A STUDY INTO THE THERMAL PERFORMANCE OF LOW-RISE OFFICE BUILDINGS IN GHANA

Christian Koranteng[1] and Ardeshir Mahdavi[2]
[1]Department of Architecture
Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[2]Department of Building Physics and Building Ecology
Vienna University of Technology, Austria

ABSTRACT

This paper illustrates the results of the thermal conditions in a selected number of office buildings in Kumasi, Ghana. The monitored data was used to evaluate indoor environmental conditions and to calibrate a number of thermal simulation models of the buildings toward reduction of cooling requirements. Moreover, the impact of thermal retrofit measures in reducing carbon dioxide emissions was assessed and the amortization times for investments in such retrofit measures were estimated. Improvements in building fabric and controls (with payback times of 3 to 12 years) could reduce buildings' cooling loads (20% to 35%) and CO_2 emissions around 27%.

INTRODUCTION

In Ghana, the growing demand for energy is caused by, amongst other factors, the increasing use of air-conditioners in buildings. This is mainly the consequence of Ghana's regional (warm and humid) climatic characteristics (Figure 1).

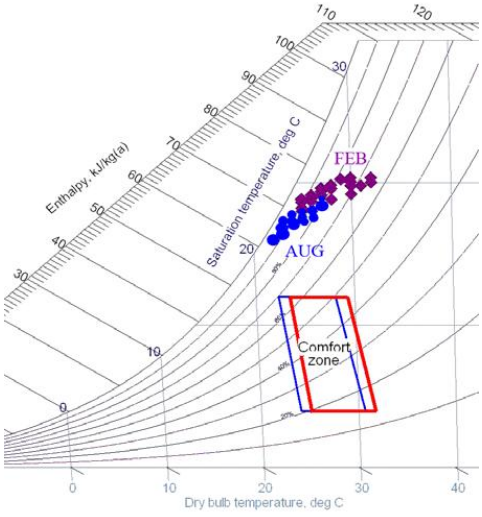

Figure 1 Mean hourly outdoor temperature and relative humidity values in Kumasi for representative days in the months of February and August (based on data generated via Meteotest 2008)

Moreover, the energy supply falls short of demand. The Energy Commission Ghana (ECG, 2007) reports that the energy use of households increased from 26% (of total national energy use) in 2000 to 37% in 2005. Within the same period, energy use of the commercial sector doubled (7% to 14%). In 1990, Ghana had a surplus of electricity of 3545 GWh, whereas in 2004, a deficit of 203 GWh was recorded.

Currently, the local practices in building design and construction are typically not supported by systematic analysis and evaluation of thermally relevant building features (orientation, envelope, glazing ratio, shading devices, and thermal mass). Thus, design decision making is not sufficiently informed by relevant expertise regarding energy-efficient building design methods and technologies.

In this context, the present paper pursues the following objectives:

a) Long-term monitoring and evaluation of the thermal conditions (including interviews on occupants thermal perception) in a selected number of office buildings in Kumasi, Ghana.

b) Generation of calibrated simulation models of these buildings.

c) Simulation-based exploration of thermal retrofit options toward reduction of cooling demand.

d) Assessment of carbon dioxide (CO_2) emissions and retrofitting evaluation.

METHOD

Selection of buildings

Five office buildings in Kumasi were selected for the studies (see Table 1 and Figure 2 to 6). These buildings are representative of the majority of existing low-rise office buildings in Kumasi. The applied cooling systems typically involve split air-conditioning units.

Table 1
Overview of the selected office buildings with function, net floor area (in m2) and thermal controls

