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Simulation-based Assessment of the Thermal Performance of High-rise Office Buildings in Ghana

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Authors' contributions

This work was carried out in collaboration between all authors. Author BS designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Authors CK and JA managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The lack of empirical data and practical advice on thermal performance and efficient use of energy in our buildings are gradually becoming a burden to the country. Amidst the recent development in the usage of curtain walls for office buildings, high utilization of energy and poor thermal comfort issues have become paramount. Given the warm-humid climatic characteristics of Ghana, energy requirements for cooling of office buildings represent a growing burden for the environment and the economy. The current paper explores the implications of alternative design options for the thermal performance of four high-rise office buildings in Accra, Ghana. Multiple design alternatives were considered involving various glazing types, shading and shading schedules, thermal insulation options, lighting, various ventilation options and thermal mass. A numeric thermal simulation application was used to model the performance of these alternatives parametrically. Simulation results were expressed in terms of annual cooling loads (active building operation scenario) and mean overheating (passive building operation scenario). Careful combination of improvement measures (such as efficient glazing, thermal mass, façade insulation, night ventilation, efficient electrical lighting, form and orientation) has a significant potential to reduce buildings' cooling loads

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(31% – 49%) in the climatic context of Accra. Over-heating tendencies were also reduced from 8.6K to 3.9K depending on the air-change-rate per hour (ACH).

Keywords: Simulation; energy; thermal performance; sustainable; office buildings.

1. INTRODUCTION

Energy is considered a key element in the sustainable development of all countries. Over the years, research has revealed that buildings alone account for about 40% of the global energy consumption and contribute over 30% of CO_2 emissions [1] whiles the commercial sector accounts for 11% of CO_2 production [2]. In a typical office building, energy is among other factors, used to provide comfortable indoor conditions (in terms of lighting, air-conditioning, etc.), power office equipment and enhance the smooth running of office activities. Usually, lighting and air-conditioning are the major installations consuming much energy in office buildings. Lighting uses 15% of energy in commercial buildings, and large amounts of that energy can be saved by using well designed lighting controls that can take advantage of the natural light available [3]. In the UK, lighting account for between 13% - 16% of energy use and 18% - 25% of CO2 emissions in a typical office building [4]. In the United States (US), lighting alone accounts for 25% of the energy usage [4]. The [2], in its international energy outlook, forecasts that energy use in the built environment will grow by 34% in the next 20 years at an average rate of 1.5% per year. In 2030, consumption attributed to the domestic and commercial sectors is forecast to be 67% and 33% respectively [5].

Air-conditioning use leads to an increase in the absolute energy consumed for space cooling, with attendant high peak electricity demand [6]. The large amounts of electricity consumed from thermal generating plants, releases large quantities of CO_2 and its emissions into the atmosphere [7]. Following increasing energy cost and negative environmental impacts, energy savings and sustainable development of buildings are of utmost concern to the building industry [8]. Required energy use for cooling office buildings in Ghana represents a growing burden for both the economy and the environment. Over the years, Ghana's energy sector has been challenged with demand always outstripping supply. Projections made by the Volta River Authority (VRA) of Ghana revealed that in 2012, Ghana‘s total electricity generation capacity was 3,491MW, with contribution by thermal sources increasing to 55% [9]. In the capital city of Accra alone, [10] estimated that commercial land use experienced slighter higher consumption rates, averaging from 10,000 kWh per month upwards to 50,000 kWh per month.

According to [10], urbanisation in Ghana was expected to increase from around 40% in 2000 to about 55% in 2012 and eventually to 60% by 2020. Moreover, a little more than a third of the urban population lives in Greater Accra and is expected to reach around 40 percent by 2020. It has been projected that Ghana will need more than 7 times its 2007 electric power capacity by 2020 if it should succeed in developing its economy into a middle income one [11]. A study carried out by the [12] in the Ministry of Mines and Energy (MOME) building in Ghana revealed that air-conditioners were responsible for 50% of the total energy consumed in the building annually. It was followed by office equipment (17.7%), internal lighting (17.1%), Miscellaneous (8.8%) and external lighting (6.4%). Altogether, the building consumed a total annual energy of 238,090kWh. From the above, air-conditioning and lighting are seen to be among the major energy consumers in buildings and as such effort to conserve energy cannot be whole without these two variables.

