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DISSERTATION

AN EXPLORATION OF THE THERMAL PERFORMANCE OF OFFICE BUILDINGS IN GHANA

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaften unter der Leitung von

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ABSTRACT

This dissertation presents results of the study of the building performance of office buildings in Ghana. The views of the office occupants concerning indoor climate represent an additional focal point of the present research. Given the regional climatic characteristics of Ghana (warm and humid), energy requirements for cooling of office buildings represent a growing burden for the environment and the economy. In many instances, the building design is not supported by a detailed analysis and evaluation of thermally relevant features as well as options related to orientation, envelope, glazing ratio, shading devices, and thermal mass. Thus, design decision making is not sufficiently informed by relevant expertise pertaining to energy-efficient building design methods and technologies.

In this context, the research presented here is concerned with the following objectives:

- Long-term monitoring of the thermal conditions in (and energy performance of) a selected number of office buildings in Kumasi, Ghana.
- Generation of calibrated simulation models of these office buildings.
- Simulation-based exploration of design options toward a general reduction of cooling requirements in office buildings in Ghana.
- Assessment of occupants' subjective views on their office climate and interaction with building systems.

Five office buildings in Kumasi were selected for the study. These buildings have different sizes, functions, and occupants in different age groups. From September 2007 to August 2008, indoor and outdoor climatic conditions (mainly temperature and relative humidity) were monitored, using data loggers. To evaluate the existing indoor climate conditions, measured air temperature and relative humidity were plotted in psychrometric charts. Interviews with occupants were conducted to record their views on indoor environment and installed systems. In the process, 64 office occupants answered a set of questions.

Overall, the calibrated simulation results suggest that certain measures regarding building fabric and controls can improve the buildings' energy performance. Specifically, certain combinations of improvement measures (such as better windows, natural ventilation, and efficient electrical lighting) have a significant potential to reduce buildings' cooling loads (20 – 35%) in the climatic context of Kumasi.

In addition, the plotted measured data on psychrometric charts seem to justify that occupants have adapted to high humidity levels and therefore found maximum humidity values of 80 – 85% to be tolerable, provided temperature values did not exceed 29°C. This would call for the reconsideration of thermal comfort scale assumptions for the climatic context of Kumasi, Ghana.

Furthermore, the analyzed data from the interviews and questionnaire (among other factors) show that occupants are interested in receiving training on the effective and efficient operation of building systems, which would aim at increasing satisfaction, comfort and reducing energy performance of office buildings.

Keywords: Cooling loads, simulation, energy, efficiency, building systems, system controls, occupants, psychrometric chart, active, passive, environment, comfort, satisfaction, thermal, operation, evaluation.

KURZFASSUNG

Diese Dissertation präsentiert die Ergebnisse der Studie über die Gebäudeleistung von Bürogebäuden in Ghana. Die Ansichten der BenutzerInnen bezüglich des Innenklimas stellen einen zusätzlichen Schwerpunkt dieser Forschungsarbeit dar. Durch die regionalen Klimaverhältnisse (warm und feucht), wird der Energieverbrauch zum Kühlen der Bürogebäude zu einer immer grösseren Belastung sowohl für die Umwelt als auch für Ghanas Wirtschaft. Häufig ist dem Entwurf weder eine detaillierte Analyse der thermische relevanten Eigenschaften vorausgegangen, noch werden Optionen für Orientierung, Bauhülle, Verglasungsrelation, Beschattung und Masse ausreichend untersucht. Das bedeutet, dass Entscheidungsprozesse nicht oder nur unzureichend auf die relevante Expertise gestützt sind.

Die vorgestellte Forschungsarbeit basiert auf folgenden Zielen:

- Langzeitstudie über das Innenraumklima und den Energieverbrauch von ausgewählten Bürogebäuden in Kumasi, Ghana.
- Erstellung kalibrierter Simulationsmodelle dieser Gebäude.
- Untersuchung von auf Simulation basierten Entwurfsalternativen mit dem Ziel die erforderliche Kühlung von Bürogebäuden zu verringern.
- Beurteilung des subjektiven Empfindens der BenutzerInnen bezüglich Raumklima und Anwendung von Bausystemen.

Für die Studie wurden funf Bürogebäude in Kumasi ausgewählt. Diese Gebäude haben verschiedene Grössen, mit unterschiedlicher Funktionalität, und BenutzerInnen aus diversen Altergruppen. Klimabedingungen (Temperatur und Luftfeuchtigkeit) wurden von September 2007 bis August 2008, sowohl im Innenbereich als auch aussen, mit Sensoren gemessen. Am Ende der Studie wurden die BenutzerInnen der Gebäude nach ihrer Einschätzung des Innenraumklimas und nach der Funktionalität der installierten Systeme gefragt. Insgesamt nahmen 64 Büroangestellte an der Befragung teil. Die Messwerte für Raumtemperatur und Luftfeuchtigkeit wurden auf psychrometrische Tabellen übertragen, um so das Innenraumklima zu beurteilen.

Die Ergebnisse der kalibrierten Simulation deuten darauf hin, dass Massnahmen im Bereich der Bau- und Kontrollelemente die Energiebilanz eines Gebäudes verbessern können. Vor allem durch eine Kombination von Verbesserungsmassnahmen (wie Fenster, Belüftung, Beleuchtung) ist es möglich, den Energieverbrauch der Bürogebäude in Kumasi signifikant zu reduzieren (um 20 – 35%) Ausserdem kann aufgrund der Ergebnisse in den psychrometrischen Tabellen angenommen werden, dass die Bewohner in Kumasi sich an die regionalen klimatischen Verhältnisse angepasst haben, und ein relativ hohe Luftfeuchtigkeit (80 – 85%) als tolerierbar empfinden, vorausgesetzt die Lufttemperatur beträgt weniger als 29°C. Das bedeutet, dass die angenommene thermische Komfortzone für Kumasi, Ghana auf der psychrometrischen Tabelle neu überdacht werden sollte.

Ferner zeigt die Auswertung der Befragung, dass sich die BürobenutzerInnen für Schulungen zum effizienten Umgang mit Bausystemen interessieren. Dies könnte zu mehr Zufriedenheit und Wohlbefinden und schliesslich zur Reduzierung des Energieverbrauchs in Bürogebäuden beitragen.

Hauptworter: Kühllast, Simulation, Energie, Effizienz. Bausysteme, Kontrollsysteme, Psychrometrische Tabelle, Aktiv, Passiv, Umgebung, Wohlbefinden, Thermisch, Benutzung, Evaluieren.

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Dedicated to: *Seth Maxwell (Snr.) and Mercy Koranteng*

Ulrich and Christa Gäbler

Table of content

1 INTRODUCTION

1.1 Overview

In Ghana, energy supply has not met the demand and as a result, a load shedding program was implemented in the year 2006, which ran through part of 2007. With the growth in demand for housing and commercial facilities and a resulting increase in energy use, the building sector has the potential to contribute immensely to the efficient use of energy, by adopting sustainable design strategies. Orientation, form, glazing size, glazing type, shading devices, colour of external surfaces, wall types, air change rates, internal gains, set point for cooling, infiltration, floor types, ceiling types, roof types and landscape are key factors for energy performance and thermal comfort in sustainable architecture. These issues are mostly ignored in environmental design. Most new construction projects and renovated buildings in Ghana show a lack of energy efficiency in design. This is seen in the rampant use of curtain walls, sliding windows and air conditioners in buildings with disregard to the above-mentioned building elements and principles. With energy consumption increasing as opposed to energy production, it is necessary to adopt sustainable design methods in order to reduce the demand for energy.

This research focused on five office buildings in Kumasi, Ghana. They are of different sizes, with different functionality and house persons of diverse age groups. Over a period of one year (September 2007 to August 2008), data loggers were installed in the office spaces to record the thermal conditions in (and energy performance of) the buildings. Every 10 minutes, room temperature, relative humidity and task illuminance levels were recorded. Moreover, some loggers were installed in the immediate vicinity of the buildings to record outdoor environmental conditions. The data was used as a basis to generate calibrated simulation models of the buildings towards a simulation-based exploration of design options, with the prime aim of reducing cooling requirements in office buildings. At the end of the study period, 64 occupants were interviewed on their views regarding indoor environment and installed building systems.

Chapter 1 deals with motivational reasons for the study and background of related research in the area of occupants' behaviour, building control systems, energy performance and sustainable design principles. Chapter 2 describes the case studies, approach of the study, properties of the sensors and software used, data collection and processing. Chapter 3 presents the results of the study under the subheadings listed below:

(i) Psychrometric analysis (thermal comfort)
(ii) Energy Performance (active scenario)
(iii) Thermal Performance (passive scenario)
(iv) Interviews
    - Indoor Environment, thermal and visual comfort
    - Operation and accessibility of building systems
    - Awareness of the building control systems' functionality
    - Implications of user control actions on energy performance
    - User preferences of workspace organization

- Needs and health complaints

Chapter 4 discusses the results gathered by analysing the content in the previous chapter, via the subheadings. The conclusion is presented in chapter 5. This is followed by references, list of figures, tables and appendices.

1.2 Motivation

The world's energy crisis in 1973 and the inability of developing countries to guarantee the supply of energy have triggered studies into the sustainable use of energy. The world's reserves of crude oil are being used up rapidly and this has resulted in the increase of oil prices. Light sweet crude oil hit a record price of 100 US Dollars per barrel on the second day of the year 2008 (WNN 2008), and by the third week of March 2008, the price of a barrel rose to 104 US Dollars. This trend continued and as of May/June, 2008, the price of a barrel increased to a record high level of 130 US Dollars. The high oil price has a negative effect on the economies in developing countries.

In Ghana, the growth in demand for energy is, among other factors, caused by the numerous air-conditioned commercial buildings being constructed, especially in the metropolitan areas of Accra and Kumasi. The supply of energy has failed to meet its demand. The Energy commission, Ghana, (ECG 2007) reports, energy consumption of households increased from 26% in 2000 to 37% in 2005. Within the same period, energy consumption of the commercial sector actually doubled, (7% to 14%). In 1990, Ghana had a surplus of electricity of 3545 GWh and in 2004 a deficit of 203 GWh was recorded.

This upward trend of increasing demand for energy culminated in the load shedding program in the year 2006/2007.

In the building sector, the increased use of air-conditioners, inefficient curtain walls and sliding windows, and the lack of sustainable design principles, especially in office buildings have contributed to the energy situation. Occupants, building elements and design strategies also have a direct link to energy efficiency, thermal comfort and satisfaction in office buildings. The effects of occupants behaviour on buildings and eventually on energy performance are to a large extent known to be unfavourable, however, the exact impact is insufficiently investigated, especially in developing countries. In a related study, the effects of occupants and control systems on energy performance were found to reduce cooling loads by 50%, if the behaviour of occupants is considered (Mohammadi 2007).

The way forward is to look at sustainable and efficient means in the design of buildings and use of our natural resources. The application of simulation at the early stages of design could help as a decision support tool in testing design alternatives and in the validation of building designs on their performance. Designers should make the right decisions from the start and verify them before proceeding to the detailing stage. Statistically, about 20% of the decisions made at the early design stage affect about 80% of later decisions (see Mourshed and Keane 2003). Against this background, and due to the increase in green house gas emissions, the European Union Council Directive 93/76 required member states to develop and implement energy certifications for buildings (Szokolay 2005).

In this context, the present research is concerned with the following objectives:

- Long-term monitoring of the thermal conditions in (and energy performance of) a selected number of office buildings in Kumasi, Ghana.
- Exploration of the capabilities of simulation tools in building design, especially in the context of Ghana.
- The effective prediction of the performance of building elements and environmental control systems, based on calibrated models.
- Simulation-based exploration of design options toward a general reduction of cooling requirements in office buildings in Ghana.
- Consideration of the effects of occupants' behaviour on building energy performance.
- Understanding user needs and behaviour in office buildings, thereby helping to promote satisfaction, to increase comfort and productivity, and to decrease energy consumption.
- Motivating authorities and designers in the building sector to create energy efficiency codes, policies and the use of simulation in probing design alternatives.

1.3 Background

1.3.1 Energy performance and behaviour of occupants

Energy use and conservation in buildings have centred around four main areas; setting of environmental standards (e.g. not cooling a building to 22°C when 27°C could be comfortable), building form and fabric, environmental control installations and the choice of energy source including renewable alternatives (Szokolay 2004).

Szokolay sums up the main areas of recent research in the area of energy conservation as follows:

(a) Building: Day lighting, shading, natural ventilation, thermal mass, solar air preheating, improved windows, air infiltration control and passive solar heating.

(b) Installations: Controls of heating, ventilation, air-conditioning (HVAC) systems, energy-efficient HVAC, economizer cycle, exhaust air heat recovery, energy-efficient lamps, photovoltaic and solar water heating.

From the above, it is clear that the behaviour of the occupant on energy conservation is a measure that has been neglected. However, user actions in office buildings are mainly an attempt to avoid discomfort, and they have effects on energy performance. When indoor conditions become unpleasant, occupants tend to use the available building systems in order to create satisfying indoor conditions (Nicol and Roaf 2005). Moreover, the energy implications of these actions are mostly not considered. To some extent, the building elements may not be energy efficient and the problem is worsened by negative energy conscious behaviour (Mahdavi *et al.* 2007). In a related study, the effects of the behaviour of occupants and control systems on energy performance resulted in a potential reduction of cooling loads by 50% (Mohammadi 2007).

It is therefore prudent to consider building occupants in the process of finding measures to reduce energy performance of office buildings.

One of the earlier research on the behaviour of occupants was conducted by Hunt (1979). Hunt demonstrated that frequently, during continuous occupation, all luminaries in a room are switched on at the beginning of the working day, and switched off at the end of the working day. Furthermore, Hunts' findings correspond to Love (1998) and Pigg *et al.* (1996) that the switching on and off of luminaries happens upon arrival and when leaving the office at the end of the day.

Inoue *et al.* (1988) illustrated that the operation of shades is proportional to the depth of sunlight penetration into the office space. Further, the threshold of direct solar radiation on the façade, triggering the closing of shades is 50 $W.m^{-2}$ but when irradiance decreased, most of the shades were left closed. This implies that the occupants relied on artificial lighting which resulted in internal heat gains that had to be cooled and consequently increased cooling loads.

Lindsay *et al.* (1992) also concluded that the operation of shades in office buildings was as a result of solar radiation and the position of the sun in relation to the façade.

In a number of office buildings studied, Pigg *et al.* (1996) concluded that the shades on the northern façade were used less than on the southern side and that 37% of the occupants operated the shades in order to reduce glare on their computer screens.

This depicts the necessity of designers to use sustainable design principles in the orientation of buildings and workspaces since otherwise, the effect on energy consumption could be negative.

In an extensive study of naturally ventilated buildings in a number of countries, Nicol (2001) found out that in European offices, a temperature of 22°C corresponded to 50% opening of windows, which increased to 80% when the outdoor temperature rose to 33°C. He concluded that there is a strong relationship between temperature and the operation of windows in all countries.

In a study of office buildings, Herkel *et al.* (2005) came to the conclusion that the opening and closing of windows occurred when the occupants arrive or leave their workspaces and usually, windows are closed at the end of the day.

The summary above shows the importance of the study of user behaviour in office buildings in relation to satisfaction, thermal comfort and energy performance.

1.3.2 Comfort

Alongside the provision of space for diverse activities, designers' main task is to ensure that occupants are comfortable and satisfied with their indoor environment. This generally leads to higher productivity, especially in office buildings. Designers usually provide building systems, which must be operated by the occupants in an attempt to attain comfort.

However, comfort is a complex factor in determining well-being of occupants since numerous aspects must be considered.

1.3.2.1 Definitions

A summary of definitions has been compiled by Heerwagen, (2004 pp.42) stating, *"Givoni defines thermal comfort as the absence of irritation and discomfort due to heat or cold, or in a positive sense, as a state involving pleasantness. Dagostino suggests that thermal comfort means being able to carry on any desired activity without being either chilly or too hot. Alternatively, Fanger states that thermal comfort is that condition of mind, which expresses satisfaction with the thermal environment. Fanger further notes that, because of biological variance, establishing a condition that will satisfy everyone is not likely to be achievable. Rather, the designer or the builder should instead seek to create a condition that will satisfy the largest number in a group of probable occupants. Yaglou, says that comfortable air conditions are those under which a person can maintain a normal balance between production and loss of heat, at normal body temperature and without sweating".*

1.3.2.2 Main factors

The main factor is the body's capability of balancing its own temperature with the thermal environment. This thermal balance depends on the internal heat load and energy flow (thermal exchange) of the body, which is executed through the processes of conduction, convection, radiation and evaporation (perspiration and respiration) (Gut and Ackerknecht 1993). The main conditions allowing heat to be lost are air temperature, humidity, air velocity and mean radiant temperature (Lechner 2001). Other minor factors are age, sex, clothing, health and activity.

1.3.2.3 Tropical scales

For tropical regions, a comfort range of between 23°C to 29°C with a relative humidity of 30% to 70% is suggested by Brooks (1963). In addition, Koenigsberger *et al.* (1974) have proposed 22°C to 27°C with an optimum temperature of 25°C. Keneally (2002) is of the opinion that the general consensus of suitable design set point for tropical buildings are between 24°C to 25°C and 55% to 65% relative humidity. Ferstl (2005) suggests 22°C to 26°C and 30 to 80% relative humidity as optimal values for indoor comfort.

1.3.2.4 Neutrality temperature (adaptive model)

According to Hyde (2000), the neutrality temperature is the temperature at which a person should be neither too hot nor too cold and the comfort zone is 2°C below and above the neutrality temperature. On the other hand, Szokolay (2004) has set the comfort zone for 90% acceptability to be 2.5°C above and below the neutrality temperature, after, Auliciems (1981).

$$Tn = 17.6 + 0.31 * To.av \qquad \textbf{Eq. 1}$$

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

1.3.3 Orientation, form and energy performance

In his book “Architectural Design for Tropical Regions”, Salmon (1999 pp.124-125), has the following views on passive designs: *“Buildings should be able to respond to changes in climate by rejection of solar heat and have the thermal integrity to maintain internal comfort, despite the influence of climatic forces acting on the building envelope. In addition, the building should be able to retain cool, in order to maintain comfort. In this regard, the exact solar orientation is not critical.”* He however establishes that analyses of sun paths and wind directions have shown that elongated buildings should be oriented to the south. In addition, the best orientation for wind is the southwest whilst a compromise of 22.5° (south-southwest) should give the best orientation.

Lauber (2005) made a recommendation that was slightly different from that of Salmon. He proposes +/- 30° from the prevailing wind direction as the best orientation for buildings in warm and humid countries. This will result in a building with the elongated side oriented 15° south of southwest and 15° south of southeast. The extreme options are not ideal since this would have all the areas of the elongated façade exposed to the morning and evening sun. Lauber further states that the shell of air-conditioned buildings must be insulated, windproof and airtight. This suggests an orientation away from the prevailing wind direction. He however did not suggest a precise direction for air-conditioned buildings.

According to Szokolay (2004), orientation can also be a function of aspect ratio, which has a great influence on the thermal performance of the building. Aspect ratio is the length of an elongated side of the building, usually the north and south, in relation to the shorter sides, east and west. A recommended ratio is between 1.3 and 2.0, depending on temperature and radiation conditions. Szokolay continues to say that for naturally ventilated buildings, major openings that are on the northern and southern elongated walls should face within 45° of the prevailing wind direction. This is 15° more than what Lauber suggested. On the other hand, this implies an optimum orientation of the elongated sides facing north or south, and a thermally inappropriate direction of openings facing the western sun.

Hawkes (1996) has grouped buildings into exclusive and selective modes. The exclusive mode has an automatically artificial environment. The shape is compact and tries to minimise the influence of the external environment, therefore, orientation is not important. The environment of the selective mode is controlled by automatic and manual means with a mixture of natural and artificial variables. The shape is dispersed and seeks to maximise the use of ambient energy. Orientation is an important factor in this mode. This implies that buildings in the exclusive mode are most likely to orient spaces anyhow and could have higher energy performance levels. Those in the selective mode would orientate spaces to the direction of prevailing winds; functions of spaces are important and could be a factor in the determination of the orientation.

All the factors elaborated above give an indication of the need to approach energy performance and comfort of buildings in a broader scale. Factors of the building, installations and user behaviour have to be researched and treated as major aspects needing attention for an effective impact on building performance.

In the Ghanaian context, this project should serve as a basis which must be further researched by studying more buildings and occupants in an effort to curb the high energy performance of office buildings and to raise awareness.

2 APPROACH

2.1 Overview

Five office buildings in Kumasi were selected for the studies. Each building was given a three letter code and will be referred to as such. They house different organisations, are of varied sizes and have occupants in different age groups (see Table 1).

Every 10 minutes, air temperature and relative humidity was measured by data loggers in 15 offices from September 2007 to August 2008. Additionally, 5 sensors were mounted in the immediate vicinity of the buildings to record the outdoor environmental conditions. This was necessary since hourly weather data from the Kumasi meteorological office were not available. A weather file for Kumasi was also generated via, Meteotest (2008).

The gathered data were screened, processed and analysed with the aid of various software programs (e.g. microsoft excel and psychrometric chart 2.16). The buildings were eventually modelled in a numeric simulation tool, calibrated, and design alternatives investigated towards a general reduction of cooling loads in the office buildings.

Table 1: Overview of the selected office buildings with function, net floor area (in m^2) and thermal controls

BUILDING	FUNCTION	FLOOR AREA	THERMAL CONTROLS
CAP	University	795	Mixed mode
KCR	NGO	1100	Air-conditioned
ANG	Private	365	Air-conditioned
ROY	Construction company	1740	Air-conditioned
DCD	Community	280	Naturally ventilated

At the end of the monitoring period, the occupants were interviewed regarding their views on indoor environment and installed systems. In all, 64 occupants filled a questionnaire.

2.2 Object description

2.2.1 Building CAP

Fig.1: External view of building CAP

The CAP building is a rectangular, two-storey block, with an orientation towards the north and south. The entrance to the building is positioned on the far right. It is linked to the various spaces through a veranda in front of the offices (Fig. 1). Another veranda runs along the northern side of the block and in this way provides protection for the office spaces arranged linearly on the various floor levels (see Fig. 2).

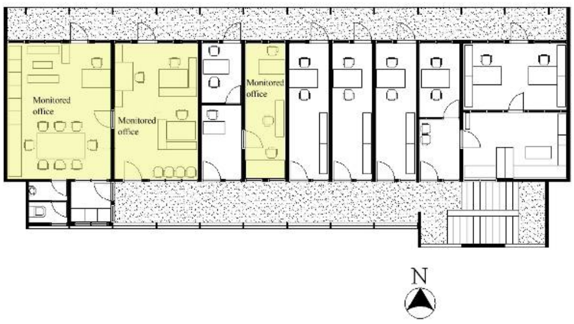

Fig.2: Schematic plan of offices in CAP

Originally, the administration block was designed as a naturally ventilated building. This is visible through the protection of the spaces by the veranda. Recently, air-conditioners have been installed in the spaces. This is demonstrated through the air-conditioned units protruding out of the windows. Generally, all the windows are glass-louvre blades and therefore not tight enough. A high amount of energy is used to maintain cool indoor temperatures.

The administration block has an area of 795m². The ground floor has spaces for offices and a library area. The first floor houses the management and other staff offices (Fig. 2). All offices are in enclosed spaces, with the exception of a few with timber louvre-partition walls.

A sample management office below has an area of about 55m² and louvre blade windows oriented towards the north. Those on the southern wall have been sealed off with a sanitary area and a mini-photo copy unit (Fig. 2). The space is cooled by a split air-condition unit, operated with a remote control (Fig. 3).

Fig.3: Sample management office

Other administrative offices are in an open plan type. The windows are also glass louvre blades with curtains serving as shading elements. The space is cooled by a window unit air-conditioner and is operated with an “on” and “off” switch behind the workspace of the section head. This means that negotiation is needed for the operation of the air-conditioner (Fig. 4). All the 40 Watts light sources in the offices are fluorescent tubes ranging from 2 to 4 in number, depending on the size of the offices, and the controls are operated manually.

Fig.4: Sample administrative offices

With the exception of the east and west facades which are exposed to direct sunlight, all the windows in the northern and southern walls are recessed and shaded by the veranda on the elongated sides of the building (Fig. 5).

Fig.5: Shading devices protecting windows

2.2.2 Building KCR

Fig.6: External view of building KCR

The KCR administration block is an L-shaped one-storey building with an orientation towards the north and south. The left wing however is orientation towards the east and west. The entrance to the building is in the angle of the two rectangular blocks. From here, one has access to both parts of the building, which are linked together on the first floor through a corridor (Fig. 6 and 7).

Fig.7: Schematic plan of offices in KCR

The KCR building has an area of 1100m². The ground floor has spaces for diverse offices, a board/conference room, storage, kitchenette and other supporting spaces. The first floor houses the management, spaces for administrative personnel and other secondary rooms. The offices, with the exception of the reception area, are all in enclosed spaces.

A sample office below is about 25m² large, and has two bay sliding windows oriented towards the north and the east. The space is cooled by a split air-condition unit operated by a remote control. The double florescent lights, 40 Watts each, are controlled manually. Due to the failing shading devices, the space is exposed to visual discomfort especially during the morning hours because of direct and reflected solar radiation (Fig. 8).

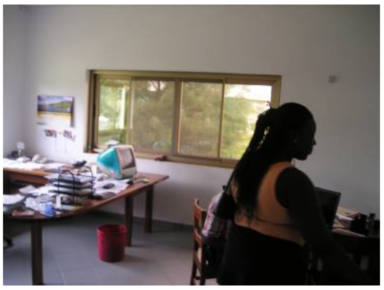

Fig.8: Sample office

Another administrative office has only one two bay sliding window. The window is oriented to the south. There are curtains on the window, which serve as a shading device during the mid-day (Fig. 9).

Fig.9: Sample administrative office

The windows in the secretary’s office are oriented towards the north and a split air-condition unit cools the space. In addition to the air-conditioner, there is a fan in the middle of the space to facilitate air flow when needed (Fig. 10).

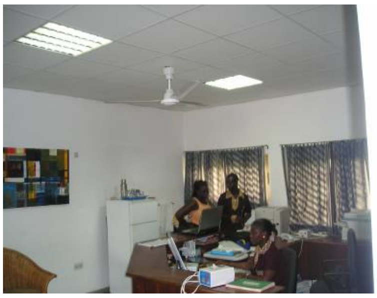

Fig.10: Secretary’s office

The building envelope lacks shading devices and the effect is the exposition of the windows to solar radiation. The windows on the first floor are partly shaded by the overhang of the roof (see Fig. 11). Though insufficient, curtains have to be used on the inside for optimum protection.

Fig.11: Overhang, partly shading exposed windows

2.2.3 Building ANG

Fig.12: External view of building ANG

The ANG building, housing a private organization, sits on the second floor of a block that contains a row of shops. The elongated side of the building is oriented towards the west. On the first floor of the building, there is a 15m²-office space, which is fully glazed to the south. The main floor is partly glazed with sliding windows and the rest of the office spaces are without window (Fig. 12).

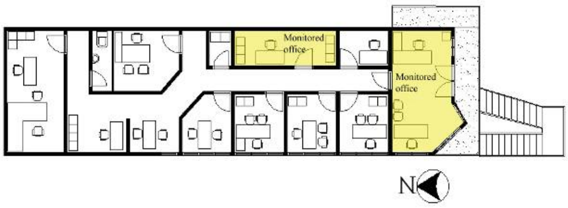

Fig.13: Schematic plan of offices in ANG

The management section is windowless on three sides of the building. The glazed portion on the southern side, though also windowless, brings in light due to the extensive glazing (Fig. 14).

Fig.14: Management section (in and out-door views)

The other administrative spaces on the main floor have three bay sliding glass windows on the western side. The windows are unprotected, as are the ones in most of the offices, and this results in high indoor temperatures during the late afternoon. Therefore, the spaces must be cooled with expensive energy to maintain comfort (Fig. 15).

Fig.15: Exposed glassing on the western façade

The remaining office spaces on the eastern side are all windowless and comfort is maintained with the aid of split air-conditioners (Fig. 16).

Fig.16: Windowless office

The shades and the lighting in the spaces are manually controlled. Again, the lights are 40 Watt fluorescent tubes which differ in number depending on the size of the spaces.

The only external shading element is the overhang at the entrance of the main block, oriented towards the south (Fig. 17).

Fig.17: Cantilevered overhang above the entrance

2.2.4 Building ROY

Fig.18: External view of building ROY

The U-shaped building of ROY has an area of 1,740m². Most of the monitored spaces (administrative and showcase areas) are unprotected from solar radiation, with an orientation towards the southwest and northwest. This gives an indication of the amount of energy that must be fed into the building to maintain comfort. With the exception of the manager's workspace, which is enclosed, all the other workspaces are in an open plan type of landscape (Fig. 18, 19).

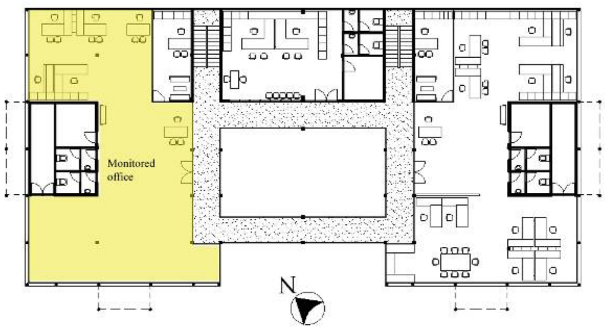

Fig.19: Schematic plan of offices in ROY

The space is cooled by split air-condition units and there are virtually no operable windows in the curtain wall façade. The 40 Watts fluorescent tube lights are manually controlled and the building has practically no internal, manually controlled shades (Fig. 20).

Fig.20: Indoor views

2.2.5 Building DCD

Fig.21: External view of building DCD

The naturally ventilated DCD building has an area of 280m². The elongated sides of the building are oriented towards the southeast. The ground floor houses most of the administrative personnel. The first floor has spaces for the management and a few members of administrative staff. The arrangement of the spaces is linear and some have a “back to back” arrangement, hindering cross ventilation (Fig. 22).

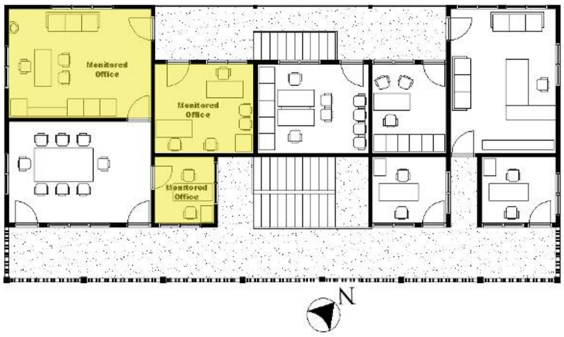

Fig.22: Schematic plan of offices in DCD

A sample office on the first floor is on the southern end with glass louvre blade windows on two sides of the wall, supporting cross ventilation. Curtains are employed as a shield against the western sun during the late afternoons (Fig. 23).

Fig.23: Sample office on the first floor

An administrative personnel office on the eastern side is protected by the veranda with a moulding decoration, bringing in diffused light and serving as shading devise against the morning sun (Fig. 24).

Fig.24: Sample office with the shading veranda

The offices in the building are mostly double occupancy type and the installed 60 Watts light sources are manually controlled. All the offices have internal shades made of curtains which are manually operated. Due to the orientation and relatively small size of some of the offices, the rooms appear dark when the curtains are operated. From the above images, it is evident that shades deployed during disturbances are left in position even in absence of the annoyance and this hinders the efficient flow of natural ventilation. In addition, only few fans have been installed in the building to aid in comfort.

2.3 Data collection

2.3.1 Overview

The research data was collected from September 2007 until August 2008. Within this period, external weather information was gathered from the Kumasi meteorological department. Data loggers were installed in and on the buildings and consequently, data-points were read out every 14 to 30 days. Building plans and information on the materials used were collected within the same period.

2.3.2 External environment

Data loggers (Hobo sensors, U12-012) produced by "Onset Inc." were mounted on the outside of the buildings to record air temperature and relative humidity (see Table 2). A weather file for Kumasi was also generated via Meteotest (2008). This was due to our inability to install a weather station on each building because of limited funds. However, the Kumasi weather station provided the daily mean minimum and maximum temperature and relative humidity values.

Table 2: Accuracy of the sensors

SENSOR	RANGE	ERROR
Air temperature	-20 to 70 ^{o}C	± 0.4 ^{o}C
Relative humidity	5 to 95 %	± 3%
Light intensity	12 to 32.000 lx	

2.3.3 Internal environment

Indoor temperature, relative humidity and light intensity were measured with the above mentioned data loggers. The sensors were mounted near the workspace to avoid occupants from depositing items on them (Fig. 25). Care was taken to avoid direct solar radiation on the sensors. They recorded the parameters every 10 minutes and the recordings were downloaded by connecting the sensors to a computer using the hoboware pro and greenline software. For further information on the data loggers see Appendix A.

The sensors were named as follows: “building number _ floor and room number _ sensor ID _ installation date”. For instance, “1_106_103_070910” means first case study building _ first floor, room six _ third sensor on the first floor _ installed on September 10, 2007.

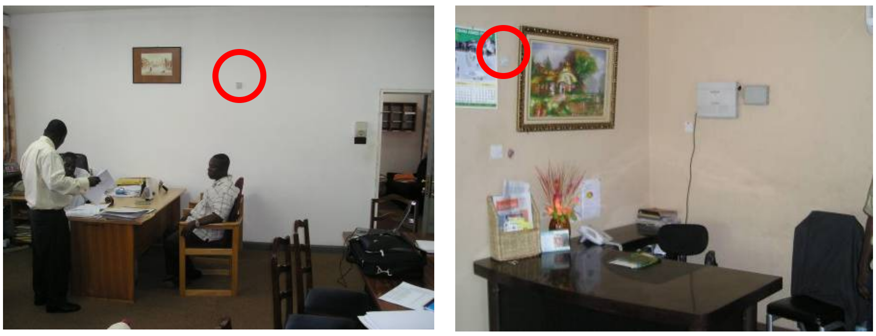

Fig.25: Position of the data loggers in sample offices

2.3.4 Interviews

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

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

In all, 64 occupants completed the questionnaire, 24 from CAP and 10 each from the other buildings. For information on the questionnaire see Appendix B.

2.3.5 Energy performance

Monthly electricity bills, providing information on monthly consumption of the buildings were available for ANG, ROY and DCD. In the other buildings, no meters were installed and therefore, no information on energy consumption could be obtained.

2.4 Data processing

At the beginning and end of the observation period, the hobo sensors were tested to verify their reliability and performance. This was done by launching them in a test bed at the Department for Building Physics and Building Ecology laboratory and processing the data in MS Excel (Fig 26). The calculated standard deviation resulted in an accuracy of +/- 0.09 and +/- 0.02 which showed the closeness of the measured data points when compared to the mean values.

Fig.26: Examining the performance of the sensors in the lab

To a large extent the data gathered was processed with Microsoft Excel, because of its high compatibility with a number of other applications. Other software applications used in the study were Greenline, Hoboware pro, AutoCAD, Meteotest, Tas simulation tool, Psychrometric chart pro, PMVcalc v2 and Adobe Photoshop.

Greenline was used to launch and read the files from the data loggers. The downloaded data points were screened in Hoboware pro software, after which the data points were exported to a MS Excel file for further processing. Below is an image of the hoboware pro application (Fig. 27).

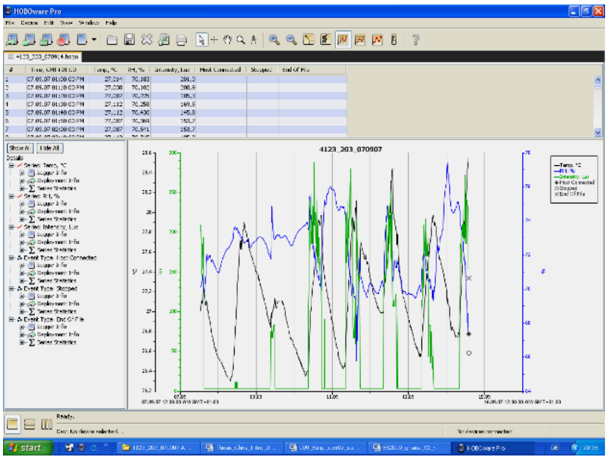

Fig.27: Hoboware pro interface

In MS Excel, the text files were imported, screened, and built together in monthly tables. Since the data recorded was in an interval of minutes, a formulae sheet was generated to produce mean hourly values, making it easier to compare them with the data generated from the Meteotest weather file. Various options on the data were generated (e.g. minimum, maximum, mean values, etc.) and graphed for pre-analysis.

In the Tas simulation programme, the building plans were imported from the AutoCAD application and a model was generated with the information gathered on the building elements and spaces (Fig. 28). The weather file from Meteotest was used to run the simulation and the output data was exported back into the MS Excel application to calculate mean and hourly sums (Fig. 29).

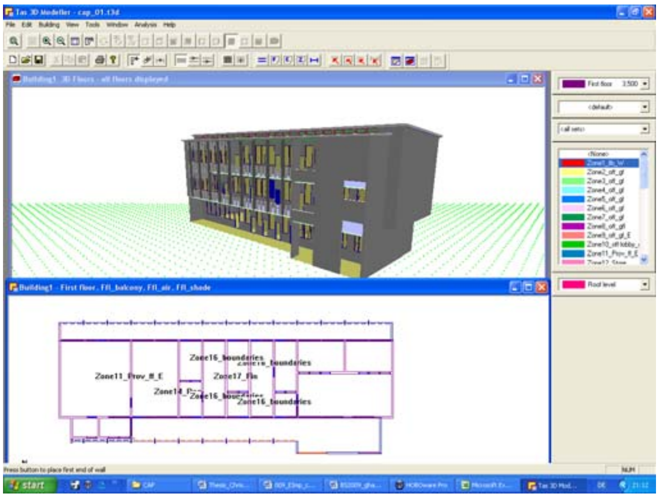

Fig.28: A model of the CAP building in Tas

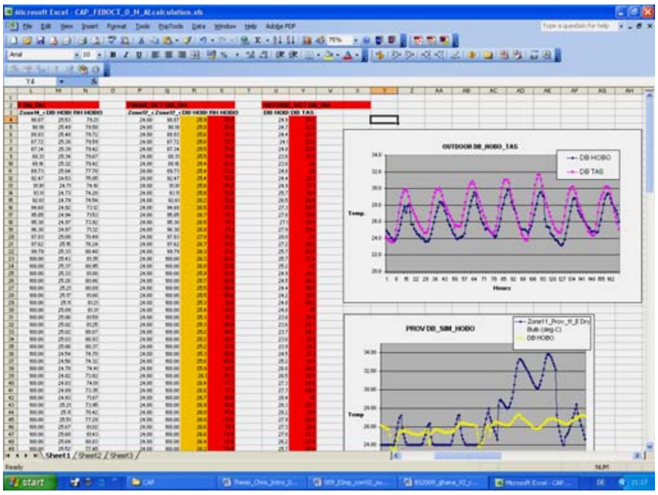

Fig.29: An MS Excel file of data generated from Tas output data

In Psychrometric chart pro, data from an MS excel output file was used to generate a graphical representation of the comfort zone with the monthly data points (Fig. 30).

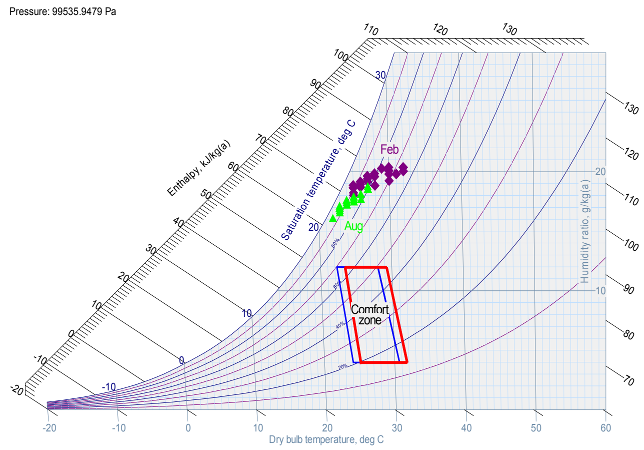

Fig.30: Mean hourly outdoor temperature and relative humidity values (for a reference day) in Kumasi for representative days in the months of February and August (based on data generated via Meteotest 2008)

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

The software, PMV calc v2 was used to calculate the predicted mean vote (PMV) and the predicted percentage of dissatisfied occupants (PPD) after Fanger (1973). This was achieved by inputting the clothing values, metabolic rates of the occupants, air velocities, indoor temperatures and relative humidity values of the occupied spaces. The output results were tabulated and analysed.

In correspondence to the psychrometric chart and PMV methods above, the psychrometric charts were extended to study the effects of physiological cooling resulting from air movement (see Szokolay 2004, pp. 40-41).

Lastly, Adobe Photoshop was used to edit the digital images.

