THERMAL PERFORMANCE OF OFFICE BUILDINGS IN GHANA

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ABSTRACT

Using a simulation application and a sample of five existing office buildings, we parametrically explored building features and measures that could improve the thermal performance of office buildings in Kumasi, Ghana. To improve the reliability of the simulation results, the simulation models were calibrated using long-term continuous measurements on environmental conditions (air temperature, relative humidity) inside and in the immediate vicinity of the selected objects. The simulation results demonstrate that changes in the building fabric (e.g. better window constructions) and controls (e.g. the use of natural ventilation) can improve the buildings' energy performance. Specifically, certain combinations of improvement measures (such as better windows, natural ventilation, and efficient electrical lighting) could be shown to significantly reduce cooling loads (20% to 35% depending on the building).

INTRODUCTION

Given the regional climatic characteristics of Ghana (see Figure 1), energy requirements for cooling of office buildings in Ghana represent a growing burden for both the environment and the economy. In Ghana the growth in demand for energy is amongst other factors caused by increasing requirement for air-conditioning in buildings, especially in the metropolitan areas of Accra and Kumasi. The supply of energy has failed to meet the demand. The Energy Commission Ghana (ECG 2007) reports energy consumption of households increased from 26% (of total national energy consumption) in 2000 to 37% in 2005. Within the same period, energy consumption 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.

In many instances, the building design is not supported by a detailed analysis and evaluation of thermally relevant features and options related to orientation, envelope, glazing ratio, shading devices, and thermal mass. Thus, design decision making is not sufficiently informed by pertinent expertise pertaining to energy-efficient building design methods and technologies.

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

a) Long-term monitoring of the thermal conditions in (and energy performance of) a selected number of office buildings in Kumasi, Ghana;

b) Generation of calibrated simulation models of these office buildings;

c) Simulation-based exploration of design options toward a general reduction of cooling requirements in office buildings in Ghana.

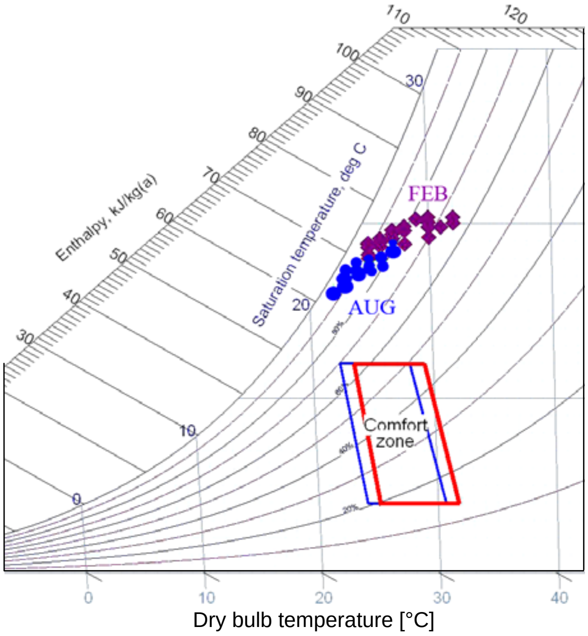

Figure 1 mean hourly outdoor temperature and relative humidity values in Kumasi for representative days in the months of February and August (based on data generated via Meteotest 2008)

APPROACH

Selection of buildings

Five office buildings in Kumasi were selected for the studies (see Table 1 and Figures 2 to 11). These buildings are representative of the majority of existing low-rise office buildings in Kumasi and house different functions (university offices, private companies, municipal offices, etc.). The applied cooling systems typically involve split air-conditioning units.

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. The location of the installed data loggers inside each building are marked in the respective floor plans (see Figures 3, 5, 7, 9, and 11).

Monitored environmental data

Indoor temperature and relative humidity were monitored using the previously mentioned data loggers. The monitoring period was from September 2007 to August 2008. The accuracy of the respective sensors is given below (Table 2).

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. Thus, data loggers of the previously mentioned type (see Table 2) were applied to monitor outdoor air temperature and outdoor relative humidity.