Against the above background, the current paper explores the implications of various alternative design options in view of the thermal performance (cooling requirements and over-heating tendencies) of multi-storey office buildings in Accra, Ghana. The objective is to identify those building design and operation alternatives that would reduce the cooling requirements and overheating tendencies of the office buildings within the climatic context of Accra, Ghana. Thermally relevant features and options related to glazing, shading devices and deployment schedules, thermal mass, night ventilation, efficient lighting and facade insulation were investigated into parametrically.

2. LITERATURE REVIEW

2.1 Windows/Glazing

Windows in buildings help in several ways to keep the building comfortable. Windows provide building occupants with the opportunity to view outside and it also allow fresh air into a building when it is opened. [13,14] together gives an apt description of glazed windows. The authors describe glazed windows as components that allow natural light, offer a visual communication with outdoors, reduce the structural load and enhance the aesthetic appearance of buildings. A shaded and well positioned window on a building can go a long way into reducing the energy usage of the building as reported by [15]. Furthermore, the area of exterior wall to the area of windows/glazing can also affect the thermal conditions within a building, thus the window-to wall ratio (WWR) of the building.

In our part of the world today, (Ghana) the use of extensive glazing is the order of the day. Commercial buildings with high WWR have a damaging consequence on energy conservation. [16] confirms the aforesaid assertion and comments that 'the WWR is increased by the trend in curtain wall because of its attractiveness. This increases the cooling load but decreases the heating load because of the season and solar radiation, which means that the proper WWR should be considered'. [17] commented on glazing in their report. The authors stated that 'in terms of energy flows, glazing can be characterized by two parameters: Firstly, the total solar energy transmittance 'g', which denotes the share of the incoming solar energy, which is converted into heat inside the indoor space. Secondly, the thermal transmittance 'U' that describes how much heat is transferred through the glazing per square meter and Kelvin temperature difference between inside and outside. Whiles the WWR of a building plays an important role by aiding day lighting into a space [18]; it is known to be the most influential parameter on energy demand [19]. [20] studied the effect of window position and window size on the energy demand for heating, cooling and electric lighting. The total energy demand was calculated with the dynamic thermal program Capsol which simulates the total yearly energy demand for lighting, heating and cooling. The study concluded that facades should have a WWR of about 30% of the façade area, where the window is positioned in the top half of the facade. WWR between 20 to 40% is also very acceptable whiles greater WWR does not have any effect on the lighting loads. The study further asserted that when a window position is considered, it does have a significant effect on the primary energy demand for lighting [20].

2.2 Shading

Shading of opening/windows is one of the methods for reducing the energy consumption of buildings while ensuring views to the outside. Shading can be inside or outside. According to [16], 'the ideal shading is to block solar radiation but achieve acceptable ventilation and view. In this regard, outside shading has more efficiency than inside shading. Inside shading leads to radiation between the shading and window. Outside shading blocks solar radiation before it reaches the window. Sometimes, installed options for external shading can be limited by high rise buildings or the characteristics of buildings. The design of the outside requires the azimuth of the sun, view, ventilation and maintenance to be considered'.

2.3 Thermal Mass

The thermal mass of a building material describes the ability of that material to absorb heat, store, and later release it to either outdoor or indoor. Thermal mass can delay heat transfer through the envelope of a building, and help keep the interior of a building cool during the day when the outside temperature is relatively high [21]. When thermal mass is exposed to the interior, it absorbs heat from internal sources and dampens the amplitude of the indoor temperature swing [22]. This is particularly beneficial during warm periods, when the internal heat gain during the day is absorbed. This helps to prevent an excessive temperature rise and reduction in the risk of overheating [23]. A building with high thermal mass has the ability to absorb heat and provide a cooling effect which comes from the difference between the surface (radiant) temperature and that of the internal air. [15] accounts that absorptance/reflectance will strongly influence the solar heat input. [24] agrees with [15] by asserting that porous materials with low specific heat exhibit low thermal mass effects. In addition, good thermal conductivity and low reflectivity are also required for effective passive cooling by thermal mass.

