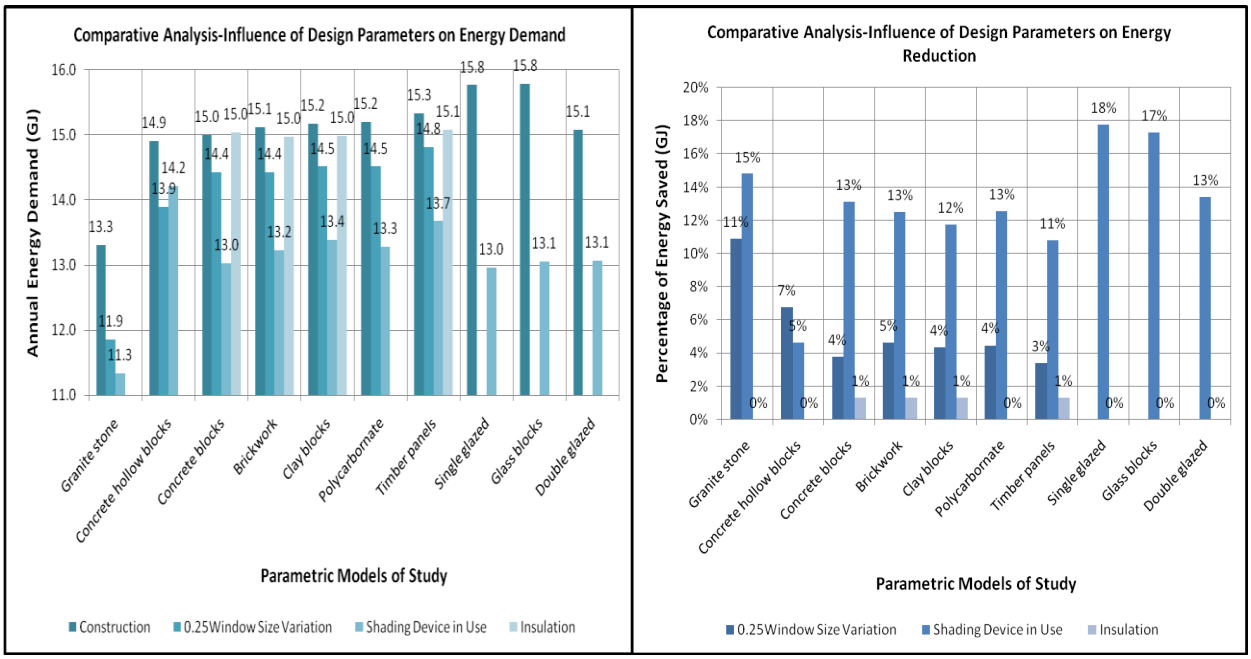



*Figure 74: Analysis of the influence of various design parameters on parametric models*

Comparative analysis of parametric models shows that design parameters have different extent of influence on the cooling energy demand for air-conditioned buildings. The following is the summary which can be deduced from the analysis presented in the Figure 75 above.

**(a) Shading devices**

Comparative analysis of the parametric models shows that shading devices have greater influence on the reduction of the cooling energy demand than all other design parameters as Fig. 74 illustrates. The application of shading devices reduces annual cooling energy demand for an average of 11% to 13% for masonry constructions and 16% for transparent (glazed) constructions e.g. curtain walls. The highest gain in reduction of annual cooling energy demand is experienced in single and double glazed parametric models which are 17% and 18% respectively.

**(b) Window size variation**

Comparative analysis shows that the variation of the window size by 50% results in reduction of annual cooling energy demand by an average of 5-6% as illustrated in Fig. 74. The highest energy reduction is experienced in granite stone model which is 11%. There was no variation of window sizes in glazed façade.

**(c) Insulation**

Comparative analysis of the parametric models which tests the influence of the use of insulation as a design parameter shows that it has an insignificant influence on the reduction of cooling energy demand. Parametric models which were tested to investigate the influence of insulation like concrete blocks, brickwork, clay blocks and timber panels shows that it reduces the cooling energy demand by 1% only.

**(d) Materials/constructions**

Comparative analyses of constructions which are defined by materials are as presented in the Fig. 75. Analysis shows that majority of constructions have minor differences when comparisons are drawn with their cooling energy demand. The major difference is experienced for granite stone, single glazed and glass blocks. While granite stone model has lower annual cooling energy demand, single glazed and glass blocks have the highest annual cooling energy demand.