OBJECT	FUNCTION	FLOOR AREA	THERMAL CONTROL
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

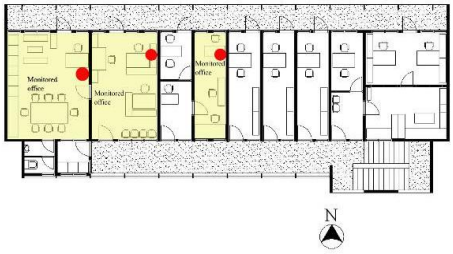

Figure 2 Schematic plan of offices in CAP

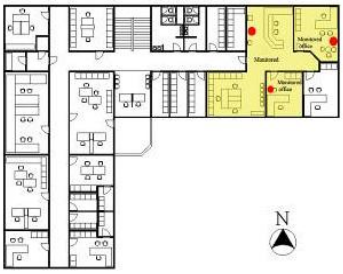

Figure 3 Schematic plan of offices in KCR

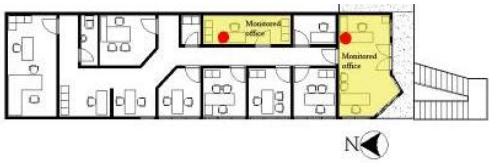

Figure 4 Schematic plan of offices in ANG

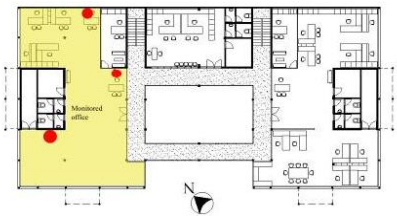

Figure 5 Schematic plan of offices in ROY

Figure 6 Schematic plan of offices in DCD

Air temperature and relative humidity values were measured both inside (in a number of office rooms in each building) and outside the buildings over a period of 12 months (September 2007 to August 2008). The location of the installed data loggers inside each building are marked in the respective schematic floor plans (Figure 2 to 6).

Monitored environmental data

Detailed meteorological data for Kumasi could not be obtained. Only daily maximum and minimum values of air temperature and relative humidity were available. Due to budgetary constraints, dedicated weather stations could not be used at each building's location. Therefore, low-cost data loggers were also applied to monitor outdoor air temperature and outdoor relative humidity.

Indoor thermal conditions

To evaluate the existing indoor climate conditions, measured air temperature and relative humidity values were plotted in psychrometric charts. Further, the occupants were interviewed on their views on indoor climate. In all, 64 occupants answered a set of questions.

Calibration of the simulation tool

A thermal simulation application (EDSL, 2008) was used to explore measures that could improve the thermal performance of office buildings in Ghana. To enhance the reliability of this parametric exploration and effectively evaluate the designs, the simulation models were calibrated based on measured data (this is against the background that system performance declines with time, precise prediction of internal loads, etc). We followed a strategy documented in previous publications (see, for example, Mahdavi et al., 2007). As 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. Thereby the assumed infiltration values (day/night ACH = 2-20/0,5-3 h^{-1}) was

based on the different fenestration of the buildings (louvre blade, sliding glass and curtain wall).

Parametric study of thermal improvement scenarios (Active case)

Using the calibrated thermal performance simulation models, we explored various improvement options (concerning glazing and shading, ventilation, thermal mass, efficient lighting) that could reduce cooling loads as well as the need for extensive active devices for air-conditioning. Information regarding the various scenarios considered for the simulations is summarized in Tables 2 and 3. Cooling energy loads (sensible and latent) were used as the performance indicator (active operation assumption).

Table 2
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}; occupants' load = 10 to 14 W.m^{-2}; equipment load = 1 to 7 W.m^{-2}; floors carpeted, no attic space
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 3
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 elec. 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}

Parametric study of thermal improvement scenarios (Passive case)

In the passive operation assumption (PC, Table 3), combined improvement scenarios (high mass, efficient lighting, improved windows and natural ventilation) were deployed to explore the possibility of operating the building without air-conditioning. To evaluate the resulting thermal comfort conditions, three options were considered:

First, the mean overheating (OH_m) was used (see Eq. 1).

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

Here $\theta_{i,j}$ denotes 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 (neutrality temperature for 90% acceptability (Szokolay, 2004)) 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 reference indoor temperature (neutrality temperature) for Kumasi was calculated to be - depending on the time of the year - between 25.4 °C (August) and 26.5 °C (February).

Second, the temperature and relative humidity values, together with assumption regarding clothing value (*CLO* = 0.7), metabolic rate (*MET* = 1), and air speed (0.07 to 0.21 m.s^{-1}) were used to determine the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) (Fanger, 1973). Thereby, based on the results of previous research on natural ventilation (Proeglhof, 2004), the following relationship (Eq. 2) was applied to convert air change rate assumptions into air speed assumptions:

$$v = (ACH + 3.43)/63.1 \qquad (2)$$

Here, *v* denotes air speed (in m.s^{-1}) and *ACH* air change rate (in h^{-1}).