2.4 Night Ventilation

Night ventilation and natural ventilation are known to reduce the energy use in buildings around the world. For instance, [25] confirmed that night ventilation reduced the mean room temperature by 1.2 K during working hours for a building in Freiburg/Germany. So did [26], who also found the average reduction of the indoor temperature in an office building in Greece to be between 1.8 and 3 K after using night ventilation. Natural ventilation on the other hand can reach much higher ventilation rates than mechanical ventilation systems, which are especially designed for fresh air supply [27]. However, energy savings by natural ventilation can mostly only be evaluated when simulation tools are used as reported by [28]. A range of studies using measurements and simulations in schools and offices showed that air change rates between 5 and 22 per hour for cross ventilation and 1 - 4 for single-sided ventilation, could provide comfortable indoors whiles reducing energy used. [29,30,31]. [28] in their studies reported that 'simulations showed that night ventilation is only suitable in buildings with sufficient and accessible thermal mass of about 75–100 kg/m^2 of floor space. The internal gains have to be limited to 30 W/m^2 of floor area'. In a tropical climate, [32] observed that the improvements in comfort by natural ventilation ranged between 9% and 41% (Kuala Lumpur in April). According to the authors, in a temperate climate the improvements vary between 8% and 56%. A result which showed that natural ventilation has a good potential in both tropical and temperate climates [33]. The current paper explores the implications of alternative design options for the thermal performance towards the reduction of energy used in four high-rise office buildings in Accra, Ghana.

3. METHODOLOGY AND DESCRIPTION OF THE CASE STUDY

Parametric simulation with the Thermal Analysis Software (Tas) was used as a means of comparing the thermal performance of the buildings. Tas is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems [34]. It has a 3D graphics-based geometry input that includes a CAD link. Tas Systems is a HVAC systems/controls simulator, which may be directly coupled with the building simulator. It performs automatic airflow and plant sizing and total energy demand. Tas combines dynamic thermal simulation of the building structure with natural ventilation calculations, which include advanced control functions on aperture opening and the ability to simulate complex mixed mode systems (ibid).

Four high-rise office buildings (with different orientations) in Accra, Ghana were selected as subjects for the study as illustrated in Fig. 1. The glazing properties of the buildings, total internal gains for people, lights and equipment as used for the base case cooling loads is shown in Table 1.

Eight glazing options were considered for the improvement simulation scenarios. Two shading options (internal and external) with varied deployment schedules, 4 façade insulation preferences were also probed into. The design parameters were examined individually before they were combined to form the various scenarios. Table 2 presents an overview of the various options that were studied. Altogether, 120 scenarios (different combinations of options in Table 2) were simulated, thus 40 scenarios for each building. Since detailed and comprehensive outdoor weather information was not available, segments of a synthetic weather file for Accra was identified and used: generated via [35]

Two kinds of simulation were performed: One was simulation of cooling loads (active building operation assumption), and the other; Mean-overheating (free-running building operation assumption). For the computation of the mean overheating (OH$_m$), the following formula was used:

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

Where θi,j denotes the mean indoor air temperature (°C) at hour j (averaged over all simulated office zones in the floor), θr the reference indoor air temperature for overheating (°C), and n the total number of occupied office hours. The term θi,j - θr was considered for those hours when θi,j > θr. Mean overheating (OH$_m$) was computed for two different sets of assumptions pertaining to the applicable values for the reference overheating temperature θr (Table 3B).

The first set was the concept of Neutrality Temperature [36] as cited in [15]. This is derived as a function of the mean monthly outdoor air temperature. The second set was based on a constant reference overheating temperature of 26°C. The design alternatives that were simulated were the base case, the best improvement scenario from the active case combined with different air change rates (ACH 1/0.5: 1/10: 5/10: 10/10) to create a comfortable thermal environment during the passive case.