Table 1

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

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

Figure 2 External view of building CAP

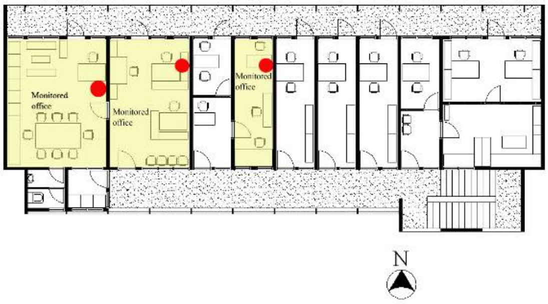

Figure 3 Schematic plan of offices in CAP

Figure 4 External view of building KCR

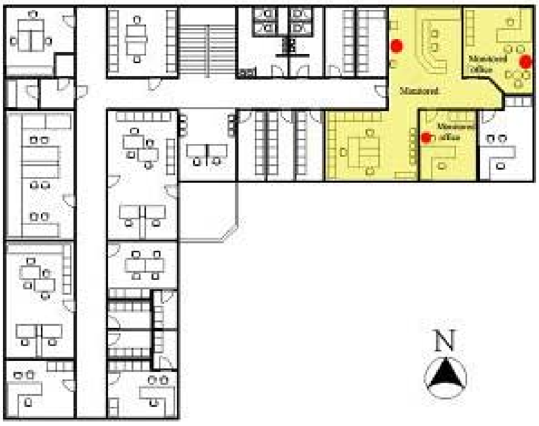

Figure 5 Schematic plan of offices in KCR

Figure 6 External view of building ANG

Figure 7 Schematic plan of offices in ANG

Figure 8 External view of building ROY

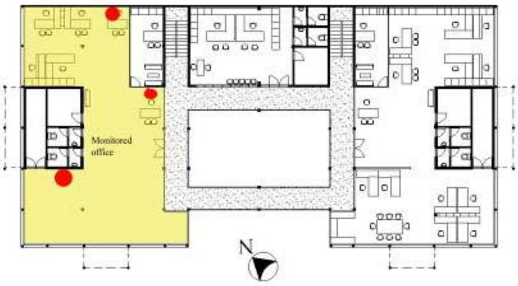

Figure 9 Schematic plan of offices in ROY

Figure 10 External view of building DCD

Figure 11 Schematic plan of offices in DCD

Table 2
Accuracy of the sensors

SENSOR	RANGE	ERROR
Air temperature	-20 to 70 °C	± 0.4 °C
Relative humidity	5 to 95 %	± 3%

Calibration of the simulation tool

A thermal simulation application (EDSL 2008) was used to explore possible measures that could improve the thermal performance of office buildings in Ghana. This software tool simulates dynamically the thermal performance of buildings and their systems. The application solves the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. Conduction in the fabric of the building is treated dynamically using two methods for the analysis of wall heat flows. For state-representation finite difference methods are applied whereas conductive heat flows at the surfaces of walls and other building elements are calculated with response factor method. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation exchange is modeled using the Stefan-Boltzmann law. Long-wave radiation from the sky and the ground is treated using empirical relationships (EDSL 2007).

To make the process more reliable, the simulation models needed to be calibrated. Toward this end, 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.

Parametric study of thermal improvement scenarios

Using the calibrated thermal performance simulation models of the aforementioned five office buildings, we explored various improvement options (concerning glazing and shading, ventilation alternatives, thermal mass, efficient lighting) that could reduce cooling loads and the need for extensive active devices for air-conditioning. 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. Table 4 refers only to deviations from the respective base case (BC). Cooling energy loads (sensible and latent) was used as the performance indicator.

RESULTS

Measured external air temperature values

Figure 12 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.

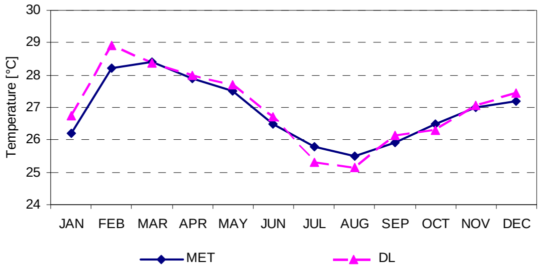

Figure 12 Comparison of mean outdoor temperature measurements at office locations (DL) with Kumasi weather station data (MET)

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. To illustrate this point, Figures 13 to 15 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.