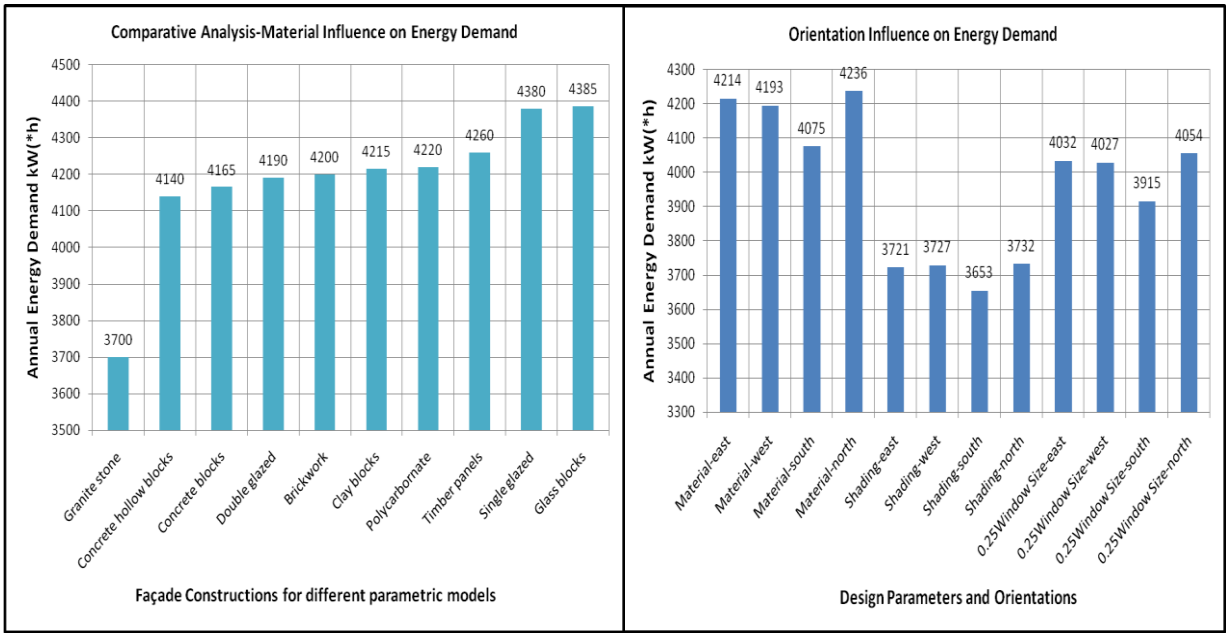



*Figure 75: Influence of constructions and orientation on cooling energy demand*

**(e) Orientation**

Comparative analysis of the influence of design parameters on orientation are as illustrated in the Fig. 75. It can be shown that orientation has very little influence on the cooling energy demand as previously mentioned. The performance of the parametric models in terms of the energy demand is almost the same in all orientations with the exception of south orientation which seems to have a better average result. With the application of other design parameters e.g. shading, the improvement is high but the same pattern shown with material is experienced as shown in the Fig. 75.

### 6.3.2 Free-running buildings

Comparative analysis of parametric models shows that design parameters have different extent of influence on the indoor thermal comfort in free-running buildings. The following is the summary which can be deduced from the analysis presented in the Figure 76 and 77.

**(a) Shading devices**

Comparative analysis of the parametric models shows that shading devices have greater influence on the indoor thermal comfort in free-running buildings than all other design parameters as Fig. 76 illustrates. The application of shading devices increases the margin trend of the free-running temperature within the comfort limits. Analysis presented in the Fig.76 shows that the free-running temperature of the single glazed parametric model is mostly within the comfort zone after the application of shading. The influence of shading on the improvement of the indoor thermal comfort is higher for glazed parametric models as it is illustrated in the Fig.76.

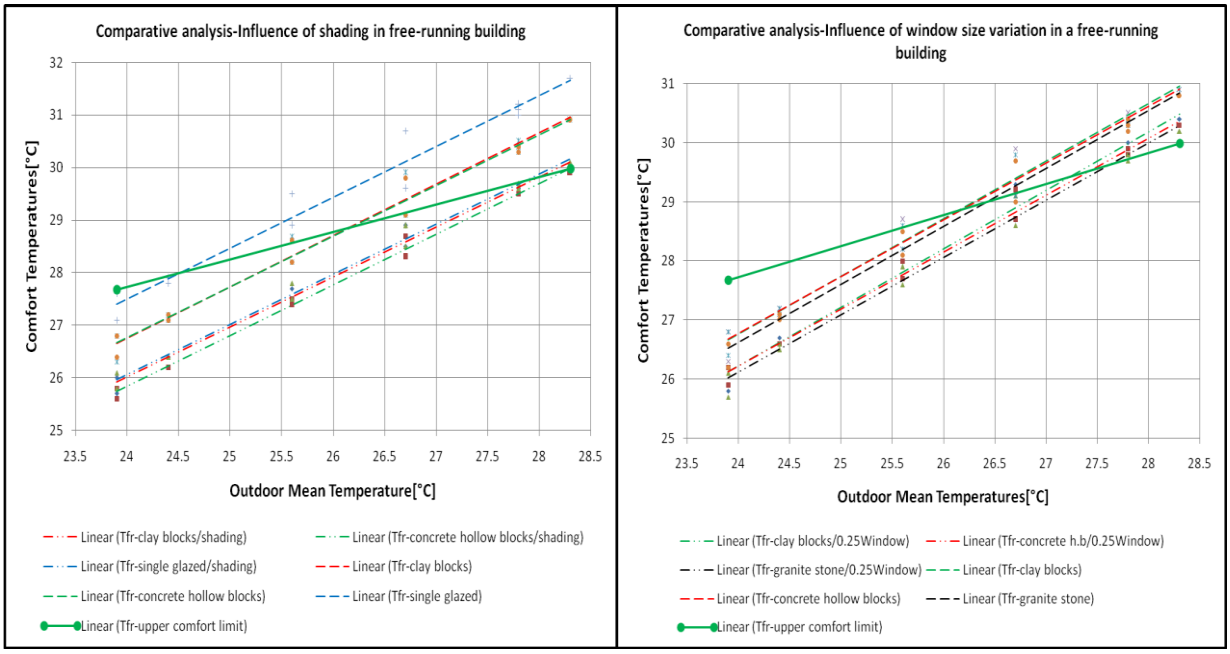



*Figure 76: Influence of shading and window size variations on the indoor comfort*

**(b) Window size variation**

Comparative analysis shows that the variation of the window size by 50% has a positive influence on the indoor thermal comfort as illustrated in Fig. 76. Analysis of clay, granite stone and concrete hollow blocks models shows a change on the trend margin of their indoor comfort temperature. The free-running temperatures shifts more within the comfort zone after a change on the window size as illustrated in the Fig. 76. However the extent of the influence is not as much as the one experienced by the use of the shading devices in the parametric models.