Table 1. Overview of base case simulation scenarios

Parameters	**R.T.**	**P.T.**	**H.T.**	**W.T.C.**
Base case temp.(ºC)	26	26	26	26
Occupancy sensible (W/m²)	7	7	8	4
Occupancy latent (W/m²)	1	1	2	0.8
Electric lighting loads (W/m²)	3	8	7	5
Infiltration-ACH (h^{-1}) Day-Night	1/0.5	1/0.5	1/0.5	1/0.5
Equipment sensible (W/m²)	5	8	20	3
Window U_{value} ($W.m^{-2}.K^{-1}$)	2.8 (double glazing)	2.8 (double glazing)	5.6 (single glazing)	2.9 (double glazing)
Window g_{value}	0,5	0.6	0.7	0.6
Thermal mass	Tiled Acoustic ceiling	Tiled Acoustic ceiling	Tiled Acoustic ceiling	Tiled Acoustic ceiling
Shading options	Internal blinds	Internal blinds	Internal blinds	Internal blinds

Table 2. Overview of all simulated improvement options

Parameter	**Code**	**Description**
Office window orientation	N-W	North-West windows at the R.T. and the W.T.C. buildings
	S-W;N-E	South-West and North East windows at the H.T. building
	S	South windows at the P.T. building
Glazing	$G_{0.5}$	Double glazing; $g=0.5;U=1.7W \cdot m^{-2} \cdot K^{-1}$
	$G_{0.4}$	Double glazing; $g=0.4;U=1.8W \cdot m^{-2} \cdot K^{-1}$
	$G_{PT0.4}$	Double glazing; $g=0.4;U=2.8W \cdot m^{-2} \cdot K^{-1}$
	$G_{0.3}$	Double glazing; $g=0.3;U=2.6W \cdot m^{-2} \cdot K^{-1}$
	$G_{0.2}$	Double glazing; $g=0.2;U=1.6W \cdot m^{-2} \cdot K^{-1}$
	$G_{S0.3}$	Single glazing; $g=0.3$; $U=5.7W \cdot m^{-2} \cdot K^{-1}$
Glazing Cont'd	$G_{S0.24}$	Single glazing; $g=0.24$; $U=5.7W \cdot m^{-2} \cdot K^{-1}$
	$G_{S0.18}$	Single glazing; $g=0.18$; $U=5.7W \cdot m^{-2} \cdot K^{-1}$
Efficient electrical lighting loads	L_e	$2W.m^{-2}$
Day time ventilation	$DV_{m.1}$	Day/Night ACH = $10/0.5h^{-1}$
	$DV_{m.2}$	Day/Night ACH = $10/10h^{-1}$
Night ventilation	$NV_{m.1}$	Mode 1; Day/Night ACH = $1/10h^{-1}$; 6pm-6am
	$NV_{m.2}$	Mode 2; Day/Night ACH = $1/10h^{-1}$; 9pm-6am
	$NV_{m.3}$	Mode 3; Day/Night ACH = $1/10h^{-1}$; 10pm-6am
	$NV_{m.4}$	Mode 4; Day/Night ACH = $1/10h^{-1}$; 12am-6am
	$NV_{m.5}$	Mode 5; Day/Night ACH = $1/10h^{-1}$; 1am-6am
	$NV_{m.6}$	Mode 6; Day/Night ACH = $1/10h^{-1}$; 2am-6am
Shading option	SO_e	External blinds
	SO_i	Internal blinds
	BS_{PT11}	11am – 2pm
	BS_{11}	11am – 4pm :South windows
	BS_{HT11}	11am – 5pm
Blind deployment schedule	BS_{PT12}	12pm – 3 pm
	BS_{12}	12pm – 5pm :SW windows
	BS_1	1pm – 5 pm :SW windows
	BS_2	2pm – 5 pm
	BS_F	8am – 5 pm (Continuous deployment)
Thermal mass	TM_a	Without carpet and acoustic ceiling (suspended ceiling)
Façade insulation	I_5^1	With 50 mm insulation outside only (U = 0.46)
	I_{10}^1	With 100 mm insulation outside only (U = 0.24)
	I_5^2	With 50 mm insulation outside and inside (U = 0.24)
	I_{10}^2	With 100 mm insulation outside and inside (U = 0.12)

Ridge Towers (R. T.). South-East : North-West orientation.15 floors; 14,355.68sqm.