Third, the indoor air temperatures and relative humidity values were plotted on psychrometric charts together with respective comfort zones derived based on the adaptive thermal comfort theory (Szokolay, 2004). Given the high relative humidity values, an extension of the comfort zone was considered via higher fan-induced air velocities (0.5 - 1.5m.s^{-1}) to harness the effect of physiological cooling (Szokolay, 2004).

Energy use, CO2 emissions and retrofitting evaluation

Moreover, the energy use and associated CO_2 emissions as well as energy expenses were estimated

for the base case (BC) and combined improvement scenarios (CI). Toward this end, simulated cooling loads, assumed efficiency of the split air-conditioning systems, unit price of electricity, and assumptions pertaining to applicable energy mix in Kumasi, Ghana (IEA, 2006) were deployed. The retrofitting options were assessed economically, taking the energy use saving potential into account and using a simple payback analysis approach.

RESULTS

Measured external air temperature values

Figure 7 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 official weather station. These results suggest a good agreement.

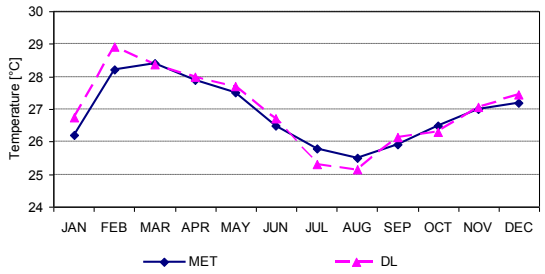

Figure 7 Comparison of mean outdoor temperature measurements at office locations (DL) with Kumasi weather station data (MET)

Indoor thermal conditions

Selected psychrometric charts (for buildings CAP and KCR) with measured indoor temperature and relative humidity values are given in Figure 8 and 9.

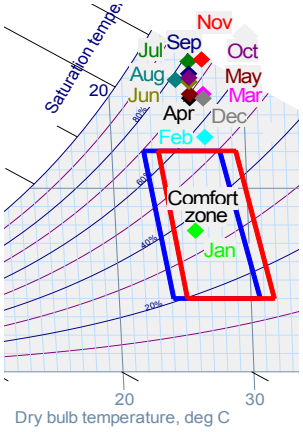

Figure 8 Mean daily temperature and relative humidity values (averaged over all days in a month) in CAP building.

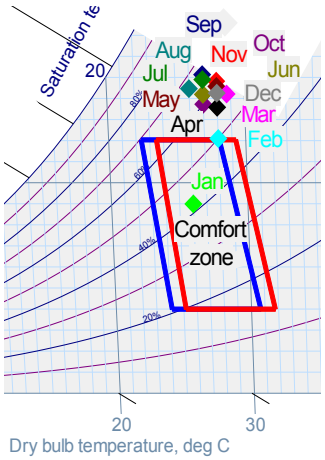

Figure 9 Mean daily temperature and relative humidity values (averaged over all days in a month) in KCR building (based on measured data from 8 am to 5 pm)

Figure 10 demonstrates the occupants subjective view of thermal conditions prevailing at the workspaces. The results on their aggregate opinion suggests satisfactory conditions contrary to the psychrometric chart plots (Figure 8 and 9). The representations of the plots outside the comfort zone are due to the higher relative humidity values and not the temperature.

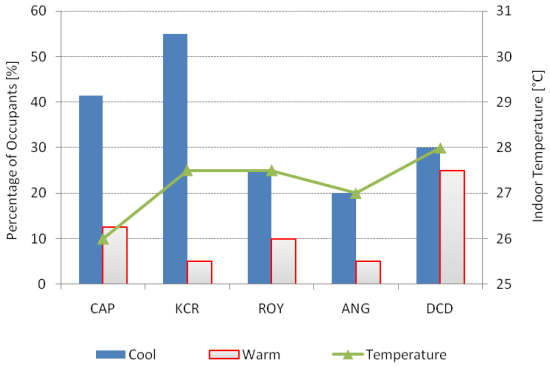

Figure 10 Occupants perception of thermal comfort during the year

Weather file versus measured data

As mentioned earlier, simulation model calibration was performed using segments of a standard weather file with a good fit to our local measurements. Figure 11 and 12 show samples of time intervals where the weather file data (WF) and our measurements at building sites (DL) showed a relatively good agreement. These weather file segments were subsequently used to predict indoor temperature values and compare those with the respective measured temperatures.