2.4.1 Calibration of the simulation models

As mentioned previously, a numeric simulation tool (EDSL 2008) was used to explore possible measures that could improve the thermal performance of office buildings in Ghana. To make this process more reliable, the simulation models needed to be calibrated. Since detailed and comprehensive outdoor weather information was not available, we identified segments of a synthetic weather file for Kumasi (generated via Meteotest 2008) that matched our own measurements of outdoor conditions. Indoor air temperatures were then simulated using the above mentioned weather file segments and compared with the measured indoor air temperatures (Fig. 31).

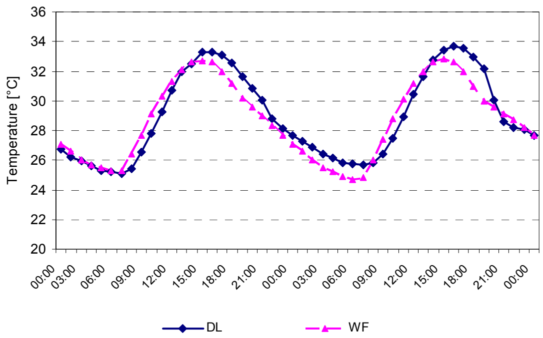

Fig.31: Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (ANG)

Predictions of the calibrated simulation models compared well with the measured values. To illustrate this, the relationship between measured and simulated indoor air temperature in terms of regression lines resulted in the following correlation coefficient values :

- CAP 0.84
- KCR 0.80
- ANG 0.53
- ROY 0.90
- DCD 0.87

2.5 Data analysis

The data points gathered were plotted in MS Excel graphs, compared, and conclusions were drawn on their accuracy. For example, Fig. 32 shows the comparison of our outdoor temperature measurements "DL" (averaged over the office locations) with an average temperature "MET" obtained as the mean of maximum and minimum temperatures recorded by the Kumasi's weather station. These results suggest a good agreement between our measurements and those from Kumasi's official weather station.

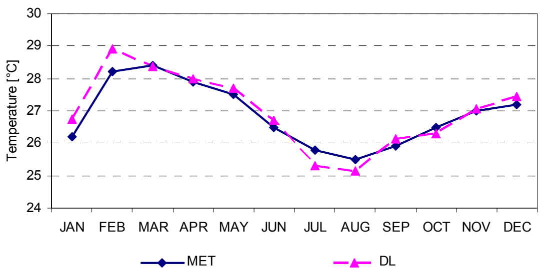

Fig.32: Comparison of mean monthly outdoor temperature measurements at building locations (DL) with Kumasi weather station data (MET)

2.5.1 Parametric study of thermal improvement scenarios

Using the calibrated thermal performance simulation models of the aforementioned five office buildings, various improvement options (concerning glazing, shading, ventilation alternatives, thermal mass and efficient lighting) that could reduce cooling loads and the need for extensive active devices for air-conditioning (26°C set point temperature) were explored.

The performance indicator for the thermal analysis, in this case the active scenario, was cooling (sensible and latent) energy loads ($KWh.m^{-2}a^{-1}$). The sensible cooling energy load was simulated without the component of occupants' latent load. The total energy load comprises both aspects of the occupants' sensible and latent loads.

Information regarding the various scenarios considered for the simulations is summarized in Table 3 and 4. Table 3 provides the base case scenarios for the five buildings. For detailed material properties see Appendix C. Table 4 refers only to deviations from the respective base case (BC).

Table 3: Overview of base case simulation scenarios

CODE	SCENARIO	DESCRIPTION
BC1	Base case CAP	U_{walls} = 3.4 $W.m^{-2}.K^{-1}$; U_{window} = 5.8 $W.m^{-2}.K^{-1}$; g_{window} = 0.82; day/night ACH = 1/0.5 h^{-1}; lighting load = 6 $W.m^{-2}$; floors carpeted, no attic space; occupants' (sensible & latent) load = 10 -14 $W.m^{-2}$
BC2	Base case KCR, ANG, DCD	Similar to BC1, but attic space with: $U_{attic\ floor}$ = 3.4 $W.m^{-2}.K^{-1}$; U_{window} = 2.7 $W.m^{-2}.K^{-1}$; g_{window} = 0.49; floors carpeted, attic space
BC3	Base case ROY	Similar to BC1, but: U_{window} = 5.5 $W.m^{-2}.K^{-1}$; g_{window} = 0.66, floors carpeted, no attic space

Table 4: Overview of simulated improvement scenarios

CODE	SCENARIO	DESCRIPTION
IWA	Improved wall insulation	U_{walls} = 0.4 $W.m^{-2}.K^{-1}$;
IWI	Improved windows	U_{window} = 1.8 $W.m^{-2}.K^{-1}$; g_{window} = 0.29;
IAT	Improved attic fl. insulation	$U_{attic\ floor}$ = 0.4 $W.m^{-2}.K^{-1}$
TMA	Thermal mass	Floor carpets removed
NVE	Night ventilation	Day/night ACH = 1/10 h^{-1}
NVT	TMA+NVE	See TMA and NVE
ELI	Efficient elect. lighting	Lighting load = 2 $W.m^{-2}$
CI1	Combined improvements CAP, ROY	U_{window} = 1.8 $W.m^{-2}.K^{-1}$; g_{window} = 0.29; day/night ACH = 1/10 h^{-1}; Lighting load = 2 $W.m^{-2}$
CI2	Combined improvements KCR, ANG, DCD	$U_{attic\ floor}$ = 0.4 $W.m^{-2}.K^{-1}$; U_{window}=1.8; day/night ACH = 1/10 h^{-1}; Lighting load = 2 $W.m^{-2}$

Furthermore, combined improvement scenarios (see Table 4) were simulated with different air change rates (ACH) to create a comfortable thermal environment during the passive case analysis. The main concern here was the mean overheating (OH_m) (see Eq. 2).

$$OH_m = \sum_{j=1}^{n} \frac{\theta_{i,j} - \theta_r}{n} \qquad \textbf{Eq. 2}$$

Where $\theta_{i,j}$ represents the mean indoor air temperature (°C) at hour j (averaged over all simulated office zones in the floor), θ_r the reference indoor air temperature for overheating (°C), and n the total number of occupied office hours. The term $\theta_{i,j} - \theta_r$ was considered for those hours when $\theta_{i,j} > \theta_r$.

The indoor environmental parameters, in this case temperature and relative humidity values, were combined with the clothing values, metabolic rates and air velocities to determine the predicted mean vote (PMV) and the predicted percentage of dissatisfied occupants (PPD), using the software application “PMVcalc_V2, (n.d.)”. The ACHs were converted to air velocities based on a study on natural ventilation by Pröglhof (2004).

Finally, the indoor temperatures and relative humidity values were plotted on psychrometric charts. Given the high relative humidity values, an extension of the comfort zone on the psychrometric chart was considered by using air velocities of 0.5 to 1.5m.s^{-1}. This approach was based on the work of Szokolay (2004). The equations used are the neutrality temperature (see Eq. 1), the slope of the standard effective temperature (SET) lines (Eq. 3) and the apparent cooling effect of air movement (dT) resulting in physiological cooling (Eq. 4 and 5).

$$\mathbf{DBT/AH = 0.023 * (T - 14)} \qquad \textbf{Eq. 3}$$

Where DBT is dry bulb temperature in °C, AH is absolute humidity in g.kg^{-1}, and T is temperature in °C.

$$\mathbf{dT = 6 * Ve - 1.6 * Ve^2} \qquad \textbf{Eq. 4}$$

Where dT is change in temperature, Ve is effective air velocity

$$\mathbf{Ve = V - 0.2} \qquad \textbf{Eq. 5}$$

Where V is air velocity in m.s^{-1}, valid up to 2m.s^{-1}

2.6 Limitations

The initial objective of the study was to have a broad monitoring of activities regarding building systems and user behaviour in the offices. This meant that diverse sensors were to be used in monitoring (the outdoor environmental conditions, occupants, probabilities and time of switching on the lights, fans, air-conditioners and shades operation, etc). However, due to budgetary constraints, we had to focus on indoor environmental parameters and the prime aim of reducing cooling loads in the buildings.

Secondly, curtain wall office buildings were the initial focus as case studies but permission sought was not granted (Fig. 33).

Fig.33: Images of initial case study buildings

Some of the reasons given were issues relating to security since most of the buildings were operated as banks. Where permission was initially granted, the managers became sceptical about the sensors and later refused to cooperate.

Thirdly, building energy consumption could not be obtained from two of the case studies because it was not measured. Where consumption data was received, they were not realiable and could not be used in the study. For instance, the naturally ventilated building with a small amount of work performed on computers showed a higher energy consumption data than some air-conditioned buildings.

Furthermore, a malfunction of the sensors led to a loss of data as soon as the battery capacity reduced by 35% (this happened from the 5th of November until the 12th of December 2007 as well as between 21st of June and 20th of July 2008). This was unexpected since according to the manual, the sensors were to function until a capacity reduction of 70%. Colleagues who used the same type of sensors in a related study did not have this problem and therefore we could not find any tangible reason for its occurrence. We then decided to download the data every 14 days and to replace the batteries at a regular interval.

3 RESULTS

3.1 Overview

Out of the 897,580 data points and over 500 graphical and simulated outputs generated, presented here are the summary results which have been grouped in five areas. They are the calibration results, psychrometric analysis, energy performance (active case), passive scenario and results of the interviews.

3.2 Calibration results

3.2.1 Measured external air temperature values

Fig. 32 showed the comparison of our outdoor temperature measurements "DL" (averaged over the office locations) with an average temperature "MET" obtained as the mean of maximum and minimum temperatures recorded by the weather station in Kumasi.

These results suggested a good agreement between our measurements and those from Kumasi's official weather station.

3.2.2 Weather file versus measured data

As mentioned earlier, simulation model calibration was performed using segments of a standard weather file with a good match to our local measurements. To illustrate this point, Fig. 34 to 38 show time intervals where the weather file data (WF) and our measurements at building sites (DL) showed a relatively good agreement.

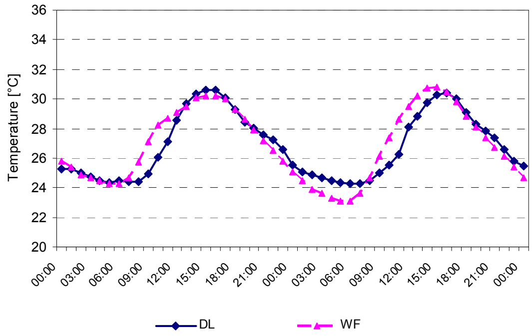

Fig.34: Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (CAP)

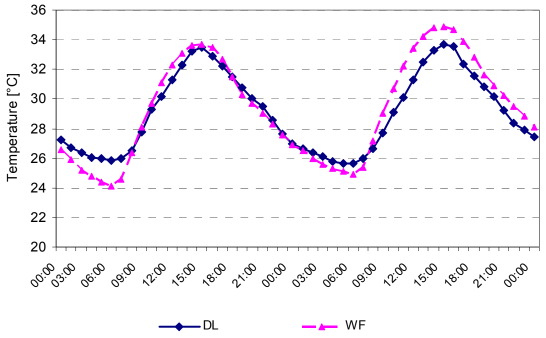

Fig.35: Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (KCR)

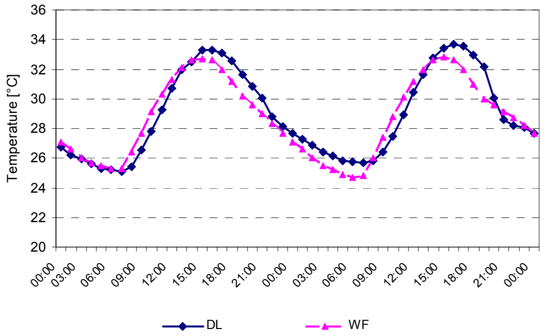

Fig.36: Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (ANG)

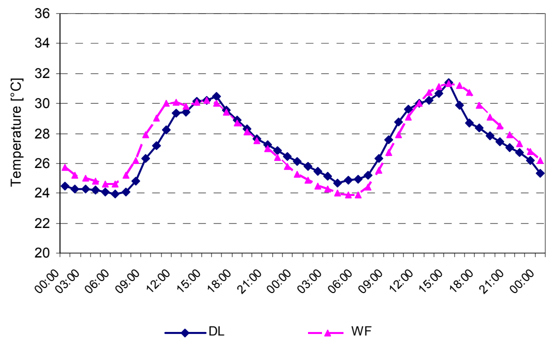

Fig.37: Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (ROY)

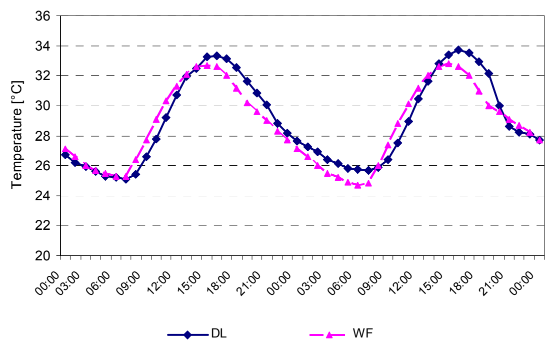

Fig.38: Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (DCD)

3.2.3 Comparison of measurements and simulation results

Predictions of the calibrated simulation models compared well with the measured values. To illustrate this, Fig. 39 to 43 provide measured versus simulated indoor air temperatures.

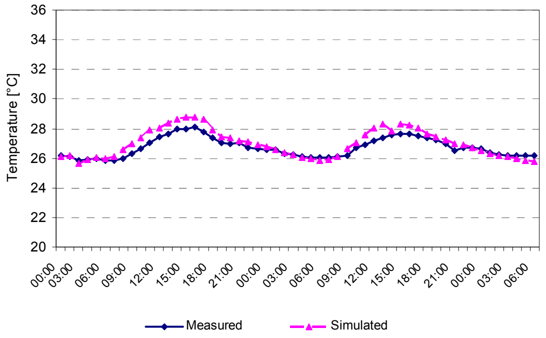

Fig.39: Measured versus simulated indoor air temperatures in CAP

Fig.40: Measured versus simulated indoor air temperatures in KCR

Fig.41: Measured versus simulated indoor air temperatures in ANG

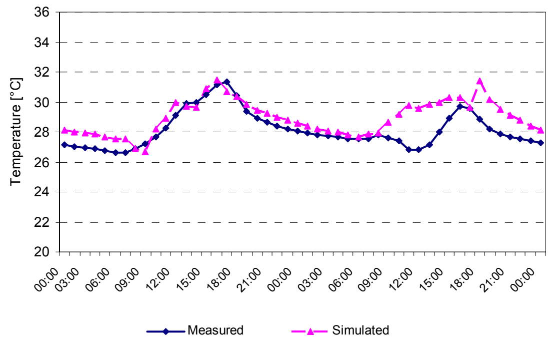

Fig.42: Measured versus simulated indoor air temperatures in ROY

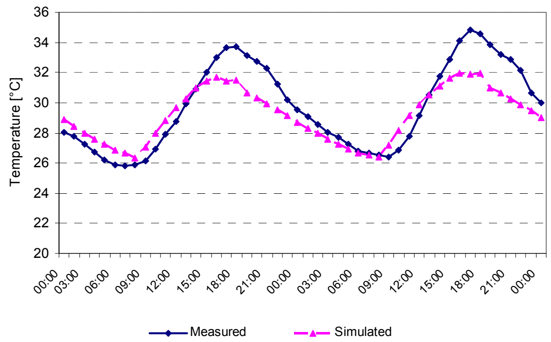

Fig.43: Measured versus simulated indoor air temperatures in DCD

3.3 Psychrometric Results

The adaptive model based on the work of Auliciems (1981) and the recommendation by Szokolay (2004) for 90% acceptability has been used to derive the comfort zone for Kumasi (see Table 5). The maximum, minimum and mean hourly values during the working hours were plotted on the psychrometric chart (Fig. 44 - 58).

Table 5: Neutrality temperature for 90% acceptability

	JAN	**FEB**	MAR	APR	MAY	JUN	JUL	**AUG**	SEP	OCT	NOV	DEC
To.av.	26.5	**28.6**	28.4	27.9	27.6	26.6	25.5	**25.3**	26.0	26.4	27.0	27.3
Tn + 2.5	28.3	**29.0**	28.9	28.8	28.7	28.3	28.0	**27.9**	28.2	28.3	28.5	28.6
Tn	25.8	**26.5**	26.4	26.3	26.2	25.8	25.5	**25.4**	25.7	25.8	26.0	26.1
Tn - 2.5	23.3	**24.0**	23.9	23.8	23.7	23.3	23.0	**22.9**	23.2	23.3	23.5	23.6

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

Tn = neutrality temperature (°C)

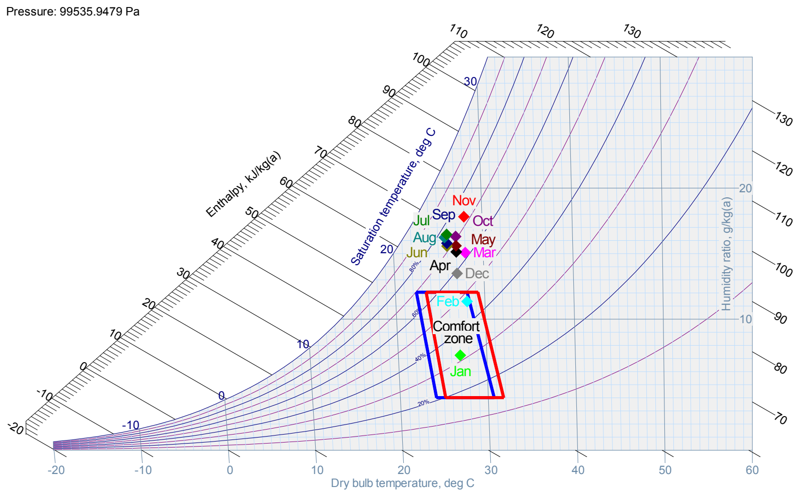

Fig.44: Maximum daily temperature and relative humidity (averaged over all days in a month) of offices in CAP (based on measured data from 8 am to 5 pm)

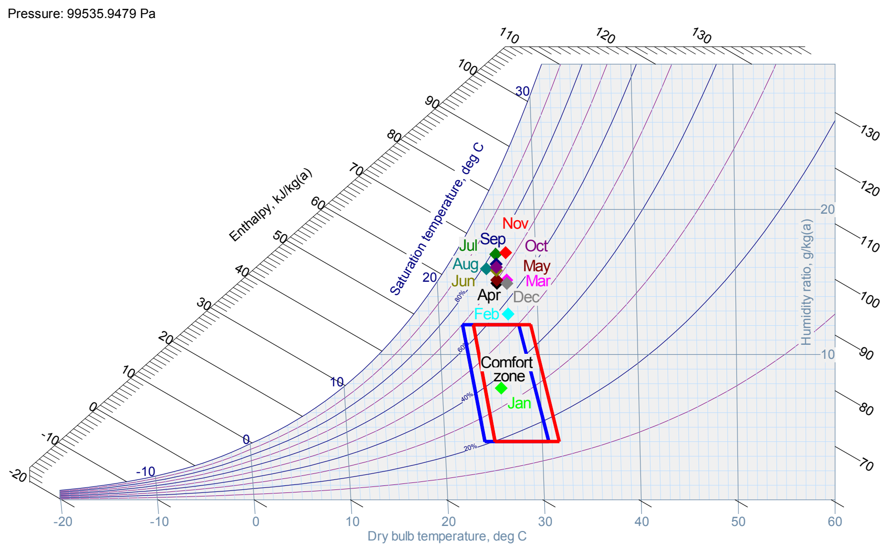

Fig.45: Mean daily temperature and relative humidity (averaged over all days in a month) in CAP (based on measured data from 8 am to 5 pm)

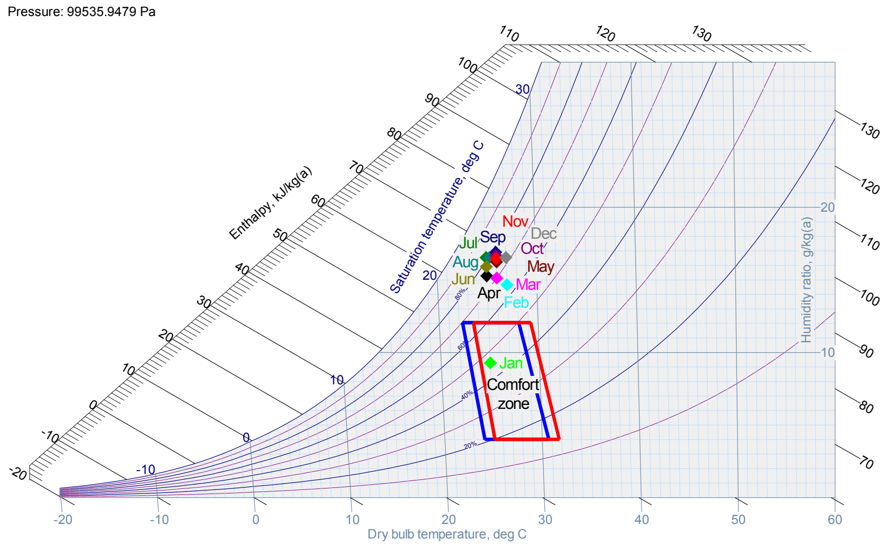

Fig.46: Minimum daily temperature and relative humidity (averaged over all days in a month) in CAP (based on measured data from 8 am to 5 pm)

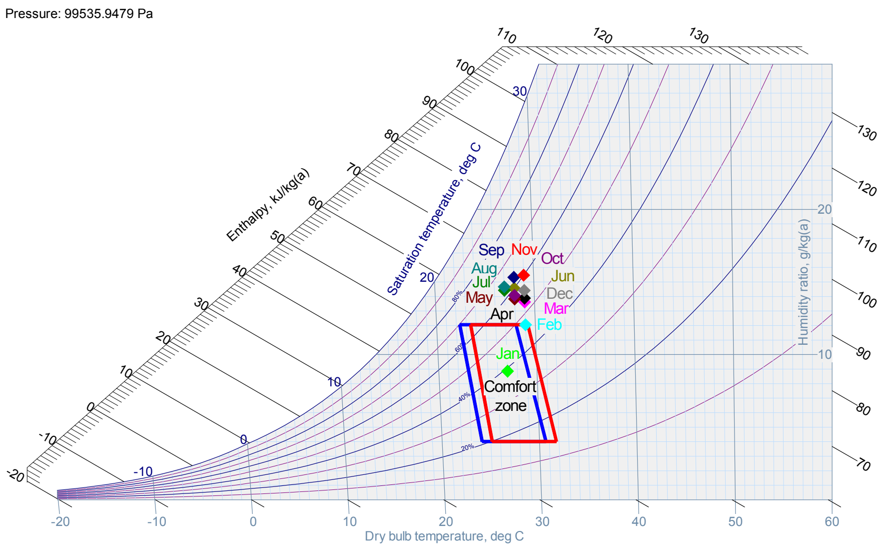

Fig.47: Maximum daily temperature and relative humidity (averaged over all days in a month) of offices in KCR (based on measured data from 8 am to 5 pm)

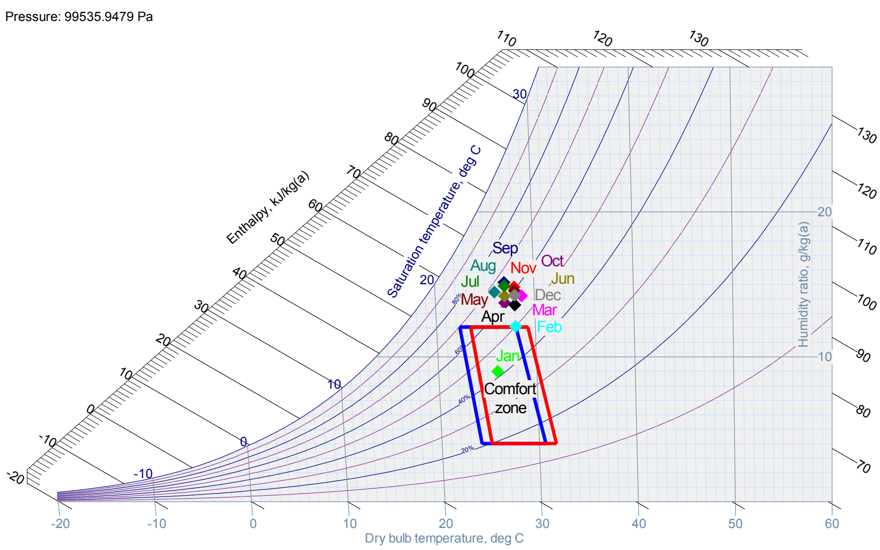

Fig.48: Mean daily temperature and relative humidity (averaged over all days in a month) in KCR (based on measured data from 8 am to 5 pm)

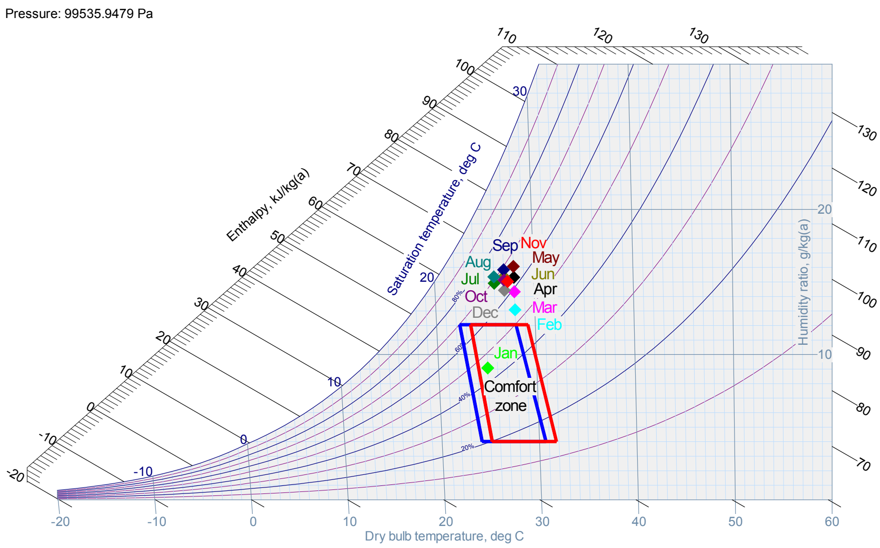

Fig.49: Minimum daily temperature and relative humidity (averaged over all days in a month) in KCR (based on measured data from 8 am to 5 pm)

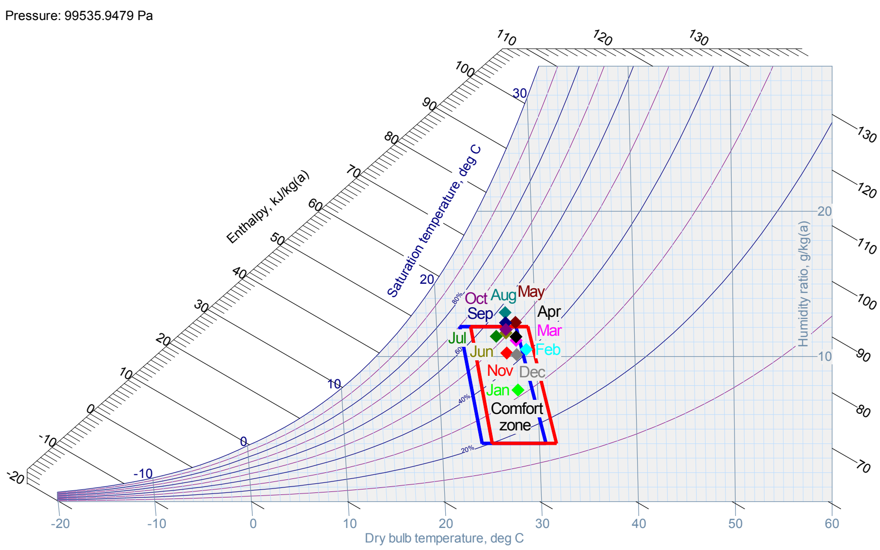

Fig.50: Maximum daily temperature and relative humidity (averaged over all days in a month) of offices in ANG (based on measured data from 8 am to 5 pm)

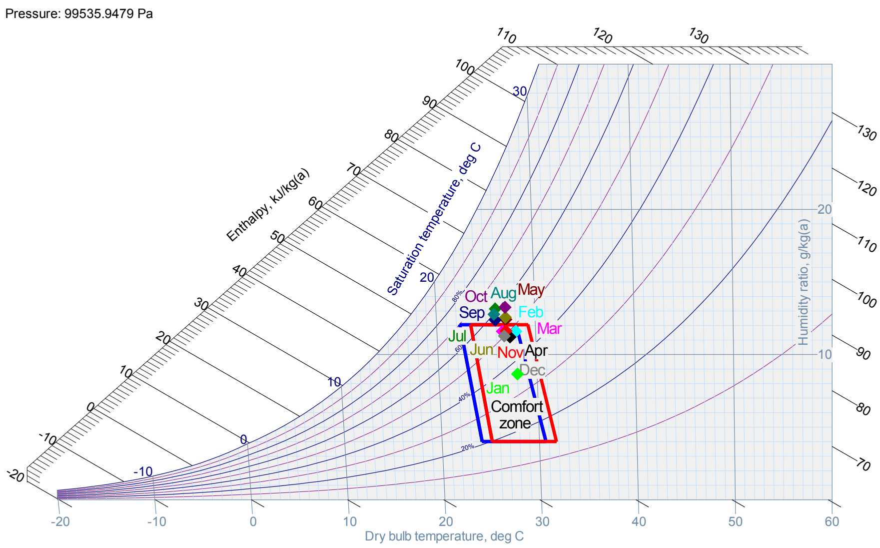

Fig.51: Mean daily temperature and relative humidity (averaged over all days in a month) in ANG (based on measured data from 8 am to 5 pm)

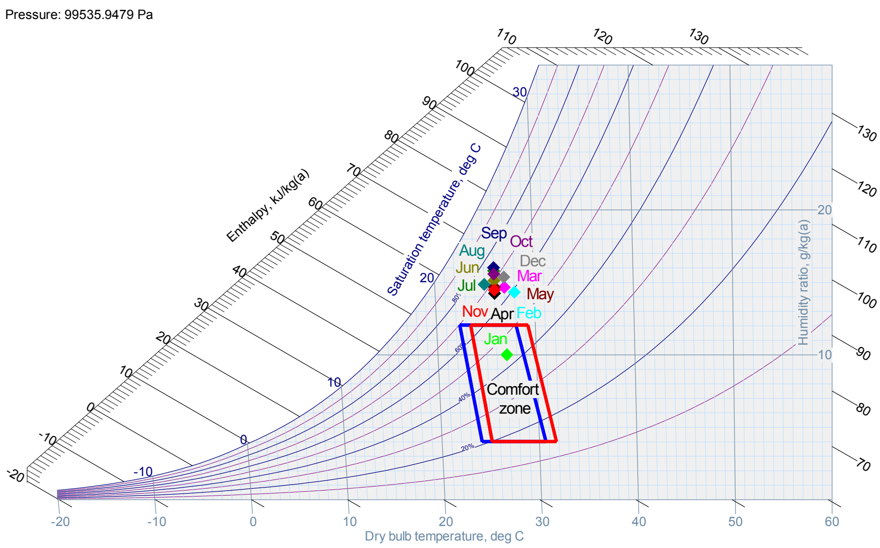

Fig.52: Minimum daily temperature and relative humidity (averaged over all days in a month) in ANG (based on measured data from 8 am to 5 pm)

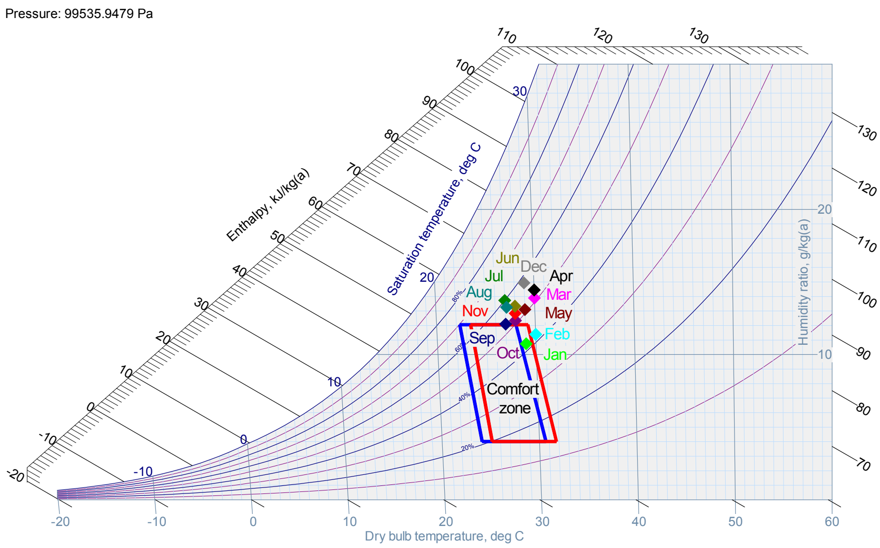

Fig.53: Maximum daily temperature and relative humidity (averaged over all days in a month) of offices in ROY(based on measured data from 8 am to 5 pm)

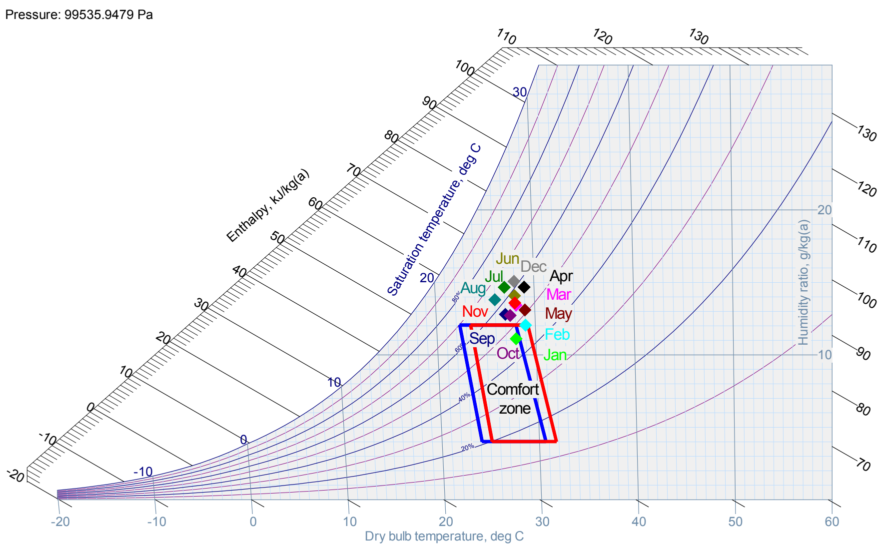

Fig.54: Mean daily temperature and relative humidity (averaged over all days in a month) in ROY (based on measured data from 8 am to 5 pm)

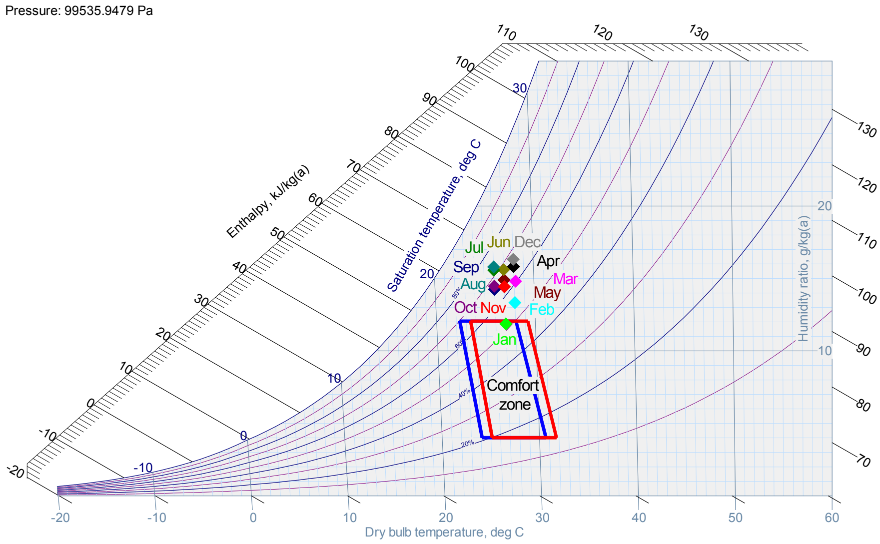

Fig.55: Minimum daily temperature and relative humidity (averaged over all days in a month) in ROY (based on measured data from 8 am to 5 pm)

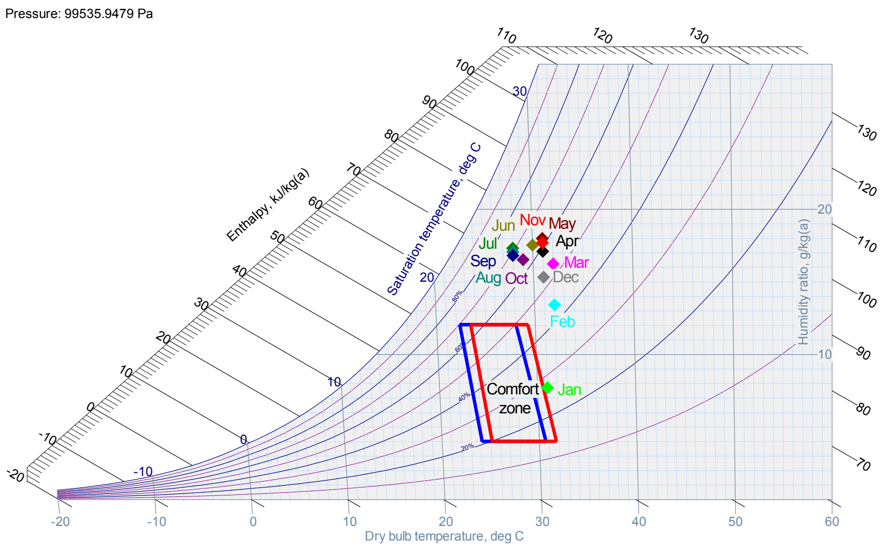

Fig.56: Maximum daily temperature and relative humidity (averaged over all days in a month) of offices in DCD (based on measured data from 8 am to 5 pm)

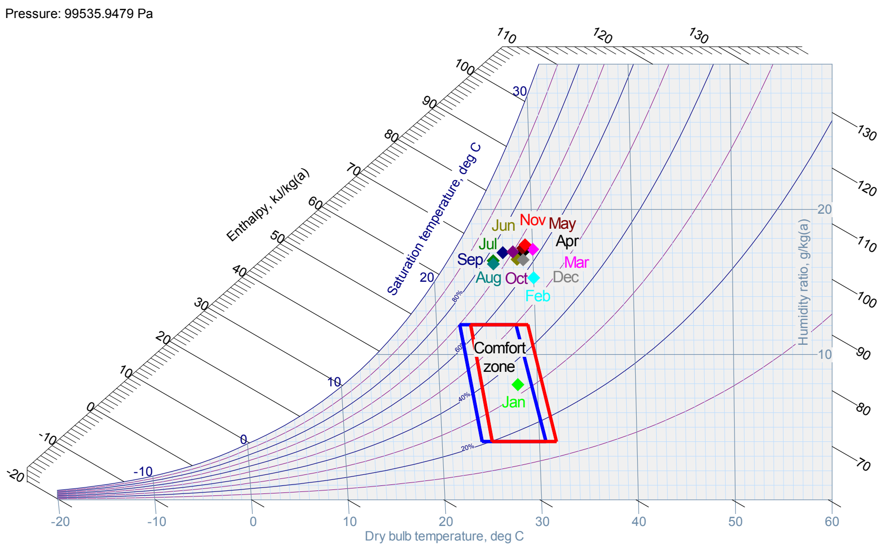

Fig.57: Mean daily temperature and relative humidity (averaged over all days in a month) in DCD (based on measured data from 8 am to 5 pm)

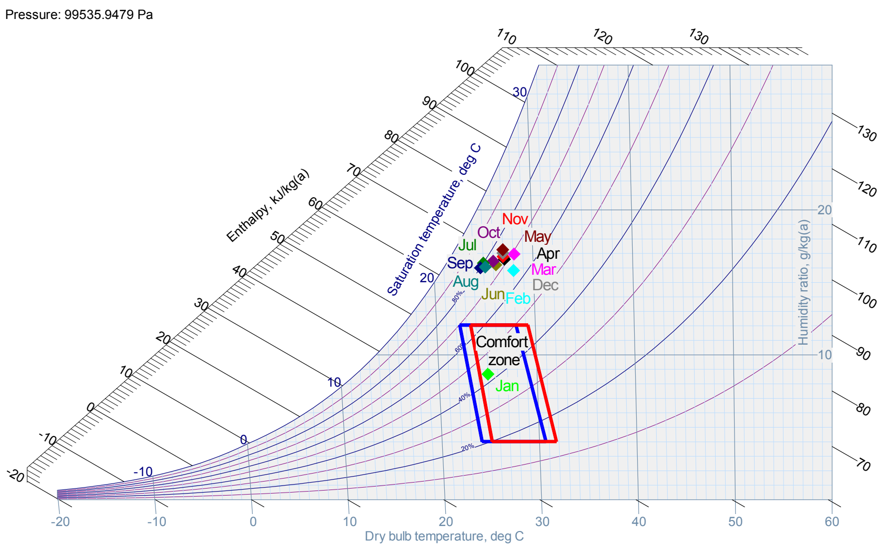

Fig.58: Minimum daily temperature and relative humidity (averaged over all days in a month) in DCD (based on measured data from 8 am to 5 pm)

3.4 Active scenario results

A summary on the results (annual cooling loads in $KWh.m^{-2}.a^{-1}$) of the parametric simulation (active case) is presented (Fig. 59 – 64 and Table 6 - 11). For the description of codes for various cases see Table 3 and 4.