Heritage Towers (H. T.). East -West orientation.15 floors; 9,340.86sqm.

Premier Towers (P. T.). East -West orientation.13 floors; 10,263.00sqm.

World Trade Center (W.T.C.). South-East:North -West orientation.15 floors; 14.556.78sqm

Fig. 1. 3-dimensional and schematic plan views of the case study buildings

The simulated indoor environmental parameters, temperature and relative humidity values, were combined with the clothing values, metabolic rates and various air velocities after [15] to determine the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied occupants (PPD), using the software application "PMVcalc_V2, (n.d.)". The different air velocities used were 0.1 m/s, 0.5m/s, 1m/s and 1.5 m/s. According to [15], the subjective reactions to air movement include:

<0.1m/s	stuffy
To 0.2	unnoticed
To 0.5	pleasant
To 1	awareness
To 1.5	draughty
>1.5	annoying

4. RESULTS AND DISCUSSION

The results of the study are presented. They provide evidence of the cooling loads and overheating reduction tendencies in the buildings. Fig. 2 shows the initial cooling loads for all the buildings.

Figs. 3 and 4 show the various simulated annual cooling loads (kWh.m^{-2}.a^{-1}) for the ten scenarios that best reduced the base-case cooling loads and their associated percentage reduction for R.T. and the W.T.C. buildings. Figs. 5 and 6 show the afore-mentioned parameter for the P.T. and the H.T. buildings.

For the passive scenario (free-running building operation assumption), various air-change-rates per hour (ACH) were explored with the best scenario (BS) from the active case (active building operation assumption). The design alternatives simulated were based on thermal mass, improved glazing, efficient lighting, and façade insulation. Refer to Table 3 for the two sets of assumptions pertaining to the applicable value for the reference overheating temperature.

The ACH that gave the best results for R.T., W.T.C., and H.T. was 10/10 whiles for P.T, 1/0.5 was able to provide a good indoor environment. Below are the graphical representations of the best air-change rates with their associated PMV-PPD values (Figs. 7 to 14).

4.1 Discussion

For the R.T. building, the total simulated annual cooling load for the base case (BC, Fig. 2) was 115.34 kWh.m^{-2}.a^{-1}. The probed alternative of a more efficient glazing type with a better shading coefficient (0.3) resulted in a significant reduction of the base case cooling loads by 14.1%. The effect was that only 30% of solar radiation could be transmitted through the glass as compared to the 50% for the base case scenario. All the various improvements combined to form the scenarios did reduce the base case cooling loads by significant values (Table 3A). The best ten scenarios did reduce cooling loads by 28 to 31% with scenario 22 reducing cooling loads by the highest percentage (Fig. 3). This result is significant and has been achieved through improved and efficient building elements, as well as sustainable design principles. For the mean overheating tendencies, the constant temperature (C.T.) of 26ºC [37] when considered recorded a higher mean-overheating: 3K more than that of the neutrality temperature (Tn) (Fig. 7).