### (c) Insulation

Comparative analysis of the parametric models which tests the influence of the use of insulation as a design parameter in a free-running buildings shows that it has an insignificant influence on the indoor thermal comfort.

Parametric models which were tested to investigate the influence of insulation like concrete blocks and brickwork shows that it bring very little changes on the indoor thermal comfort.

However, the noticeable positive improvement can be observed in a clay model as it is illustrated in the Fig. 77. All other parametric models show insignificant changes on the indoor comfort after the use of insulation.

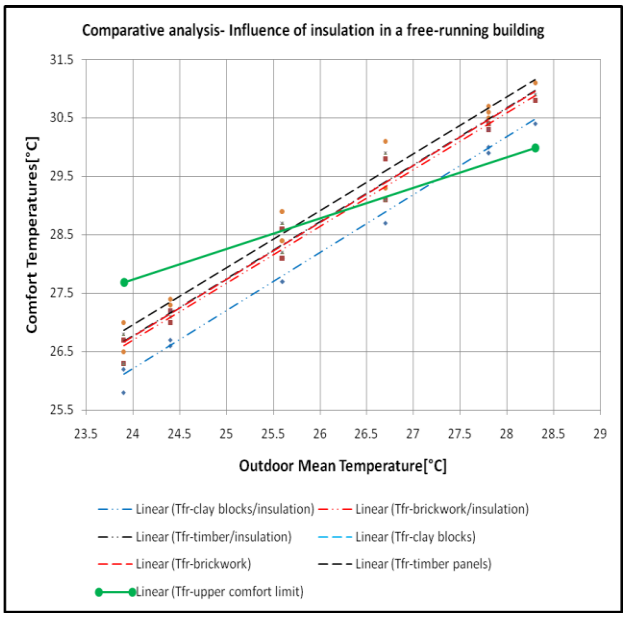



*Figure 77: The influence of insulation on the indoor comfort in a free-running building*

### (d) Orientation

Comparative analysis of the influence of orientation on the indoor thermal comfort of a free-running building is as illustrated in the Fig. 78. It can be shown that orientation has very little influence on the indoor thermal comfort in a free-running building.

The performance of the parametric model in terms of the indoor thermal comfort is almost the same in all orientations with the exception of south orientation which shows better average results than other orientations. This distinctive better performance of the south orientation concur with the comparative analysis of orientaion in air-conditioned building where south orientation was noted to have lower cooling energy demand.

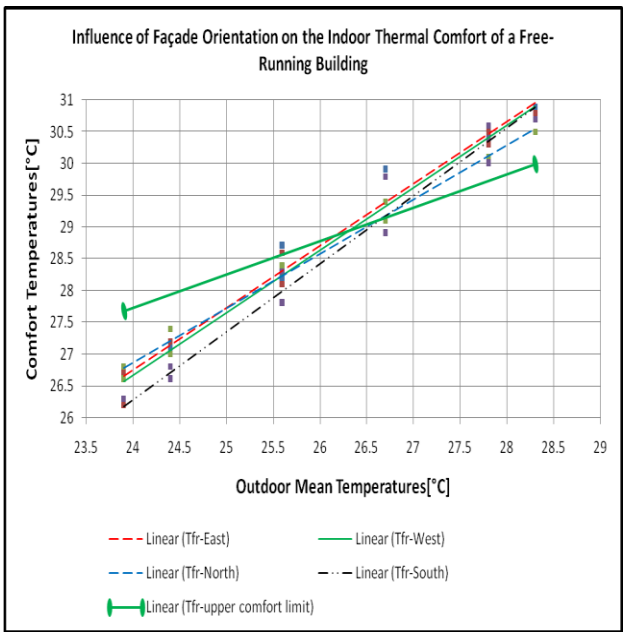



*Figure 78: The influence of orientation on the indoor comfort in a free-running building*

## 6.4 ATG Method (Adaptive Temperature Limits)

The Dutch ISSO-74 Adaptive Temperature Limits guideline (ATG) was formerly introduced for the assessment of the thermal comfort in buildings in 2004. The ATG-method was developed as an alternative for the former GTO-guideline, which is based on the analytical PMV model (Kurvers, van der Linden, & van Beek, 2007). In the ATG method naturally ventilated buildings are defined as “buildings with operable windows and ceiling fans within small single- or dual occupant offices that afford high degrees of adaptive opportunity”, this definition comply partly with a definition of free-running building in this study with

exception of the fact that mechanical ventilation is also allowed in free-running building. Also air-conditioned buildings in ATG method are defined as “sealed centrally air-conditioned buildings with open plan floor layouts” that provide minimal adaptive opportunities and where the occupants are presumed to have no option to open/close windows.

This study uses ATG method to establish the number of hours which are above the comfort limit and to investigate the influence of various design parameters on the indoor thermal environment. The comfort limits are expressed in line with the international guidelines for indoor environmental quality. There are two levels of the indoor comfort limits which are pointed out in this study; these are 80% acceptability and 80% acceptability with maximum ventilation. These levels are related with -/+2°C and -/+3°C comfort limits (Nicol F. , 2004) for Nicols/Humphreys method and 80% acceptability and 80% acceptability with maximum ventilation for ATG method as illustrated in the Fig. 80 .