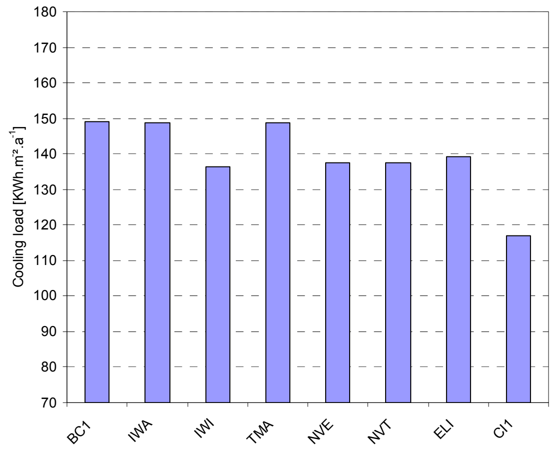

Fig.59: Simulated cooling loads (CAP) for different scenarios

Table 6: Simulated sensible, latent and total cooling loads (CAP) for different scenarios

	Sensible cooling load ($KWh.m^{-2}.a^{-1}$)	Latent cooling load ($KWh.m^{-2}.a^{-1}$)	Total cooling load ($KWh.m^{-2}.a^{-1}$)
BC1	109.1	39.9	149.0
IWA	108.8	39.9	148.7
IWI	96.6	39.9	136.5
TMA	109.0	39.9	148.9
NVE	97.6	39.9	137.5
NVT	97.5	39.9	137.4
ELI	99.3	39.9	139.2
CI1	77.1	39.9	117.0

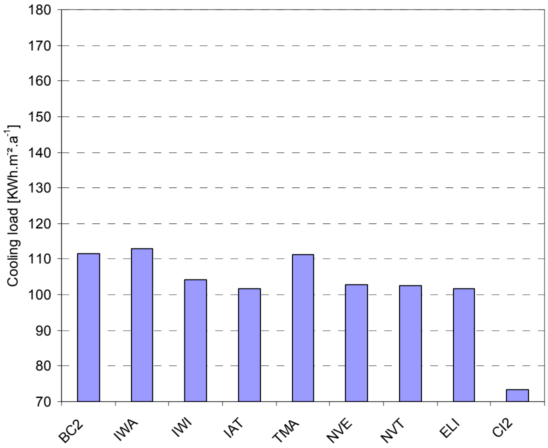

Fig.60: Simulated cooling loads (KCR) for different scenarios

Table 7: Simulated sensible, latent and total cooling loads (KCR) for different scenarios

	Sensible cooling load ($KWh.m^{-2}.a^{-1}$)	Latent cooling load ($KWh.m^{-2}.a^{-1}$)	Total cooling load ($KWh.m^{-2}.a^{-1}$)
BC2	84.3	27.2	111.5
IWA	85.5	27.2	112.9
IWI	76.9	27.2	104.1
IAT	74.6	27.2	101.8
TMA	84.1	27.2	111.3
NVE	75.6	27.2	102.9
NVT	75.3	27.2	102.6
ELI	74.6	27.2	101.8
CI2	46.1	27.2	73.4

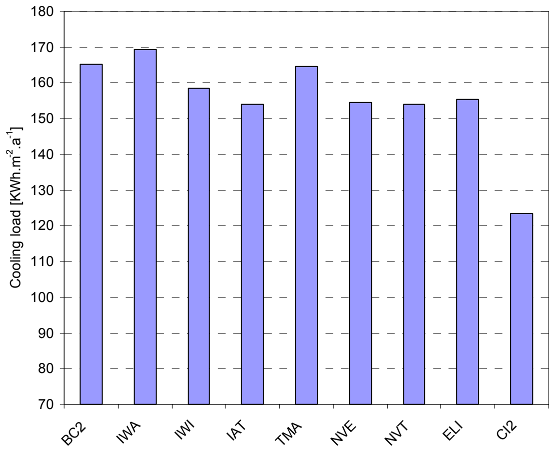

Fig.61: Simulated cooling loads (ANG) for different scenarios

Table 8: Simulated sensible, latent and total cooling loads (ANG) for different scenarios

	Sensible cooling load ($KWh.m^{-2}.a^{-1}$)	Latent cooling load ($KWh.m^{-2}.a^{-1}$)	Total cooling load ($KWh.m^{-2}.a^{-1}$)
BC2	132.7	32.5	165.2
IWA	137.0	32.5	169.5
IWI	125.9	32.5	158.4
IAT	121.5	32.5	154.0
TMA	132.0	32.5	164.5
NVE	122.0	32.5	154.5
NVT	121.4	32.5	153.9
ELI	123.0	32.5	155.5
CI2	90.9	32.5	123.4

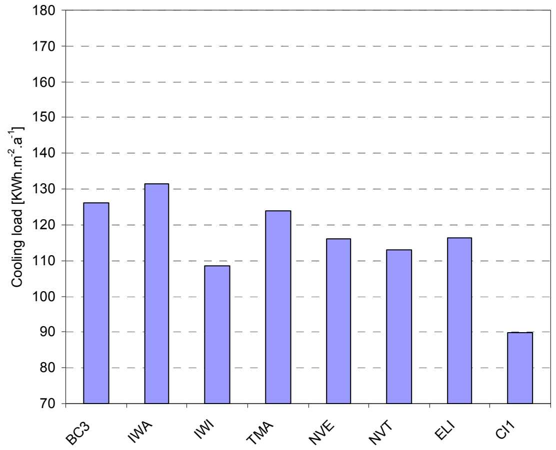

Fig.62: Simulated cooling loads (ROY) for different scenarios

Table 9: Simulated sensible, latent and total cooling loads (ROY) for different scenarios

	Sensible cooling load ($KWh.m^{-2}.a^{-1}$)	Latent cooling load ($KWh.m^{-2}.a^{-1}$)	Total cooling load ($KWh.m^{-2}.a^{-1}$)
BC3	94.5	31.7	126.2
IWA	99.6	31.7	131.3
IWI	76.6	31.7	108.4
TMA	92.3	31.7	124.0
NVE	84.5	31.7	116.2
NVT	81.4	31.7	113.1
ELI	84.7	31.7	116.4
CI1	58.0	31.7	89.7

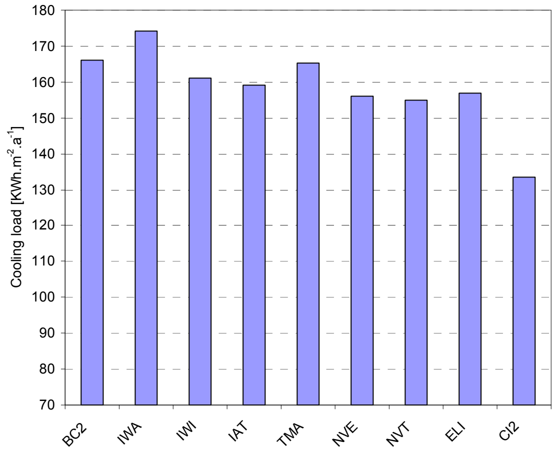

Fig.63: Simulated cooling loads (DCD) for different scenarios

Table 10: Simulated sensible, latent and total cooling loads (DCD) for different scenarios

	Sensible cooling load ($KWh.m^{-2}.a^{-1}$)	Latent cooling load ($KWh.m^{-2}.a^{-1}$)	Total cooling load ($KWh.m^{-2}.a^{-1}$)
BC2	128.8	37.4	166.2
IWA	136.7	37.4	174.1
IWI	123.8	37.4	161.2
IAT	121.8	37.4	159.2
TMA	127.9	37.4	165.3
NVE	118.6	37.4	156.0
NVT	117.6	37.4	155.0
ELI	119.6	37.4	157.0
CI2	96.0	37.4	133.4

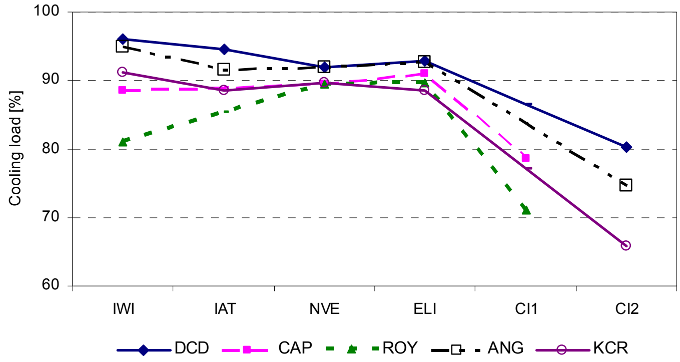

Fig.64: Simulated cooling loads (in percentage of the respective base cases) for all buildings and for selected scenarios

Table 11: Simulated cooling loads (in percentage of the respective base cases) for all buildings and for combined improvement (CI1 and CI2) scenarios

	Base case cooling load (%)	Total cooling load (%)	Reduction (%)
CAP	100	78.5	21.5
KCR	100	65.8	34.2
ANG	100	74.7	25.3
ROY	100	71.1	28.9
DCD	100	80.3	19.7

3.5 Passive scenario results

The aim was to investigate alternatives leading to reductions in indoor temperature when the buildings function without the air-conditioners. Here, the mean overheating was the main performance indicator (see Eq. 2). The mean indoor air temperature at hour "j" (averaged over all simulated office zones in the floor) was subtracted from the reference neutrality temperature (see Table 5) for overheating and divided by the total number of occupied office hours. Only cases where the indoor temperature was higher than the reference temperature were considered.

The design alternatives simulated were based on high mass (no carpet), improved windows, efficient lighting and different ventilation rates (see Tables 3 and 4, Fig. 65 - 69).

For further results on other simulated alternatives and psychrometric chart plots, see Appendix D.

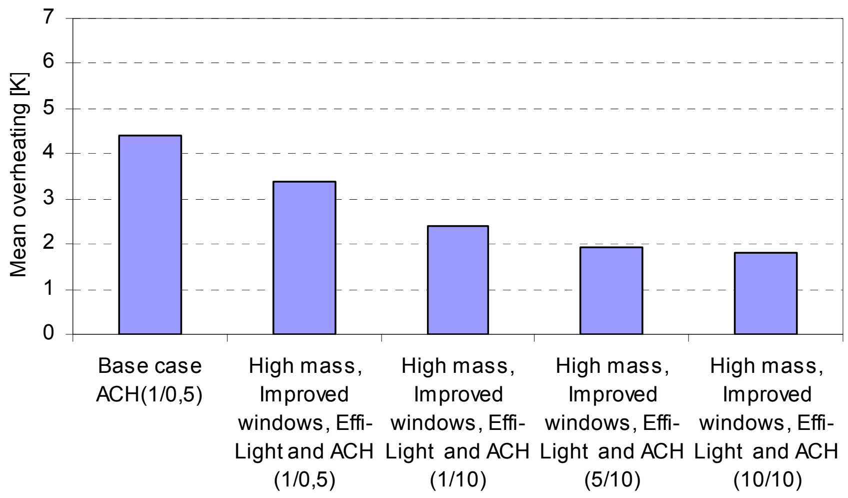

Fig.65: Simulated mean overheating (CAP) for different scenarios

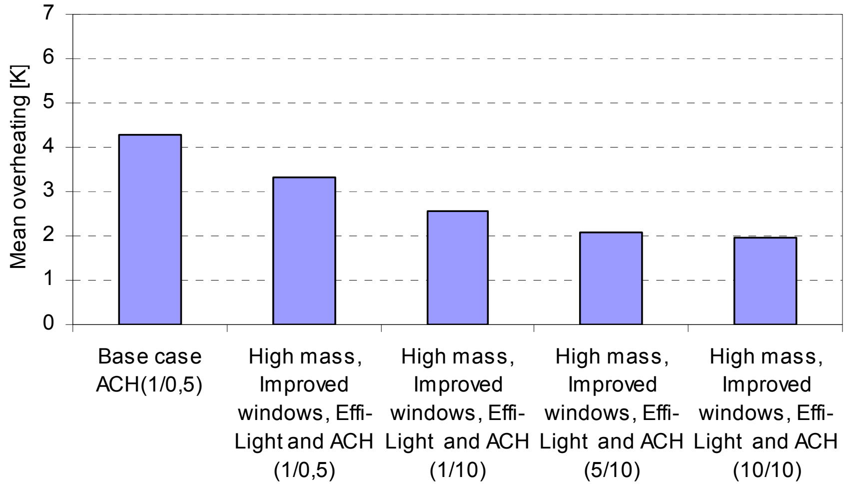

Fig.66: Simulated mean overheating (KCR) for different scenarios

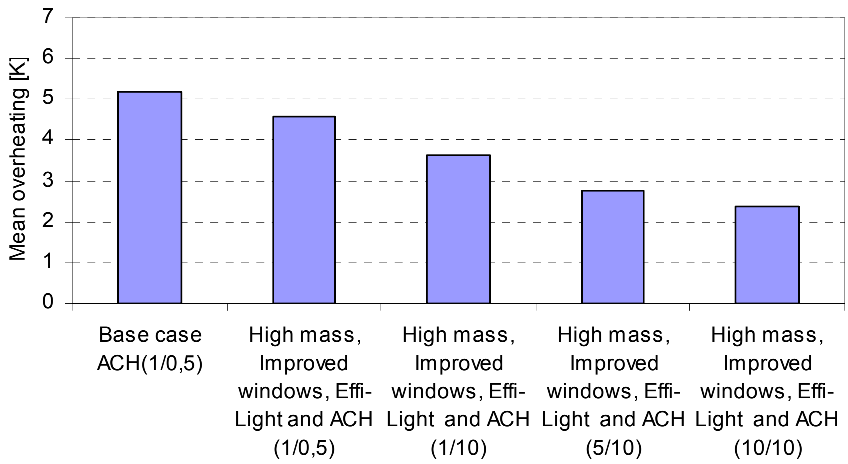

Fig.67: Simulated mean overheating (ANG) for different scenarios

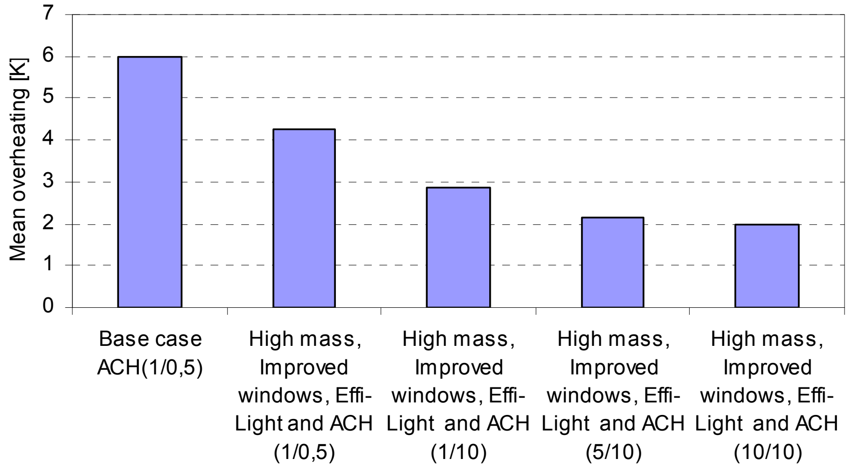

Fig.68: Simulated mean overheating (ROY) for different scenarios

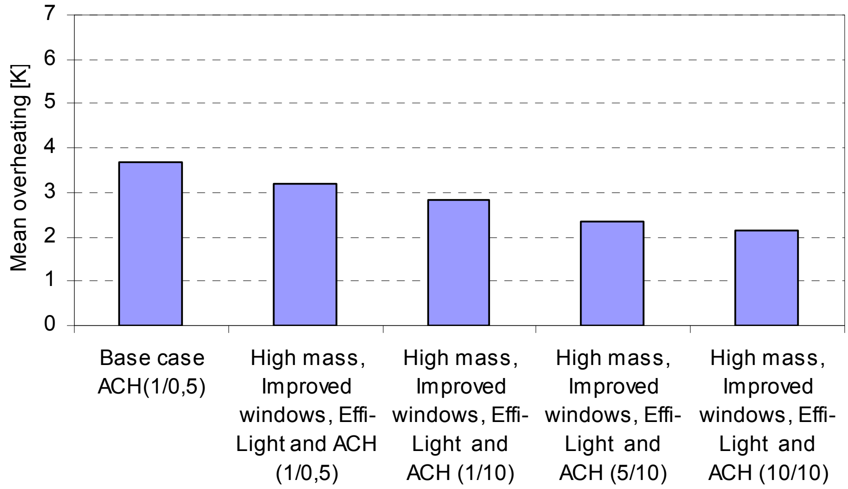

Fig.69: Simulated mean overheating (DCD) for different scenarios

The above results were further analysed using the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) method after Fanger (1973). A clothing value (CLO) of 0.7, MET of 1 and air velocities of 0.07 to 0.21m.s^{-1} were used as input values in addition to the indoor temperature and relative humidity values. The work of Pröglhof was used to convert the ACH to air velocities (see Eq. 6). Table 12 summarizes the results on the above. Table 13 shows the PMV scale after Fanger.

$$\mathbf{V = (ACH + 3.43)/63.1} \qquad \textbf{Eq. 6}$$

Where V is air velocity and ACH is the air change rate;

(r^2 = 0,96 for cross ventilated spaces).

Table 12: Mean monthly hourly PMV and PPD for all the buildings (based on simulated data from 8 am to 5 pm)

	Base case ACH(1/0,5)		High mass, Improved windows, Effi-Light and ACH (1/0,5)		High mass, Improved windows, Effi-Light and ACH (1/10)		High mass, Improved windows, Effi-Light and ACH (5/10)		High mass, Improved windows, Effi-Light and ACH (10/10)	
	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD	PMV	PPD
CAP	2.81	93.49	2.5	88.31	2.16	78.60	1.82	65.04	1.59	55.52
KCR	2.77	91.63	2.45	85.73	2.15	77.22	1.82	64.26	1.57	54.47
ANG	3.05	95.03	2.85	92.73	2.54	87.22	2.15	75.52	1.84	64.29
ROY	3.28	97.08	2.76	92.35	2.31	82.60	1.88	66.87	1.62	56.33
DCD	2.55	87.51	2.39	83.85	2.23	79.19	1.92	67.89	1.67	58.21

Table 13: PMV scale

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Subsequently, the indoor temperatures and relative humidity values were plotted on psychrometric charts. Given the high relative humidity values, an extension of the comfort zone on the psychrometric chart was considered (see Szokolay 2004). Apparently, the cooling effect of air movement ($0.5 m.s^{-1}$ - $1.5 m.s^{-1}$), resulting in physiological cooling, could increase the number of working hours in the comfort zone. Table 14 summarizes the results on the above.

Table 14: Percentage of hours in the comfort zone (PHCZ) with respect to the different air velocities (based on simulated data from 8 am to 5 pm).

CAP	Base case ACH(1/0,5)	High mass, Improved windows, Effi-Light and ACH (1/0.5)	High mass, Improved windows, Effi-Light and ACH (1/10)	High mass, Improved windows, Effi-Light and ACH (5/10)	High mass, Improved windows, Effi-Light and ACH (10/10)
PHCZ_0.5 $m.s^{-1}$	3.33	6.67	18.33	31.67	42.50
PHCZ_1.0 $m.s^{-1}$	25.00	40.83	63.33	73.33	**76.67**
PHCZ_1.5 $m.s^{-1}$	55.00	71.67	94.17	96.67	98.33
KCR					
PHCZ_0.5 $m.s^{-1}$	4.17	11.67	21.67	31.67	41.67
PHCZ_1.0 $m.s^{-1}$	30.0	45.83	64.17	70.83	**73.33**
PHCZ_1.5 $m.s^{-1}$	55.00	69.17	89.17	96.67	95.00
ANG					
PHCZ_0.5 $m.s^{-1}$	1.67	4.17	10.00	20.00	28.33
PHCZ_1.0 $m.s^{-1}$	20.00	25.00	42.50	60.00	**65.00**
PHCZ_1.5 $m.s^{-1}$	43.33	50.00	66.67	79.17	90.83
ROY					
PHCZ_0.5 $m.s^{-1}$	0.83	3.33	14.17	30.00	47.50
PHCZ_1.0 $m.s^{-1}$	11.67	32.50	54.17	67.50	**71.67**
PHCZ_1.5 $m.s^{-1}$	34.17	54.17	80.00	94.17	96.67
DCD					
PHCZ_0.5 $m.s^{-1}$	10.00	12.50	17.50	28.33	40.00
PHCZ_1.0 $m.s^{-1}$	42.50	50.00	57.50	66.67	**68.33**
PHCZ_1.5 $m.s^{-1}$	66.67	72.50	79.17	91.67	96.67

3.6 Interview results

The results of the interviews conducted are presented in (Fig. 70 - 111). For details on the questionnaire see Appendix B. The outcome of the questionnaire has been grouped into six sub-headings:

(i) Indoor Environment, thermal and visual comfort
(ii) Operation and accessibility of building systems
(iii) Awareness on the functionality of building control systems
(iv) Implications of user control actions on energy performance
(v) User preferences of workspace organization
(vi) Needs and health complaints

3.6.1 Indoor environment, thermal and visual comfort results

The results on the questions pertaining to indoor environment, thermal and visual comfort from the occupants in all the buildings are presented. Twenty four occupants from CAP and ten each from the remaining case study buildings answered a set of questions.

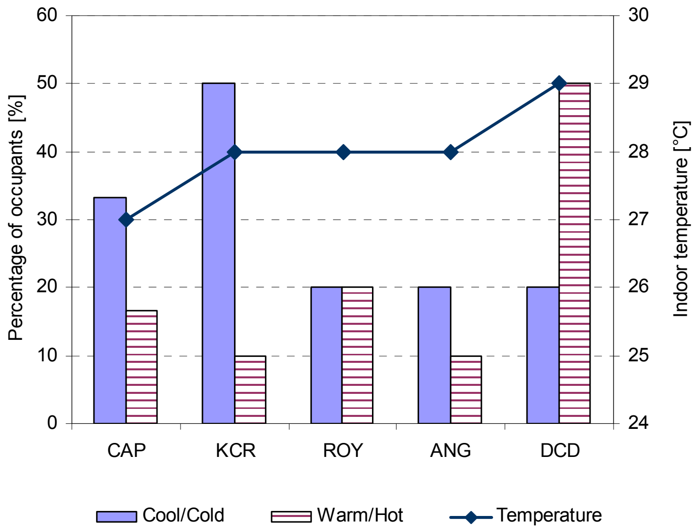

Fig. 70: Percentage of occupants who find their offices cool/cold or warm/hot and the three-month mean working time indoor temperature during the dry season

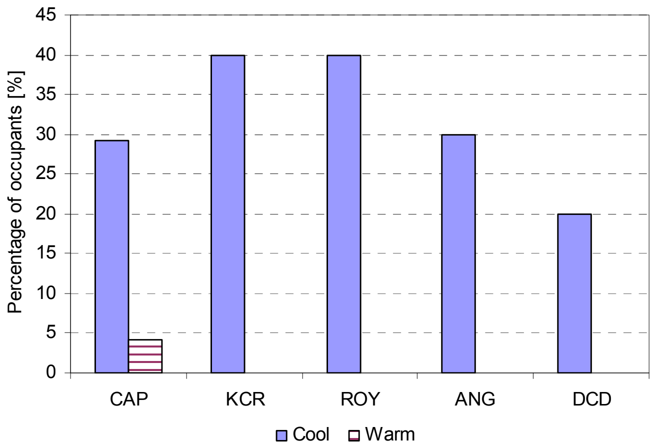

Fig. 71: Percentage of occupants who prefer to feel cool or warm during the dry season

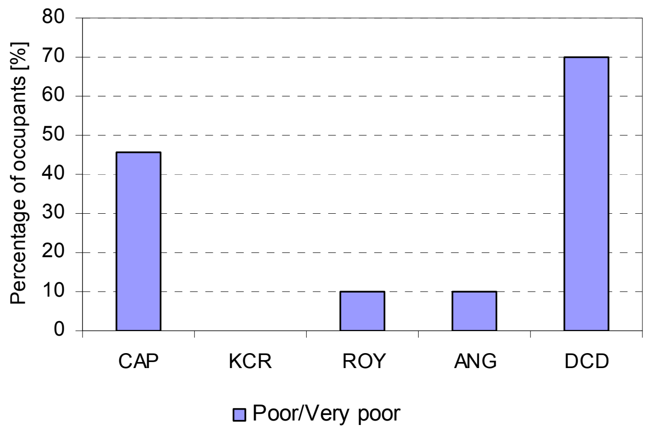

Fig. 72: Percentage of occupants who have a general feeling that the air quality was "poor/very poor" during the dry season

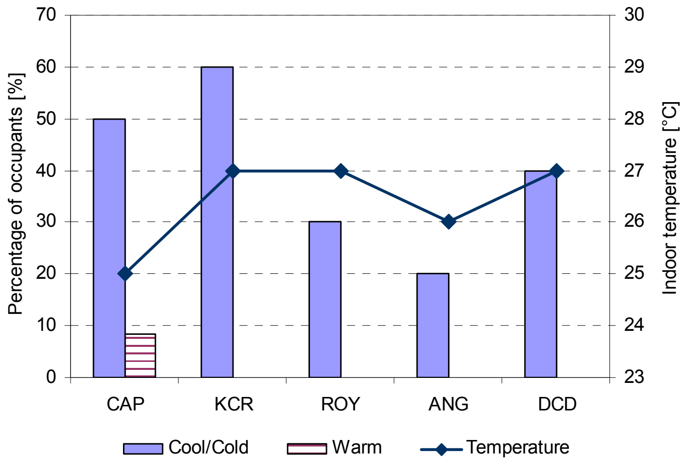

Fig. 73: Percentage of occupants who find the offices cool/cold or warm and the three-month mean working time indoor temperature during the rainy season

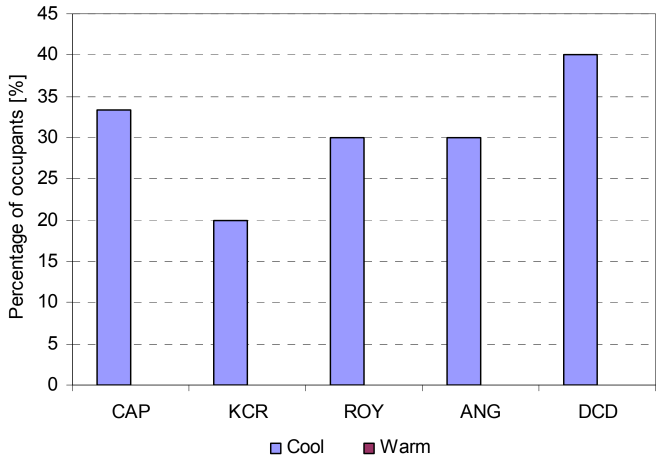

Fig. 74: Percentage of occupants who prefer to feel cool or warm during the rainy season

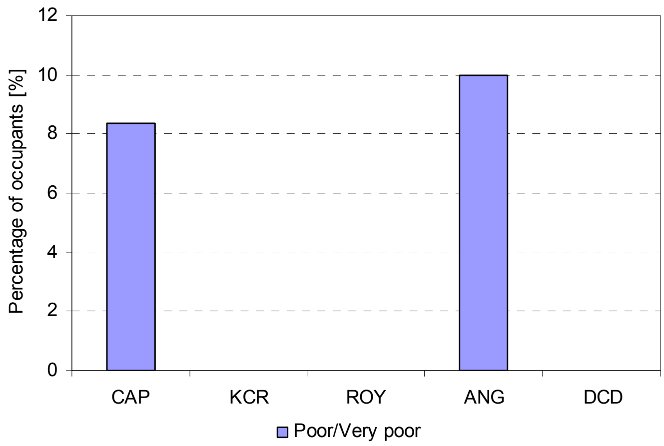

Fig. 75: Percentage of occupants who have a general feeling that the air quality was "poor/very poor" during the rainy season

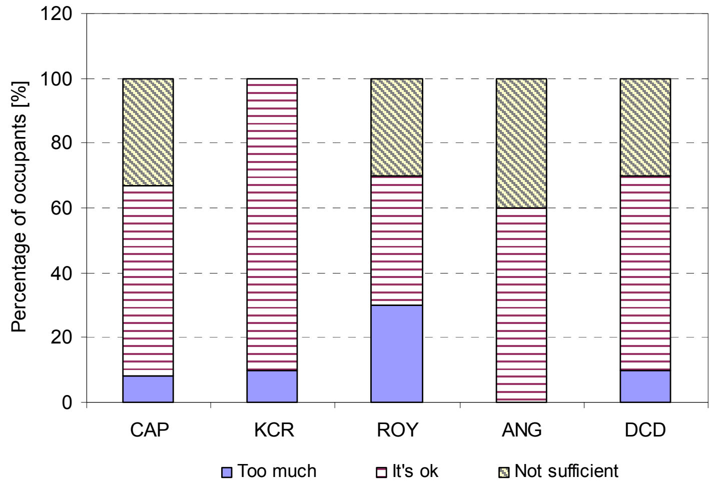

Fig. 76: Percentage of occupants' opinion on daylight sufficiency

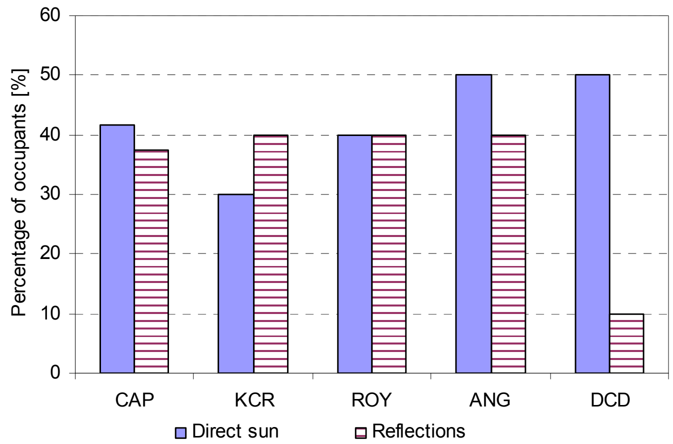

Fig. 77: Annoyance due to direct incident sunlight and light reflections off computer screens

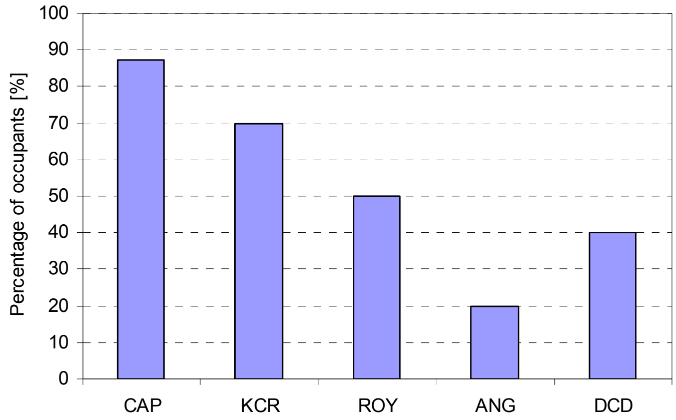

Fig. 78: Percentage of occupants who think that plants have positive effects on indoor climate

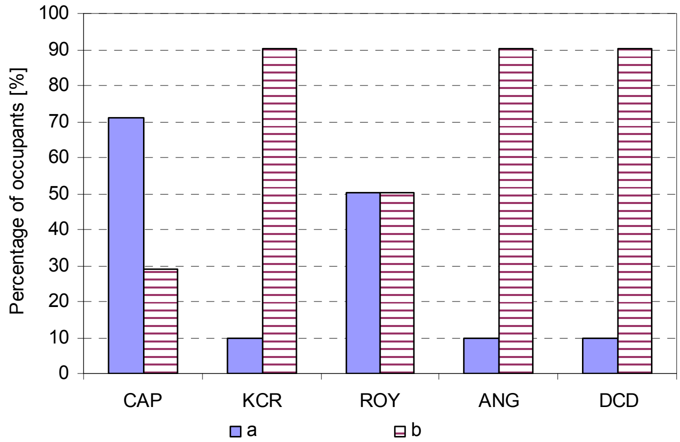

Fig. 79: Percentage of occupants who wish to work in (a) a naturally ventilated building and (b) an air-conditioned office environment

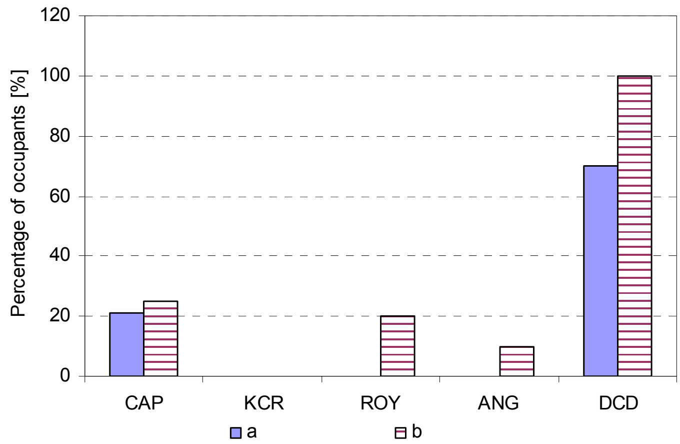

Fig. 80: Percentage of occupants who generally feel negative about their office environment (a) at the beginning of the interview and (b) at the end of the interview

3.6.2 Results on operation and accessibility of building systems

The main goal on the operation and accessibility of building systems was to find out the modalities of operation, difficulty involved, and satisfaction with the available building systems.

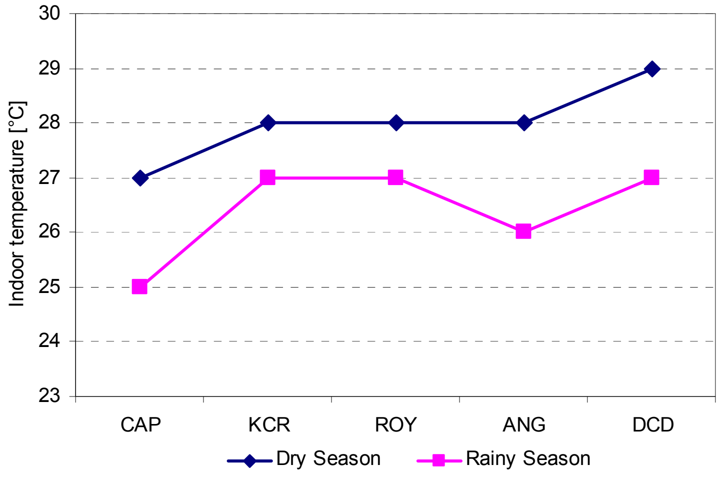

Fig.81: Three-month mean working time indoor temperature during the dry and rainy season

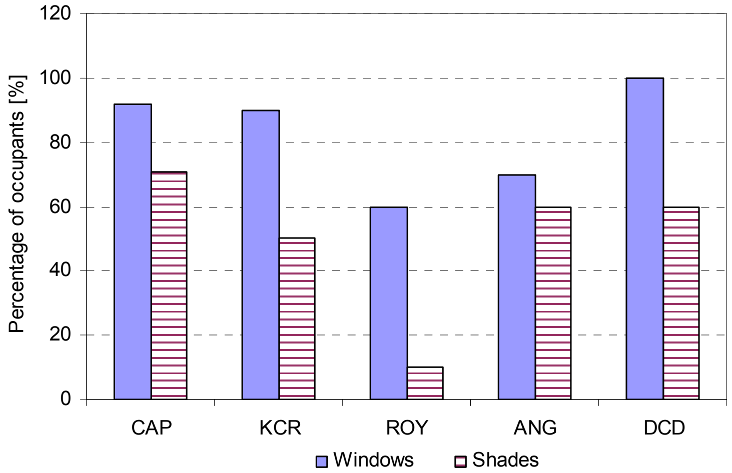

Fig.82: Percentage of occupants to whom the operation of windows and shades were important

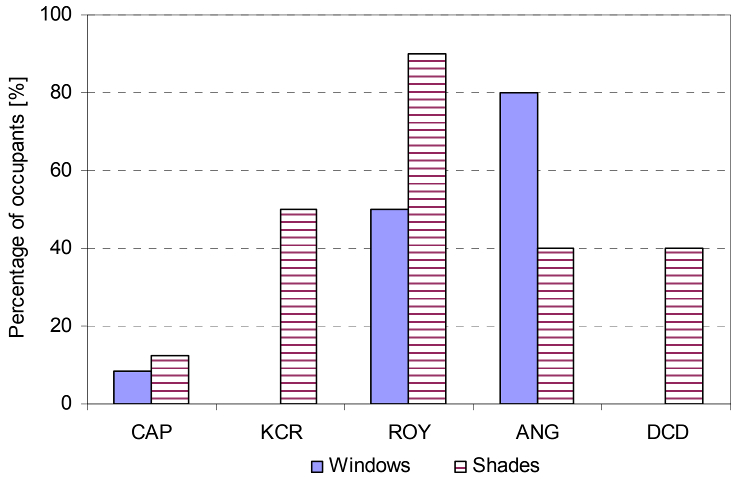

Fig.83: Percentage of occupants who had difficulty in the operation of windows and shades

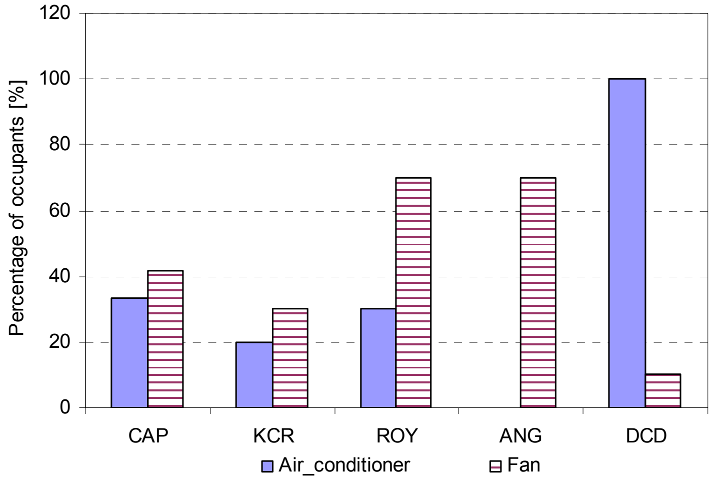

Fig.84: Percentage of occupants who were not satisfied with the availability and/or position of the air-conditioner and fan to workspace

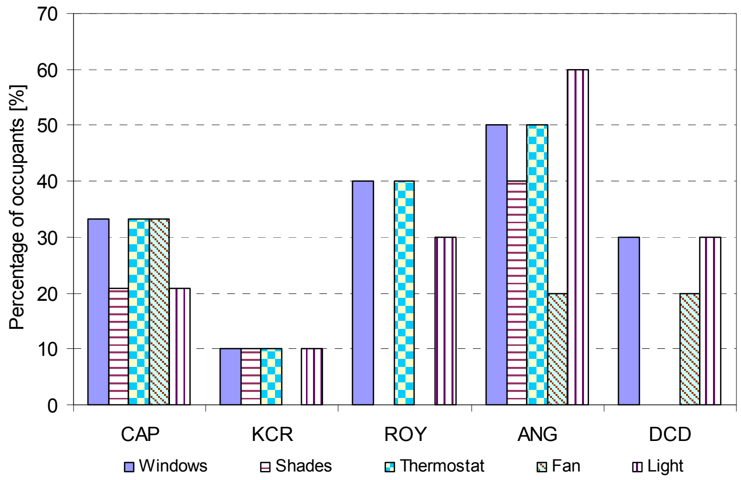

Fig.85: Percentage of occupants who had to negotiate with colleagues before operating building systems

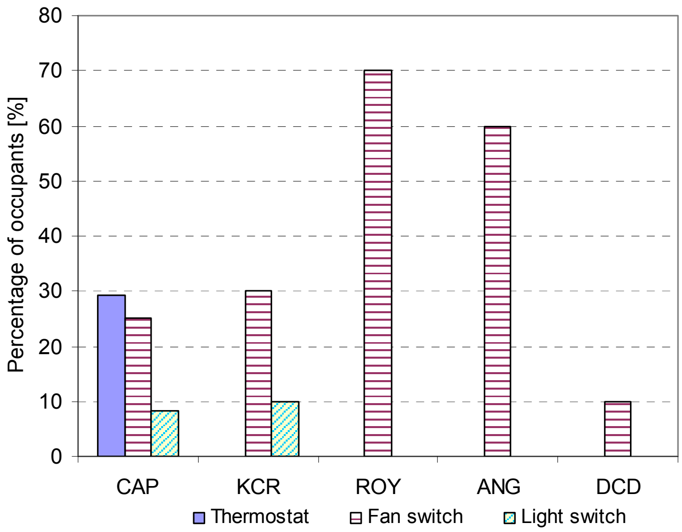

Fig.86: Percentage of occupants to whom building systems were not easily accessible

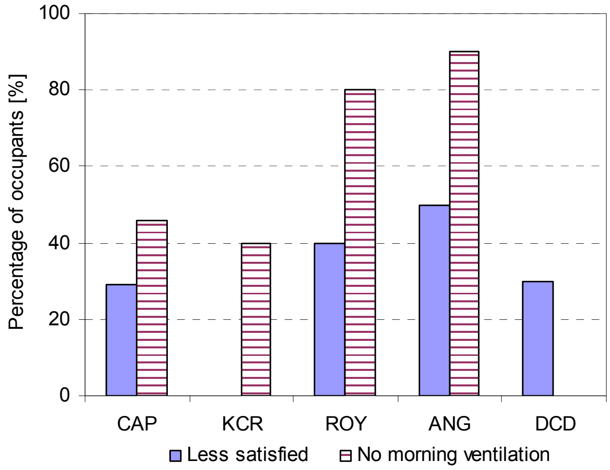

Fig.87: Percentage of occupants who were less satisfied with the possibility to ventilate and rarely/never had a morning flush before using the air-conditioner in their offices

3.6.3 Results on awareness on the functionality of building control systems

The possible reason of poor indoor climate could be that occupants are not sufficiently informed and trained on the functionality of building control systems. This section illustrates the outcome of the interview.