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}; 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 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 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}

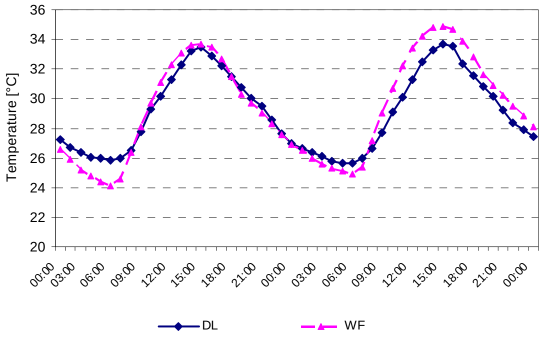

Figure 13 Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (KCR)

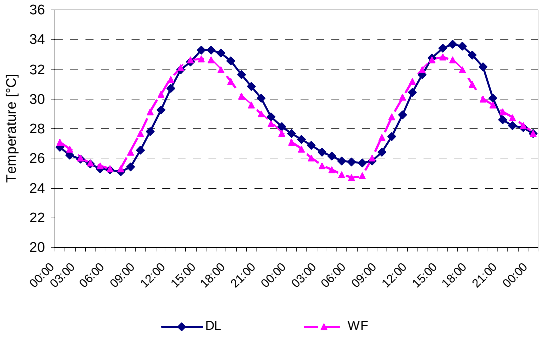

Figure 14 Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (ANG)

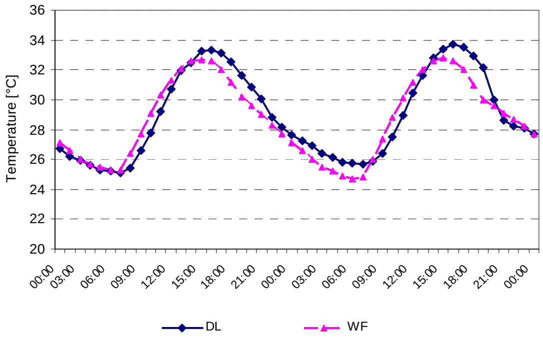

Figure 15 Outdoor air temperatures from weather file segments (WF) used for simulation calibration in comparison with measurements (DL) at building location (DCD)

Comparison of measurements and simulations

Predictions of the calibrated simulation models compared well with the measured values. To illustrate this, Figures 16 and 17 provide examples of measured versus simulated indoor air temperatures in CAP and KCR. Moreover, Figure 18 provides an overview of the relationship between measured and simulated indoor air temperature (in terms of regression lines) for four of the five reference buildings. The respective correlation coefficient values are summarized in Table 5.

Table 5
Correlation coefficient values pertaining to the comparison of measured and simulated temperatures in four reference buildings