Table 3A. Overview of the best 10 simulation scenarios for the R.T. Building out of 40 scenarios

Scenario	Glazing	Efficient lighting	Night ventilation	Shading option	Blind deployment schedule	Façade insulation
1	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_5^1
2	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_1	I_{10}^1
3	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_2	I_5^1
4	$G_{0.3}$	L_e	$NV_{m.4}$	SO_e	BS_{12}	I_{10}^1
15	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	-	I_5^1
22	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	I_{10}^1
26	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_{10}^1
27	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	I_5^1
28	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_1	I_{10}^1
34	$G_{0.3}$	L_e	$NV_{m.1}$	SO_i	-	I_{10}^1

Table 3B. The two sets for the reference overheating temperature θr (ºC)

	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
Tn + 2.5	29.1	28.7	28.2	28.2	28.5	28.9	26.3	29.2	29.2	29.4	29.5	29.4
Constant 26°C	26	26	26	26	26	26	26	26	26	26	26	26

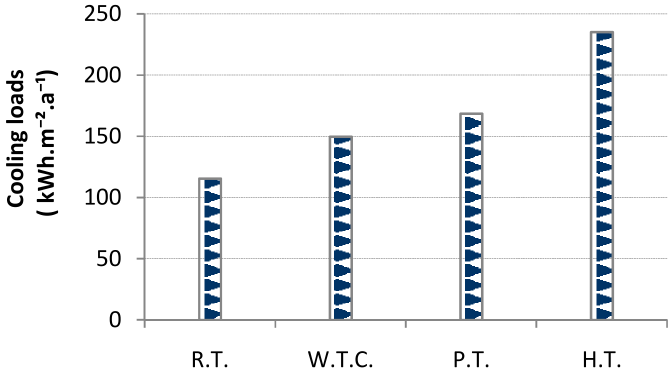

Fig. 2. Base-case cooling loads for all buildings

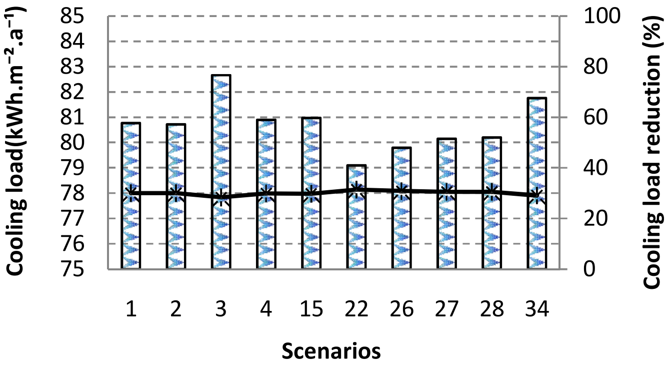

Fig. 3. R.T.'s simulated annual cooling loads (kWh.m-2.a-1) for the ten best scenarios and their percentage reductions

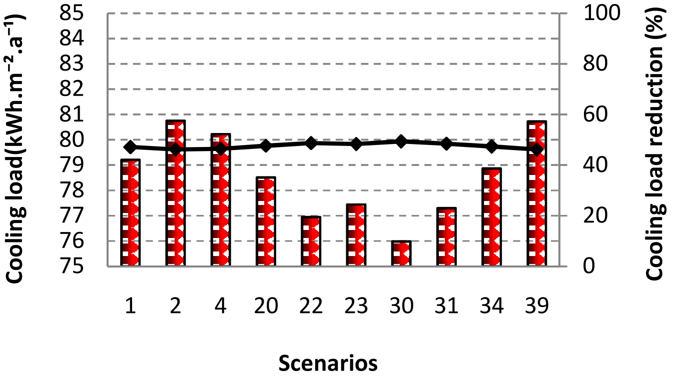

Fig. 4. W.T.C.'s simulated annual cooling loads (kWh.m-2.a-1) for the ten best scenarios and their percentage reductions

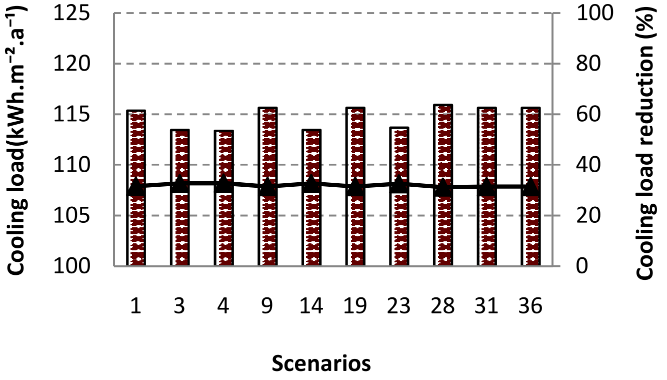

Fig. 5. P.T.'s simulated annual cooling loads (kWh.m-2.a-1) for the ten best scenarios and their percentage reductions