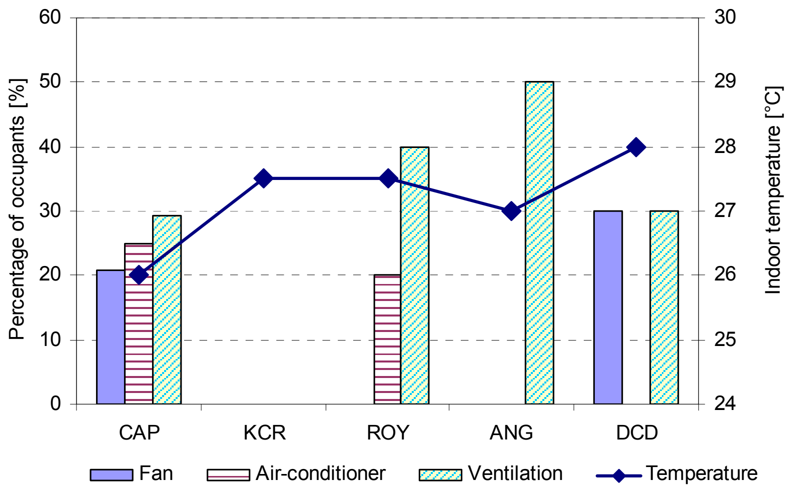

Fig.88: Percentage of occupants who were dissatisfied with building control systems and mean yearly indoor temperature of the buildings

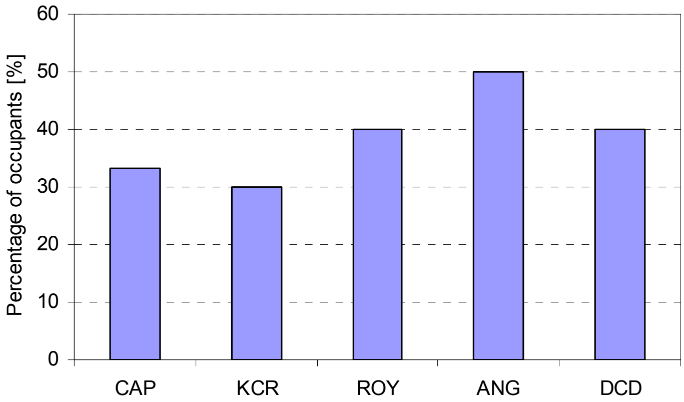

Fig.89: Percentage of occupants who were insufficiently informed about how ventilation worked in their offices

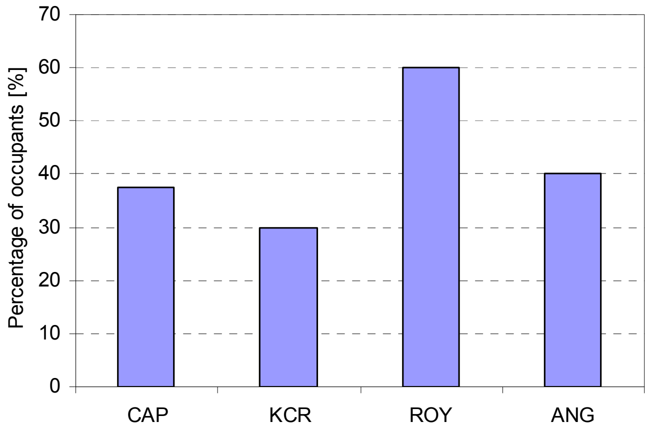

Fig.90: Percentage of occupants who were insufficiently informed about how air-conditioning worked in their offices

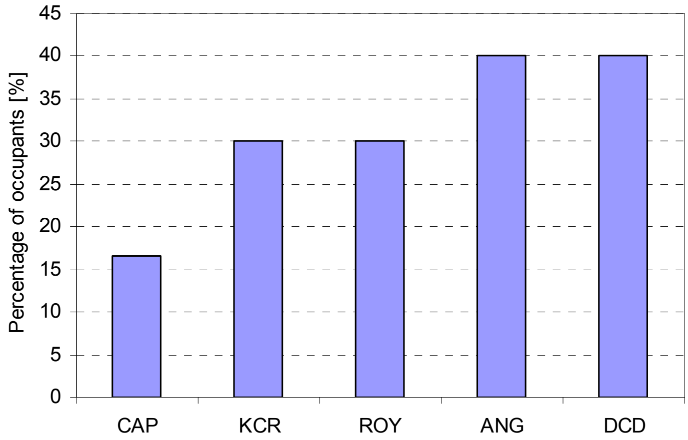

Fig.91: Percentage of occupants who were insufficiently informed about how lighting worked in their offices

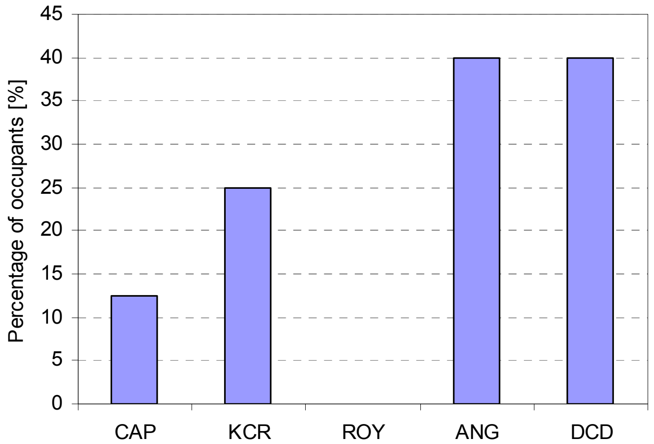

Fig.92: Percentage of occupants who were insufficiently informed about how blind protection worked in their offices

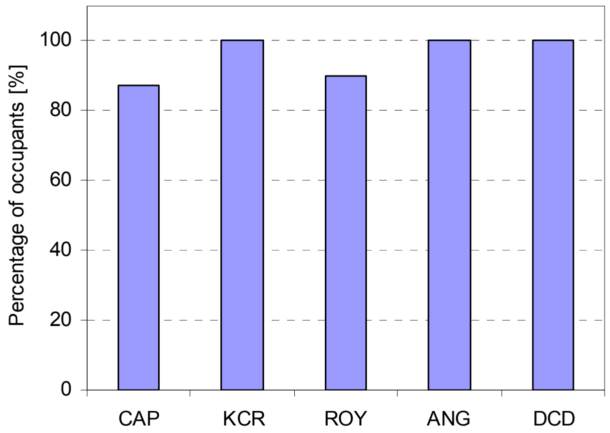

Fig.93: Percentage of occupants who had never had training in building systems

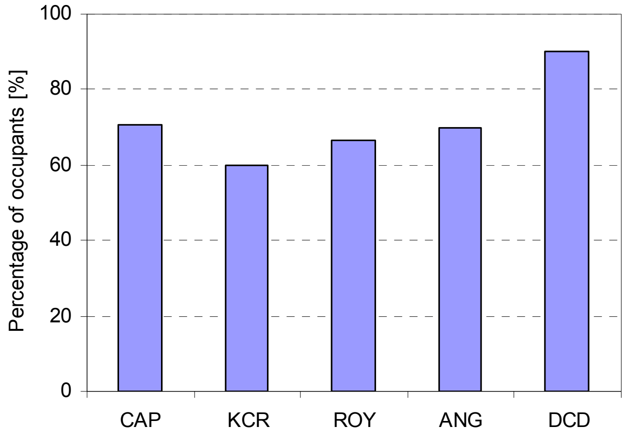

Fig.94: Percentage of occupants who were interested in receiving training in building systems

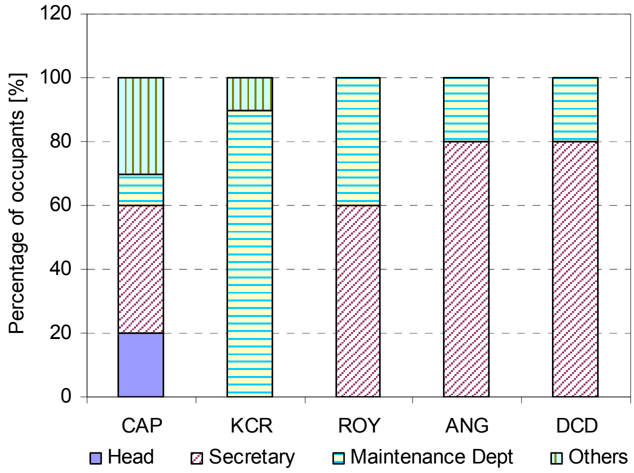

Fig.95: Percentage of occupants and reference point in case of problems with building systems

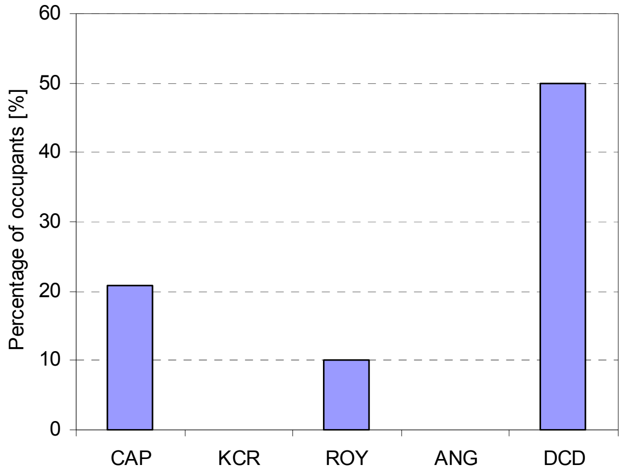

Fig.96: Percentage of occupants who were dissatisfied with system services and support in their offices

3.6.4 Results on energy implications of user control actions

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

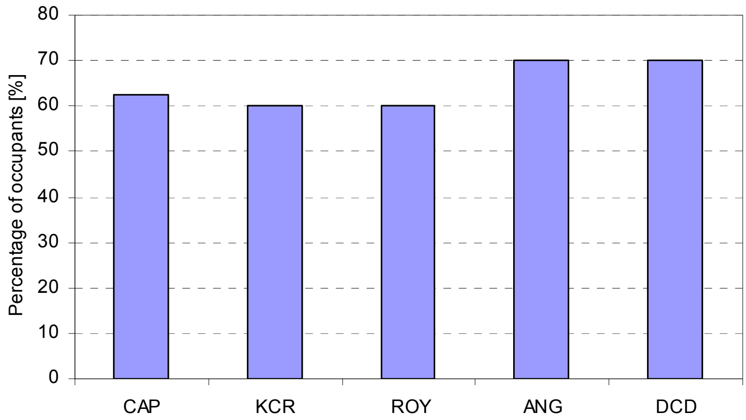

Fig.97: Percentage of occupants who believed that control actions influenced building energy consumption

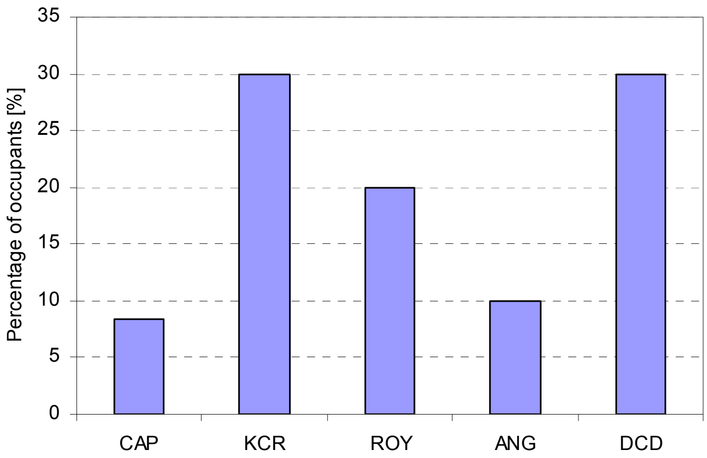

Fig.98: Percentage of occupants who did not consider energy conservation when operating building systems

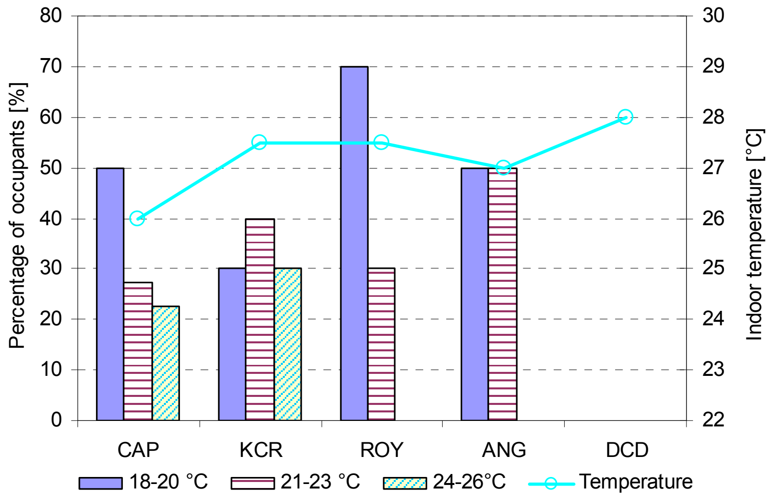

Fig.99: Percentage of occupants, their thermostat settings and mean yearly indoor temperatures

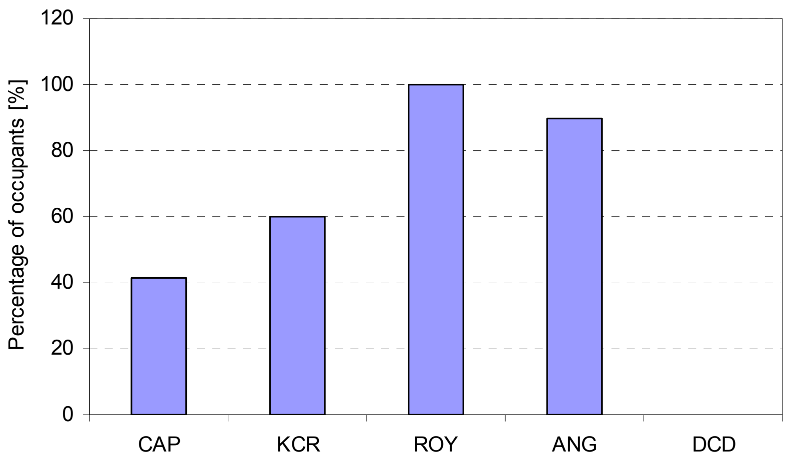

Fig.100: Percentage of occupants who generally left the air-conditioners on during short absences from the office

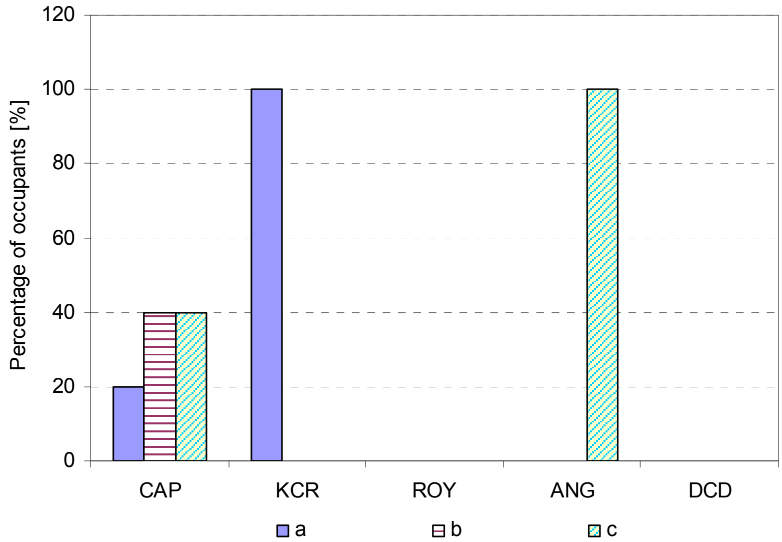

Fig.101: Percentage of occupants who would switch off the air-conditioner (a) less than one hour (b) between one and two hours and (c) above two hours, when absent from the office

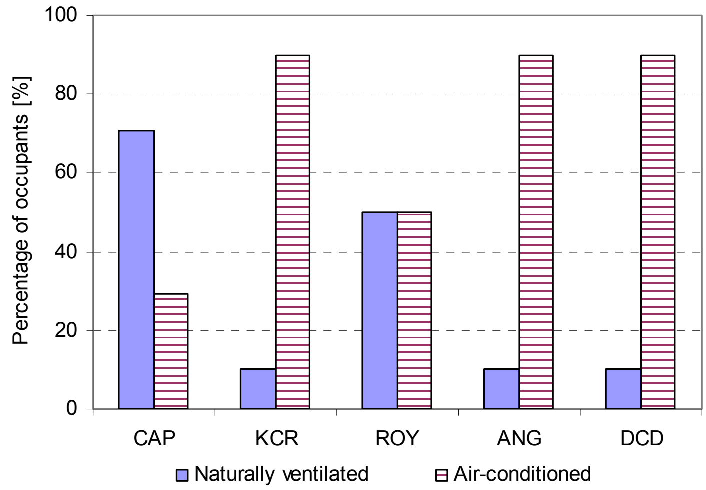

Fig.102: Percentage of occupants and their preference for office environment

3.6.5 User preferences results

Mostly, the wishes of building occupants are neglected or not considered by facility managers and designers. Ultimately, occupants becomes dissatisfied with their working environment. The results presented show features considered most important for building occupants.

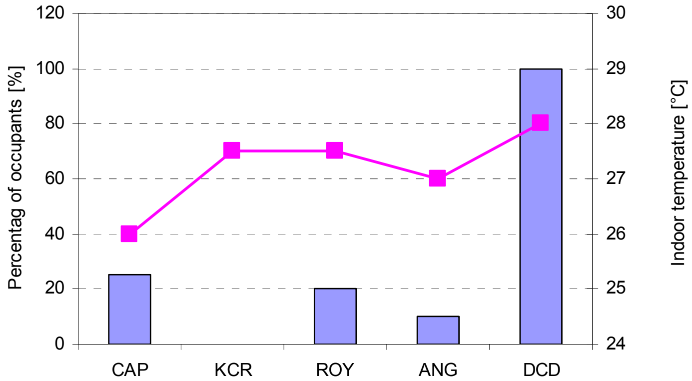

Fig.103: Percentage of occupants who generally found their office climate poor and the mean yearly indoor temperature

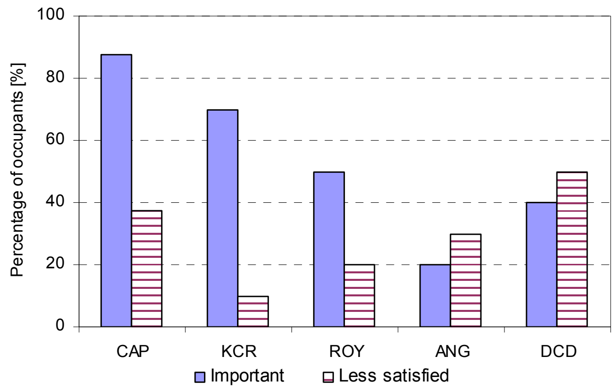

Fig.104: Percentage of occupants to whom the effects of plants on indoor climate were important and those who were less satisfied with available possibilities of workspace personalisation (plants, photos, furniture, etc.)

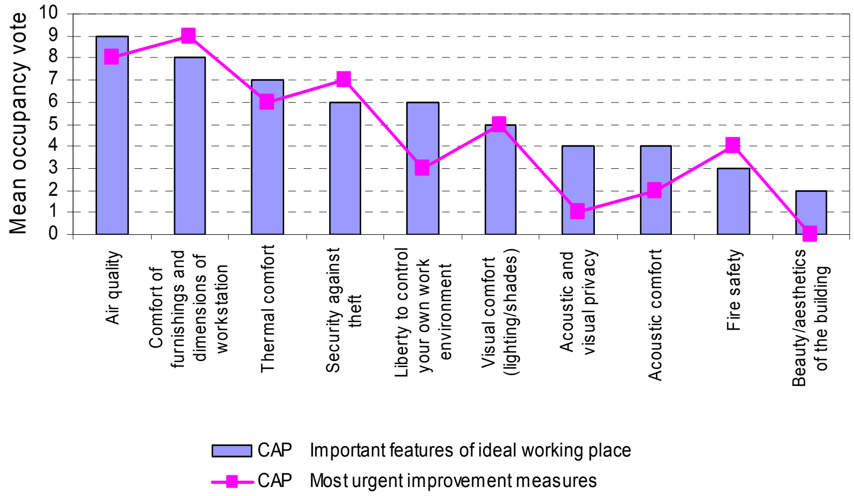

Fig.105: Rank on features of ideal working place and improvement measures considered urgent, with vote 10 being the most important feature/measure

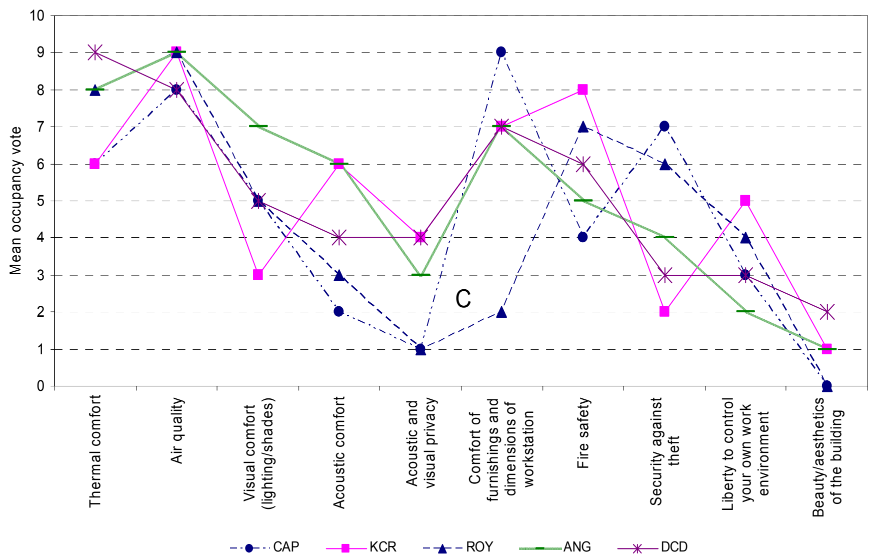

Fig.106: Ranking on improvement measures considered most urgent in all the buildings, with vote 10 being the most important measure

3.6.6 Needs and complaints results

The negative effects of poor indoor environment on health are widely known. The main aim of this section of the interview was to trace possible health problems to inefficient building systems. The illustrated results show health complaint levels in the various buildings.

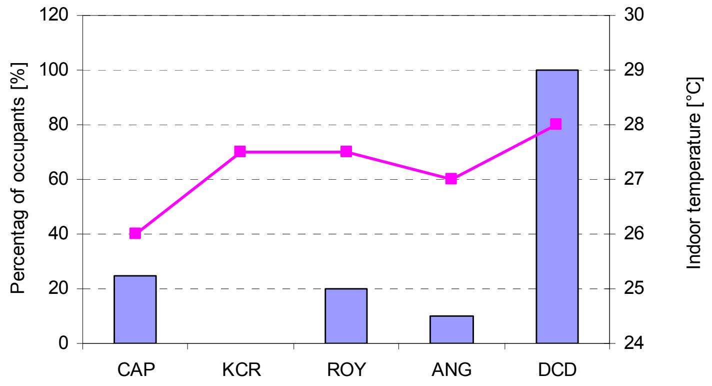

Fig.107: Percentage of occupants who generally found their office climate poor and the mean yearly indoor temperatures

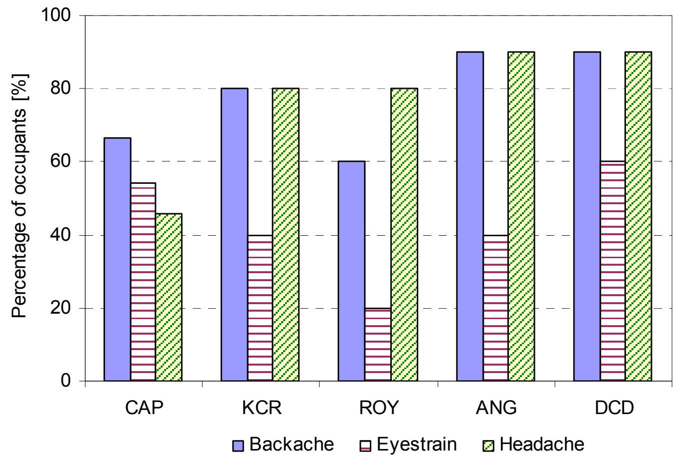

Fig.108: Percentage of occupants who had backache, eyestrain and headache as health complaints

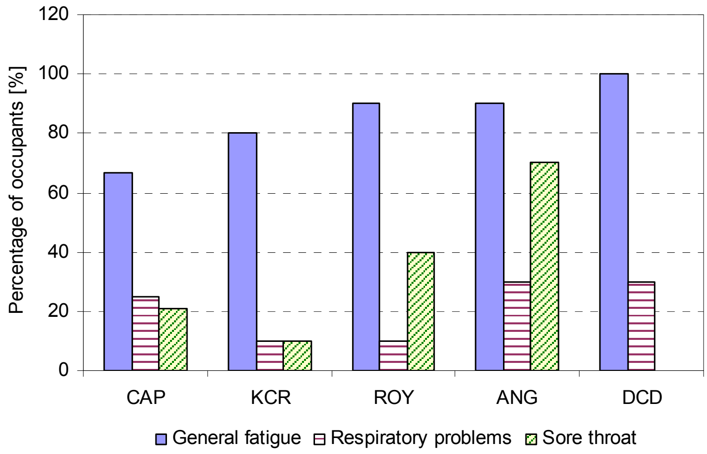

Fig.109: Percentage of occupants who had general fatigue, respiratory problems and sore throat as health complaints

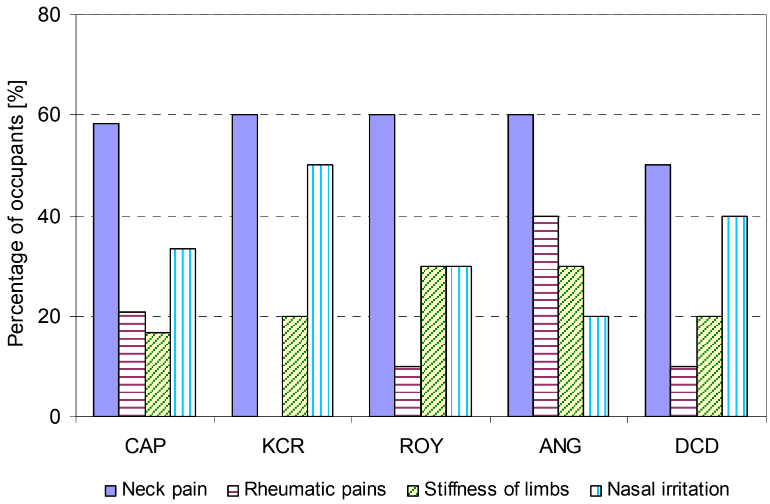

Fig.110: Percentage of occupants who had neck pain, rheumatic pains, stiffness of limbs and nasal irritation as health complaints

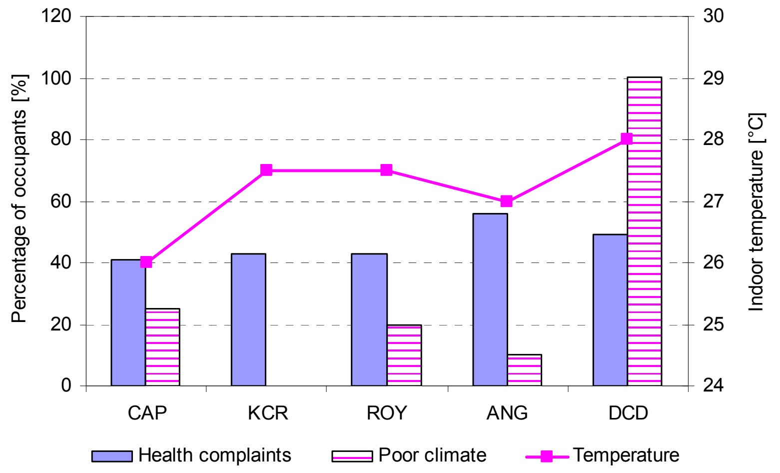

Fig.111: Percentage of occupants who had diverse health complaints, perception of poor office climate and mean indoor temperature of the workspaces

4 DISCUSSION

4.1 Overview

The discussion in this section follows the order of the groupings on the summary results. These are the calibration results, psychrometric analysis, active case scenario, passive case scenario and results of the interviews.

4.2 Calibration results

4.2.1 Measured external air temperature values

The comparison of our outdoor temperature measurements "DL" (averaged over the office locations) with an average temperature "MET" obtained as the mean of maximum and minimum temperatures recorded by the Kumasi's weather station (Fig 32) showed a good agreement between our measurements and those from Kumasi's official weather station. Therefore, the basis of using the data from the loggers is justified, even though slight differences of about 0.5°C were visible in the months of January, February, July and August.

4.2.2 Weather file versus measured data

As mentioned earlier, simulation model calibration was performed using segments of a standard weather file with a good match to our local measurements. To illustrate this point,

Fig. 34 to 38 show samples of time intervals where the weather file data (WF) and our measurements at building sites (DL) showed a relatively good agreement. Consequently, the generated weather file could be used to support the analysis.

4.2.3 Comparison of measurements and simulation values

Predictions of the calibrated simulation models compared well with the measured values. To illustrate this, Fig. 39 to 43 provide measured versus simulated indoor air temperatures.

4.3 Psychrometric analysis

The mean hourly temperature and relative humidity values in Kumasi for representative days in the months of February and August are shown in Fig. 29. During the warmest period (dry season), mean temperature levels are high, and in some cases exceeding 30°C. However, the mean temperature levels hardly exceed 28°C during the rainy season, especially in the months of June, July and August. The relative humidity values are rather high, averagely 80%, and the effect is a feeling of discomfort. This is a characteristic of warm and humid countries, where temperature and relative humidity values are high, solar radiation is intense and cloudy conditions exist most of the time.

The indoor air temperature values (mean monthly hourly maximums, minimums and hourly means, during the working hours) recorded have been plotted on psychrometric charts to analyse the thermal conditions existing in the office spaces in relation to the comfort zone (Fig. 44 – 58).

4.3.1 CAP building

The mean monthly hourly maximum temperature and relative humidity values of the offices in CAP, based on measurements from 8am to 5pm indicate that with the exception of the months of January and February, all months were above the comfort zone (Fig. 44). The average relative humidity decreased from the outdoor value of 80% to 70%. The temperature values measured were below 28°C. However, the high humidity levels resulted in most of the months being outside the comfort zone.

In Fig. 45, the mean monthly hourly temperature values measured resulted in only the month of January being comfortable. The month of February is only slightly above the comfort zone. The mean relative humidity is around the 70% mark.

The mean monthly hourly minimum temperature and relative humidity also resulted in the month of January being in the comfort zone. The mean temperature values were around the 25°C mark but the corresponding humidity levels were relatively high (Fig. 46).

This evaluation results from the effects of the occupants on building systems, the efficiency of the systems in relation to the outdoor environmental conditions. In average, the temperature values were below 28°C and this means that most of the occupants could still consider their indoor climate to be comfortable. The high humidity levels might not be a serious problem due to adaptive capabilities. To evaluate the office spaces on the measured temperatures alone would score the building as a comfortable working environment. The effects of humidity on occupants in the climatic context of Kumasi need to be investigated further.

4.3.2 KCR building

The mean monthly hourly maximum temperature and relative humidity values in KCR resulted in the months of January and February being in the comfort zone, even though the month of February is on the border line of the comfort zone (Fig. 47). The mean relative humidity values of the months outside the comfort zone decreased to about 58% when compared to the CAP building. The recorded maximum temperature value was around 30°C. The discrepancies could be as a result of the efficiency of the air-conditioners and the different room sizes.

In Fig. 48, the mean monthly hourly temperature and relative humidity values are represented. Comfortable months are January and February. The maximum temperature value was around 29°C and a mean relative humidity level of 60% was recorded.

The mean monthly hourly minimum temperature and relative humidity values resulted only in January being in the comfort zone. The mean temperature values were around the 27°C mark with the relative humidity value at 65%.

The rather poor performance of this building as opposed to CAP could be due to the building form and orientation. CAP is a rectangular block without windows on the east and western sides unlike the L-shaped building of KCR. The behaviour of occupants and building system efficiency are also factors that could lead to thermal comfort problems in workspaces.

4.3.3 ANG building

At ANG, the mean monthly hourly maximum temperature and relative humidity values resulted in almost all the months being in the comfort zone (Fig. 50). The month of August was just above the comfort zone. The mean maximum temperature value was about 30°C, but the relatively lower humidity levels of around 50% resulted in the months being in the comfort zone.

The mean monthly hourly temperature and relative humidity values (Fig. 51), caused five months to be outside the comfort zone. The mean temperature values were between 24 and 28°C. An increase in the humidity levels resulted in this representation.

Even though the mean monthly hourly minimum temperature values in the offices were low (averagely 25°C), the relatively high humidity levels caused all the months with the exception of January to be uncomfortable (Fig. 52).

Possible reasons leading to this performance are the windowless offices (65% of the offices), orientation of the building, the relatively small sizes of the offices as compared to the other buildings, the efficiency of the air-conditioners and lastly the behaviour of the occupants.

4.3.4 ROY building

High mean temperature values were measured in the curtain wall building of ROY; a maximum value of 30°C in February, March and April (Fig. 53). Unlike January, the months of February, October and September were on the border of the comfort zone. Comparatively, the maximum temperature values were higher in ROY than in the buildings discussed above.

The effect of the mean monthly hourly temperature and relative humidity levels (Fig. 54), resulted in the reduction of the air temperature to a mean value of 28°C. The mean relative humidity value was about 58%.

The situation at the hourly minimum values (Fig. 55) is similar to the behaviour in the other buildings. The humidity levels were high resulting in all the months (January on the border line) being outside the comfort zone.

The performance of the ROY building could be caused by the relatively high amount of glass on the façade and the effects of direct and reflected solar radiation. There are no shading devices on three sides of the monitored spaces and this worsens the situation when inefficient glass and building systems are employed.

4.3.5 DCD building

From Fig. 56, the naturally ventilated building of DCD could be said to be uncomfortable. The mean maximum temperature value recorded (32°C) is higher than in all the other buildings. An average mean temperature value of 30°C was computed. However, the mean humidity level is about 60%. This could be due to the effect of ventilation, reducing the humidity levels more than the air-conditioned buildings.

The mean monthly hourly values of temperature and relative humidity could justify the month of January as being comfortable (Fig. 57). The highest mean temperature value was 30°C and the lowest 26°C. The mean relative humidity level was approximately 70%.

The mean hourly minimum values did not deviate much from the above (see Fig. 58) and only the month of January was comfortable.

The performance of this building could be due to the lack of efficient or even non-existence of some building systems such as fans. The office spaces were badly arranged and therefore, cross ventilation was impossible. The attitude of occupants in the operation of shades is also a factor, since curtain shades remained drawn even in the absence of annoyance by solar radiation, resulting in a reduction of air speed.

Generally, the environment in all the buildings was uncomfortable, since most of the months were represented outside the comfort zone. The reasons are manifold and some could have to do with the behaviour of occupants (see Mahdavi *et al.* 2007). It has been found that occupants generally tend to switch on lights upon arrival in the office and to switch them off at the close of work, leading to high thermal loads (Hunts 1979, Love 1998 and Pigg *et al.* 1996). Shading devices on the southern side of the building are left closed or partly open till close of work (Inoue *et al.* 1988). The behaviour of occupants in relation to energy performance has been found to be favourable if occupants are trained and energy conscious in dealing with efficient and flexible building systems (see Mohammadi 2007, Lambeva 2007 and Mokamelkhah 2007). Sustainable design principles should be followed in a consequent manner, to produce a favourable indoor climate, comfort and satisfaction (Lechner 2001 and Salmon 1999). The use of fans has been found to help in the evaporative potential of the skin and should be a priority in all office buildings, especially in naturally ventilated types, since their effect is a thermal sensational reduction of air temperature values of 2 – 3°C (Hyde 2000).

The impression gained from the measurements, and the plots on the psychrometric charts as opposed to the observation of the occupants seem to justify the assumption that occupants are adapted to high humidity levels and therefore found maximum humidity levels of 80 – 85% to be tolerable, if temperature values did not exceed 29°C. This would call for an in-depth study of the comfort scale for the climatic context of Kumasi, Ghana.

4.4 Active scenario

The results of the parametric simulation, in this case the active scenario, are discussed (Fig. 59 – 64). They contain the base case simulation results and tested improvement measures (see Tables 3 and 4). These are discussed from building to building.

4.4.1 CAP building

The simulated annual cooling load (sensible and latent) for the base case (BC1, Table 3) was 149 $KWh.m^{-2}.a^{-1}$ (see Fig. 59, Table 6). The building is a rectangular block, oriented towards the north-south and shaded by verandas on the elongated sides.

The probed alternative of improving the wall quality through the addition of 10cm insulation resulted in an insignificantly reduced cooling load of 0.2%. This could be due to the walls already well shaded by the veranda, providing protection from direct and reflected solar radiation.

By using a more efficient type of windows with a better shading coefficient (0.29), cooling loads reduced by 8.4%. The effect was that only 29% of radiation could be transmitted through the glass as compared to the 82% at the base case scenario.

Thermal mass was however insignificant. This was achieved by removing the carpet of the floors to expose the mass to thermal absorption gains. The result could be related to the less diurnal difference (5 - 8°C), which was too low to bring about a positive effect.

Night ventilation had a reduction effect of 7.7% as compared to the base case. However, when combined with thermal mass, no significant change was registered. The cooling effect was rapidly used up since the outcome was modest as a result of the diurnal difference stated above.

The use of efficient lighting reduced the loads by 6.6%. This was because the reductions in lighting gains had a positive effect on cooling loads.

All the improvements combined resulted in cooling load reductions of 21.5%. This result is significant and has been achieved through improved and efficient building elements, as well as sustainable design principles of orientation and shading.

4.4.2 KCR building

The base case load of the L-shaped building had a cooling load of 111.5 $KWh.m^{-2}.a^{-1}$ (Table 7). The improvement to the wall by adding insulation increased the loads by 1.3%, although a reduction of 0.2% was calculated at CAP (Fig. 60). This gives an indication of heat gained and generated within the building, retaining because of the better construction element.

A 6.6% reduction in loads was calculated by improving the windows. Efficient and shaded windows seem to contribute positively to reductions in cooling loads.

The attic floor was improved by adding 10cm of insulation and this resulted in 8.7% reductions in cooling load. Attic spaces are usually characterized by very high temperatures and insulation reduced the conductive heat gains into the working spaces, which resulted in less energy use.

The effect of thermal mass was insignificant; a reduction of only 0.2% was recorded. However, 7.7% reductions were recorded by making use of the night ventilation. A further reduction of 0.3% was recorded when night ventilation was used in combination with the thermal mass. Again, reasons of low diurnal change could have rendered this principle useless.

Approximately 8.7% reductions in cooling loads were calculated by reducing the lighting loads through the use of efficient lights.

All the combinations together produced a significant reduction of 34.2% in cooling loads. The comparatively high depth of the building block in combination with the form could also have contributed to these positive effects.

4.4.3 ANG building

A cooling load of 165.2 $KWh.m^{-2}.a^{-1}$ was simulated for the base case scenario at the ANG building (Fig. 61, Table 8). This rectangular form was on the second floor of the building block with the elongated sides oriented towards the west.