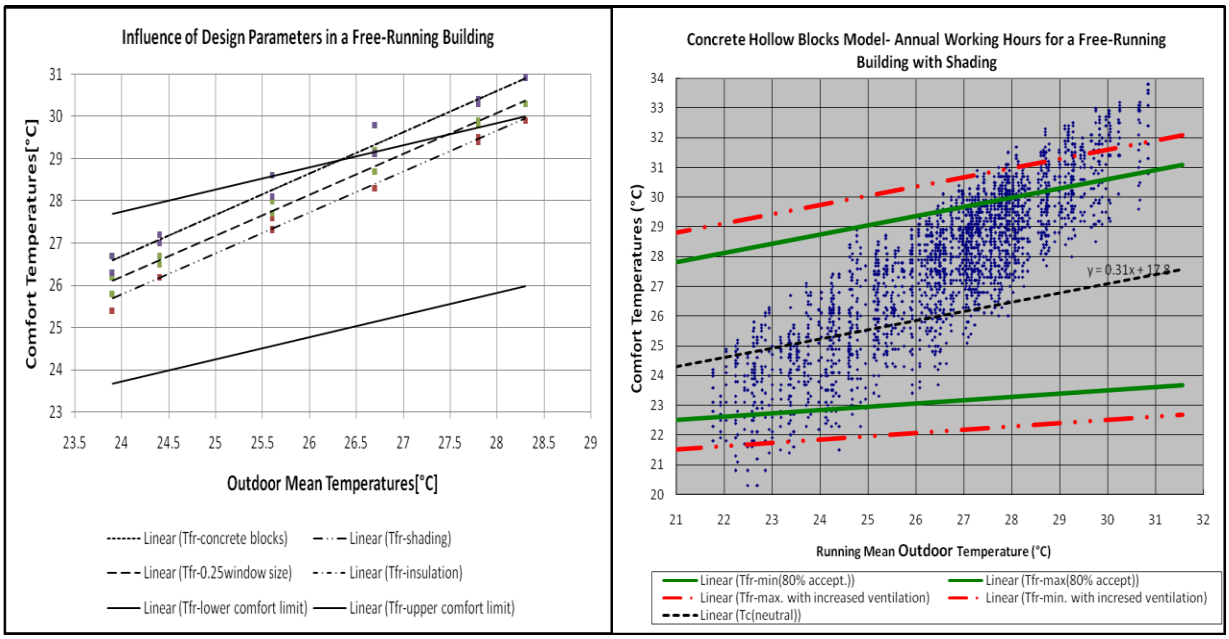



*Figure 79: Humphrey method with +/- 2°C comfort zone and ATG method with 80% acceptability*

ATG method uses running mean outdoor temperature (RMT) along horizontal axis instead of outdoor monthly mean temperature and operative temperature on the vertical axis. Operative temperature is taken as the arithmetic mean of the air temperature and the radiant temperature. This RMT is calculated from the averages of the maximum and minimum outdoor (air) temperature of the day under the study and three preceding days. The formula for RMT is as follows:

*Equation 5*

$RMT = [(1*T_{today}+0.8*T_{yesterday}+0.4*T_{\text{day before yesterday}}+0.2*T_{\text{day before day before yesterday}})/2.4]$

(van der Linden, Kurvers, Raue, & Boerstra, 2007)

The formula for Comfort temperature (Operative temperature) upper and lower limits for 80% acceptability is as follows:

*Equation 6*

$\Theta_{\text{operative}} :< 21.3 + 0.31\Theta_{e,\text{ref}}$ for upper limit and $\Theta_{\text{operative}} :> 19.45 + 0.11\Theta_{e,\text{ref}}$ for lower limit (Behaaglijkheid, 2004)

### 6.4.1 Analysis by ATG Method

Comparative analysis of the indoor thermal environment by ATG method is as presented in the Fig. 81. Parametric models are ranked in the order of their performance starting with the lowest number of hours beyond the upper comfort limit (80% acceptability). Analysis of results shows that the extent of the influence of design parameters on the indoor thermal environment is the same for both Humphrey's method and ATG as summarised below:

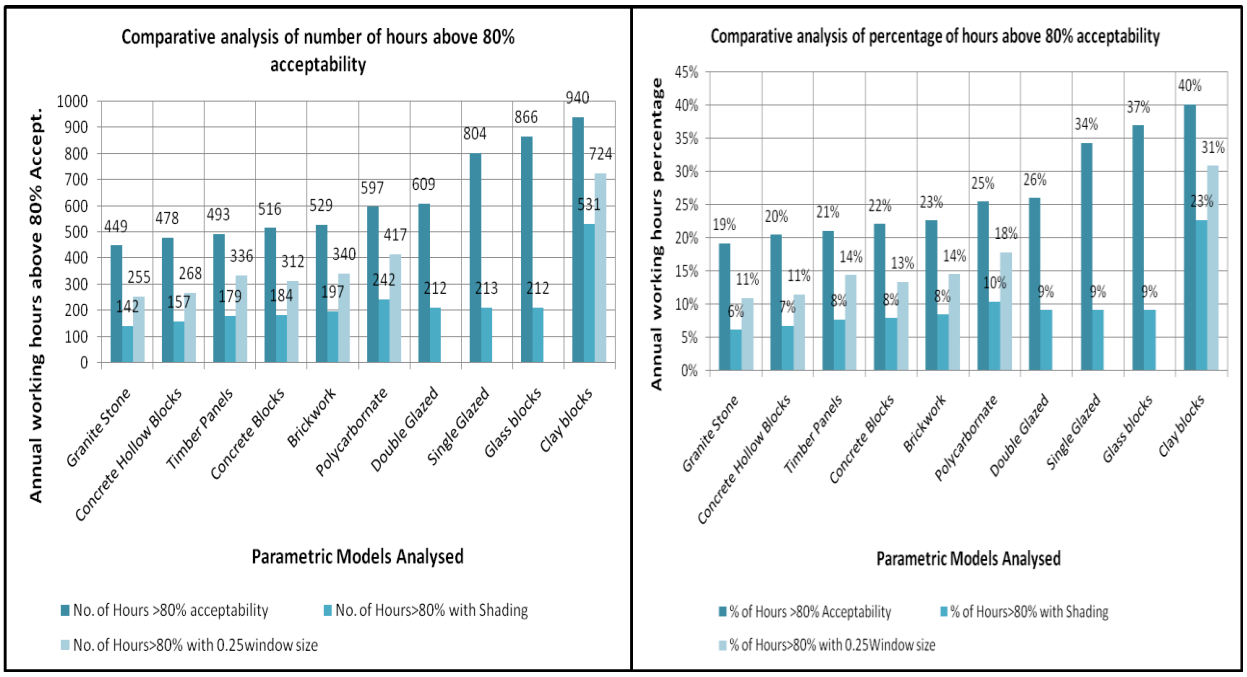



*Figure 80 : Number and percentage of annual working hours above 80% acceptability limit*

**(a) Variation of window size**

Comparative analysis shows that the variation of the window size by 50% reduces the number of hours beyond the 80% acceptability limit by an average of 12% as illustrated in Fig. 81. The influence is higher when the 80% acceptability limit with increased ventilation is used where the percentage is lowered to an average of 6%.

**(b) Shading**

A rank of individual design parameters in terms of the performance concludes that shading has the highest influence on reduction of the number of hours which are beyond the comfort limit when materials/construction alone is used as illustrated in the Fig.81 and 82. For the 80% acceptability limit, the use of shading reduces the number of hours which are beyond this limit from an average of 23% to 8%. In each parametric model, shading shows significant improvement on the indoor thermal environment. Comparative analysis presented in Fig. 82 shows significant positive results when the 80% acceptability limit with increased ventilation is used.

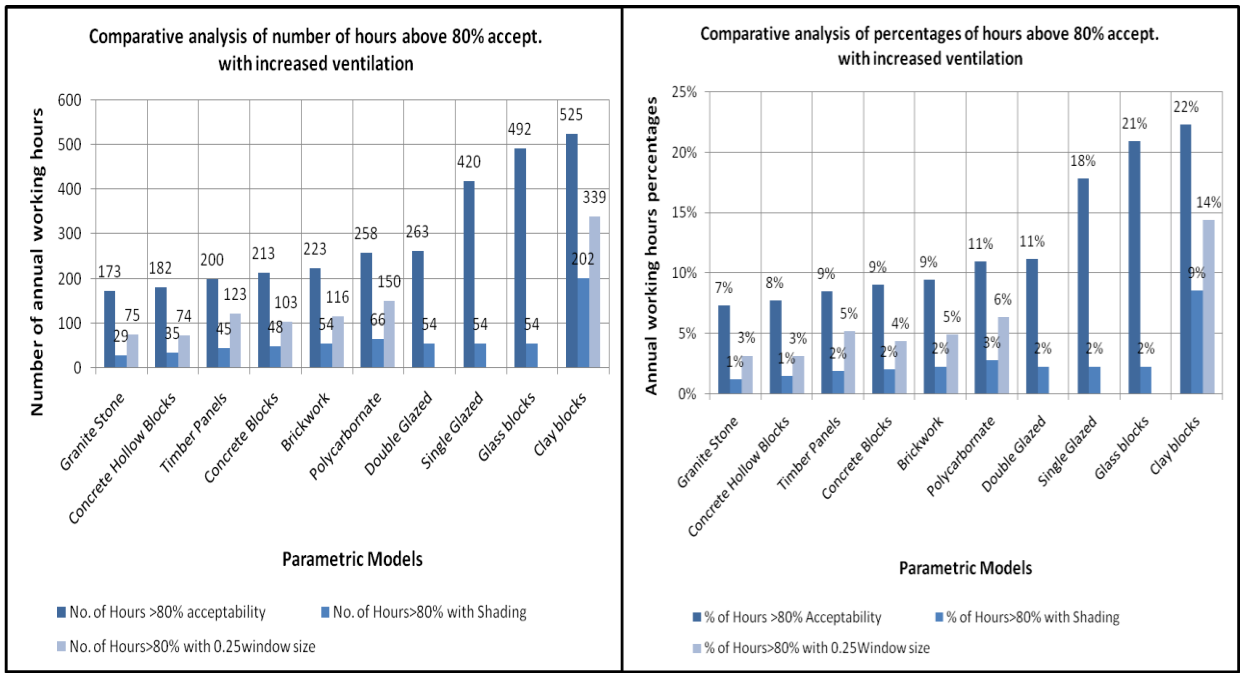



*Figure 81: Number and percentages of annual working hours above 80% acceptability limit with increased ventilation*

### 6.5 Comparative Analysis

Comparative analysis between Humphrey's and ATG method can be done by comparing the performance of parametric models for both methods. A rank of the performance of each parametric model in both methods is as presented in the Table 23. Analysis of parametric models by Humphrey's method shows that the indoor thermal environments of free-running buildings have a direct relation to the total thermal transmittance of the façade with exception for glazed materials.