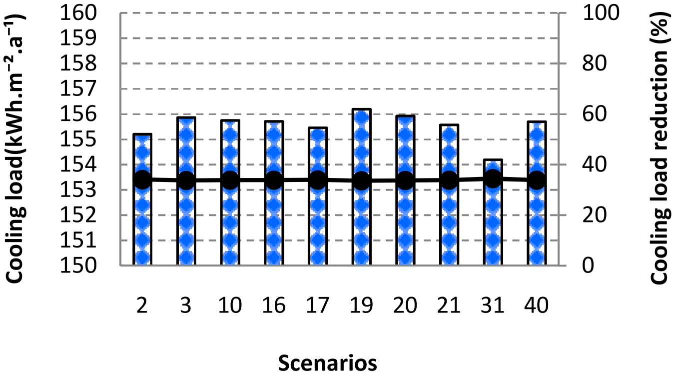

Fig. 6. H.T.'s simulated annual cooling loads (kWh.m-2.a-1) for the ten best scenarios and their percentage reductions

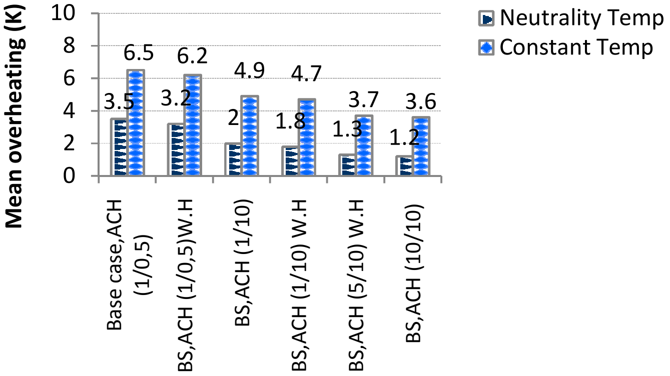

Fig. 7. Mean overheating for different ACH scenarios (R.T.)

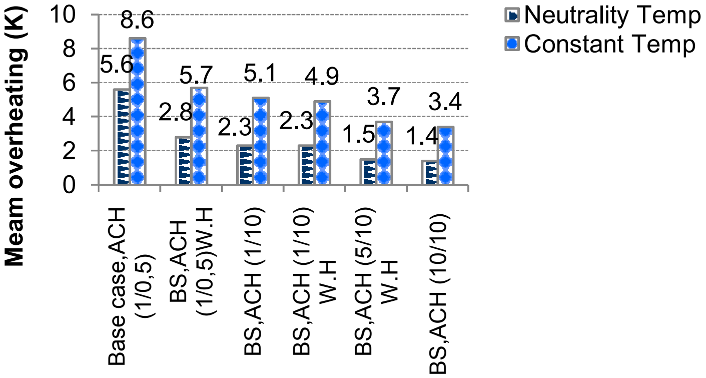

Fig. 8. Mean overheating for different ACH scenarios (W.T.C.)

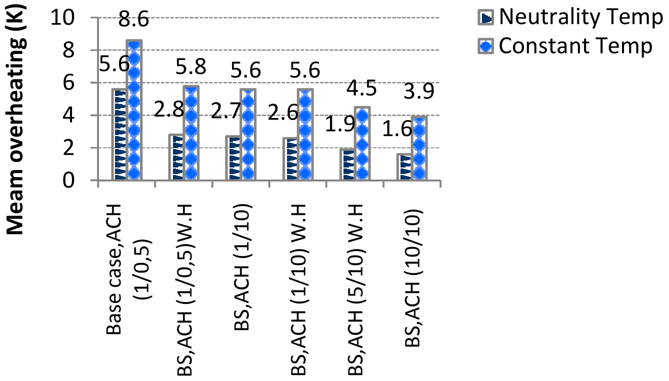

Fig. 9. Mean overheating for different ACH scenario (H.T.)