There was an increase of 2.6% in cooling loads when the walls were improved with insulation. Thermal mass and thermal mass in combination with night ventilation did not produce a significant change as compared to the effect of night ventilation alone.

However, positive effects could be simulated for the improvements in windows, attic insulation, night ventilation and efficient lighting.

All the simulated improvements resulted in a significant reduction of 25.3% cooling loads.

4.4.4 ROY building

The curtain wall building had an initial cooling load of 126.2 $KWh.m^{-2}.a^{-1}$. Adding insulation to the wall only increased the cooling loads by 4% (Fig. 62, Table 9). We can therefore conclude that the application of insulation to walls does not result in an improvement towards the reduction of cooling loads, as opposed to the recommendation by Lauber (2005).

As high as 14.1% reductions in cooling loads was simulated and this significant value was a result of the better shading coefficient of the glazing. Possibly, more reductions could have been simulated if there had been external shading on the façade, helping to reduce the direct, intense and reflected solar radiation. The energy penalty as against the almost 100% visual link to the external environment should be considered, especially at this stage of global uncertainties, both financially and on resources. Designing buildings with sealed windows and without reference to solar orientation, with high standards of comfort but without reference to operating costs, with the newest technology but without much sense of what tomorrow might bring must be reconsidered, as the non-sustainable use of resources poses a danger to humanity.

Thermal mass reduced cooling loads by 0.7%. All the other buildings recorded insignificant reductions of less than 1%.

Reductions of 7.9% were recorded by making use of night ventilation. Night ventilation in combination with thermal mass reduced the loads further by 2.5%. As much as 7.8% reductions was obtained from the use of efficient lighting.

A significant value of 28.9% was achieved when the improvements were combined.

4.4.5 DCD building

The rectangular block oriented towards the south east had an initial cooling load of 166.2 $KWh.m^{-2}.a^{-1}$. The alternative improvement of using insulation rather increased the cooling loads by 4.8% (Fig. 63, Table 10). Improved windows and attic insulation reduced the cooling loads by 3 and 4.2% respectively. There were few windows in the building and the effect was the relatively lower reduction in cooling loads.

Less than 1% reduction was achieved by the use of thermal mass whereas 6.1% could be obtained by using night ventilation. However, night ventilation in combination with thermal mass brought about an insignificant change in cooling load when compared to the effects of night ventilation alone. A reduction of 5.5% in cooling loads could be simulated by reducing the lighting gains through the use of efficient lights.

The total result from the positive combinations was a significant reduction of 19.7% in cooling loads.

Further reductions could have been achieved if attention had been given to sustainable design principles of form, orientation and shading. Designers are advised to make use of the positive effects of the natural environment, transform the environmental burden and use the building as the basis of its defence before the implementation of active control devices (Heerwagen 2004). According to Wagner *et al.* (1980), by orienting rectangular buildings with the right aspect ratio (1:2.5), 50% glassing and planting shaded tress all around, cooling loads of 30 and 25% could be saved respectively. The effect of uncontrolled ventilation or leakage through cracks in the building envelope also leads to increased cooling loads (Carmody 2007) and should therefore be avoided. Other recommendations are sun protection and thermal insulation of the building shell, which has to be windproof and airtight (Lauber 2005). However, thermal insulation does not help to reduce cooling loads in the climatic context of Kumasi, Ghana, as suggested by Lauber.

4.4.6 Summary on all buildings

The result obtained from the calibrated simulation models warrant certain conclusions:

- Improvement of the thermal insulation of the external walls did not generate a corresponding improvement in the energy performance of the buildings. This circumstance can occur in (and is known from) buildings that are cooling load dominated and are related to the heat retaining effect of better-insulated walls.
- The improvement of the thermal insulation of the attic space floors (in cases where such a space exists) does noticeably improve the thermal performance, due to the reduction of conductive heat flows from these typically overheated spaces.
- An increase in the buildings' thermal mass – as simulated via the virtual removal of the floor carpeting – did not noticeably reduce the buildings' cooling loads.
- Increased night-time natural ventilation improved the thermal performance of the buildings, albeit in a modest fashion. This is due to the rather small diurnal temperature range in Ghana: the night temperature does not drop low enough to effectively cool the building mass. The combination of higher thermal mass and

increased night-time ventilation was only insignificantly better than natural ventilation alone.

- A clear improvement was gained from the installation of better window products. This is mainly due to the better shading effectiveness of (and the commensurate reduction of the solar gains through) the alternative window constructions.
- Reducing the internal gains through the installation of more efficient electrical lighting systems has a noteworthy potential in reducing the buildings' overall cooling loads.
- Specifically, combinations of selected modifications (such as better windows, natural ventilation, and efficient electrical lighting) appear to have a synergistic effect, leading to a significant reduction of buildings' cooling loads. As the simulation results for combined measures CI1 and CI2 (Table 4) suggest (see Figures 59 to 64 and Table 6 to 11), cooling loads could be reduced (depending on the building) somewhere between 20 and 35%.

Overall, the simulation results suggest that certain measures regarding building fabric and controls can improve the buildings' energy performance. Specifically, certain combinations of improvement measures (such as better windows, natural ventilation, and efficient electrical lighting) have a significant potential to reduce buildings' cooling loads in the climatic context of Kumasi.

4.5 Passive scenario

The buildings under the study were assumed to be running in the passive state, thus without air-conditioners, in order to observe the temperature levels in the spaces. Here, the mean overheating was the main performance indicator (see Eq. 2). Only cases where the indoor temperature was higher than the reference temperature were considered.

The predicted mean vote (PMV) and predicted percentage of dissatisfied occupants (PPD) were calculated (see Tables 12 and 13). Finally, the indoor environmental parameters were plotted on psychrometric charts and the comfort zone was extended with the air velocities (0.5 to 1.5m.s^{-1}), after Szokolay. In the process, the number of times where the working hours were in the comfort zone could be tabulated (see Table 14).

Below is a discussion on the results based on the outcome of the simulation pertaining to the base case and alternative scenarios regarding the combinations of high mass, improved windows, efficient lighting and different ventilation rates (Fig. 65 – 69).

4.5.1 CAP building

The base case scenario at building CAP resulted in a mean overheating of 4.4K (Fig. 65). The simulated option of high mass (no floor carpet), improved windows, efficient lighting and ventilation rate (air change rate (ACH), day/night) of 1/0.5 ACH decreased the mean overheating by 1K to 3.4K. An increase of the night ventilation rate to 10ACH reduced the mean overheating further to 2.4K. In addition to the probed scenario, the day time ventilation rate was increased to 5ACH, which resulted in a mean overheating of 1.9K. Since the effect of natural ventilation during the day proved to be positive, the air change rate was further augmented to 10ACH, thus 10/10 ACH, and the effect was a final decline of the mean overheating to 1.8K.

The final value of 1.8K could be achieved through the positive factors with regard to sustainability. The CAP building is a rectangular block, with a north – south orientation. This orientation favoured the impact of natural ventilation, since the prevailing wind direction in Kumasi is from the southwest and northeast. Moreover, the office spaces were organised linearly, without many partition walls and therefore cross ventilation could be utilised to the maximum. In addition to the above, the building had verandas on the north and southern elongated sides, shading the office spaces from direct and reflected solar radiation. According to Wagner *et al.* (1980), by orienting rectangular buildings with the right aspect ratio (1:2.5), 50% glazing and planting shaded tress all around, cooling loads of 30 and 25% could be saved respectively (not withstanding the positive effects on thermal comfort). A ratio of 1:1.64 is also recommended by Watson (1983). Szokolay (2004) recommends an aspect ratio of 1: 1.3 to 2.0 for elongated buildings, depending on the climate, and walls with major openings (on the elongated side) to face within 45° of the prevailing wind direction.

Through the shades on the building, annoyance levels could be reduced, since a decrease of conductive gains was minimized. Further, the positive effects of plants in the landscape leads to a more comfortable environment, less energy needed for indoor comfort, reductions in greenhouse gas emissions and a filtering potential on pollutants (Salmon 1999 and Wagner *et al.* 1980).

However, the percentage of dissatisfied occupants, after Fanger (1973), was 55.52% with a predicted mean vote of 1.59 (see Table 12 and 13), implying that the spaces were warm. By increasing air speed to 1 $m.s^{-1}$ through the use of fans, 77% of the time during the working hours resulted in comfortable conditions (see Table 14).

4.5.2 KCR building

In Fig. 66, the results of the parametric study on the above building are presented. The base case scenario had a mean overheating of 4.3K. The effects of higher mass, improved windows and efficient lighting decreased the overheating level by 1K. A further increase of the ventilation rates, (1/10, 5/10 and 10/10 ACH) finally resulted in a mean overheating of 2K.

This was 0.2K more than at CAP building and could be due to the design parameters of the building. The L-shaped building of KCR had a north – south orientation with windows on all sides of the façade. This made it prone to the development of high indoor temperature levels in the office spaces oriented towards the east and west, because of the effects of solar radiation. With the exception of the roof overhang partially shading some of the windows on the first floor, all walls and windows were without shading devices. Even some of the office spaces were without internal shades and this led to the development of high temperatures. Generally, shading the exterior, interior, and surrounding areas of a structure is the first line of action to minimize the temperature build-up due to ambient air or solar incidence. A further disturbance were the conductive gains from the attic space, which are known to have high temperature values, especially during the afternoons.

A PPD of 54.47% and a PMV of 1.57 was tabulated. Comfort could be increased by using air motion to effect physiological cooling. The percentage of time that resulted in the comfort zone (PHCZ) was 73.33%.

4.5.3 ANG building

A high base case mean overheating of 5.2K was recorded at ANG. This has been the highest so far and the effects of high mass, efficient windows and lighting could reduce the mean overheating (Fig. 67). The alternative scenarios of using day and night time ventilation could decrease the mean overheating to a value of 2.4K.

The relatively poor performance of this building could be due to the improper orientation of the rectangular block to the western sun. This led to higher conductive gains in the building since the building also lacked shading devises to act as a protective shield against the intense solar radiation. Attention should be given to a good orientation, wind direction and a high window to wall ratio (Lechner 2001). Heat gained from the attic space also contributed to the poor performance and the problem was worsened by the windowless nature of most of the offices. This meant that heat trapped in the building could hardly escape since few escape routes were available. The arrangement of the offices did not support cross ventilation since where this would have been possible, the rear office had to make use of borrowed air from the corridor and other offices. Landscape effects on ventilation and air quality could not be utilised due to the nature of the surroundings.

At building ANG, the PPD increased to 64.29% with a PMV of 1.84 (warm indoor conditions). The PHCZ of 65% was the lowest in all the case studied buildings (see Table 14).

4.5.4 ROY building

The curtain wall office building with few operable windows had the highest base case mean overheating of 6K (Fig 68). This was due to the effect of solar radiation, since there was no shading on three sides of the building. The increase in radiation led to the higher conductive gains in the office spaces, which resulted in high net radiant exchange and discomfort (Heerwagen 2004). However, the improved alternatives of efficient window, thermal mass and efficient lighting could lessen the overheating to 4.3K. The positive effects on the use of natural ventilation finally reduced the mean overheating to 2K.

The better result in comparison to the base case scenario was also due to the shading protection provided by the quality glazing. Since the office type was an open-landscape, air could freely circulate in the building to support evaporative cooling. The thermal mass (no carpeted floor) supported storage of cool air, leading to temperature drops. The orientation of the building had a negative effect on thermal gains. Among other factors, the thermal gains problems were due to the fact that a large area at the eastern and western sides of the building fabric was exposed to intense solar radiation. The author’s view that this practice is to be avoided is shared by Szokolay (2004), Givoni (1981) and Lauber (2005).

The achieved PPD, PMV and PHCZ values were 56.33%, 1.62 (warm) and 71.67% respectively.

4.5.5 DCD building

At DCD, (Fig. 69) a base case mean overheating value of 3.7K was recorded and through the improvement scenarios, the mean overheating dropped to 2.1K.

The south eastern orientation of the building, though significantly better than the western orientation of ANG, could have led to the temperature development in DCD. This was compounded by the double baking arrangement of the office spaces that prevented natural and cross ventilation in most of the offices.

At DCD, 58.21 percentage of people were predicted to be dissatisfied with the indoor climate because they perceived it to be warm. At air speed of $0.5 m.s^{-1}$ (pleasant), a PHCZ value of 40% was calculated. When the air speed was increased to $1\ m.s^{-1}$ (perceived awareness), a PHCZ value of 68.33% was tabulated which increased to 96.67% at an unpractical air velocity of $1.5 m.s^{-1}$ (draughty and papers begin to fly away) in office buildings.

4.5.6 Summary on all buildings

The above passive scenario results generate important principles that should be considered in future passive buildings.

- Form and orientation principles in the sitting and arrangement of office spaces have to be given enough attention to support thermal comfort.
- Less depth and linearly arranged office spaces benefit more from ventilation than corridor and double banking types.
- Sufficient windows on both sides of buildings for the purpose of cross ventilation have a positive effect on thermal comfort.
- Attic ventilation is necessary to reduce the conductive gains from this overheated space.
- Natural ventilation is the key issue in passive design, though efficient building elements also lead to temperature reductions.
- The positive effects of landscape elements should be exploited, since the factors of comfort, satisfaction, less pollutants and a better air quality are positive aspects in relation to occupants comfort in buildings (Salmon 1999 and Wagner *et al.* 1980).
- Wing walls could be used to support the distribution and flow of natural ventilation in spaces oriented away from the prevailing wind direction.
- Lastly, with reference to Table 5 (Neutrality temperature), the highest value of 29°C was calculated. The highest recorded temperature levels in the office buildings was in the region of 31°C. This temperature is high and could lead to thermal discomfort in the spaces. However, the use of fans has been found to positively support evaporative cooling by providing a physiological cooling sensation of up to 3°C (Hyde 2000 and Ferstl 2003). In most of the buildings studied, this would mean an indoor

temperature value of 28°C, which could be comfortable in most office buildings in the climatic context of Kumasi. Therefore, it is recommended to always use fans for the purpose of physiological cooling in all indoor spaces.

4.6 Interviews

A summary on the evaluation results of the interviews is presented and discussed in the following subheadings:

- Indoor Environment, thermal and visual comfort
- Building control systems
- Implications of user control actions on energy performance
- Needs and complaints

4.6.1 Indoor environment, thermal and visual comfort

During the dry season, most occupants perceived the offices to be “cool/cold” with the highest percentage reported at KCR (50%), followed by CAP (33%). Twenty percent of the interviewees from the rest of the buildings found the offices also to be cool/warm. On average, 20% of all occupants perceived the offices to be “warm/hot” during the dry season (see Fig. 70). The discrepancies in the perception of the workers could be due to orientation of the buildings, missing shading devices and thermal comfort related factors. Since the early mornings were sometimes chilly with low temperatures (averagely 23 °C), occupants usually increased clothing (clo-value), which generally remained unchanged during the hot afternoons. However, a relatively large number of occupants preferred to feel cool, whilst only a small number, about 5% from CAP, wanted to feel warm (Fig. 71).

A relatively large number of interviewees (40%) perceived the offices to be cool/cold and 30% preferred to feel cool during the rainy season (Fig. 73 and 74). No one wanted to feel warm during the rainy season. The use of fans is therefore recommended since they can increase comfort by enhancing the evaporative potential of the skin, resulting in a physiological cooling of up to 3°C (Hyde 2000). Especially during the rainy season, the effect of the fans has the potential to reduce cooling loads and increase thermal comfort.

The air quality was perceived to be poor/very poor by 46% of the occupants from CAP and 70% from DCD during the dry season (Fig. 72). However, few interviewees (3%) found the air quality to be disturbing during the rainy season. The higher dissatisfaction during the dry season was due to the dusty nature of the northeast trade winds, which tend to be an annoyance in naturally ventilated buildings and mixed mode offices with louvre blade windows. This explains why at CAP and DCD, most occupants disapproved of the air quality.

The importance attached to the operation of windows was also higher at CAP and DCD, since these were the only elements that could be used to influence penetration of outdoor air, especially at DCD. The dissatisfaction with windows resulted from the fact that the windows were not providing adequate views, admitting not enough or too much daylight, preventing the reduction of heat loss and not allowing controllable ventilation as should have been the case. Generally, 30% of the occupants from the above offices expressed dissatisfaction with their windows (Fig. 83).

In addition, the percentage of occupants who generally had negative views on the office environment was high at CAP (20%) and more than 60% at DCD. In these offices, thermal comfort was in misbalance, especially at building DCD, and this was due to the thermal conditions of the environment, which depended on air temperature, humidity, air velocity and mean radiant temperature. The occupants in buildings KCR, ANG and ROY expressed satisfaction with air quality because they were able to rely on the air-conditioners during the season to create an exclusive indoor environment. Throughout the observation period of twelve months, it was noticed that artificial lighting in most offices was insufficient, that bulbs were not efficient and that spoiled ones were not replaced. Natural lighting on the other hand was seen as a nuisance due to the high glass to wall ratios in some offices and the orientation of the buildings. This explains why more than 30% of all occupants were annoyed by direct incident sunlight and reflections off computer screens (Fig. 77). In cases where buildings are shaded but have problems with solar radiation at the workstations, occupants tend to deploy the shades and rely only on artificial lighting, which, when inefficient, may lead to poor visual environment and dissatisfaction. Averagely, over 40% of interviewees attached importance to the operation of windows and shades (Fig. 82). However, the frequent operation of shades has the tendency to result in insufficient lighting at workstations.

4.6.2 Building control systems

The occupants reported a high level of importance attached to the operation of windows and shades (see Fig. 82). However, dissatisfaction with available building control systems was also expressed. This was mainly due to the difficulty in the operation and access to the system actuators. Generally, occupants were also dissatisfied with the lack of some building control systems (windows, fans, air-conditioners and shades) in the offices. The lack of information and difficulty in the operation of building control systems and system controls reduces workspace satisfaction. To increase workspace satisfaction, flexible and efficient building control systems have to be installed at the workspaces. Generally, satisfaction with building control systems was higher in the air-conditioned buildings than in the naturally ventilated working environment.

Dissatisfaction with the positions of the fans and air-conditioners was also expressed. A significant number of occupants reported insufficient knowledge on building control systems. In air-conditioned buildings, averagely 40% of the interviewees reported insufficient knowledge on the use of the air-conditioner (Fig. 90). Surprisingly, 72% of the occupants were interested in receiving training on the operation of building control systems (Fig. 94). This trend corresponds with the results of a study conducted in a number of office buildings (see Mahdavi *et.al* 2007).

4.6.3 Implications of user control actions on energy performance

The relatively large number of occupants who had insufficient knowledge on building control systems is alarming. This indicates the misuse of control systems and probable high-energy use and poor performance of some of the buildings due to lack of information. This is in relation to why, given the relevant technical properties of any buildings environmental system, user interactions with buildings' environmental systems do not necessarily lead to desired conditions (Loftness *et al.* 1995). The use of intelligent and flexible building control systems in combination with well informed occupants have the potential to reduce cooling loads.

The percentage of occupants who did not make use of cool outdoor air in the mornings to flush the offices before using the air-conditioners was high (Fig. 87). Most occupants set the thermostat to 18 - 20°C (Fig. 99), which is low and shows how user behaviour could affect energy consumption in office buildings. The low set point of the air-conditioner could be as a result of the high infiltration and exfiltration of air through the building envelope, especially the louvre blade windows.

A significant number of the occupants (over 60%) did not generally switch off the air conditioners during short absences from the offices (Fig. 100). Out of approx. 60% who thought that control actions could influence energy performance, about 15% did not consider energy consumption while operating building control systems (Fig. 98). Occupants’ tendency to express high-energy conscious behaviour could not be justified through their behaviour via the evaluation and the long term observation period.

4.6.4 Needs and complaints

All the occupants from all the buildings voiced similar improvement measures. The most urgent was air quality, thermal comfort, and comfort of furnishes and dimensions of workspace. These were followed by liberty to control your own environment, acoustic and visual privacy and lastly, beauty/aesthetics of the building (Fig. 106). The high expression of improvement measures correlates with the over 40% of occupants who had diverse health complaints (Fig. 108 to 111). The sources of the complaints could be poor air quality, poor lighting, and glare problems. The high values on health complaints correspond with the results of a study on office buildings by Mokamelkhah (2007). The investment in ergonomic furniture will boost worker satisfaction, increase comfort and productivity. Lastly, facility managers must train and inform workers on building control systems and make sure that indoor temperatures remain within the comfort zone, thereby helping to decrease health complaints in office buildings. However, the general indication gained from research in office buildings seems to ascertain the fact that irrespective of the nature of available thermal controls, health complaints tend to be high.

The percentage of occupants who wished to work in naturally ventilated buildings was high in CAP and ROY, even though the majority of workers wished for an air-conditioned office environment (Fig. 79). The wish for an air-conditioned environment especially in naturally ventilated buildings is understandable. The preference of office climate is however in disagreement to a survey done in Darwin, Australia, which showed that there is little preference for air-conditioned building over non-air-conditioned, but it solidifies the fact that satisfaction in mixed mode thermal control buildings is higher than in air-conditioned buildings (Salmon 1999). The occupants conveyed the knowledge that plants have positive effects on indoor climate, even though virtually no indoor plant was seen in the offices during the twelve month observation period. Among the positive effects of plants in the landscape are a more comfortable environment, less energy needed for indoor comfort, reduction of greenhouse gas emissions and filtering potential on pollutants.

4.6.5 Summary on all buildings

- Most people preferred to feel cool during the dry and rainy seasons. The air quality was a problem during the dry season, especially in the mixed mode (45%) and naturally ventilated (70%) buildings due to the relatively high infiltration levels of dusty northeast trade winds. This calls for well functioning and easily accessible building control systems.
- The highest dissatisfaction with the indoor environment was reported at DCD, (85% of the occupants), the naturally ventilated building. It is not surprising that the wish for an air-conditioned office environment was a priority here. Generally, orientation and shading must be considered as important measures both in the placement of the building and design of office spaces. These relate to the use of day lighting as a lighting design factor, which needs to be enhanced.
- The implementation of a good maintenance programme can increase the comfort of office spaces and boost employees' productivity.
- A significant number of occupants found building control systems to be important and their availability must be a priority. The user should be able to operate building control systems to bring about desired comfort. The importance attached to the operation of windows and shades was higher (80%) in the mixed mode and naturally ventilated buildings than in the air-conditioned types (55%). In addition, the positions of building control systems must be well planned to enhance comfort. This

calls for training of the occupants on the proper use of environmental control systems in office buildings.

- To positively affect the energy performance of office buildings, the occupants need to be trained on the proper use of environmental control systems and the resulting energy implications. The wish of 72% of the occupants for training on control systems should be embraced.
- The desire for better air quality, thermal comfort and ergonomic furniture and dimensions of workspace are understandable.

The results of the study show that attention to building control systems, users' needs and behaviour could help refine and improve the design, quality and energy performance of office buildings.

5 CONCLUSION

5.1 Overview

The conclusion in this section is in the following order: psychrometric analysis, active case scenario, passive case scenario and results of the interviews.

5.2 Psychrometric analysis

The existing indoor conditions plotted on the psychrometric chart resulted in almost all the months being represented outside the comfort zone.

This was caused by the high humidity values even though the temperatures in most of the cases were below 29°C. The impression gained during the observation period and evaluation of the questionnaire on indoor climate was that occupants had adapted to high humidity levels and therefore found maximum humidity levels of 80 – 85% acceptable, if temperature values did not exceed 29°C. This would call for the adjustment of the comfort scale for the climatic context of Kumasi, Ghana.

Numerous studies have demonstrated that the behaviour of occupants with regard to building systems affect thermal performance of buildings. This calls for the right use of building systems to contribute to satisfaction and comfort.

5.3 Active case scenario

Overall, the simulation results suggest that certain measures regarding building fabric and controls can improve the buildings' energy performance. The application of insulation to attic floor spaces, the use of efficient windows and lights contributed to decreased cooling loads. Natural ventilation and most importantly, the combination of the improvement measures significantly reduced cooling loads between 20 and 35%.

These positive measures, when implemented, have the potential to contribute positively to the energy situation in Ghana.

5.4 Passive case scenario

To improve thermal performance of office buildings, the effective use of natural ventilation cannot be over-emphasised. This could be supported through sustainable principles (of form, orientation, window to wall ratio, attic ventilation, landscape elements, etc) and most importantly, the use of fans to provide physiological cooling sensations.

5.5 Interviews

The behaviour of occupants has been found to affect the thermal performance of office buildings. The outcome of the interviews showed negative practices in the use of building systems. In addition, most workers lacked training in the proper use of the environmental control systems, especially the air-conditioners. However, a rather larger number of respondents wanted to have training on the efficient use of installed systems and this desire must be embraced to help increase satisfaction, comfort and decrease energy consumption of office buildings.

Lastly, the provision of flexible and efficient building systems should be compulsory and facility managers are advised to ensure the proper functioning of the installed systems and system controls.

5.6 Future research

The objective of future studies would be a broad monitoring of activities regarding building systems and user behaviour in curtain walled office buildings. This should be based on the use of diverse sensors in monitoring environmental conditions and user behaviour in buildings.

Secondly, the effects of higher relative humidity (80 -85%) and moderate temperatures (24 – 29°C) on comfort has to be studied in detail, towards possible adjustment of the comfort zone on the psychrometric chart for Kumasi.

Thirdly, the search on efficient building elements and effective scenarios has to continue. This should be supplemented by creating awareness in the building sector on the effectiveness of the use of simulation and efficient building elements in building performance and sustainable architecture.

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7 LIST OF FIGURES

8 LIST OF TABLES

9 LIST OF EQUATIONS

Nr.	Description	Page
Eq. 1	Tn = 17.6 + 0.31 * To.av Where Tn is the neutrality temperature and To.av is the mean outdoor temperature of the month	10
Eq. 2	$$OH_m = \sum_{j=1}^{n} \frac{\theta_{i,j} - \theta_r}{n}$$ Where $\theta_{i,j}$ represents the mean indoor air temperature (°C) at hour j (averaged over all simulated office zones in the floor), θ_r the reference indoor air temperature for overheating (°C), and n the total number of occupied office hours. The term $\theta_{i,j} - \theta_r$ was considered for those hours when $\theta_{i,j} > \theta_r$.	40
Eq. 3	DBT/AH = 0.023 * (T – 14) Where DBT is dry bulb temperature in °C, AH is absolute humidity in g/kg, and T is temperature in °C.	41
Eq. 4	dT = 6 * Ve – 1.6 * Ve^2 Where dT is change in temperature, Ve is effective air velocity	41

Eq. 5	$Ve = V - 0.2$ Where V is air velocity in m/s, valid up to $2m.s^{-1}$	41
Eq. 6	$V = (ACH + 3.43)/63.1$ Where V is air velocity and ACH is the air change rate; (r^2 = 0,96 for cross ventilated spaces).	67

10 APPENDICES

10.1 Appendix A: Information on data loggers

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

Image of data logger

10.2 System settings

System settings in the Control Panel:

Regional and Language Options:

Regional Options:

Standard format "English (UK)"

Location "Austria"

Customize:

Numbers:

Decimal Symbol "," [Comma]

No. of digits after decimal "2"

Digit grouping symbol "."

Digit grouping "123.456.789"

Negative sign symbol "-" [Minus]

Negative number format "-1,1"

Display leading zeros "0,7"

List separator ";" [Semicolon]

Measurement system "Metric"

Currency:

Currency symbol "$"

Positive currency format "$1,1"

Negative currency format "-$1,1"

Decimal symbol "," [Comma]

No. of digits after decimal "2"

Digit grouping symbol "."

Digit grouping "123.456.789"

Time:

Time sample "13:03:08"

Time format "HH:mm:ss"

Time separator ":" [Column]

AM symbol [left empty]

PM symbol [left empty]

Date

Calendar "2029"

Short date sample "28.04.2005"

Short date format "dd.mm.yyyy"

Date separator "." [Point]

Long date sample "Thursday, 28.04.2005"

Long date format "dddd, dd.mm.yyyy"

10.3 How to also name the Sensors / Files

Please use the following code-system when you install sensors or reset sensors:

302_112_041126

1. Digit = Project Number

1 = VIC D-Tower North Facade

2 = VIC D-Tower West Facade

3 = E-Tel / Eisenstadt

4 = TU - Freihaus

5 = UNIQA / Vienna

6 = BH Hartberg

7 =

2.-3. Digit = Room Number

Start with 01, 02, 03, ….. (mark the number in a plan)

(If necessary: 2.Digit=floor; 3.Digit=Room number)

As Separator use underscore "_"

4. Digit = Sensor Type

1 = IT-200

2 = Hobo

3 = Hobo (Temp only)

4 = Camera Files

5 = Weather Station

6 = Log for heating control

7 = APLogs

8 = MIKS

9 = SolRad

v = photos, plans, questionnaire, etc.

5.-6. Digit = Sensor Number

Start with 01, 02, 03, … in each room (mark the number in a plan)!

[For the Weather Station: 11 v med (WSM)

12 v max (WSS)

20 te

30 RH

40 SR]

As again underscore "_" as Separator

7.-12. Digit = Date

YYMMDD (every time you reset the sensor, you will have to change the date)

This means that the example above is the E-Tel building: **3**02_112_041126

Room number two: 3**02**_112_041126

It is an IT-200 sensor: 302_**1**12_041126

And it is the sensor number twelve: 302_1**12**_041126

The measurement start is on the 26th November 2004: 302_112_**041126**

If you have to add something to the filename use again "_": 302_112_041126_**testa**

Installing the sensors mark them correctly, using the same system:

302_112_041126 **including** the installation date and plot the position of the sensor in a plan.

10.4 How to save the data

Please use the following guideline to save data carefully:

HOBO LOGGER (both types) using Greenline Software

You will have to save the HOBO Logger data twice:

- once as original HOBO File (*.hobo,*.hob)
- and second as Text File (*.txt).

When you readout the data the Greenline software saves the data automatically as HOBO File in a folder you choose. (Use for that purpose one folder for each sensor and name that folder using the code-system you already know, not using the date stamp (for example: 465_201)).

Please save both, the original HOBO File and the Text File in that folder.

Follow these 3 steps to read and save data:

1. Select in “Exporting and Display” (File Menu / Preferences Window) the following:

Export Settings:

select - Export Serial #, Deployment # and Description

select - Export Point #

as Column Separator use **Semicolon “;”**

do not select - Separate Date and Time Columns

Date Time Display and Export Format:

Date Format: **Day Month Year**

select - Show Full 4 Digit Year

Date Separator: **Period “.”**

Time Format: **24 Hour**

Time Separator: **Colon “:”**

do not select - Use Asterisk (x) for Unit Degree (°) Symbol then press OK…

2. Now you can read the data. As mentioned before the Greenline software saves the data automatically as HOBO File (*.hobo) in a folder you choose (see above).

3. To save the data as Text File (*.txt) you can either press the “Export File” button or you choose “Export Points as Excel Text” in the “File”. Again you have to choose the folder where you want to save the file and then press save.

10.5 Appendix B: Questionnaire

The tabulated summary of the interviews is presented in this section. The first section represents results on general questions and the remaining sections show the responses on specific topics.

Summary of the interviews expressed in terms of percentage of people							
S.Nr.	**Question**	**Category**	**CAP**	**KCR**	**ROY**	**ANG**	**DCD**
1	Profile of respondent						
1.1	Gender	M	79.17	40	60	40	30
		F	20.83	60	40	60	70
1.2	Age	<25 years	4.17	20	30	10	0
		25-35 years	29.17	60	20	50	10
		36-45 years	25	0	40	0	30
		46-55 years	33.33	0	10	30	40
		>55 years	8.33	20	0	10	10
1.3	Education	SSS	8.33	20	30	10	10
		O-Level	12.5	0	10	10	30
		A-Level	16.67	0	0	30	30
		Undergraduate	12.5	40	20	30	30
		Postgraduate	50	40	40	20	0
1.4	Occupation	Managment	16.67	20	10	20	40
		Admin. Staff	50	30	90	80	60
		Lecturer	33.33	0	0	0	0
		Research Assisstant	0	50	0	0	0
1.5	How long have you been working in this company?	<1 year	8.33	10	10	20	0
		1-5 years	25	70	70	80	10
		6-10 years	20.83	20	20	0	50
		>11 years	45.83	0	0	0	40
1.6	How long have you been working in your current office?	<1 year	0	10	10	20	0
		1-5 years	70.83	90	80	80	20
		6-10 years	20.83	0	10	0	50
		>11 years	8.33	0	0	0	30

1.7	Activity you carry out most frequently in the office?	Reading and/or writing by hand	39.53	25	25	28.6	66.7
		Working on computer	44.19	50	44	38.1	6.67
		Drawing/design on paper	4.65	0	0	0	0
		Talking on telephone	11.63	25	31	33.3	26.7
1.8	What percentage of your work do you perform on your computer?	0-10%	8.7	10	30	20	100
		11-20%	8.7	0	0	0	0
		21-30%	0	0	0	0	0
		31-40%	4.35	0	10	0	0
		41-50%	0	20	0	10	0
		51-60%	17.39	10	0	10	0
		>60%	60.87	60	60	60	0
1.9	How many hours in average do you work per week?	0-30 hours	4.17	0	10	0	0
		31-40 hours	70.83	60	60	50	90
		41-50 hours	12.5	30	20	30	10
		51-60 hours	8.33	10	10	20	0
		>60 hours	4.17	0	0	0	0
1.10	Of these, how many hours do you spend at your work station?	0-30 hours	25	40	40	60	20
		31-40 hours	66.67	50	60	30	80
		41-50 hours	8.33	10	0	0	0
		51-60 hours	0	0	0	0	0
		>60 hours	0	0	0	10	0
2	**Evaluation of Indoor Environment (thermal & visual) and environmental control systems**						
2.1	What is your general feeling concerning the under listed parameter in your office during the DRY SEASON/HAMARTAN ?						
	Temperature	Very poor	12.5	0	0	0	0
		Poor	25	10	10	0	90
		Neutral	33.33	20	40	60	10
		Good	25	70	50	30	0
		Excellent	4.17	0	0	10	0
		Don't know	0	0	0	0	0

	Humidity	Very poor	4.17	0	0	0	0
		Poor	37.5	0	0	0	100
		Neutral	25	20	50	60	0
		Good	25	70	40	30	0
		Excellent	0	0	10	10	0
		Don't know	8.33	10	0	0	0
	Air quality	Very poor	0	0	0	10	10
		Poor	45.83	0	10	0	60
		Neutral	20.83	40	20	40	30
		Good	33.33	50	70	40	0
		Excellent	0	10	0	10	0
		Don't know	0	0	0	0	0
	Ventilation	Very poor	0	0	0	10	0
		Poor	29.17	0	0	10	50
		Neutral	12.5	30	50	40	40
		Good	54.17	60	50	30	10
		Excellent	4.17	10	0	10	0
		Don't know	0	0	0	0	0
	Odours	Very poor	4.17	0	0	0	0
		Poor	16.67	0	0	0	10
		Neutral	33.33	30	30	20	80
		Good	37.5	70	60	70	10
		Excellent	0	0	10	10	0
		Don't know	4.17	0	0	0	0
	Lighting quality	Very poor	0	0	0	10	0
		Poor	20.83	0	10	10	0
		Neutral	16.67	20	30	50	60
		Good	50	60	50	20	40
		Excellent	12.5	20	10	10	0
		Don't know	0	0	0	0	0
2.2	What is your general feeling concerning the under listed parameter in your office during the RAINY SEASON?						
	Temperature	Very poor	0	0	0	0	0
		Poor	4.17	0	0	0	0
		Neutral	33.33	10	40	20	20
		Good	54.17	90	50	80	70
		Excellent	8.33	0	10	0	10
		Don't know	0	0	0	0	0
	Humidity	Very poor	0	0	0	0	0
		Poor	0	0	0	0	0

		Neutral	25	20	40	10	20
		Good	75	70	50	90	80
		Excellent	0	0	10	0	0
		Don't know	0	10	0	0	0
	Air quality	Very poor	4.17	0	0	10	0
		Poor	4.17	0	0	0	0
		Neutral	20.83	10	40	30	10
		Good	62.5	90	50	60	90
		Excellent	8.33	0	10	0	0
		Don't know	0	0	0	0	0
	Ventilation	Very poor	4.17	0	0	10	0
		Poor	4.17	0	0	0	0
		Neutral	20.83	10	30	30	30
		Good	62.5	80	70	60	70
		Excellent	8.33	10	0	0	0
		Don't know	0	0	0	0	0
	Odours	Very poor	4.17	0	0	0	0
		Poor	12.5	0	0	0	0
		Neutral	33.33	10	30	20	30
		Good	45.83	80	70	80	70
		Excellent	0	10	0	0	0
		Don't know	4.17	0	0	0	0
	Lighting quality	Very poor	8.33	0	0	10	0
		Poor	12.5	0	10	0	0
		Neutral	20.83	20	20	40	60
		Good	54.17	60	60	50	40
		Excellent	4.17	20	10	0	0
		Don't know	0	0	0	0	0
2.3	Do you feel that the environment in which you work is agreeable/satisfying?	Not good at all	20.83	0	0	0	70
		Somewhat	37.5	30	20	20	30
		Agreeable	33.33	50	80	80	0
		Very agreeable	8.33	20	0	0	0
2.4	How is the average temperature in your office during the Dry Season or (Hamartan)?	Cold	4.17	0	0	10	20
		Cool	29.17	50	20	10	0
		Slightly cool	12.5	0	0	30	10
		Neutral	16.67	10	30	10	0
		Slightly warm	20.83	30	30	30	20
		Warm	8.33	10	0	10	20

		Hot	8.33	0	20	0	30
2.5	How would you prefer to feel during the Dry Season?	Cold	0	0	0	0	0
		Cool	29.17	40	40	30	20
		Slightly cool	29.17	30	20	50	50
		Neutral	29.17	30	40	20	30
		Slightly warm	8.33	0	0	0	0
		Warm	4.17	0	0	0	0
		Hot	0	0	0	0	0
2.6	How is the average temperature in your office during the Rainy Season?	Cold	8.33	0	10	20	30
		Cool	41.67	60	20	0	10
		Slightly cool	25	30	40	60	60
		Neutral	12.5	10	30	10	0
		Slightly warm	4.17	0	0	10	0
		Warm	8.33	0	0	0	0
		Hot	0	0	0	0	0
2.7	How would you prefer to feel during the Rainy Season?	Cold	0	0	0	0	0
		Cool	33.33	20	30	30	40
		Slightly cool	25	40	0	40	30
		Neutral	33.33	30	50	30	10
		Slightly warm	8.33	10	20	0	20
		Warm	0	0	0	0	0
		Hot	0	0	0	0	0
2.8	How satisfied are you with the Air-conditioning?	Very satisfied	12.5	20	0	0	0
		Satisfied	29.17	10	20	40	0
		It's ok	16.67	60	60	60	0
		Less satisfied	16.67	10	20	0	0
		Not satisfied at all	20.83	0	0	0	0
		Not applicable	4.17	0	0	0	100
2.9	Do you have control over air temperature?	Yes	58.33	90	40	60	30
		No	41.67	10	60	40	70
2.10	Do you have control over air speed?	Yes	29.17	90	40	60	30
		No	70.83	10	60	40	70
2.11	Evaluate air speed in your office	light air	45.83	30	40	20	70
		calm	41.67	70	40	60	20
		stagnant	12.5	0	20	20	10

2.12	Do you have sufficient daylight in your office?	Too much	8.33	0	0	0	0
		A bit too much	0	10	30	0	10
		It's ok	58.33	90	40	60	60
		Could be more	16.67	0	30	10	10
		Not sufficient	16.67	0	0	30	20
2.13	Are you annoyed by direct sunlight at your workstation?	Yes, frequently	8.33	0	10	0	10
		Occasionally	33.33	30	30	50	40
		Rarely	12.5	10	20	10	40
		Never	45.83	60	40	40	10
2.14	Are you annoyed by reflections or too bright surfaces on your computer screen?	Yes, frequently	12.5	10	10	10	10
		Occasionally	25	30	30	30	0
		Rarely	16.67	20	10	10	10
		Never	41.67	40	50	50	10
		Not applicable	4.17	0	0	0	70
2.15	Do you have sufficient artificial light in your office?	Too much	4.17	0	0	0	0
		A bit too much	0	0	30	0	0
		It's ok	75	100	50	90	50
		Could be more	8.33	0	20	0	30
		Not sufficient	12.5	0	0	10	20
2.16	Are you annoyed by noise in your office?	Yes, frequently	8.33	0	10	30	10
		Occasionally	41.67	30	20	40	50
		Rarely	16.67	20	30	20	40
		Never	33.33	50	40	10	0
2.17	Evaluate the distance of your workstation from the window	Too close	29.17	10	30	0	10
		It's ok	66.67	90	70	70	80
		Too far	4.17	0	0	10	10
		Not applicable	0	0	0	20	0
2.18	Evaluate the outdoor view from your office window	Very good	12.5	20	30	0	0
		Good	45.83	30	10	40	30
		Satisfactory	33.33	40	30	10	20