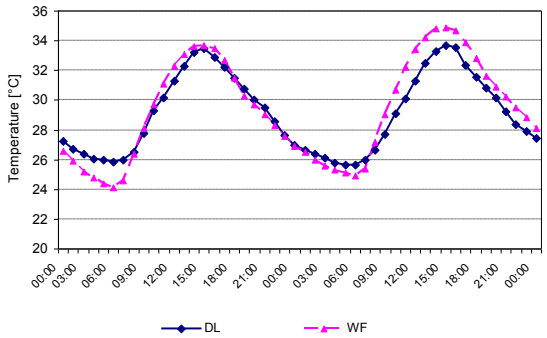

Figure 11 Outdoor air temperature segments (WF) as against measurements (DL) at building location (KCR)

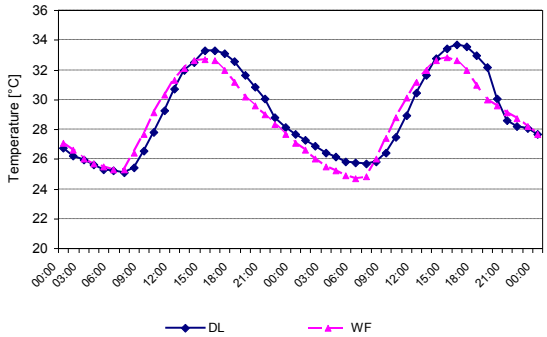

Figure 12 Outdoor air temperature segments (WF) as against measurements (DL) at building location (ANG)

Comparison of measurements and simulations

Predictions of the calibrated simulation models compared well with the measured values. Figure 13 and 14 provide examples of measured versus simulated indoor air temperatures in CAP and KCR. Moreover, Figure 15 provides an overview of the relationship between measured and simulated indoor air temperatures in terms of regression lines) in four buildings.

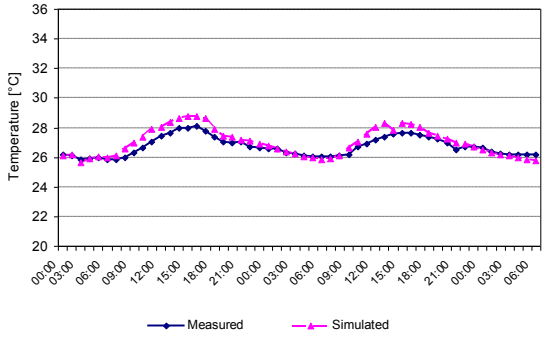

Figure 13 Measured versus simulation indoor air temperatures in CAP

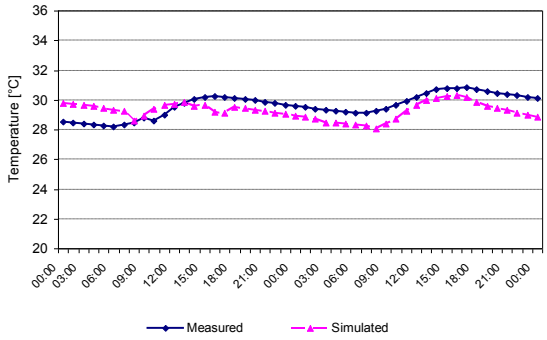

Figure 14 Measured versus simulation indoor air temperatures in KCR

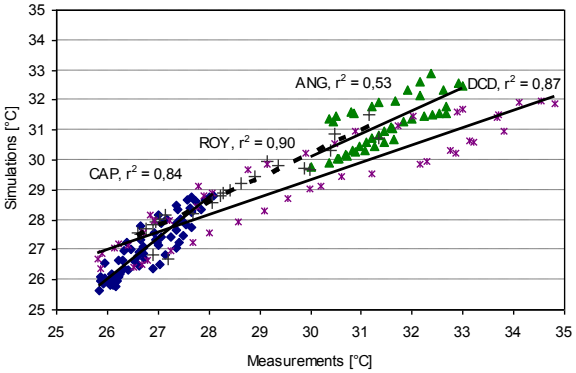

Figure 15 Overview of the relationship between measured and simulated indoor air temperatures in four reference buildings

Parametric simulations

Figure 16 to 20 shows, the simulated cooling loads (sensible and latent) for a number of scenarios (see Tables 2 and 3).