BUILDING	CORRELATION COEFFICIENT r^2
CAP	0.84
ANG	0.53
ROY	0.90
DCD	0.87

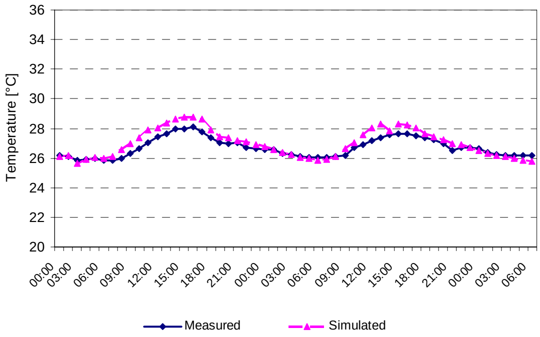

Figure 16 Measured versus simulation indoor air temperatures in CAP

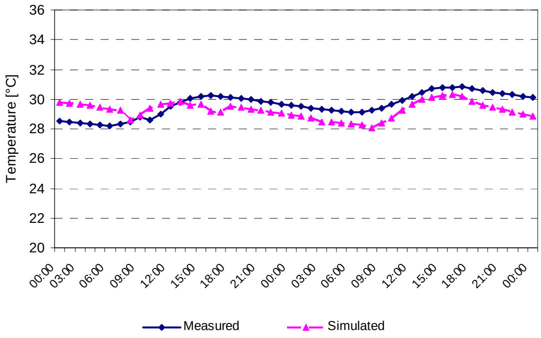

Figure 17 Measured versus simulation indoor air temperatures in KCR

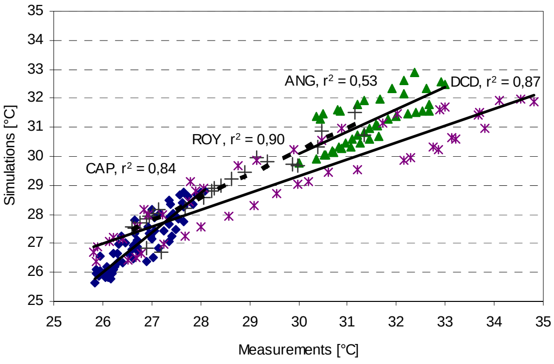

Figure 18 Overview of the relationship (regression lines) between measured and simulated indoor air temperatures in four reference buildings

Results of parametric simulations

Figures 19 to 23 show, for each building, the simulated cooling loads (sensible and latent) for a number of scenarios summarized in Tables 3 and 4. Figure 24 shows (for all buildings) the same results in percentage terms for a subset of scenarios.

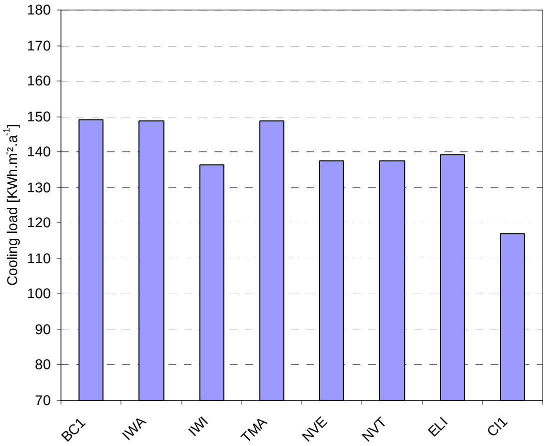

Figure 19 Simulated cooling loads (CAP) for different scenarios (see Tables 3 and 4)

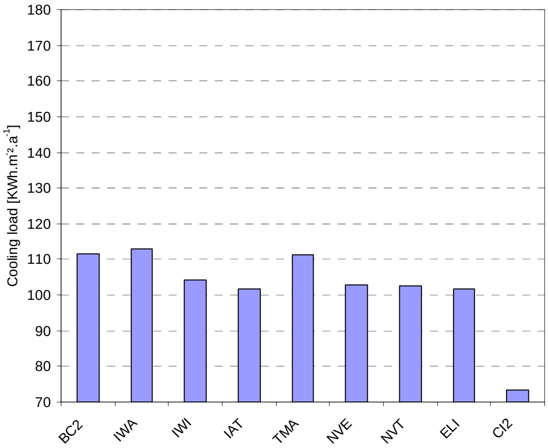

Figure 20 Simulated cooling loads (KCR) for different scenarios (see Tables 3 and 4)

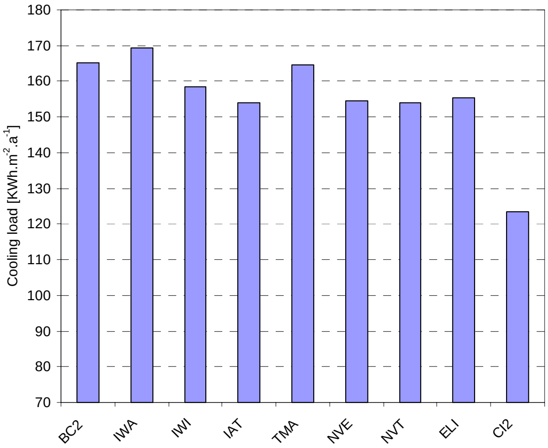

Figure 21 Simulated cooling loads (ANG) for different scenarios (see Tables 3 and 4)