		Not satisfactory	8.33	10	30	30	50
		Not applicable	0	0	0	20	0
2.19	Do you have enough privacy in your office to work undisturbed?	Yes	20.83	30	10	20	10
		It's ok	20.83	50	60	50	40
		No	58.33	20	30	30	50
3	**Operation and accessibility of the systems and system controls**						
3.1	Can you open the windows of your office if required?	Very easily	25	30	0	0	20
		Easily	37.5	40	0	10	20
		It's ok	29.17	30	50	10	60
		Complicated	4.17	0	0	10	0
		Not at all	4.17	0	50	20	0
		No window	0	0	0	50	0
3.2	How important is it for you to have the possibility to open the windows?	Very important	50	60	20	10	60
		Important	41.67	30	40	60	40
		Don't know	4.17	10	20	10	0
		Not so important	4.17	0	20	0	0
		Unimportant	0	0	0	10	0
		Not applicable	0	0	0	10	0
3.3	Are you satisfied with the possibility to ventilate your office?	Very satisfied	8.33	50	10	0	10
		Satisfied	45.83	30	20	20	30
		It's ok	16.67	20	30	30	30
		Less satisfied	20.83	0	30	20	10
		Not satisfied at all	8.33	0	10	30	20
3.4	Can you decide independently when to open/close the windows in your office or do you have to negotiate with other people?	Myself	66.67	90	60	30	70
		With others	33.33	10	40	50	30
		Not applicable	0	0	0	20	0
3.5	Do you in the morning ventilate your office before switching on the air-conditioner?	Yes, frequently	25	20	0	0	0
		Occasionally	20.83	40	20	0	0
		Rarely	16.67	20	0	40	0
		Never	29.17	20	80	50	0

		Not applicable	8.33	0	0	10	100
3.6	Can you open/close the curtains/shades easily?	Very easily	29.17	10	0	10	0
		Easily	25	30	10	10	0
		It's ok	33.33	10	0	40	60
		Complicated	0	0	0	0	10
		Not at all	0	0	0	0	0
		Not applicable	12.5	50	90	40	30
3.7	How important is it for you to have the possibility to operate the curtains/blinds?	Very important	33.33	30	0	10	20
		Important	37.5	20	10	50	40
		Don't know	4.17	0	0	0	0
		Not so important	12.5	0	0	0	10
		Unimportant	0	0	10	0	0
		Not applicable	12.5	50	80	40	30
3.8	Can you decide independently when to operate the curtains/blinds in your office or do you have to negotiate with other people?	Myself	66.67	40	10	30	70
		With others	20.83	10	0	40	0
		Not applicable	12.5	50	90	30	30
3.9	Is the thermostat (air-conditioning regulator) easily accessible to you?	Very easily	29.17	50	40	0	0
		Easily	16.67	30	10	40	0
		It's ok	25	20	50	60	0
		Complicated	4.17	0	0	0	0
		Not at all	20.83	0	0	0	0
		Not applicable	4.17	0	0	0	100
3.10	Can you regulate the temperature on your own or do you have to negotiate with other people?	Myself	62.5	90	60	50	0
		With others	33.33	10	40	50	0
		Not applicable	4.17	0	0	0	100
3.11	How satisfied are you with the position of the air conditioner to your workspace?	Very satisfied	4.17	0	10	0	0
		Satisfied	33.33	30	10	10	0
		It's ok	29.17	50	50	90	0
		Less satisfied	4.17	10	10	0	0
		Not satisfied at all	20,83,	10	20	0	0
		Not applicable	8.33	0	0	0	100

3.12	Is the fan regulator/switch easily accessible to you?	Very easily	20.83	30	20	0	10
		Easily	25	40	0	0	30
		It's ok	29.17	0	10	40	50
		Complicated	0	0	0	0	0
		Not at all	8.33	0	0	0	0
		Not applicable	16.67	30	70	60	10
3.13	Can you regulate the speed of the fan on your own, or do you have to negotiate with other people?	Myself	50	70	30	20	70
		With others	33.33	0	0	20	20
		Not applicable	16.67	30	70	60	10
3.14	Evaluate the position of the fan to your workspace:	Very satisfied	0	0	20	0	0
		Satisfied	29.17	20	0	0	20
		It's ok	29.17	50	10	30	70
		Less satisfied	4.17	0	0	0	0
		Not satisfied at all	20.83	0	0	0	0
		Not applicable	16.67	30	70	70	10
3.15	Is the light switch easily accessible to you?	Very easily	29.17	30	30	0	0
		Easily	41.67	40	10	40	40
		It's ok	20.83	20	60	60	60
		Complicated	0	0	0	0	0
		Not at all	8.33	10	0	0	0
3.16	Can you decide independently when to switch on/off the light in your office or do you have to negotiate with other people?	Myself	79.17	90	70	40	70
		With others	20.83	10	30	60	30
4	**Awareness of the functionality of the building control systems**						
4.1	How satisfied are you with the fan in your office?	Very satisfied	8.33	10	0	0	0
		Satisfied	20.83	20	10	0	0
		It's ok	29.17	40	20	30	70
		Less satisfied	12.5	0	0	0	30
		Not satisfied at all	8.33	0	0	0	0
		Not applicable	20.83	30	70	70	0

4.2	How satisfied are you with the air-conditioner in your office?	Very satisfied	8.33	20	30	0	0
		Satisfied	25	50	10	30	0
		It's ok	29.17	30	40	70	0
		Less satisfied	8.33	0	10	0	0
		Not satisfied at all	16.67	0	10	0	0
		Not applicable	12.5	0	0	0	100
4.3	Are you sufficiently informed about how the following systems work in your office?						
	Ventilation	Very well informed	37.5	20	30	0	0
		It's ok	29.17	50	30	50	60
		Insufficiently informed	33.33	30	40	50	40
	Air-conditioning	Very well informed	25	20	30	0	0
		It's ok	33.33	50	10	60	0
		Insufficiently informed	37.5	30	60	40	0
		Not applicable	4.17	0	0	0	100
	Lighting	Very well informed	50	30	40	0	10
		It's ok	33.33	40	30	60	50
		Insufficiently informed	16.67	30	30	40	40
	Blind protection	Very well informed	29.17	25	10	0	0
		It's ok	50	50	10	60	60
		Insufficiently informed	12.5	25	0	40	40
		Not applicable	8.33	0	80	0	0
4.4	Have you ever had a training concerning the systems in your office?	Yes	12.5	0	10	0	0
		No	87.5	100	90	100	100
	a. If „yes“, how do you evaluate this training?	Very good	66.67	0	100	0	0
		Ok	33.33	0	0	0	0
		Not so good	0	0	0	0	0

	b. If „no“, would you be interested in such training?	Yes	70.83	60	67	70	90
		Don't know	8.33	10	22	20	0
		No	12.5	30	11	10	10
4.5	To whom do you refer in case of a problem with the building systems (Cooling, Lighting, etc.)?	HOD	20	0	0	0	0
		Immediate Boss	40	0	60	80	80
		Maintenance Dept	10	90	40	20	20
		Others	30	10	0	0	0
4.6	Are you satisfied with the system services and support in your office?	Yes	12.5	30	20	10	0
		It's ok	66.67	70	70	90	50
		No	20.83	0	10	0	50
5	**Energy implications of user control actions**						
5.1	Do you think that you can influence building energy consumption in the way you operate building systems?	Yes	62.5	60	60	70	70
		Don't know	4.17	10	10	0	0
		No	33.33	30	30	30	30
5.2	Do you think about energy conservation, when you operate building systems?	Yes	87.5	70	60	90	70
		Don't know	4.17	0	20	0	0
		No	8.33	30	20	10	30
5.3	Choose the temperature range you normally set your air-conditioner	18-20 °C	50	30	70	50	0
		21-23 °C	27.27	40	30	50	0
		24-26°C	22.73	30	0	0	0
		27-29°C	0	0	0	0	0
		Not applicable	9.09	0	0	0	100
5.4	Do you switch off your air-conditioner during short absence from the office?	No	41.67	60	100	90	0
		Yes	45.83	40	0	10	0
		Not applicable	12.5	0	0	0	100
5.5	If yes, choose the range of time that you would normally switch	< 20 mins	0	0	0	0	0

	off the AC when you have to leave the office.	21-40 mins	6.67	50	0	0	0
		41-60 mins	13.33	50	0	0	0
		61-120 mins	40	0	0	0	0
		121-180 mins	26.67	0	0	100	0
		> 180 mins	13.33	0	0	0	0
		Not applicable	20	0	0	0	100
5.6	Which office environment would you prefer to work in?	Naturally ventilated	70.83	10	50	10	10
		Air-conditioned	29.17	90	50	90	90
6	**Personal preferences of organizing the current/ideal working space; health complaints**						
6.1	How important are the effects of plants on indoor climate to you?	Very important	41.67	40	30	20	20
		Important	45.83	30	20	0	20
		Don't know	0	20	10	20	30
		Not so important	4.17	10	30	60	20
		Unimportant	8.33	0	10	0	10
6.2	Are you satisfied with the available possibilities to personalize your working place (Furniture, Plants, Photos…)?	Very satisfied	8.33	10	0	0	0
		Satisfied	20.83	30	40	10	0
		It's ok	33.33	50	40	60	50
		Less satisfied	8.33	10	20	30	30
		Not satisfied at all	29.17	0	0	0	20
6.3	Generally, how do you find your office climate?	Very good	8.33	10	10	0	0
		Good	20.83	60	10	0	0
		It's ok	45.83	30	60	90	0
		Not so good	20.83	0	20	10	70
		Poor	4.17	0	0	0	30
6.4	What are the most important features of ideal working place from your point of view? Classify (from 1 to 10), in order of importance						
		Thermal comfort	3	2	1	1	1

	in a work environment, the items indicated (with “1” as the most important).	Air quality	1	1	2	2	2
		Visual comfort (lighting/shades)	5	5	6	6	5
		Acoustic comfort	6	6	9	5	4
		Acoustic and visual privacy	6	3	8	8	8
		Comfort of furnishings and dimensions of workstation	2	7	3	3	3
		Fire safety	7	5	4	5	5
		Security against theft	4	8	7	7	7
		Liberty to control your own work environment	4	4	5	4	6
		Beauty/aesthetics of the building	8	9	10	9	9
6.5	Which improvement measures in your office would you consider as most urgent? Classify (from 1 to 10), in order of importance in a work environment, the items indicated (with “1” as the most important).						
		Thermal comfort	4	4	2	2	1
		Air quality	2	1	1	1	2
		Visual comfort (lighting/shades)	5	7	5	3	5
		Acoustic comfort	8	4	7	4	6
		Acoustic and visual privacy	9	6	9	7	6
		Comfort of furnishings and dimensions of workstation	1	3	8	3	3
		Fire safety	6	2	3	5	4
		Security against theft	3	8	4	6	7

		Liberty to control your own work environment	7	5	6	8	7
		Beauty/aesthetics of the building	10	9	10	9	8
6.6	Do you have any health complaints?						
	Backache	Frequently	29.17	0	0	10	60
		Occasionally	37.5	80	60	80	30
		Rarely	12.5	10	20	10	10
		Never	20.83	10	20	0	0
	Eyestrain or -burning	Frequently	16.67	0	0	10	0
		Occasionally	37.5	40	20	30	60
		Rarely	25	40	50	50	40
		Never	20.83	20	30	10	0
	Headache	Frequently	12.5	20	20	30	40
		Occasionally	33.33	60	60	60	50
		Rarely	29.17	10	0	10	0
		Never	25	10	20	0	10
	General fatigue	Frequently	33.33	40	30	30	30
		Occasionally	33.33	40	60	60	70
		Rarely	20.83	20	10	0	0
		Never	12.5	0	0	10	0
	Respiratory problems	Frequently	4.17	0	0	0	10
		Occasionally	20.83	10	10	30	20
		Rarely	20.83	50	60	60	40
		Never	54.17	40	30	10	30
	Sore Throat	Frequently	4.17	0	0	10	0
		Occasionally	16.67	10	40	60	0
		Rarely	16.67	40	40	10	100
		Never	62.5	50	20	20	0
	Neck pain	Frequently	20.83	10	10	0	20
		Occasionally	37.5	50	50	60	30
		Rarely	16.67	0	40	30	20
		Never	25	40	0	10	30
	Rheumatic pains	Frequently	8.33	0	0	10	0
		Occasionally	12.5	0	10	30	10
		Rarely	16.67	20	30	30	30

		Never	62.5	80	60	30	60
	Stiffness of limbs	Frequently	8.33	0	10	0	20
		Occasionally	8.33	20	20	30	0
		Rarely	16.67	10	30	30	30
		Never	66.67	70	40	40	50
	Nasal irritation	Frequently	8.33	10	0	0	0
		Occasionally	25	40	30	20	40
		Rarely	25	10	20	20	20
		Never	41.67	40	50	50	40

10.6 Appendix C: Construction table

The tables below show detailed constructions (material properties) of the building elements with respect to the base cases.

Building Element	Material Layer	Width (mm)	Conductivity (W/mC)	Density (kg/m³)	Solar Absorp-tance Exterior	Solar Absorp-tance Interior	U-Value (W/m²C)
Wall	Plaster	10	0.5	1300	0.4	0.4	**3.4**
	Block	150	1.75	2400			
	Plaster	10	0.5	1300			
Floor_CAP, DCD	Carpet	10	0.06	186	0.65	0.7	**2.2**
	Concrete Screed	50	1.28	2100			
	Concrete	120	1.4	2360			
Floor & ceiling_KCR, ANG, ROY	Carpet	10	0.06	186	0.6	0.7	**1.3**
	Terrazzo	30	1.75	2400			
	Concrete Screed	50	1.28	2100			
	Concrete	120	1.4	2360			
	Air Cavity	200					
	Ceiling/Ply wood	30	0.16	650			
Attic floor	Plywood on purlins	30	0.16	650	0.6	0.6	**3.4**
Door Pane	Hard Wood	50	0,16	650	0.6	0.6	**2.1**
Door Frame	Hard Wood	150	0,15	700	0.6	0.6	**0.9**
Window Frame	Aluminium	30	204	2700	0.5	0.5	**5.9**

Building Element	Material Layer	Width (mm)	Conduc-tivity (W/mC)	Solar Reflect-tance Exterior	Solar Reflect-tance Interior	Solar Trans-mittance	Light Trans-mittance	U-Value (W/m²C)
Window with Blind	Fabric, open weave	1	1	0.36	0.36	0.488	0.531	**2.7**
	Air cavity	200						
	Optifloat clear	4	1	0.7	0.7			
Window Pane_ROY	Optifloat clear	12	1	0.06	0.06	0.66	0.89	**5.5**
Window Pane	Optifloat clear	4	1	0.07	0.07	0.82	0.89	**5.8**

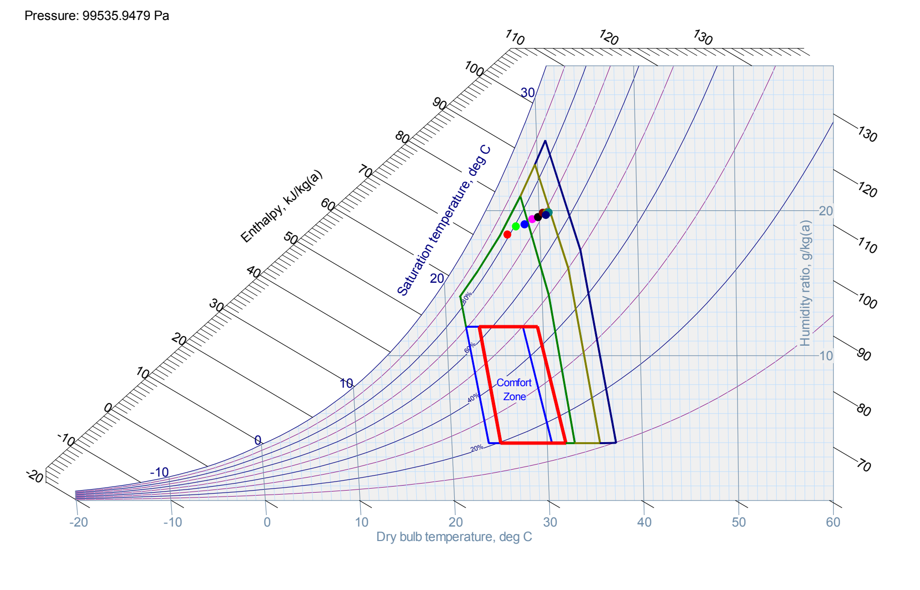
10.7 Appendix D: Passive scenario results on psychrometric charts

The psychrometric plots presented show the mean daily temperature and relative humidity (averaged over all days in a month) values (based on simulated data from 8 am to 5 pm). The values resulted from the combined improvement scenarios (of high mass, improved windows, efficient lighting and ACH of 10/10) and the illustrations show the thermal conditions pertaining in the offices with respect to the comfort zone. Further, the comfort zone has been extended by air velocities of 0.5, 1.0 and 1.5m.s^{-1} to the right and bounded by the 85% relative humidity curve to the top (see Szokolay 2004).

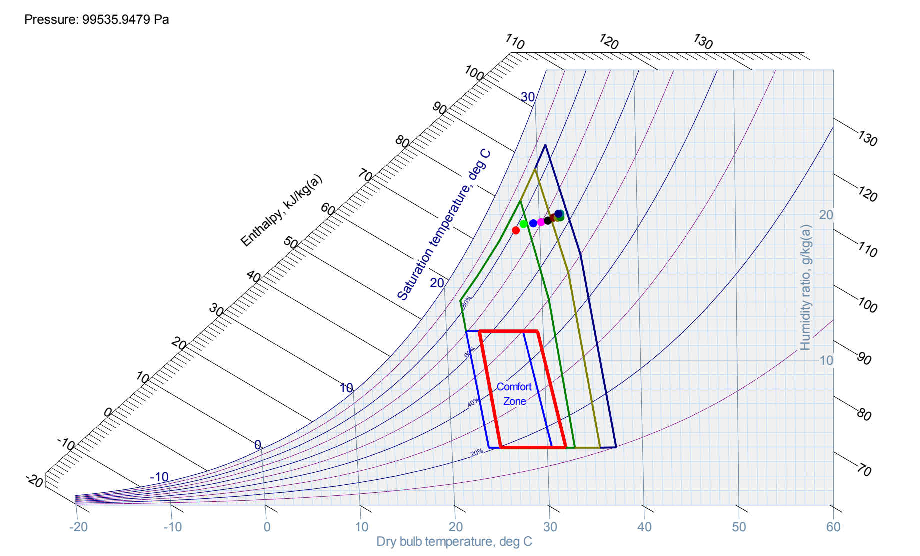
The monthly plots are presented from building to building (CAP, KCR, ANG, ROY and DCD).

Building CAP (High mass, improved windows, efficient lighting and ACH 10/10)

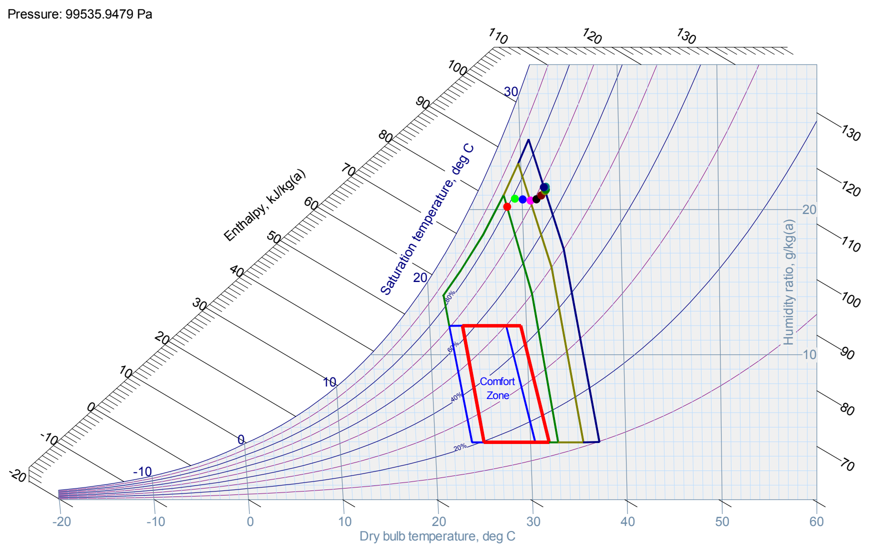
January



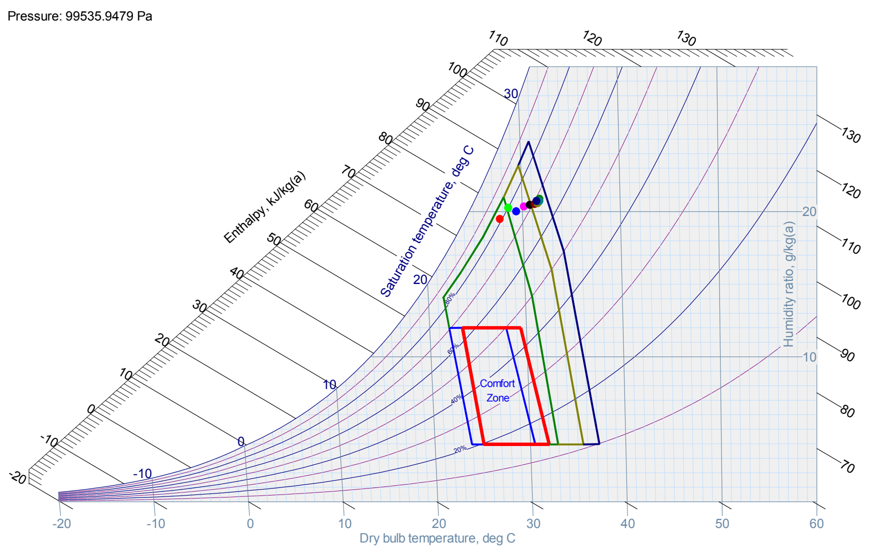
February



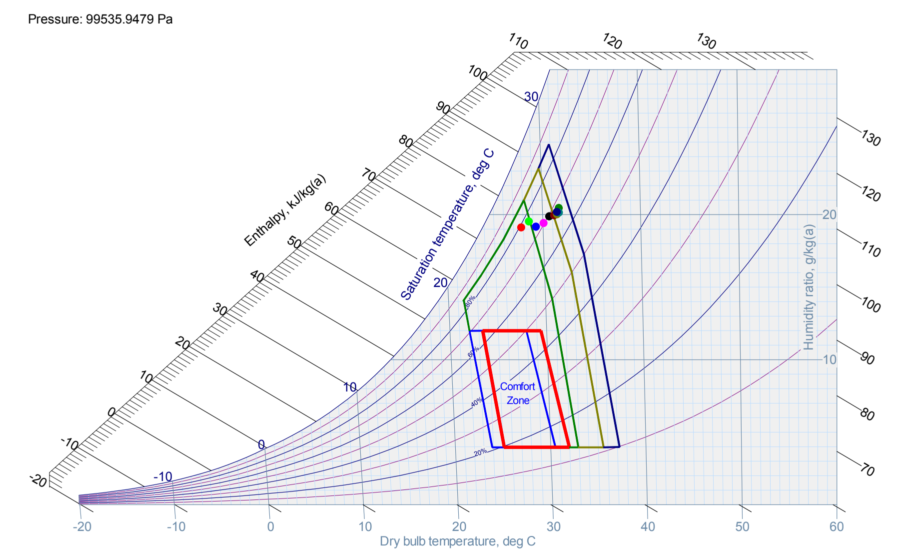
March


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort
Zone

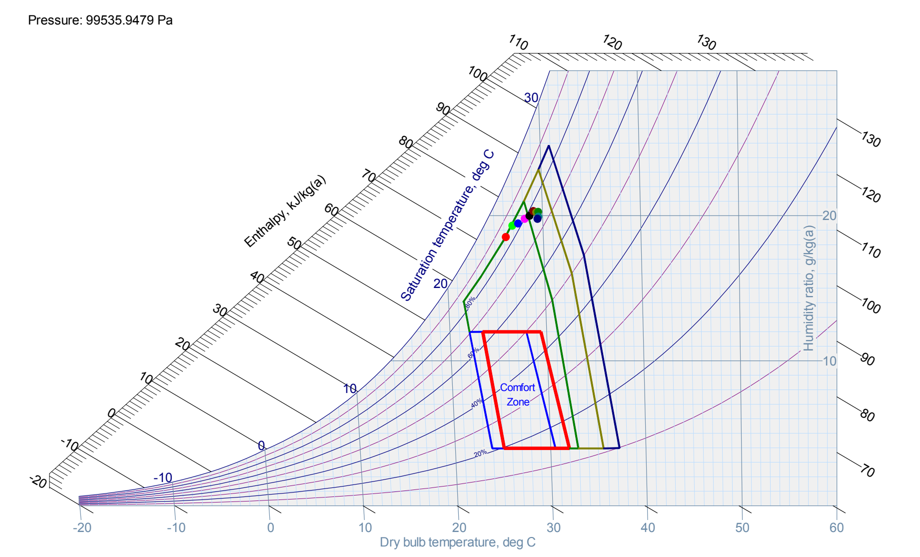
April


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort
Zone

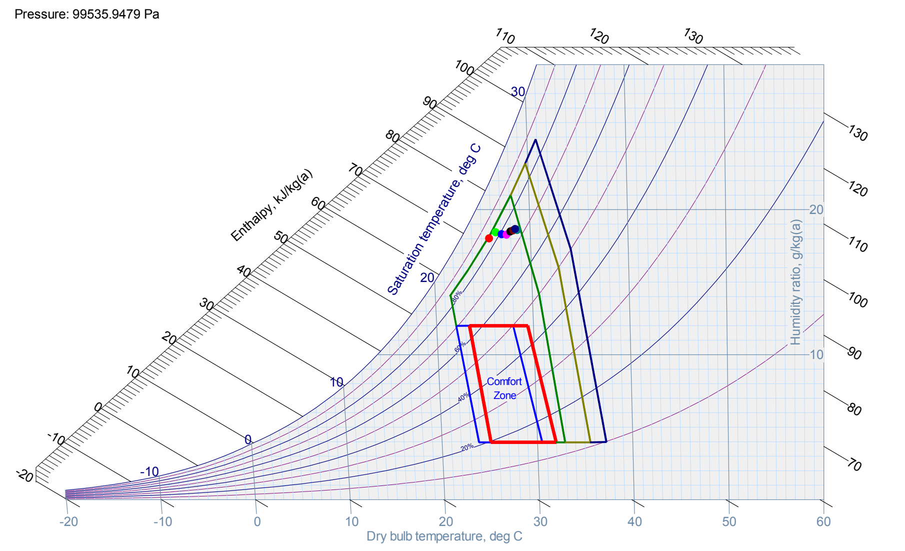
May


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort
Zone

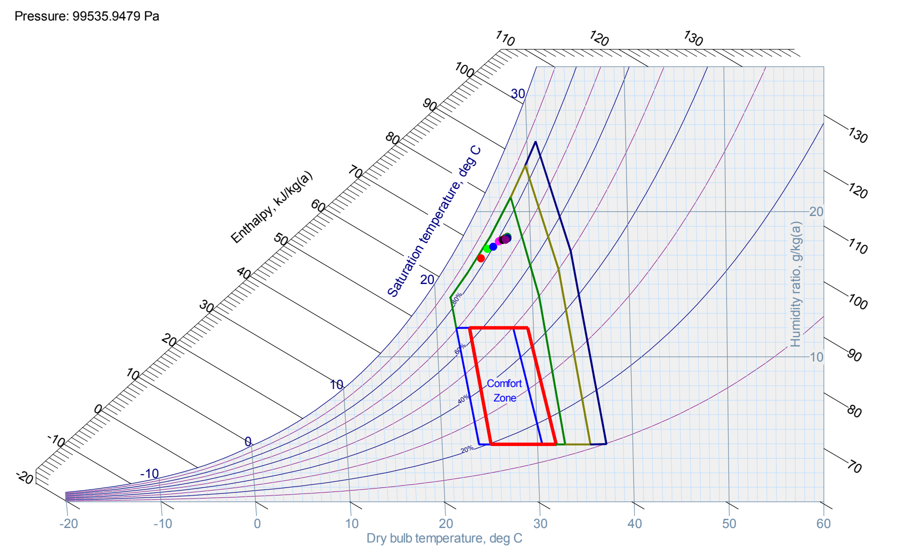
June


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort
Zone

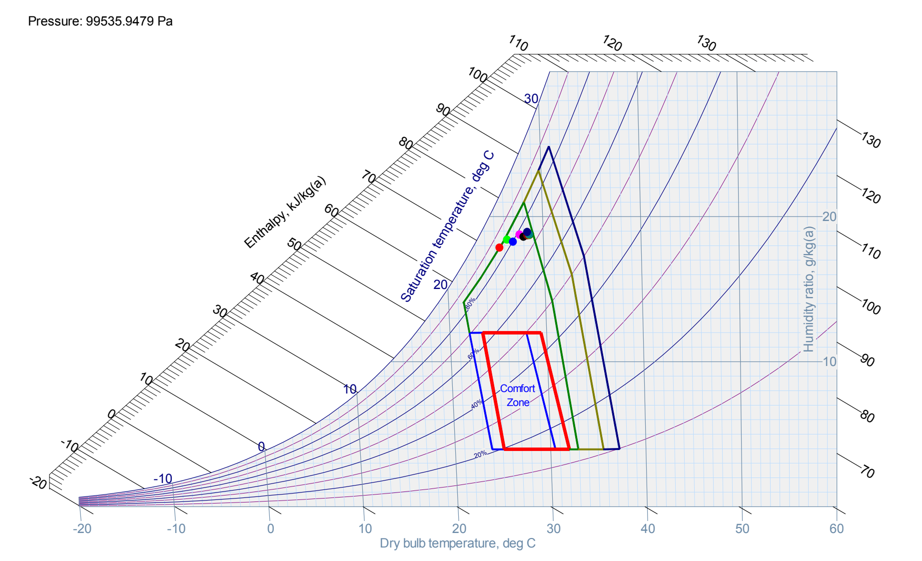
July


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

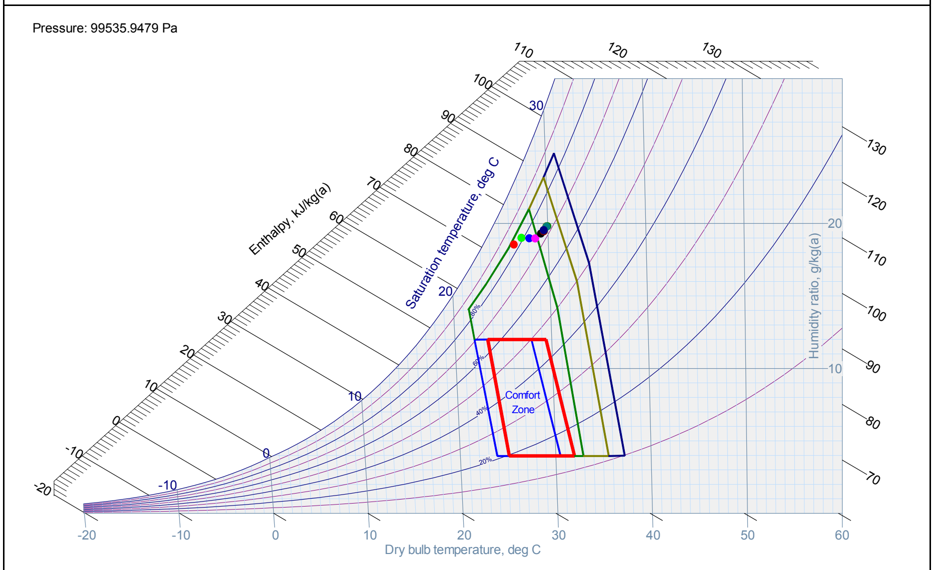
August


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

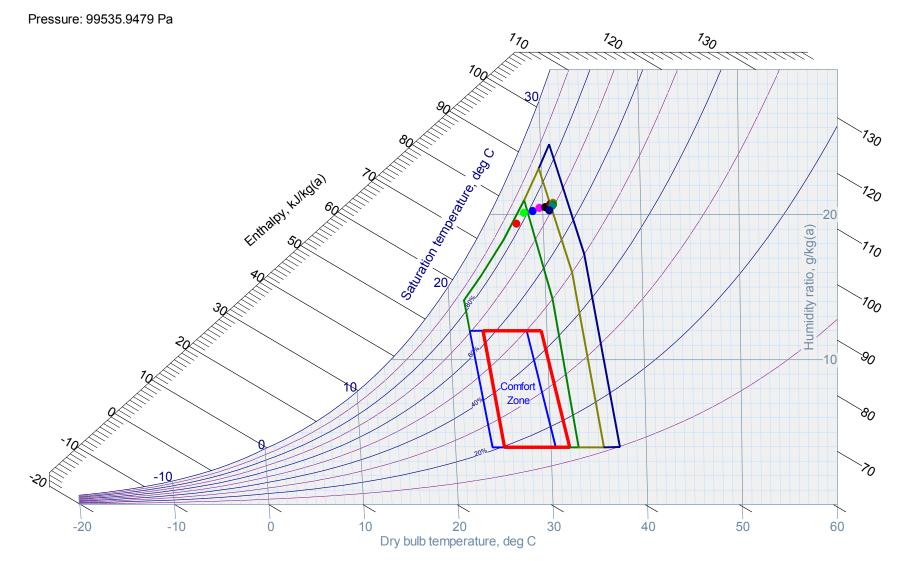
September



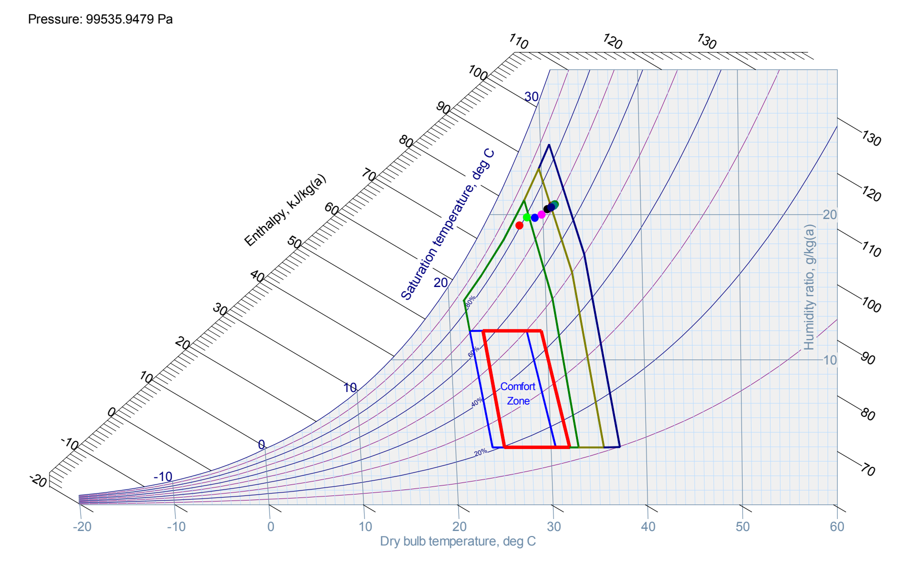
October



November

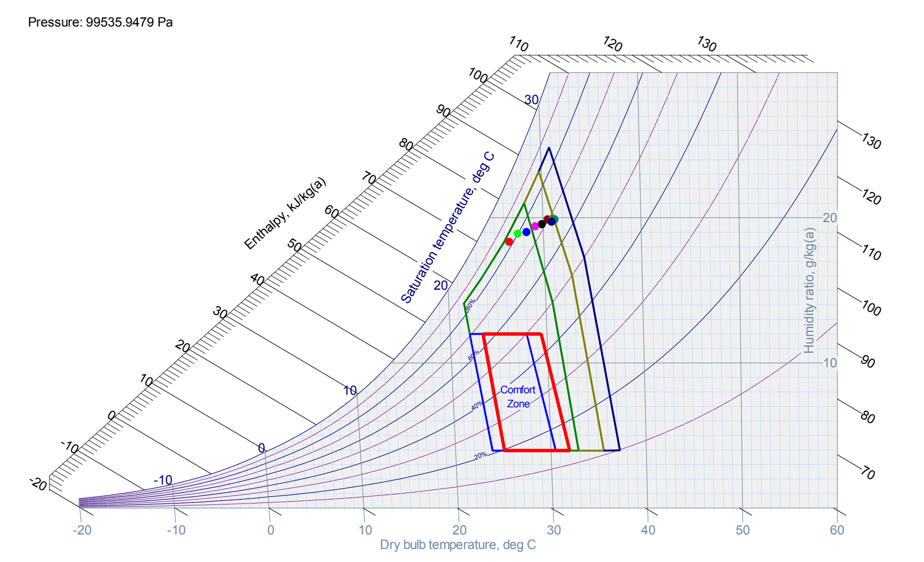


December

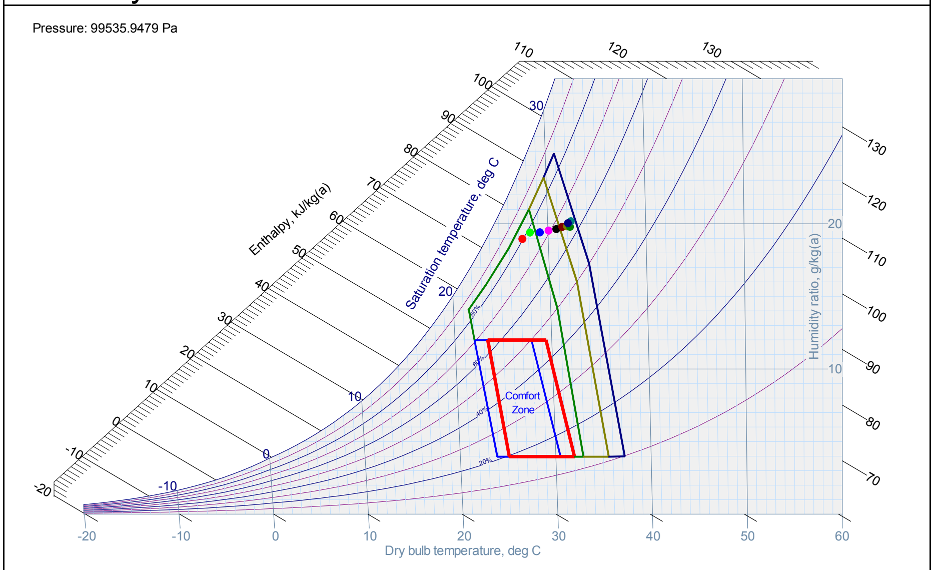


Building KCR (High mass, improved windows, efficient lighting and ACH 10/10)