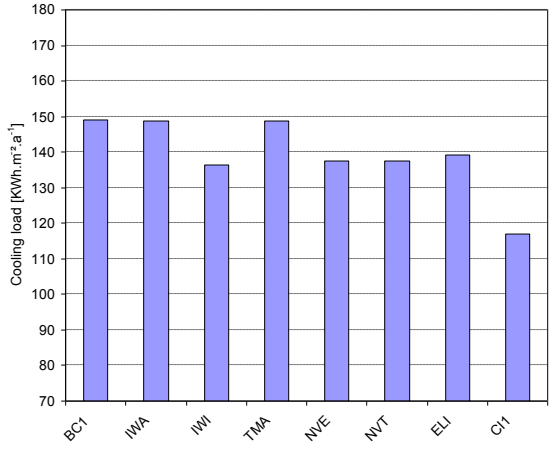

Figure 16 Simulated cooling loads (CAP) for different scenarios (see Tables 2 and 3)

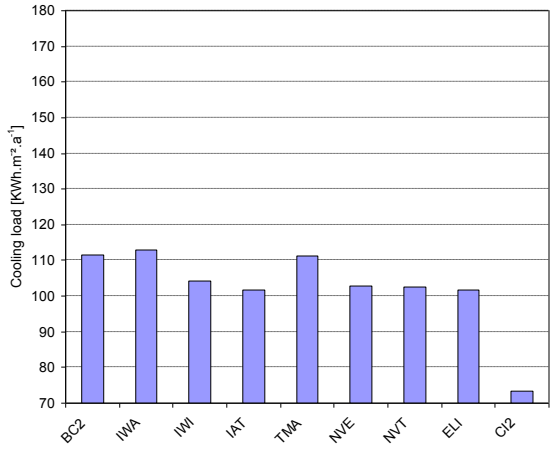

Figure 17 Simulated cooling loads (KCR) for different scenarios (see Tables 2 and 3)

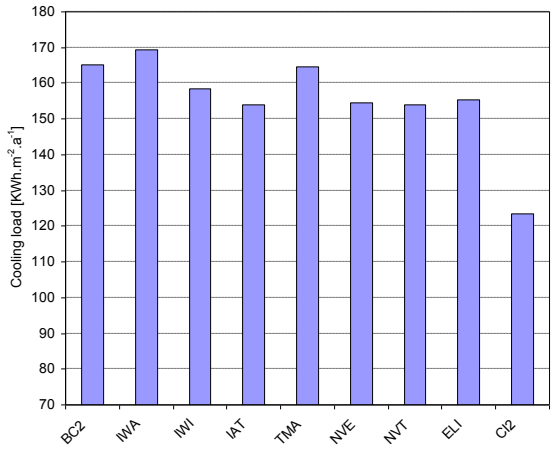

Figure 18 Simulated cooling loads (ANG) for different scenarios (see Tables 2 and 3)

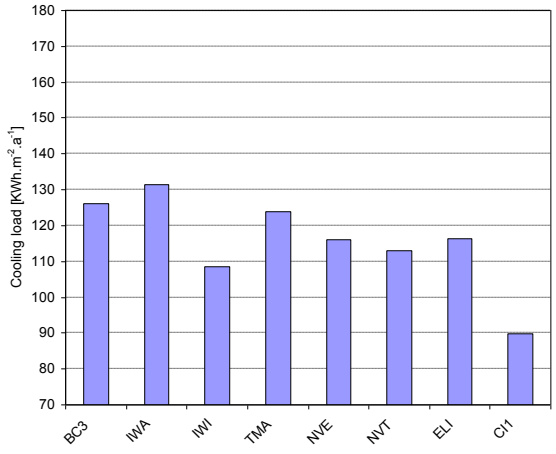

Figure 19 Simulated cooling loads (ROY) for different scenarios (see Tables 2 and 3)