*Table 23: Performance of parametric models in a free-running condition*

| HUMPHREY METHOD | | | ATG METHOD | | |
|---|---|---|---|---|---|
| Rank | Parametric Model | $\bar{U}$ ($Wm^2/K$) | Rank | Parametric Model | $\bar{U}$ ($Wm^2/K$) |
| 1 | Concrete hollow blocks | 2.95 | 1 | Granite stone | 2.95 |
| 2 | Granite stone | 2.95 | 2 | Concrete hollow blocks | 2.95 |
| 3 | Concrete blocks | 3.61 | 3 | Timber Panels | 4.09 |
| 4 | Brickwork | 3.71 | 4 | Concrete blocks | 3.61 |
| 5 | Clay blocks | 4.02 | 5 | Brickwork | 3.71 |
| 6 | Polycarbonate | 3.63 | 6 | Polycarbonate | 3.63 |
| 7 | Timber panels | 4.09 | 7 | Double glazed | 1.71 |
| 8 | Double glazed | 1.71 | 8 | Single glazed | 3.85 |
| 9 | Single glazed | 3.85 | 9 | Glass blocks | 0.71 |
| 10 | Glass blocks | 0.71 | 10 | Clay blocks | 4.02 |

A similar pattern of results are obtained when analysis is done by ATG method with exceptions of timber panels and clay bocks parametric models as illustrated in Table 23. Contrary to the observation by Humphrey's method, ATG method shows unexpected performance for clay blocks and timber panels parametric models. Analysis by Humphrey's

method shows that Clay blocks parametric model performs in line with other medium thermal mass parametric models and far better than glazed models in but it shows the least performance in ATG method. Further analysis shows that clay blocks have higher thermal conductivity as single glazed and also have higher speed of gaining heat. Since the ATG determine the average hourly temperatures, the clay model gains heat faster and maintains the higher average hourly temperature than all other model during the time of analysis (office working hours 8 am to 5 pm) in which outdoor has the highest temperatures.

It is not a focus of this study to compare these two methods of analysis but the following observations were made during analysis by both method. First, in terms of the output these two methods are not different; they give similar results with the exception of the fact that ATG is a more detailed method. Second, a general overview of the analysis of the influence of various design parameters on the indoor thermal comfort can be done by Nicol/Humphreys approach and the results are reliable as much as with ATG method. Furthermore, ATG can be used to establish further analysis on the extent of cooling needed beyond 80% acceptability limit, this is an added advantage.

# 7.1 Summary

This chapter marks the end of the research and gives a flashback on the whole research to a reader. The chapter starts with author's perspective on the outlook of the research and summarises the same by pointing out the methods used to gain the knowledge. It also gives concluding statements based on various parameters investigated in the preceding chapters. Furthermore, it winds up with recommendations on the various aspects of the study as well as highlighting areas for further study.

## 7.2 The study

This study of "*energy efficient building technologies in hot and humid climates"* resembles a bit to an abstract art by the sense that it uses the building physics knowledge to integrate various parameters like climate, building materials/constructions, user's adaptability measures and building services which may exist with the degree of independence from the building industry perspective. It requires the skills of an actuary to make a real sense out of mountains of data through the use of formulas and data processing tools which rarely caught an Architect's interests.

The key point is to be able to grasp in a chart or diagram the influence of various design parameters in the state of the indoor thermal comfort the building is currently in which then allows you to compare it with a pattern of the state you would like it to be in. This study demonstrates that it is possible to increase the level of thermal comfort in free-running buildings as well as to reduce the building's cooling energy appetite for air-conditioned buildings in hot and humid climates by the use of various design parameters. To acquire knowledge about this study the following steps were followed:

(i) A study of the character of hot and humid climates and its influence on the indoor thermal comfort as well as energy demand.

(ii) A study of thermal comfort in hot and humid climates based on the field studies by Humphrey's and Nicol Fergus and establishes appropriate comfort limits for both free-running and air-conditioned buildings.

(iii) Analysis of the indoor comfort and cooling energy demand of the existing buildings both free-running and air-conditioned.

(iv) Analysis of the influence of various design parameters on the indoor comfort and energy demand for free-running and air-conditioned buildings respectively.

(v) Comparative analysis of various design parameters to understands the extent of their influence for each parametric model.

The author has come into conclusion that all four steps can be a basis of design tool for Architects. It is often been argued that most of the simulations software are not user/architect friendly to be integrated in the design process. But through availability of powerful and easy to use thermal simulation programs, climatic issues are ought to be integrated in the design process and the influence of various design parameters can be deduced. This can further the objective of provision of better indoor thermal comfort and energy efficiency for free-running and air-conditioned buildings respectively.

This study focused on a number of design parameters that have influence on the indoor thermal comfort and cooling energy demand of the building. These design parameters

includes materials/constructions, use of shading devices, orientation, variation of window sizes and thermal insulation. Conclusions are drawn from the results based on the parameters of the study for both free-running and air-conditioned buildings.
The scope of this study is limited to a hot and humid climate (tropical region) in which specific area of the study is Dar es Salaam. The focus is on the office buildings in which the indoor comfort and cooling energy demand during working period is examined for both free-running and air-conditioned buildings. Potential for energy savings through design parameters in both free-running and air-conditioned buildings in hot and humid climates is explored and the extent of their efficiency determined.
Various construction techniques presented by parametric models are examined and analysed; a better definition of thermal comfort is set and used as basis of analysis for both free-running and air-conditioned buildings with respect to this study. Furthermore, several options focused in energy reduction in the buildings are presented as well as their extent of influence on regulating the indoor thermal comfort.
This study lies on the field of architectural science and the method of presentation is considered by the author as "architect friendly"; the focus on the simulation program (Capsol) is on the building level with a focus of determining the influence of the design parameters on the indoor thermal comfort as well as treating the building as a system which interact with its environment and its users (adaptive approach).