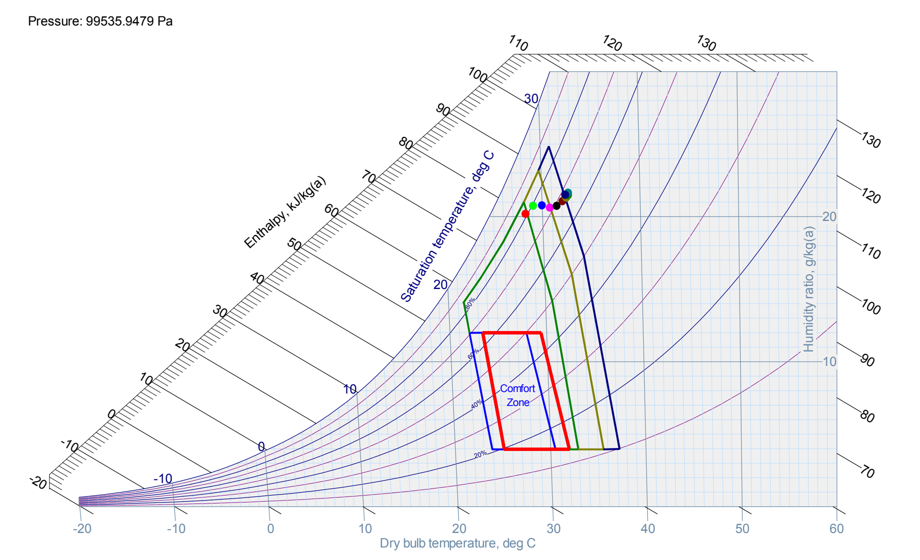
January



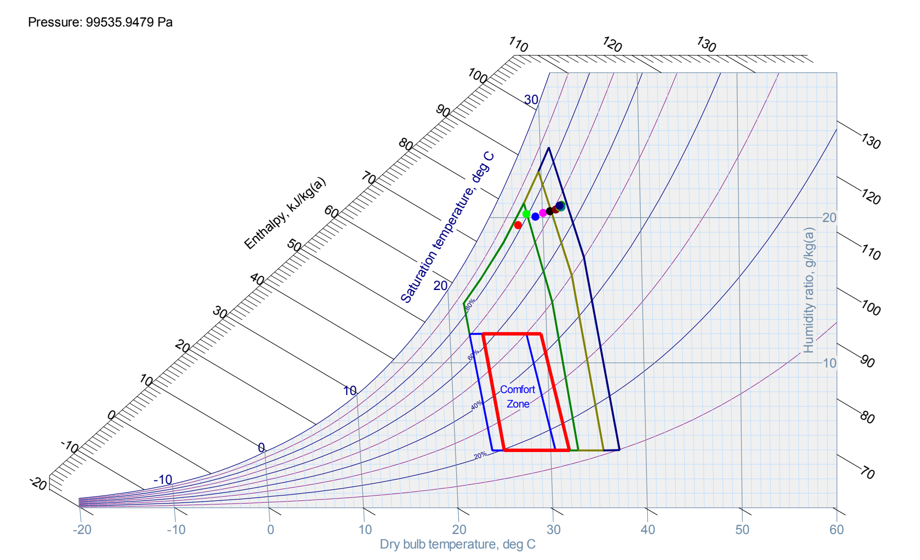
February



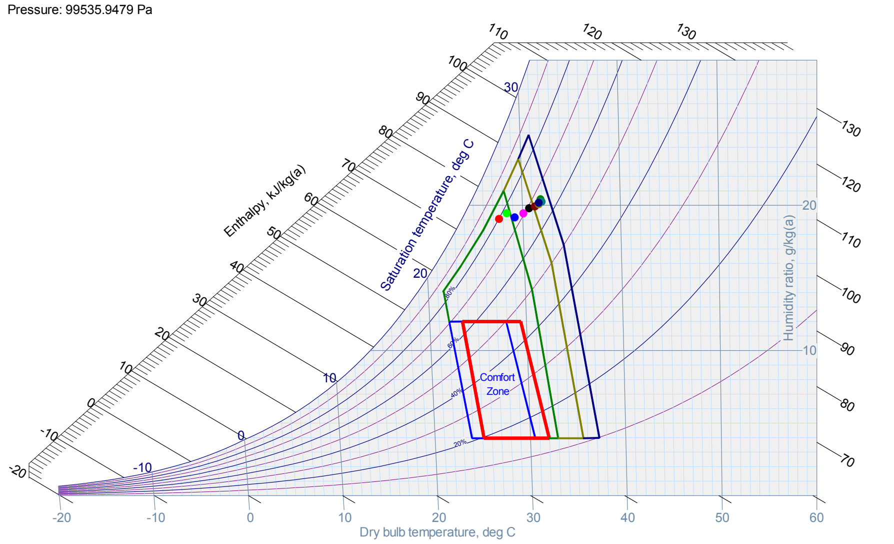
March


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

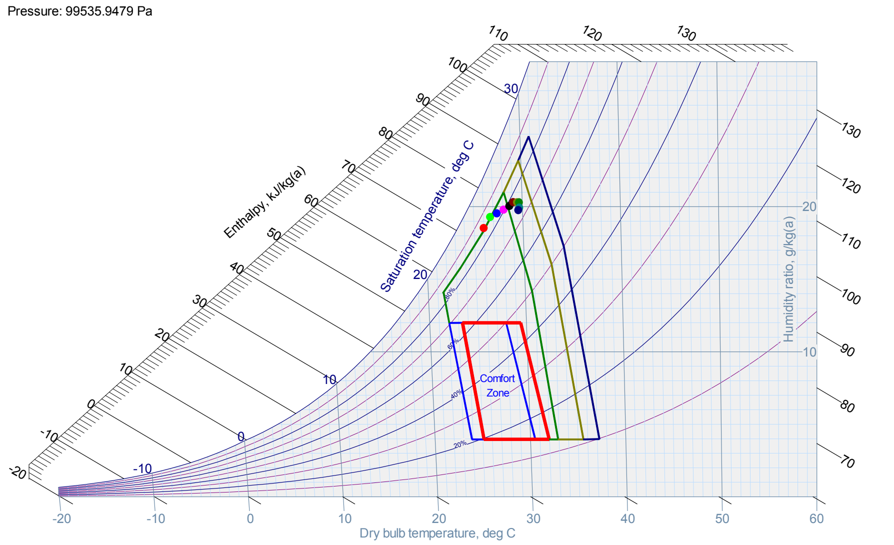
April


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

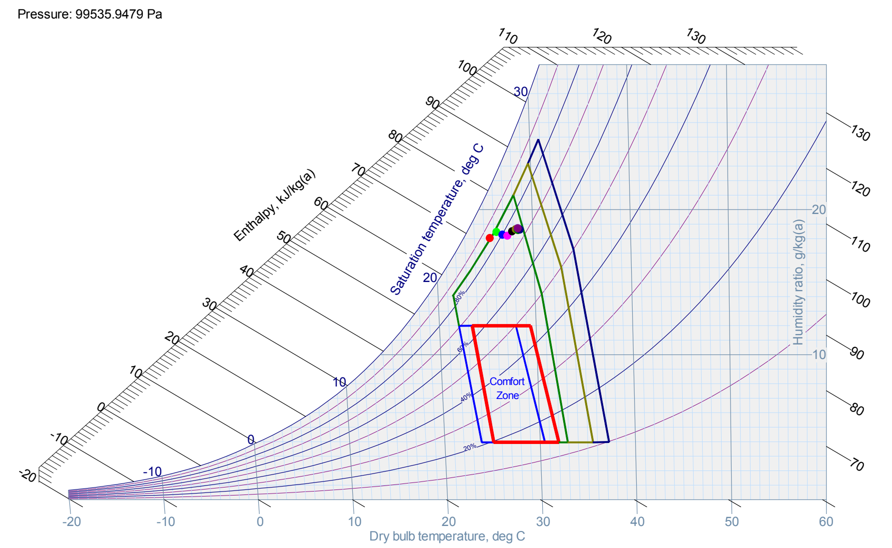
May


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

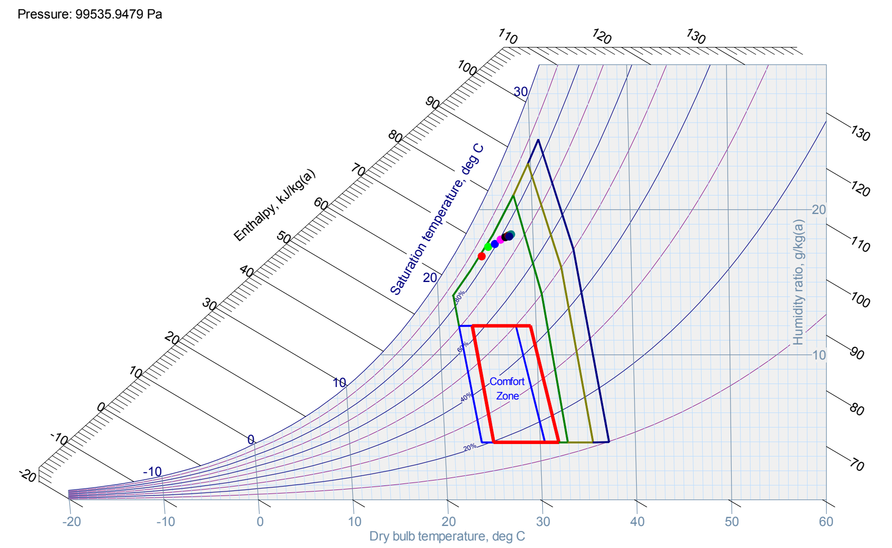
June


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

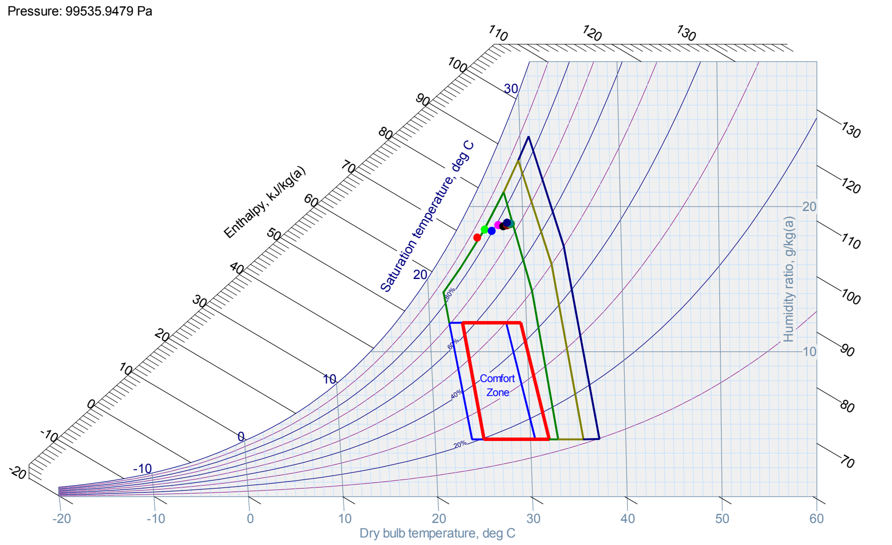
July


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

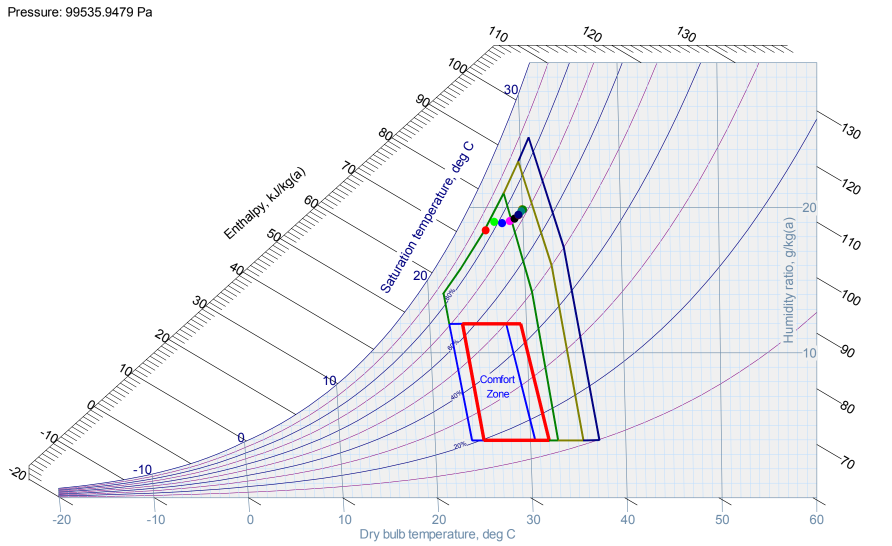
August


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

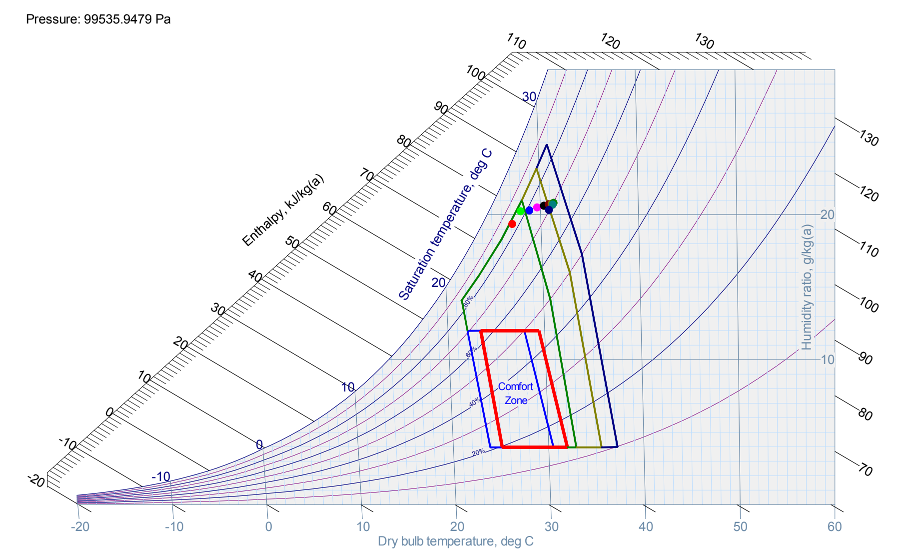
September



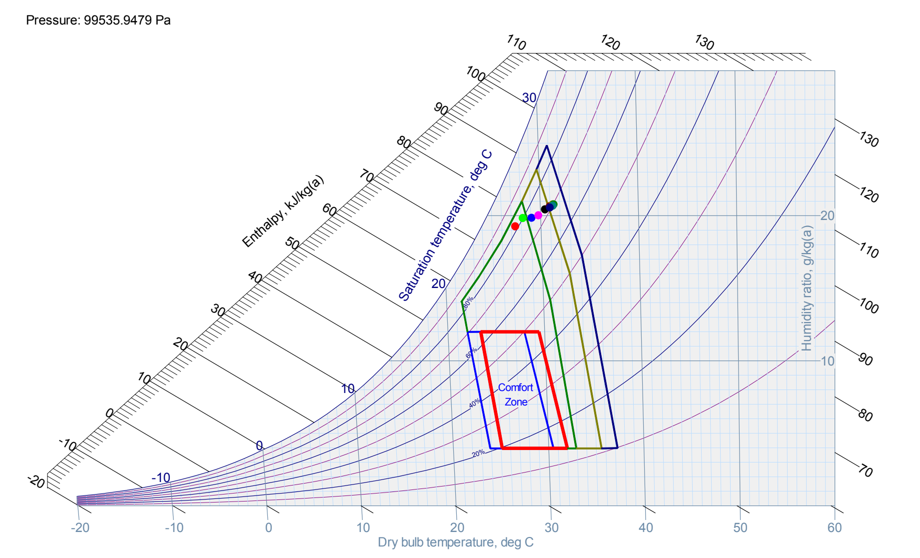
October



November

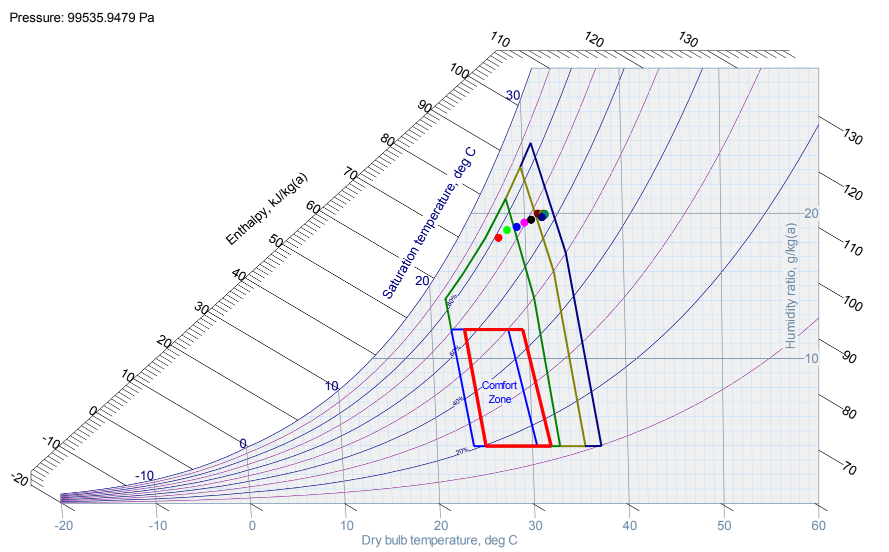


December

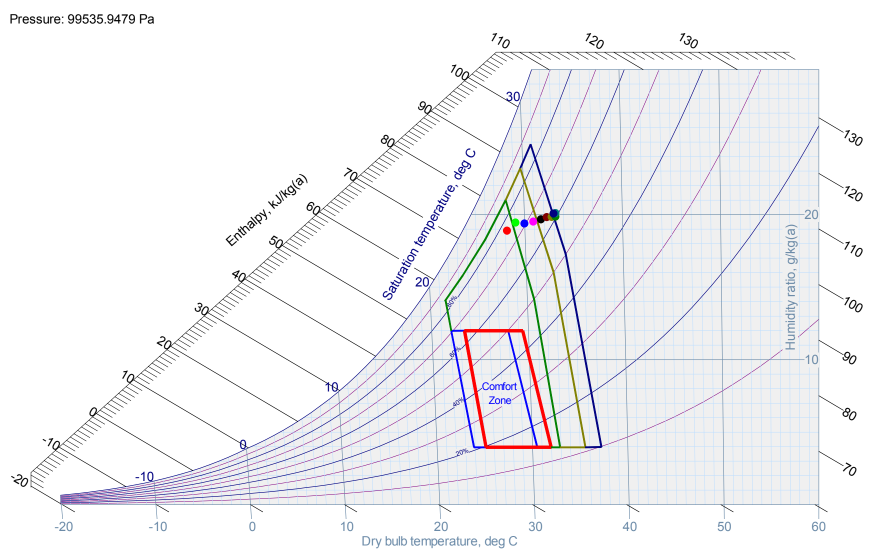


Building ANG (High mass, improved windows, efficient lighting and ACH 10/10)

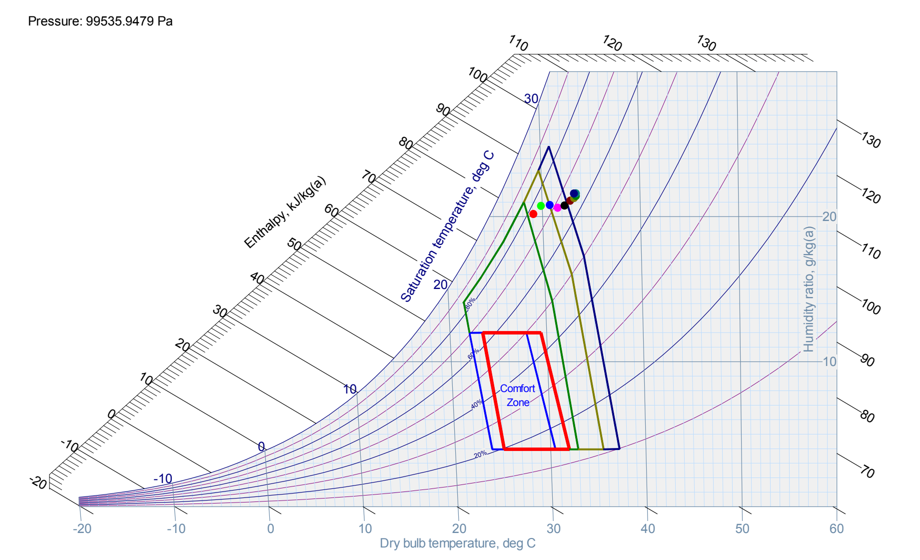
January



February

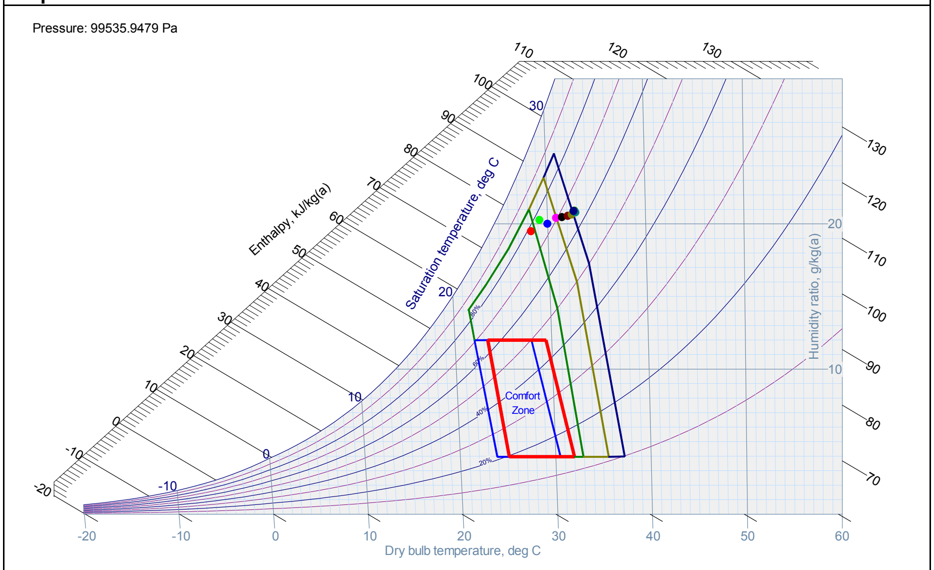


March



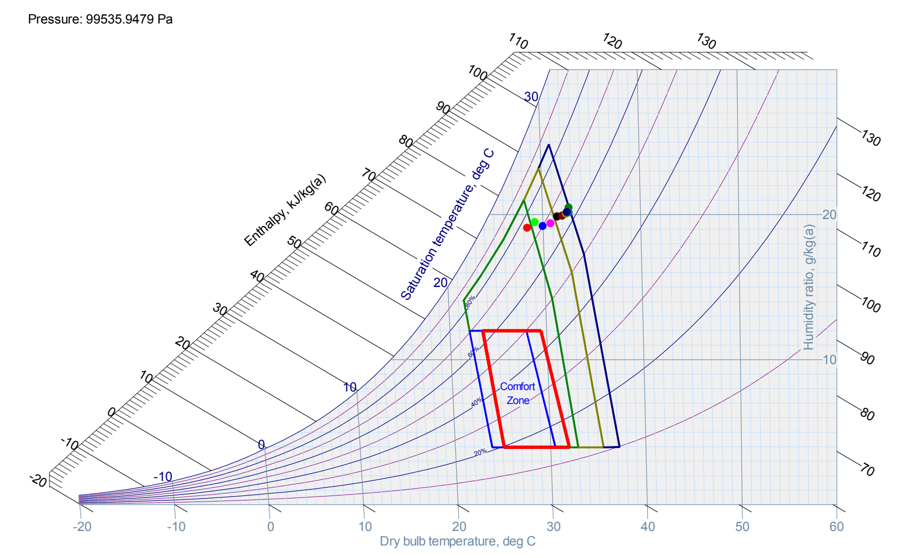
Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort
Zone

April



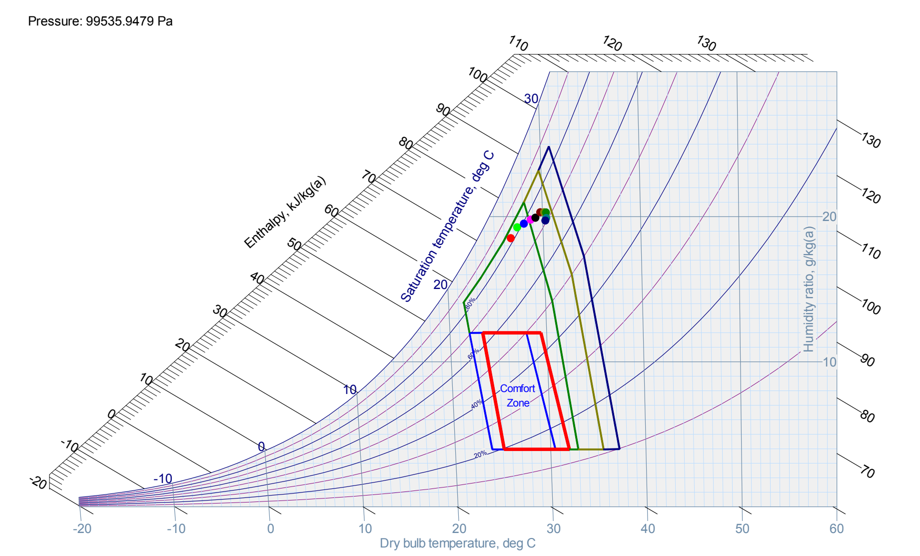
Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort
Zone

May



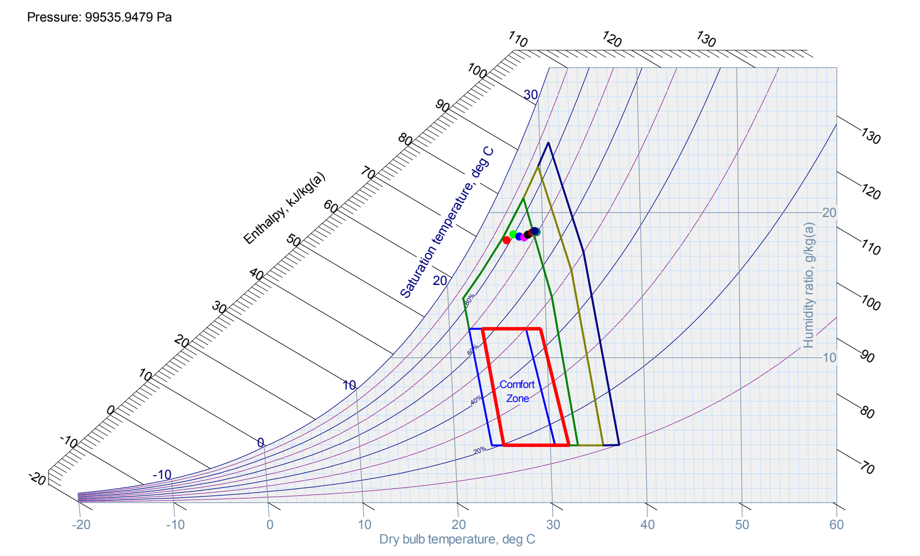
Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

June



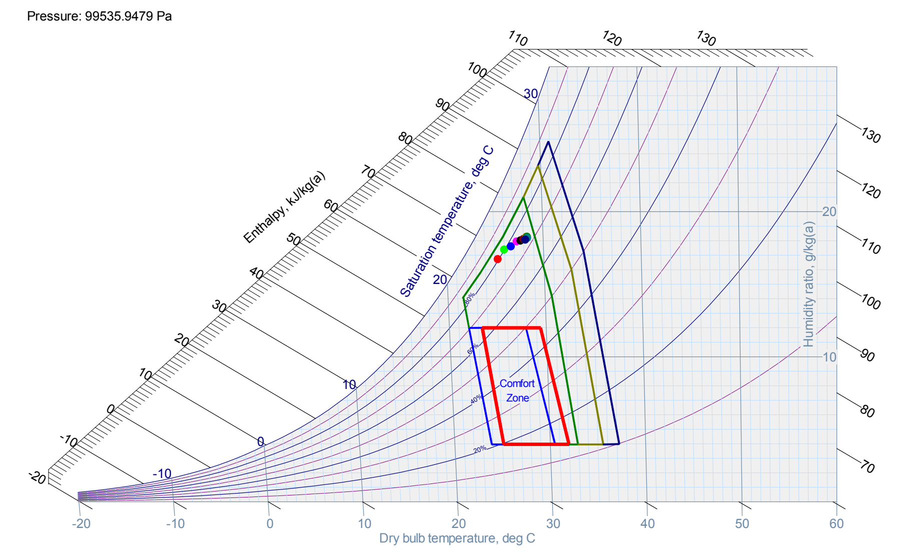
Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

July



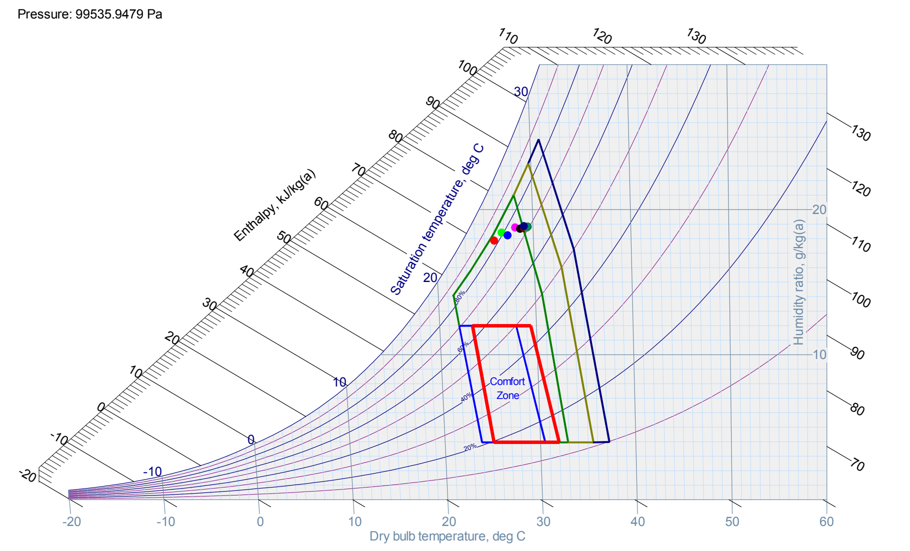
Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

August

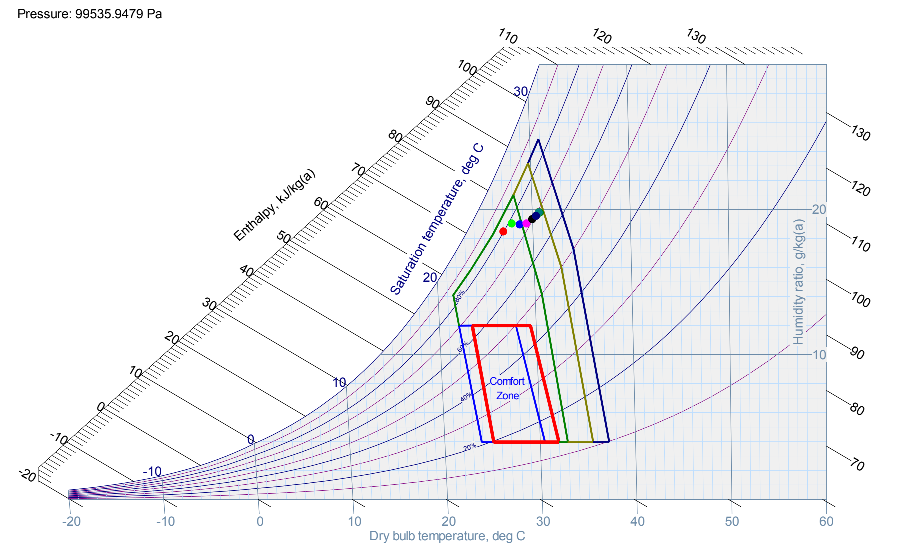


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

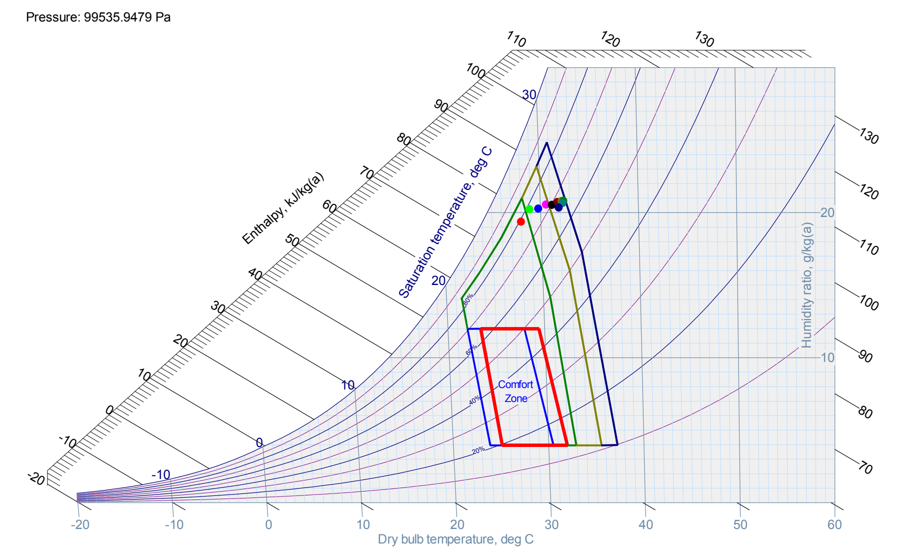
September



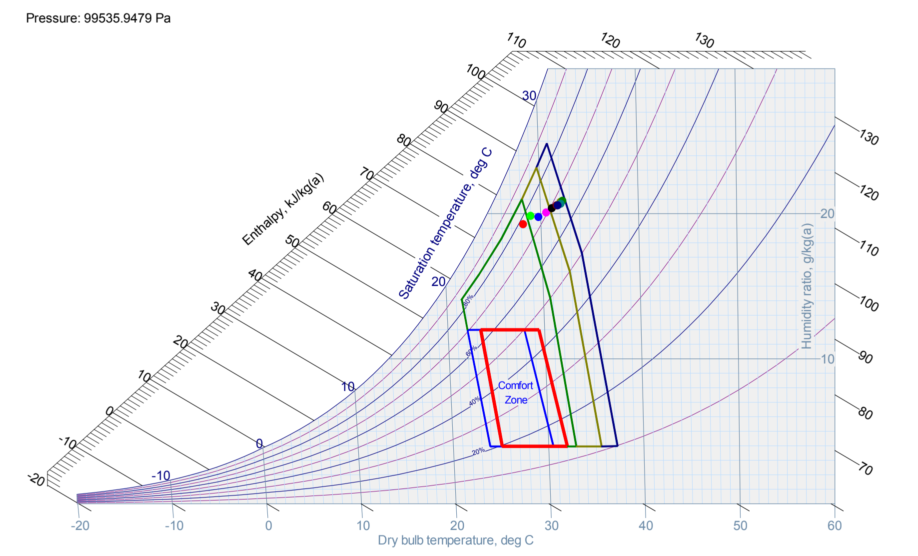
October



November

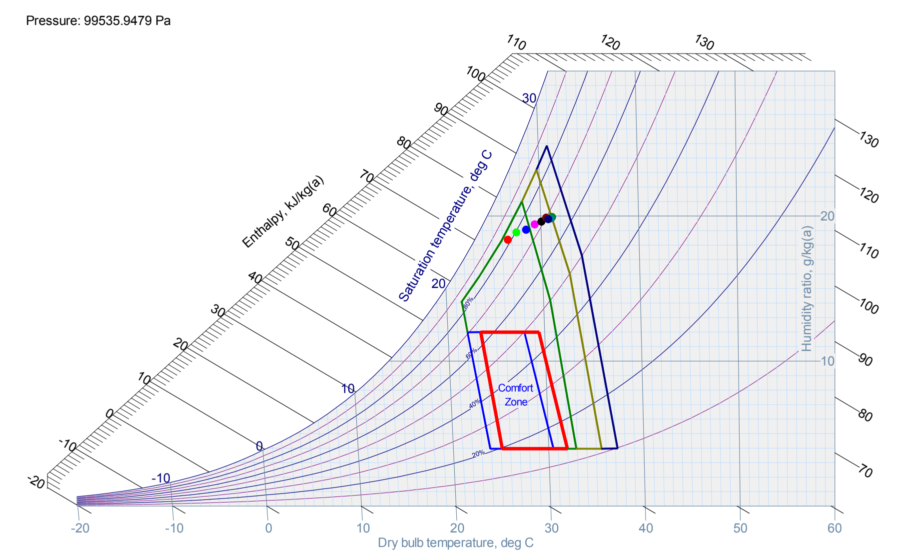


December

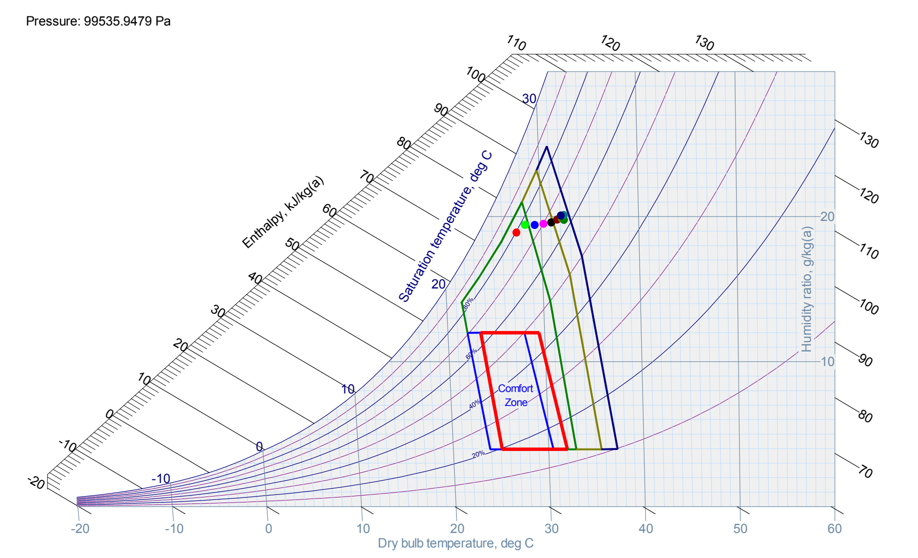


Building ROY (High mass, improved windows, efficient lighting and ACH 10/10)

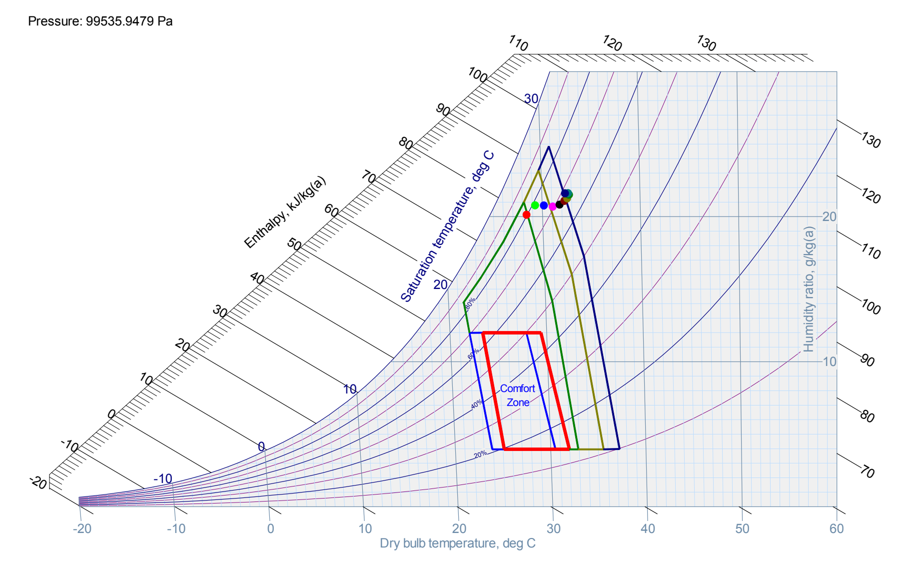
January



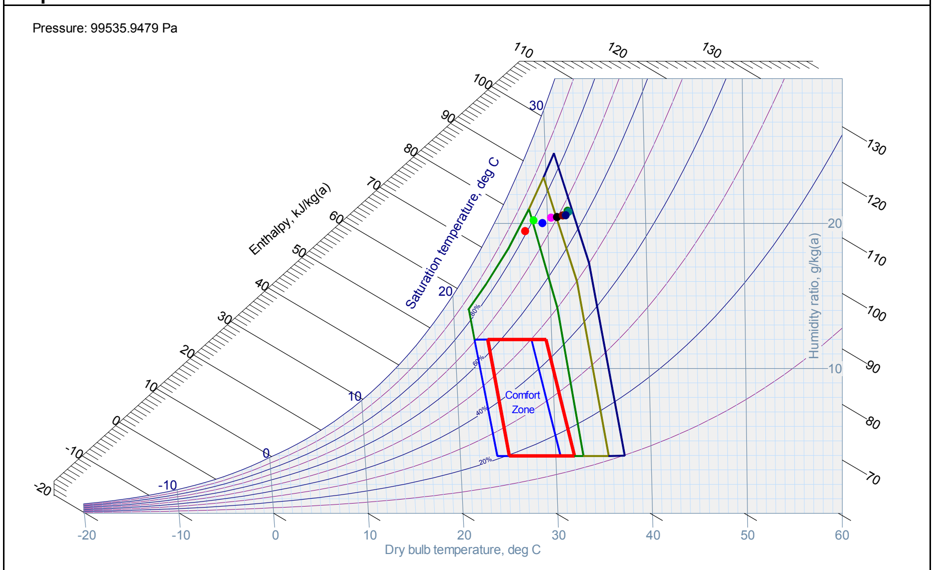
February



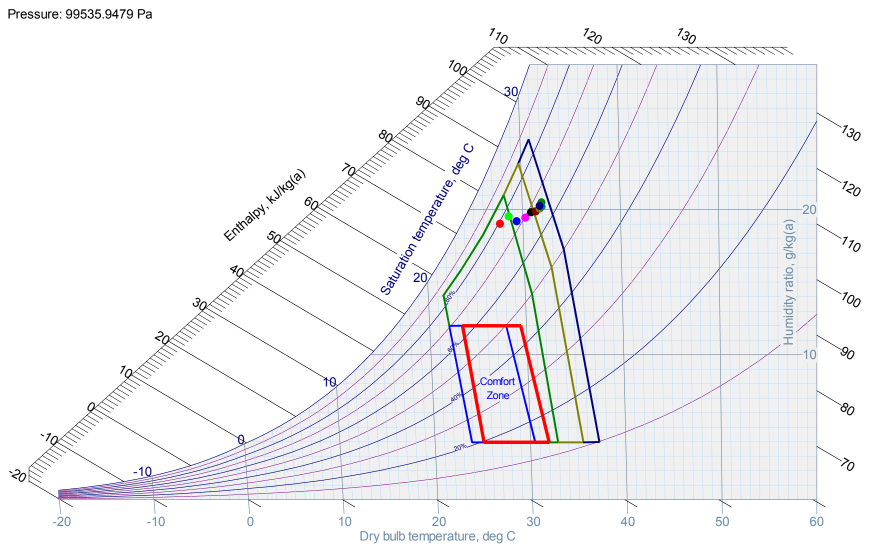
March


Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

April

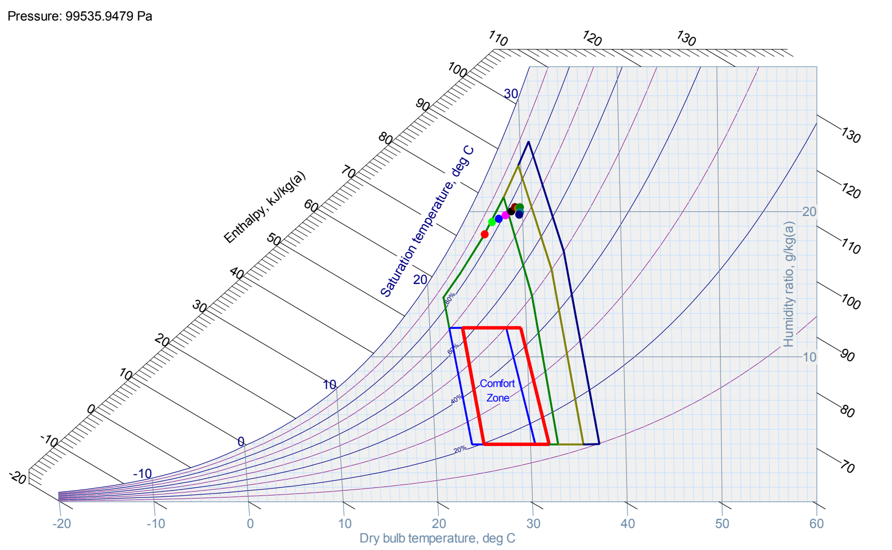

Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

May



Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

June



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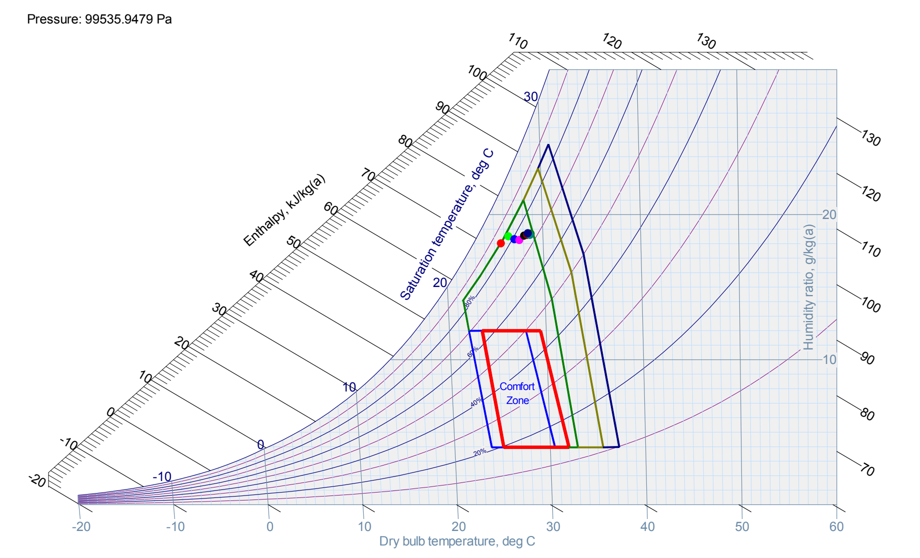
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