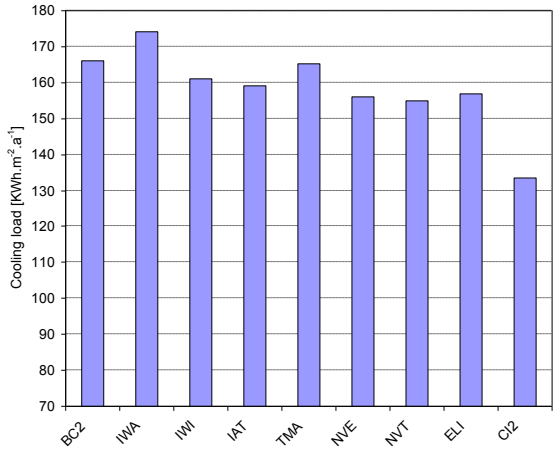

Figure 20 Simulated cooling loads (DCD) for different scenarios (see Tables 2 and 3)

In the passive building operation scenario (PC: no air-conditioning), the "base case" with ACH (1/0.5) and the combined improvement (high mass, improved windows, efficient lighting and ACH (10/10)) scenarios (PC) resulted in lower mean overheating values (OH_m) and higher fraction of working hours (FOT in %) in which the indoor air temperatures were inside the assumed comfort zones (Table 4).

Table 4
Mean overheating (OH_m in K) and fraction of time (FOT in %) with indoor conditions within the comfort zone (from 8 am to 5 pm, assumed indoor air speed 1.0 m.s^{-1})

BUILDING	BC		PC	
	FOT [%]	OH_m [K]	FOT [%]	OH_m [K]
CAP	25	4.4	77	1.8
KCR	30	4.2	73	2.0
ANG	20	5.1	65	2.4
ROY	12	6.0	72	2.0
DCD	43	3.8	68	2.1

Figure 21 shows the calculated mean daily indoor air temperature and relative humidity values for CAP together with extended comfort zones (Szokolay, 2004) corresponding to higher fan-induced air speeds (0.5, 1.0, and 1.5 m.s^{-1}).

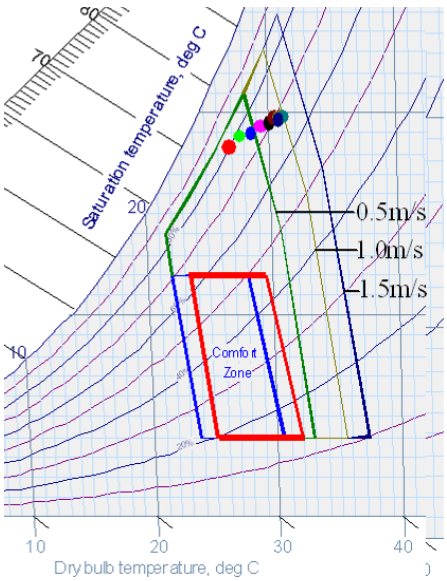

Figure 21 Mean daily temperature and relative humidity values in January at building CAP (based on simulated data from 8am to 5pm) together with thermal comfort zones corresponding to different indoor air speed assumptions

Table 5 summarizes computed mean PMV and PPD results (over the working hours) for BC and PC scenarios. Additionally, annual energy use, energy cost, and CO_2 emission reduction potential were estimated (see Table 6) based on the comparison of the BC and CI scenarios. Thereby, the following assumptions were made: unit cost of electricity in Ghana = 0.12 € per kWh, system efficiency for the split air-conditioning units = 2.6, CO_2 emission = 0.238 $kg \cdot kWh^{-1}$. Table 7 shows the estimated payback time for the thermal retrofit measures given the projected energy saving potential.

Table 5
PMV and PPD (in %) for all buildings

BUILDING	BC		PC	
	PMV	PPD	PMV	PPD
CAP	2.8	93.5	1.6	55.5
KCR	2.8	91.6	1.6	54.5
ANG	3.1	95.0	1.8	64.3
ROY	3.3	97.1	1.6	56.3
DCD	2.6	87.5	1.7	58.2

Estimated annual energy use, costs, CO_2 emission and retrofitting (payback time)

The energy use and associated CO_2 emissions as well as energy expenses estimated for the base case (BC) and combined improvement scenarios (CI) are illustrated in Table 6 and 7.