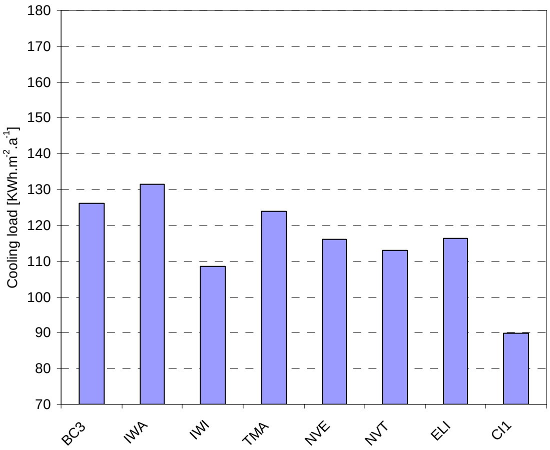

Figure 22 Simulated cooling loads (ROY) for different scenarios (see Tables 3 and 4)

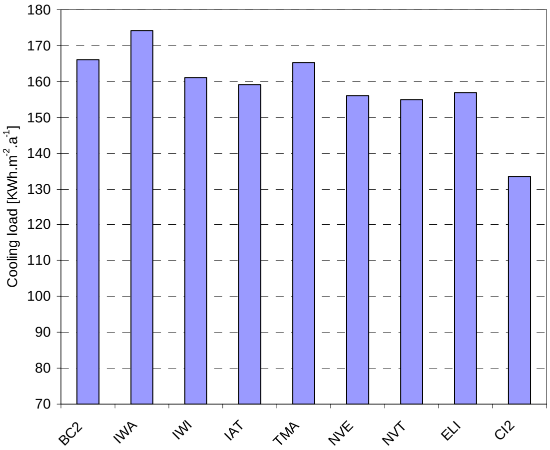

Figure 23 Simulated cooling loads (DCD) for different scenarios (see Tables 3 and 4)

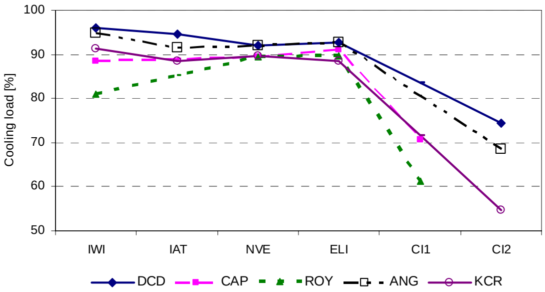

Figure 24 Simulated cooling loads (in percentage of the respective base cases) for all buildings and for selected scenarios (see Tables 3 and 4)

DISCUSSION

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

- Improvement of the thermal insulation of the external walls did not bring about 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. It can be explained via 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 exist) 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 nighttime 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 nighttime ventilation was only insignificantly better than natural ventilation alone.
- A clear improvement was resulted 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 via installation of more efficient electrical lighting systems has understandably a noteworthy potential in reducing the buildings' overall cooling loads.
- 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 4) suggest (see figures 19 to 24), cooling loads could be reduced (depending on the building) somewhere between 20 and 35%.

CONCLUSION

Given climatic conditions in Ghana, cooling energy requirements represent – especially in office buildings – an ecological and economical challenge. Yet few studies have been conducted to explore methods and means of improving the energy performance of (and thermal conditions in) buildings in Ghana. We thus applied calibrated simulation models of five existing office buildings to parametrically explore building features and operational options that could be beneficial energetically and environmentally.

The simulation results demonstrate that some improvements to the building fabric and controls can bring about better performance. Specifically, certain combinations of improvement measures (such as better windows, natural ventilation, and efficient electrical lighting) have the potential to significantly reduce the buildings' cooling loads in the climatic context of Kumasi, Ghana.

Future efforts will involve the improvement of monitoring infrastructure toward obtaining more detailed and reliable micro-climatic data in Ghana. Ongoing simulation studies explore the potential of a fully passive building operation regime as a sustainable alternative to current rather inefficient mechanical cooling practices. Thereby, the high external air relative humidity levels in Ghana represent an important challenge pertaining to required thermal comfort conditions.

Finally, efforts are being envisioned to encourage actual projects involving well-conceived thermal retrofit measures accompanied by careful scientific monitoring and performance documentation.

ACKNOWLEDGEMENT

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