July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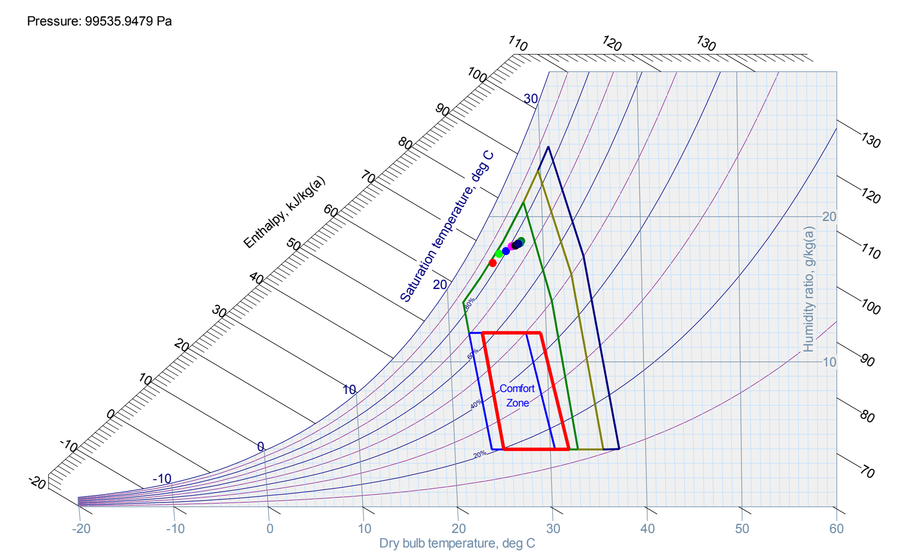
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

August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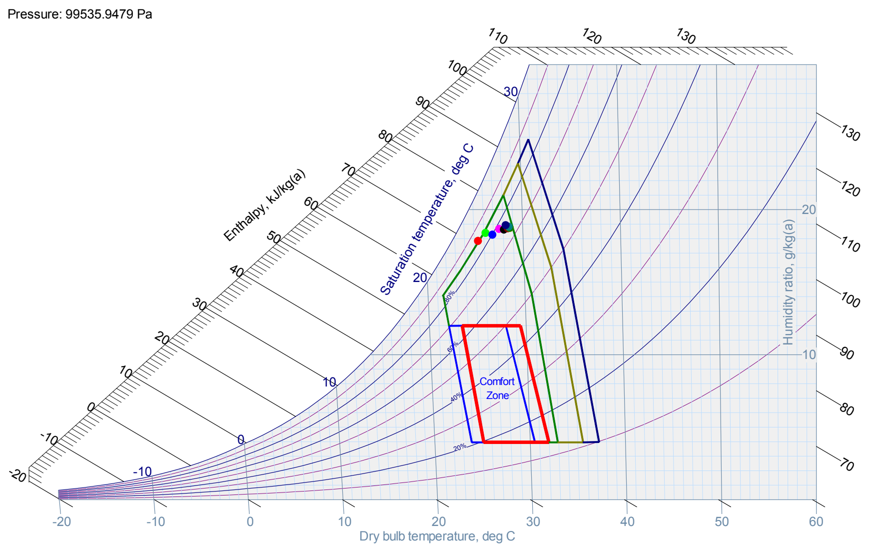
Humidity ratio, g/kg(a)
Comfort Zone
Dry bulb temperature, deg C

September



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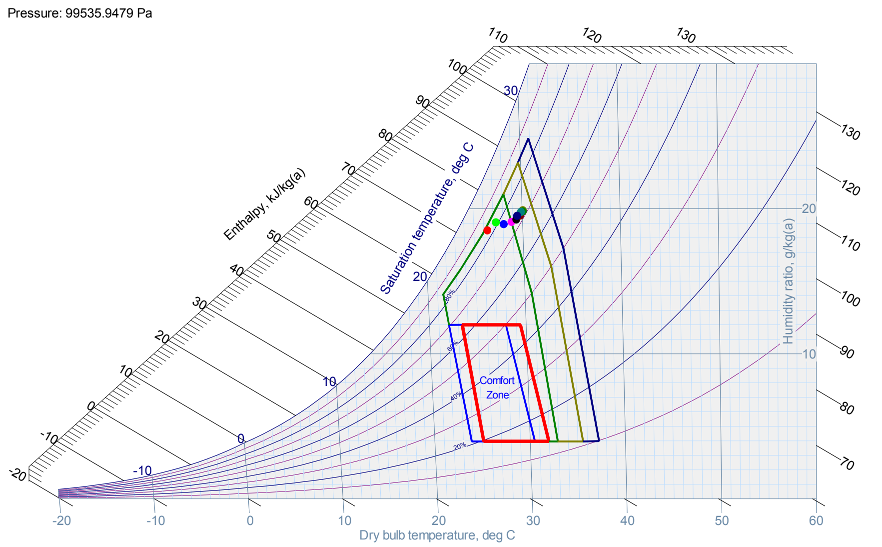

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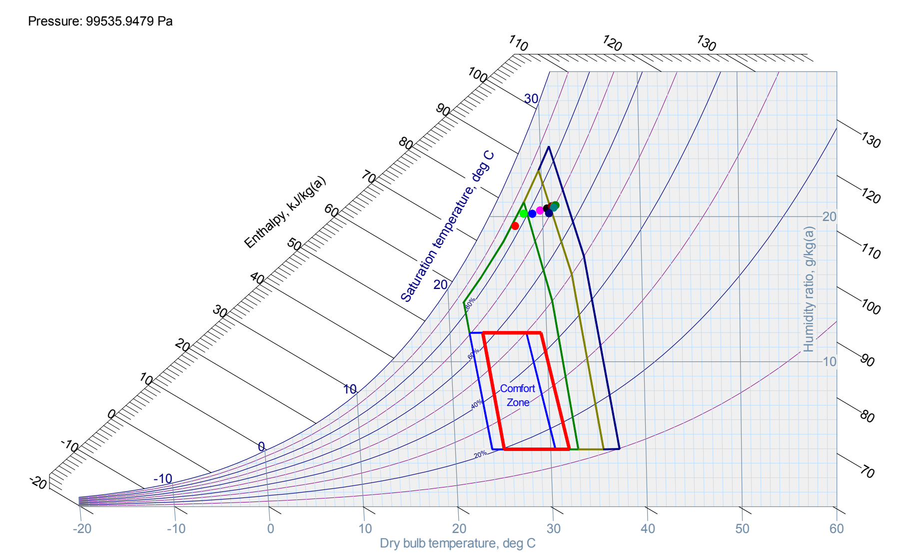

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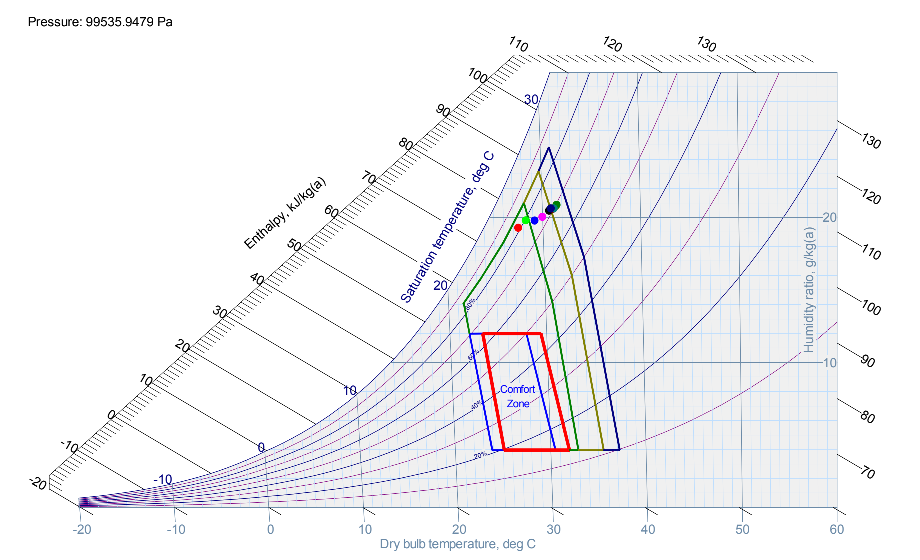
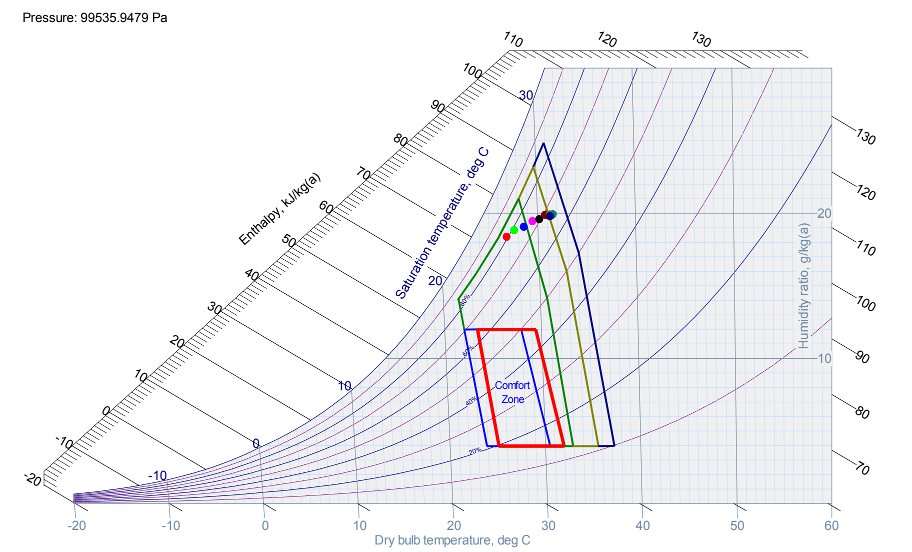


Building DCD (High mass, improved windows, efficient lighting and ACH 10/10)

January



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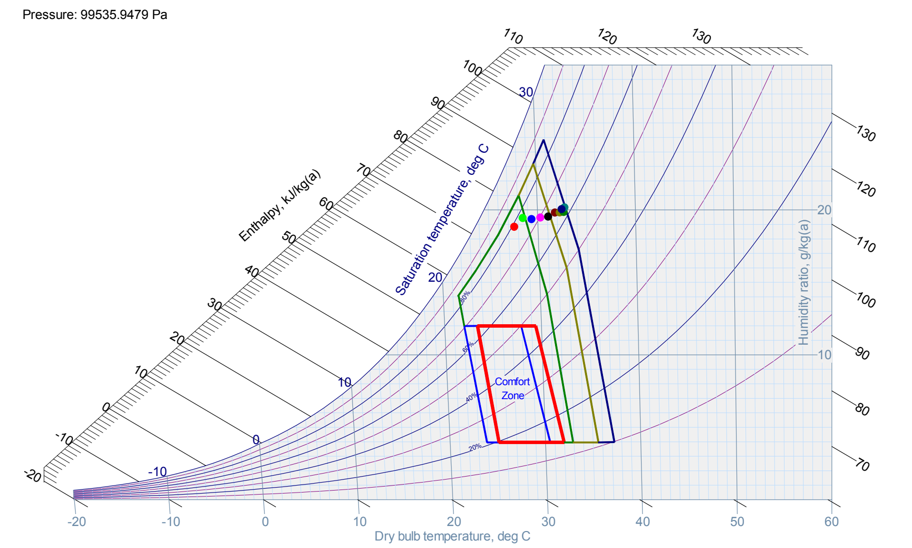

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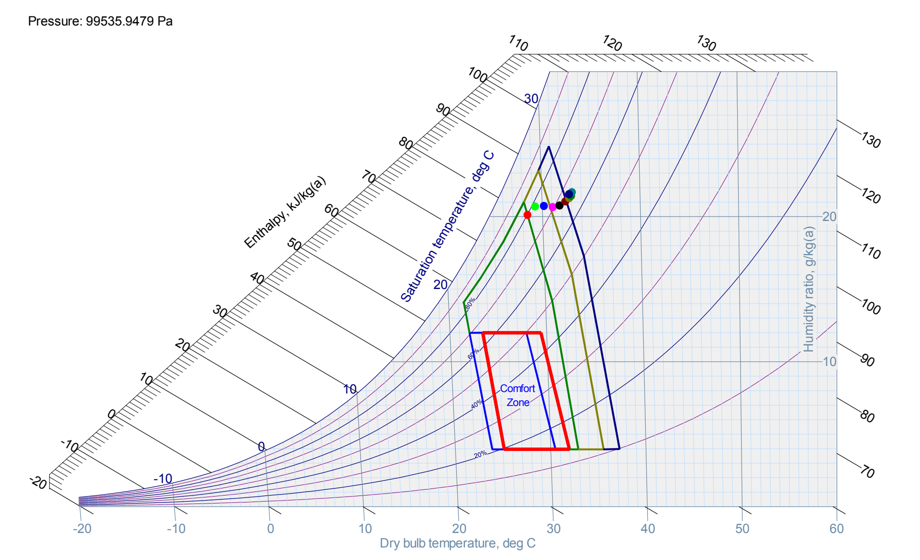
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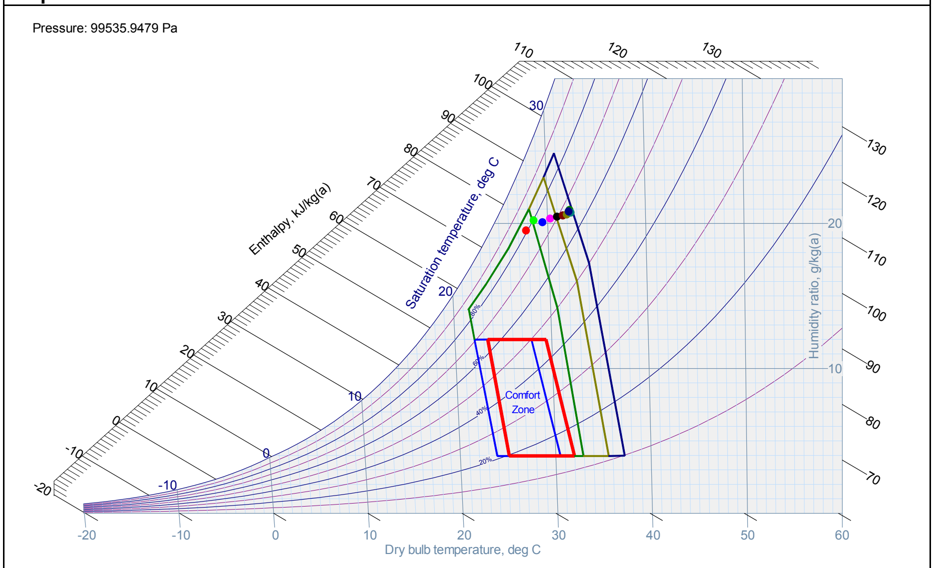
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

April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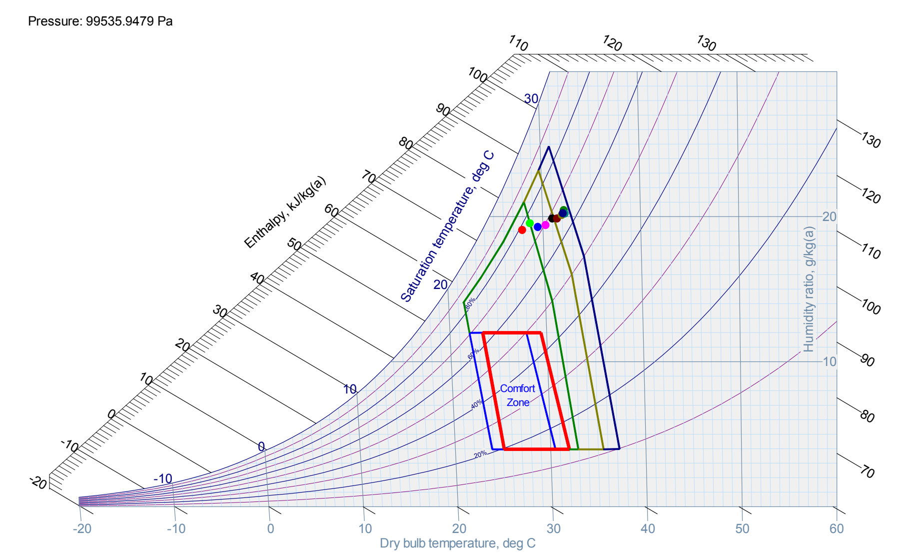
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

May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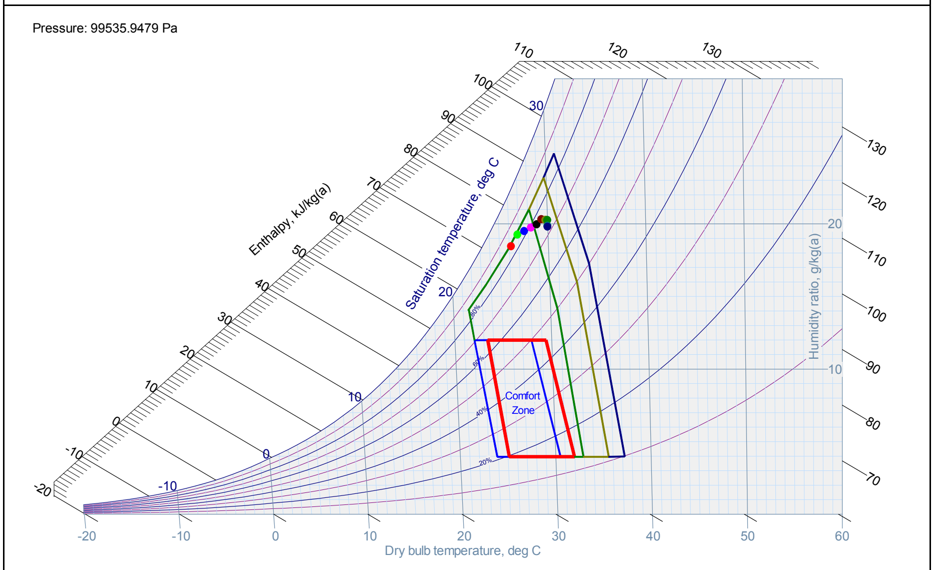
Dry bulb temperature, deg C
Comfort Zone

June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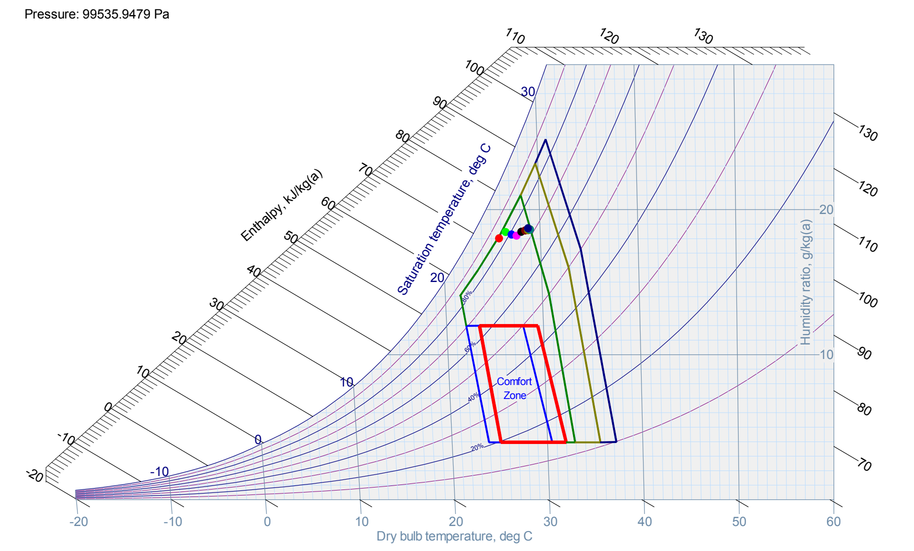
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

July



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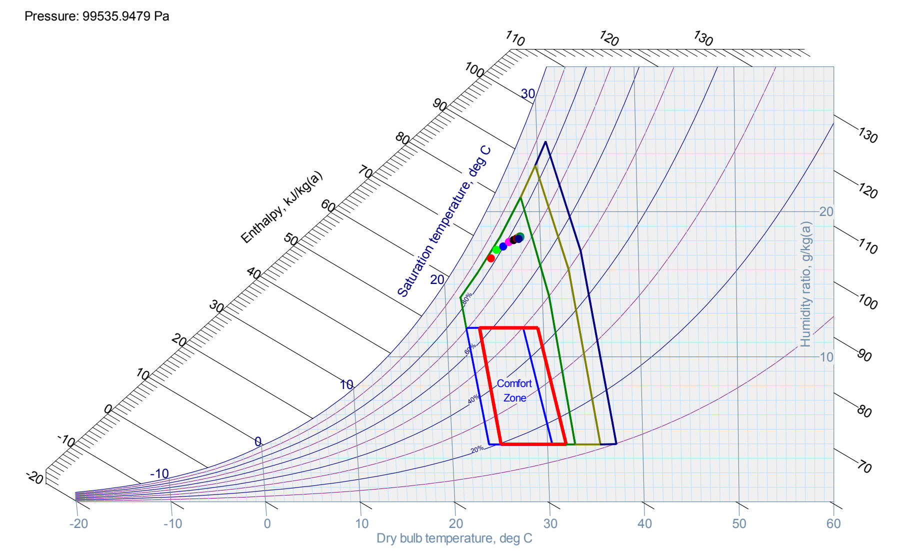
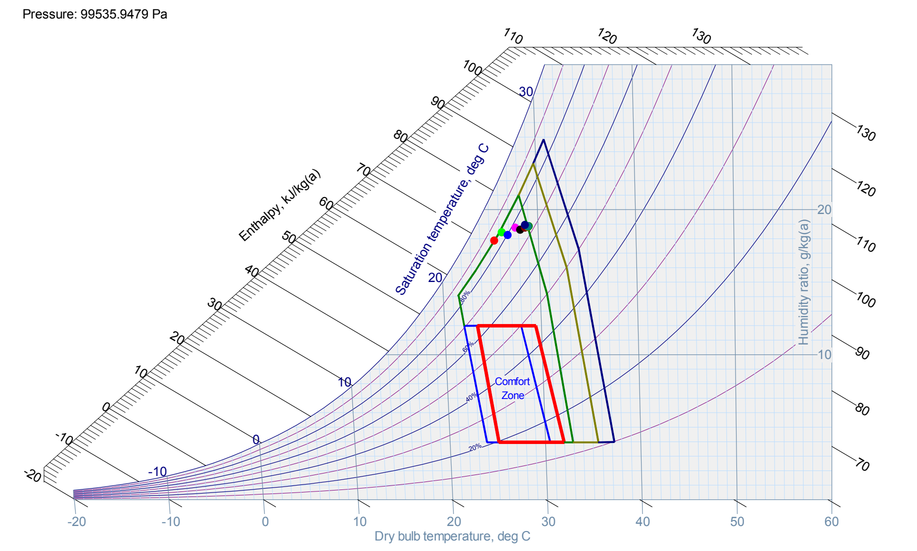
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

August



Pressure: 99535.9479 Pa
Enthalpy, kJ/kg(a)
Saturation temperature, deg C
Humidity ratio, g/kg(a)
Dry bulb temperature, deg C
Comfort Zone

September



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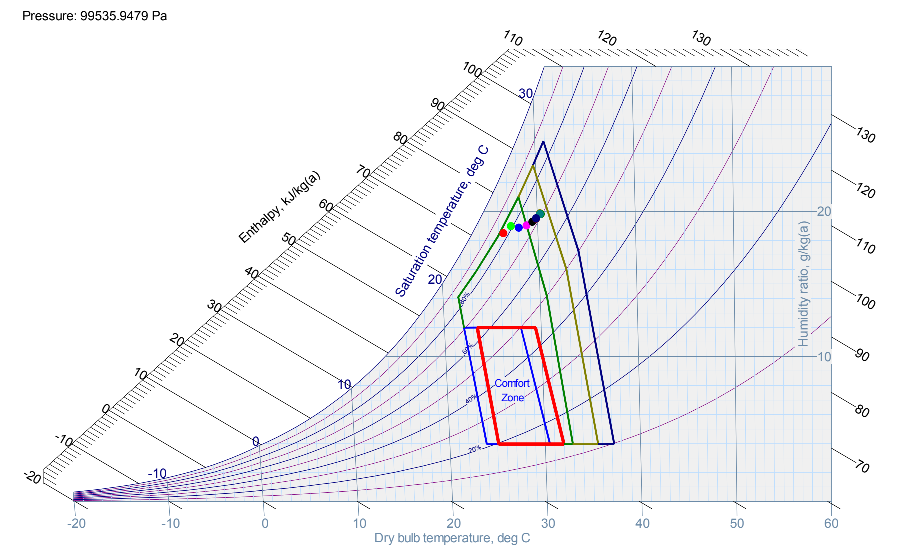
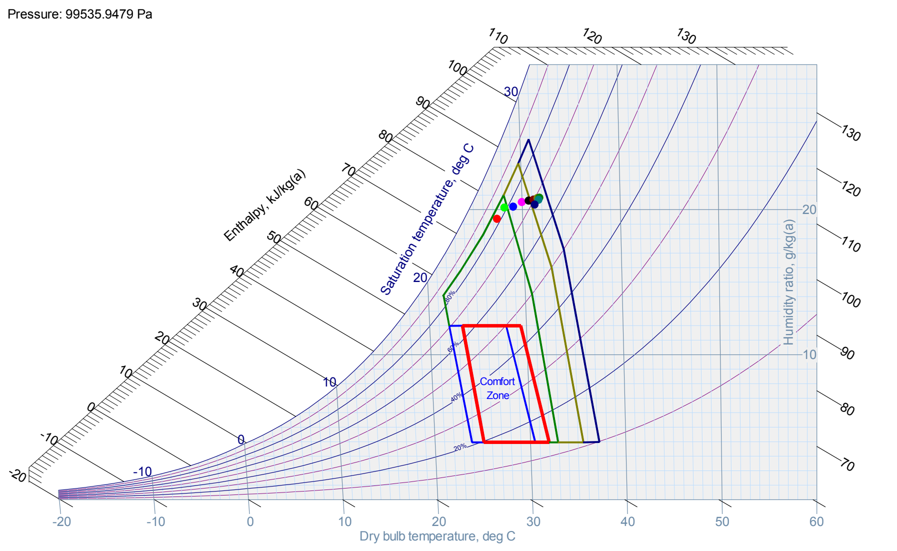
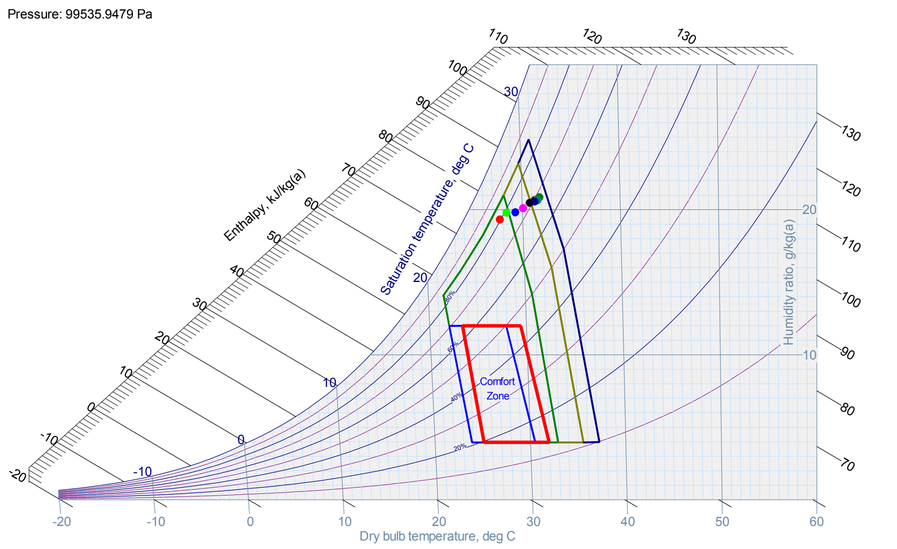


November



December



10.8 Appendix E: Energy use, CO_2 emissions and retrofitting evaluation

In the main chapter of the results on parametric simulation, (see pages 58 – 63), a summary on the outcome (annual cooling loads in $KWh.m^{-2}.a^{-1}$) of the active case was presented (see Fig. 59 – 64 and Table 6 - 11). For the description of codes for various cases see Table 3 and 4 (pages 39 - 40).

Moreover, the estimated energy use of the studied buildings has been calculated and presented. The illustrations are based on the base case (BC) and combined improvement (CI) scenarios. In all, about 48.500 Euros could be saved.

The CO_2 emissions resulted from the energy mix in Ghana and emission data from climate reports. The CO_2 savings resulting from the calculations for all buildings were ca. 100 tons.

Through retrofitting the buildings with improved windows, attic floor insulation, efficient lighting and natural ventilation, a payback time of 3 to 12 years could be calculated depending on building type.

<u>Energy use for all buildings</u>

The Tables E1 and E2 below show the annual energy use for all buildings with regard to the base case (BC) and combined improvement (CI) scenarios. The efficiency of the split unit air-condition systems (LGE 2008) were factored into the calculation of the annual energy use. Through the alternate application of the combined improvement building elements, 27% of the annual building energy use could be saved.

Table E1: Estimated annual energy use for all buildings

Building	Floor area [m²]	Cooling load (BC), [kWh.m^{-2}.a^{-1}]	Cooling load (CI), [kWh.m^{-2}.a^{-1}]	Efficiency of cooling system	Annual energy use (BC), [kWh]	Annual energy use (CI), [kWh]
CAP	795	149.00	117.00	2.60	307983.00	241839.00
KCR	1100	111.50	73.40	2.60	318890.00	209924.00
ANG	365	165.20	123.40	2.60	156774.80	117106.60
ROY	1740	126.20	89.70	2.60	570928.80	405802.80
DCD	280	166.20	133.40	2.60	120993.60	97115.20

For calculating the annual energy cost, the price of a unit of electricity for 2007 (0.12 €) was used. The annual energy cost could be reduced by 48,453.19 € (see Table E2).

Table E2: Estimated annual energy savings for all buildings

Building	Unit cost of electricity [€]	Annual energy cost (BC), [€]	Annual energy cost (CI), [€]	Annual energy savings, [€]	Annual energy savings, [kWh]
CAP	0.12	36957.96	29020.68	**7937.28**	66144.00
KCR	0.12	38266.80	25190.88	**13075.92**	108966.00
ANG	0.12	18812.98	14052.79	**4760.18**	39668.20
ROY	0.12	68511.46	48696.34	**19815.12**	165126.00
DCD	0.12	14519.23	11653.82	**2865.41**	23878.40
			Total	**48 453.91**	**403 782.60**

<u>CO_2 emissions</u>

For determining the CO_2 emissions, the energy mix in Ghana (Table E3) was referenced and percentages calculated. As high as 67% of electricity produced is generated from hydro plants. 44% of the produced electricity is used by the residential and commercial sectors.

Table E3: Energy production as at 2006 in Ghana

Item	Amount [GWh]	Percentage [%]
Oil	2810	**33.34 *(S1)***
Hydro	5619	**66.66 *(S1)***
Subtotal 01 (S1)	***8429***	
Imports	629	
Exports	755	
Subtotal 02	***8303***	
Energy sector	472	
Distribution losses	1318	15.64
Total Final Consumption	**6519**	**100**
Industry	3592	55.10
Residential	2080	31.91
Commercial	841	**12.90**
Others	6	0.09

Source: IEA (2006)

Further, the amount of carbon dioxide per kWh of generating plant based on climate reports ((Lightbucket 2008) and (Carbontrust 2008)) were used to derive the emission value for Ghana. The Tables E4 and E5 show the results (1kWh = 0,238 $kgCO_2$). The difference on emissions resulting from the BC and CI was ca. 100 tons ((see Table 6), valued at ca. 1700 €). With the European Union initiative to raise the price per ton

CO_2 to a sustainable level of about 120 € and the International Energy Agency proposing ca. 150 €, a minimum but considerable saving of about 12000 € could be achieved in the near future (IEA 2009).

Table E4: $kgCO_2$ per kWh (whole life cycle of generating plant)

Plant	Summary (av.) based on 1990 Technology	Recent values
Coal	0.914	0.52
Gas	0.444	0.194
Oil	0.679*	0.27
Hydro	0.018	0.009

**assumed value for oil resulting from the means between coal and gas emissions*

Table E5: $kgCO_2$ per kWh electricity use in Ghana

Plant	Percentage of electricity production (%)	$kgCO_2$ per kWh	Total $kgCO_2$ per kWh
Hydro	66.66	0.018	0.012
Oil	33.34	0.679	0.226
		1kWh =	**0.238**

Table E6: Estimated annual savings of $C0_2$ for all buildings

Building	Annual energy consumption (BC), [kWh]	Annual energy consumption (CI), [kWh]	$kgC0_2.kWh^{-1}$	Total $C0_2$ (BC), [kg]	Total $C0_2$ (CI), [kg]	**Annual savings, [$kgC0_2$]**
CAP	307983.00	241839.00	0.238	73299.95	57557.68	**15742.27**
KCR	318890.00	209924.00	0.238	75895.82	49961.91	**25933.91**
ANG	156774.80	117106.60	0.238	37312.40	27871.37	**9441.03**
ROY	570928.80	405802.80	0.238	135881.05	96581.07	**39299.99**
DCD	120993.60	97115.20	0.238	28796.48	23113.42	**5683.06**
			Total	**351185.71**	**255085.45**	**96100.26**

Retrofitting

A retrofitting evaluation was conducted using the savings that resulted from the combined improvement scenarios (Active case, (48453.91 Euros)).

An improved window was estimated to cost 500 € per 2.25m², efficient lighting – 10 € per bulb, natural ventilation (fan and opening mechanism per window) – 200 € and attic floor insulation costing 3 € per m².

The cost analysis resulted in a payback time of 3 to 12 years depending on building type. Tables E7 – E12 show the results on the above (from building to building).

Table E7: Installation cost estimates at CAP building

Building CAP (795 m²)					
Element	**Quantity**	**Unit area (m²)**	**Total area (m²)**	**Unit cost (€.m-²)**	**Total cost (€)**
Window	60	2.25	135	222.22	29999.70
Efficient Lighting	44	36.14	795	0.28	445.24
Ventilation mechanism	60	2.25	135	88.88	11998.80
Insulation	1	265	265	3	795.00
				TOTAL	**43238.74**

Table E8: Installation cost estimates at KCR building

Building KCR (1100 m²)					
Element	**Quantity**	**Unit area (m²)**	**Total area (m²)**	**Unit cost (€.m-²)**	**Total cost (€)**
Window	56	2.25	126	222.22	27999.72
Efficient Lighting	60	36.67	1100	0.28	616.06
Ventilation mechanism	56	2.25	126	88.88	11198.88
Insulation	1	550	550	3	1650.00
				TOTAL	**41464.66**

Table E9: Installation cost estimates at ANG building

Building ANG (365 m²)					
Element	**Quantity**	**Unit area (m²)**	**Total area (m²)**	**Unit cost (€.m-²)**	**Total cost (€)**
Window	19	2.25	42.75	222.22	9499.91
Efficient Lighting	20	36.5	365	0.28	204.40
Ventilation mechanism	19	2.25	43	88.88	3799.62
Insulation	1	350	350	3	1050.00
				TOTAL	**14553.93**

Table E10: Installation cost estimates at ROY building

Building ROY (1740 m²)					
Element	**Quantity**	**Unit area (m²)**	**Total area (m²)**	**Unit cost (€.m-²)**	**Total cost (€)**
Curtain wall	330	2.25	742.5	222.22	164998.35
Efficient Lighting	104	33.46	1740	0.28	974.36
Ventilation mechanism	330	2.25	743	88.88	65993.40
Insulation	1	580	580	3	1740.00
				TOTAL	**233706,11**

Table E11: Installation cost estimates at DCD building

Building DCD (280 m²)					
Element	**Quantity**	**Unit area (m²)**	**Total area (m²)**	**Unit cost (€.m-²)**	**Total cost (€)**
Window	29	2.25	65.25	222.22	14499.86
Efficient Lighting	16	35	280	0.28	156.80
Ventilation mechanism	29	2.25	65	88.88	5799.42
Insulation	1	140	140	3	420.00
				TOTAL	**20876,08**

Table E12: Payback time for all buildings

	CAP	KCR	ANG	ROY	DCD
Installation cost(€)	43238.74	41464.66	14553.93	233706.11	20876.08
Savings per Year (€)	7937.28	13075.92	4760.18	19815.12	2865.41
Payback Time (Years)	**5.45**	**3.17**	**3.06**	**11.79**	**7.29**

The above analysis illustrates the potential of improved building elements and the consequential sustainable energy consumption and reduction of emissions. This calls for investments in efficient and improved building systems as well as the development and implementation of building energy codes in Ghana.

As much as 20 to 35% of energy consumption and 27% of carbon dioxide emissions could be saved. The investments in retrofitting the buildings through improved systems have a short payback time (3 to 12 years).

The building industry in Ghana could contribute immensely to reducing energy use of buildings if attention is given to sustainable measures.

However, investments and technological know-how are needed to face the challenges of climate change.

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11 PUBLICATIONS

Koranteng, C., Mahdavi, A., Orehounig, C. and Pröglhof, C. (2009). Thermal Performance of Office Buildings in Ghana. In Proceedings of the 11th International IBPSA Conference, Building Simulation 2009, Glasgow, Scotland, 27–30 July, pp. 1880-1886.

Koranteng, C. and Mahdavi, A. (2010). An Inquiry into the Thermal Performance of Five Office Buildings in Ghana. CLIMA 2010, 10th REHVA World Congress, Sustainable Energy Use in Buildings, Topkaki, Instanbul, Turkey, 9-12 May, 2010

(Abstract accepted, paper in progress)

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2003 – 2007	Computers in Environmental Design
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Research Area

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Projects

2003 – 2007	Design and Construction of Various Housing and Commercial Buildings in Ghana

Education

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