## 7.3 Conclusions

There are a number of conclusions which can be drawn on this study based on the case studies, parametric models results and later analysis. This section of conclusions is going to entirely draw conclusions on the basis of parametric models results and analysis. These conclusions are going to be based on the design parameters used in the parametric models and analysis as pointed out below.

### 7.3.1 For free-running buildings

The following can be concluded with respect to the free-running buildings:

**(a) Shading devices**

This study concludes beyond a reasonable doubt that the use of shading devices as a design parameter in hot and humid climates has a strong influence. As far as the study concerns shading has the highest influence in the reduction of cooling energy and improving the indoor thermal comfort in both air-conditioned and free-running buildings respectively. This has been shown on both parametric models and analysis in preceding chapters.

**(b) Window size variation**

Variation of the window size from 50% to 25% of the façade has a significant improvement on the indoor thermal comfort in hot and humid climate. The study concludes that window size variation follows the used of shading devices on the extent of the improvement of the indoor thermal comfort.

**(c) Insulation**

The use of insulation on the walls for a hot and humid climate proves minimum success on the improvement of the indoor thermal comfort of a free-running building. This is due to the fact that it does not allow quick transfer of heat to the outside when the outdoor

temperatures are lower. Minor changes on the indoor thermal comfort can be observed for timber panels and clay blocks models partly because of their high thermal transmittance values.

**(d) Material/Construction**

This study concludes that there is a strong link between the construction/façade and the indoor thermal comfort of the free-running building. The study establishes that the indoor thermal comfort of the free-running building is inversely proportional to the total thermal transmittance of the façade construction, specifically for opaque constructions e.g. brickwork and concrete.

**(e) Internal thermal mass**

This study concludes that the use of internal walls with high thermal mass e.g. brickwork and concrete walls have a negative influence on the indoor thermal comfort in a free-running building. A further analysis draws a conclusion that a slight improvement on the indoor thermal comfort can only be gained when high thermal mass internal wall (brickwork) are used with low thermal mass external walls e.g. timber panels .

**(f) Internal load variation**

This study concludes that the reduction of internal load has a small influence on the indoor thermal comfort, specifically in a free-running building. This is attributed by fact that outdoor climate which is the main influence on indoor thermal comfort of a free-running building have very small seasonal variations. The small outdoor climate seasonal variations is a like a constant supply of the same range of temperature conditions throughout a day leaving the internal load variation with little influence on the indoor thermal comfort. Without application of other design parameters, the influence of reduction of internal load can merely be noticed in a free-running building.

**(g) Orientation**

The study concludes that orientation has a very little influence on the indoor thermal comfort of a free-running building in a hot and climate (tropical region). The study shows that all orientations gives the same average results in terms of the indoor thermal comfort with the exception of south orientation which shows better average results than other orientations. This results are attributed by the fact that the area of the study is very close to equator where the sun is often above.

### 7.3.2 For air-conditioned buildings

The following conclusions can be drawn for air-conditioned buildings:

**(a) Shading devices**

This study concludes that the use of shading as a design parameter has strong influence on the reduction of the cooling energy demand in air-conditioned buildings. The annual cooling energy demand is reduced by an average of 11% to 13% for masonry constructions and 16% for transparent (glazed) constructions e.g. curtain walls. This is due to the fact that shading greatly reduces the amount of solar radiations from outside and help to lower the indoor temperature.

**(b) Window size variation**

This study concludes that the variation of the window size has a significant influence on the reduction of the annual cooling energy demand. Further analysis draws a conclusion that a reduction of window size by 50% results in reduction of annual cooling energy demand by an average of 5-6%.

**(c) Insulation**

The use of insulation in facades in hot and humid climates has an insignificant influence on the reduction of cooling energy demand. Further investigation on the extent of insulation influence in energy reduction draws a conclusion that it reduces the cooling energy demand by 1% only.

**(d) Materials/constructions**

The study concludes that majority of constructions have minor differences in terms of the annual cooling energy demand; the main exceptions is glazed materials, specifically single glazed and glass blocks. Furthermore, analysis draws a conclusion glazed material; specifically single glazed and glass blocks have the highest annual cooling energy demand when comparisons are drawn with other façade constructions.

**(e) Internal thermal mass**

The study concludes that the influence of thermal mass from internal walls/partitions on the cooling energy demand is strongly determined by the thermal mass of the external construction/façade. Furthermore, analysis draws the conclusion that when low thermal mass façade e.g. timber panel is used, there is no change on the annual cooling energy demand regardless of the type of internal partitions used. However, when high thermal mass external façade e.g. brickwork is used, a change from timber panels as internal partitions to brickwork saves the cooling energy demand.

**(f) Internal load variation**

The study concludes that the reduction of internal load has very minor but significant influence on the cooling energy demand. Further analysis shows that for Clay model 50% reduction of internal load yield only 3% savings on cooling energy demand. The influence of the external climatic condition acts as the major determinant of the amount of the annual cooling energy demand. In fact it can be argued and concluded that any effective measures to regulate the indoor conditions should take place from the outside of the building e.g. the use of shading devices.