Table 6
Total annual energy use, costs, and CO_2 emission reduction potential (by upgrading the buildings from the base case (BC) to CI cases

BUILDING	ENERGY COST SAVING [€]	ENERGY SAVING [kWh]	CO_2 CUT-BACK [kg]
CAP	7,937	66,144	15,742
KCR	13,076	108,966	25,934
ANG	4,760	39,668	9,441
ROY	19,815	165,126	39,300
DCD	2,865	23,878	5,683

Table 7
Estimated payback time for the expenses of the thermal retrofit measures (upgrade from BC to CI)

BUILDING	RETROFFIT EXPENSES [€]	PAYBACK TIME (YEARS)
CAP	43,239	5.4
KCR	41,465	3.2
ANG	14,554	3.1
ROY	233,706	11.8
DCD	20,876	7.3

DISCUSSION

The review of the results lead to a number of observations:

- The measured temperature and relative humidity values in the offices point to deficient thermal comfort conditions (see, for example, Figures 8 and 9). However, in interviews (see Figure 10) occupants do not express a pronounced sense of discomfort. This could imply that the occupants' adaptation capability may be underestimated by the current thermal comfort scale recommendations. Furthermore, the position of the workspaces in relation to the air-conditioners, the number of occupants interviewed (subjective opinion), etc are all factors which could have affecdted the outcome (further studies recommended).
- The improvement of the thermal insulation of the attic space floors (in cases where such spaces exist) clearly improves the thermal performance, due to the reduction of conductive heat flows from these typically overheated spaces.

- Increased night-time natural ventilation did improve the thermal performance of the buildings, albeit in a modest fashion. This is due to the rather small diurnal temperature range in Kumasi: the night temperature does not sink sufficiently 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.
- Certain 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 simulation results for combined measures CI1 and CI2 (Table 2 and 3) suggest, cooling loads could be reduced (depending on the building) somewhere between 20 and 35%.
- Compared to the base case (BC), passive cooling option (PC) could reduce mean overheating down to about 2.0 K through the use of efficient building systems and natural ventilation (Table 3). Likewise, estimated PMV and PPD values show improvements by adapting the PC scenario (Table 4).
- The extension of the comfort zone with natural ventilation (1 $m.s^{-1}$) could further increase the fraction of time in which thermal indoor conditions are in the comfort zone (65 – 77%). Simulations suggest that further improvements (particularly in the warmer afternoon periods) would require mechanical cooling.
- Energy use of the buildings could be reduced (20 – 35%) through the thermal retrofit and energy efficient technical components of buildings.
- The potential toward reducing CO_2 emissions through improved energy performance (Table 6) appears to be rather modest. This is due to the composition of energy mix in Ghana: 66% of electricity generation is from hydro power plants.
- The payback times calculated for the amortization of building retrofit costs (Table 7) may be considered reasonable (3 – 12 years).

CONCLUSION

Given the climatic conditions in Ghana, cooling energy requirements represent an ecological and economical challenge. Yet only few studies have been conducted to explore methods and means of improving the energy performance and thermal conditions of buildings in Ghana. We thus applied local measurements in (and calibrated simulation models of) five existing office buildings to parametrically explore and evaluate building features and operational options that could be beneficial energetically, environmentally, and economically. The results demonstrate that improvements to the building fabric and controls can lead to a better performance. Specifically, combinations of improvement measures (such as better windows, natural ventilation, and efficient electrical lighting) have the potential to significantly improve the buildings' performance in the climatic context of Kumasi, Ghana.

REFERENCES

ECG. 2007. Energy Commission Ghana, National Energy Statistics-2005, p. 25-50.

EDSL. 2008. A-TAS Version 8.5, Environmental Design Solutions Limited, www.edsl.net.

Fanger, P.O. 1973. Thermal Comfort, McGraw Hill Book Company, New York.

IEA. 2006. www.iea.org/stats/countryresults.asp?COUNTRY-CODE=GH.

Mahdavi, A. Orehounig, K. Mikats, N. 2007. "Analyzing traditional buildings via empirically calibrated building performance models", Proceedings of IBPSA 2007 (10th International Building Performance Simulation Association Conference and Exhibitio, Beijing: China, 3-6 September 2007, ISBN 0-9771706-2-4, p. 71-78.

Meteotest. 2008. Meteonorm version 6.0, www.meteotest.ch.

Pröglhof, C. 2004. Aspekte der natürlichen Fensterlüftung – eine Fallstudie, Institute für Bauphysik und Bauökologie, TU Wien. Österreich.

Szokolay, S. 2004. Introduction to Architectural Science: The Basis of Sustainable Design, Oxford. Architectural Press.