## 7.4 Recommendations

Recommendations for this study are divided into two main categories which are free-running and air-conditioned buildings. These recommendations are mainly focused on the office buildings which is the part of the scope of the study. However to some extent they can also apply to other types of the buildings.

### 7.4.1 For free-running buildings

On the basis of this study, the following can be recommended for free-running buildings in hot and humid climates:

### (a) Façade construction/materials

When designing or specifying a façade for hot and humid climates region it is recommended to consider the total thermal transmittance of the whole façade structure rather than individual materials. This study has revealed that the indoor thermal comfort of the free-running building is entirely depending on the total thermal transmittance of the façade. The lower the total thermal transmittance the better the indoor thermal comfort of a free-running building. In fact the total thermal transmittance of between 2.0-3.5$Wm^2/K$ can be recommended. Further studies can be done to determine more accurate range with of the total thermal transmittance in relation to various constructions.

### (b) Glass in façade

In this section the reference is made to the glazed windows and doors. This study recommends the use of double glazed for windows and doors when glass is the preference. Among all types of glasses analyzed, double glazed shows better performance than the rest in free-running building. However, the average performance of the glazed façades is poor, specifically in free-running buildings.

### (c) Design Parameters

Investigation of the influence of various design parameters on the indoor comfort of a free-running building in hot and humid climates lead to the following conclusions:

Shading:

This study recommends the use of shading devices as a design parameter due to the fact that it has enormous importance on the variation of the indoor thermal comfort of a free-running building. Contrary to the fixed shading devices which are not a preference to many nowadays architects, movable shading devices available in various designs can be an alternative.

Analysis employing the ATG method reveals that shading has a potential of keeping the indoor thermal comfort of a free-running building below the maximum limit of 80% acceptability for 90% percent of annual working hours. Also further analysis shows that an average of 98% of the annual office working hours can be within the 80% acceptability when the number of air changes is increased up to n=10.

Window size variation:

This study recommends the option of reduction of window size as one of the way of regulating the indoor thermal comfort of a free-running building. However, where the shading has been used there is no need for reducing the window size. Analysis employing the ATG method shows that variation of the window size from 50% to 25% of the façade area has a potential of keeping the indoor thermal comfort of a free-running building below the maximum limit of 80% acceptability for 85% of the yearly office working hours.

Insulation:

This study does not recommend the use of insulation for a free-running building in hot and humid climate. This is due to the fact that the outdoor temperature ranges are small (4-9°C) and it does not allow a quick transfers of heat when the outdoor temperature is lower. However, this recommendation is merely focused in office buildings were façade are the major component of heat loss to the surroundings.

### 7.4.2 For air-conditioned buildings

As far as air-conditioned buildings are concerned, the main focus is not only to save cooling energy but also to achieve a good balance of the indoor thermal comfort. The following are a set of recommendations for air-conditioned buildings arising from this study:

**(a) Façade construction/materials**

Through thorough analysis of the performance of various constructions/materials in air-conditioned buildings, it is obvious that façade constructions perform differently with respect to such buildings. These performance lead to the following:

Masonry constructions: This study recommends a good consideration of the total thermal transmittance of the façade construction in air-conditioned buildings, specifically when masonry construction like brickwork and concrete blocks are used. The relationship previously mentioned in free-running building exists also in air conditioned buildings but mainly for masonry constructions.

This study has revealed that the cooling energy demand of the air-conditioned building is entirely depending on the total thermal transmittance of the façade. The lower the total thermal transmittance the lower the cooling energy demands for a free-running building. In fact the total thermal transmittance of between 2.0-3.5$Wm^2/K$ can be recommended.

Glazed façade constructions:

For various reasons architects in hot and humid climate region prefer curtain walls just like other regions, however their implication in terms of the indoor thermal comfort and cooling energy demand is questionable. Through analysis of different groups of glazed constructions like single glazed, double glazed and glass blocks, this study recommends the use of double glazed in air-conditioned buildings if it is a necessity. Double glazed shows similar pattern of performance to masonry constructions when used in air-conditioned building but fall short in free-running buildings.

**(b) Design Parameters**

Investigation of the influence of various design parameters on the indoor comfort of air-conditioned building in hot and humid climates lead to the following conclusions:

Shading:

This study recommends the use of shading in air-conditioned buildings as a design parameter due to the fact that it has enormous importance on the reduction of the cooling energy demand. Contrary to the fixed shading devices which are not a preference to many nowadays architects, movable shading devices available in various designs can be an alternative.

Analysis of the used shading devices as a design parameter shows that it has the highest influence on reduction of cooling energy demand of air-conditioned building in hot and humid climates especially for glazed facades.

Window size variation:

This study recommends the option of reduction of window size as one of the way of reducing the annual cooling energy demand in air-conditioned building. However, where the shading has been used there is no need for reducing the window size.

### 7.4.3 For further research

This study recommends further studies to be done so as:

(a) To establish the standards for constructions in hot and humid climates regions. These standards can focus on the requirements for the thermal performance of various façade constructions which are used in these regions.

(b) To establish the amount of cooling energy demand needed beyond the 80% acceptability limit when all other design parameters have been applied. This is specifically applies for critical periods of the highest thermal stresses in the buildings.

(c) To establish the possibility and appropriate conditions for mixed-mode types of buildings in these region. Based on the author's opinion mixed-mode buildings (free-running with possibility of cooling in critical periods) can address the shortcomings observed in both types.

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