The base case cooling load of the rectangular W.T.C. block was 149.75 kWh.m^{-2}.a^{-1} (Fig. 2). The building is oriented towards the north-west and south-east with a veranda shading the north-west part of the elongated sides. Various glazing options were simulated to find one that considerably reduced the base case loads. This led to cooling load reductions from 9% to 26.6%. Such high percentage was imparted due to the shading that is provided by the verandah. Also reducing the glazing area helps reduce the cooling loads [32]. In terms of form and orientation [38], the W.T.C. performs better than the R.T. Adding insulation to the façade (5 cm/

10 cm) reduced the cooling loads by 4%. This result could be due to the orientation of the building and also the tightness of the envelope [39]. The result also agrees with [40] recommendation of using façade insulation to reduce cooling loads. Table 4 shows the 10 best scenarios that led to significant cooling load reductions. The alternative increase in the day/night ventilation could decrease the mean over-heating to 1.6K for Tn and 3.6K for C.T when air-change-rate per hour is 10/10ACH (Figs. 8 and 12).

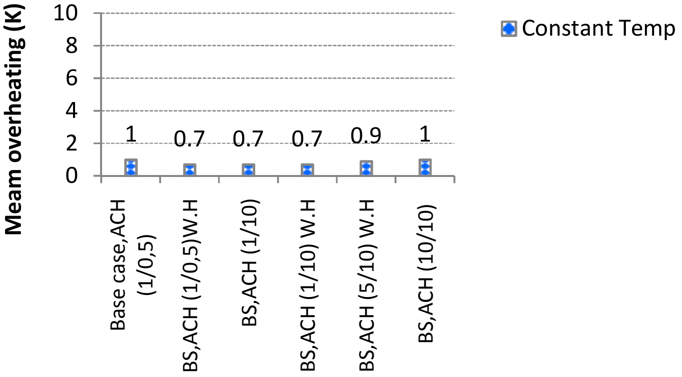

Fig. 10. Mean overheating for different ACH scenarios (P.T.)

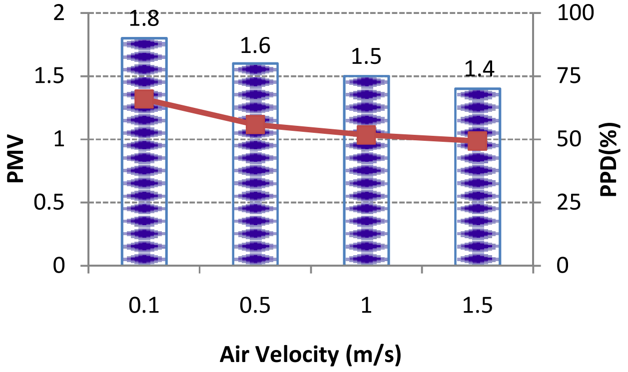

Fig. 11. PMV and PPD representation of the best ACH (10/10) for R.T. building

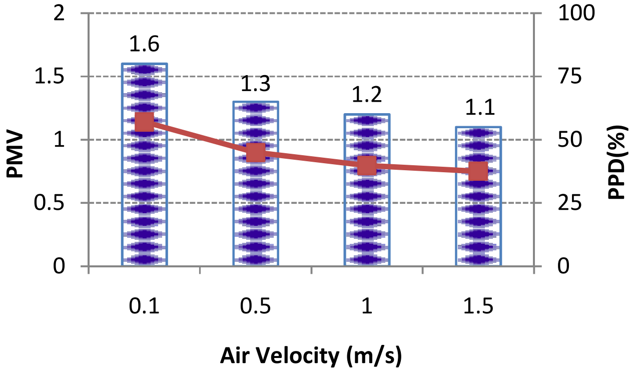

Fig. 12. PMV and PPD representation of the best ACH (10/10) for W.T.C. building

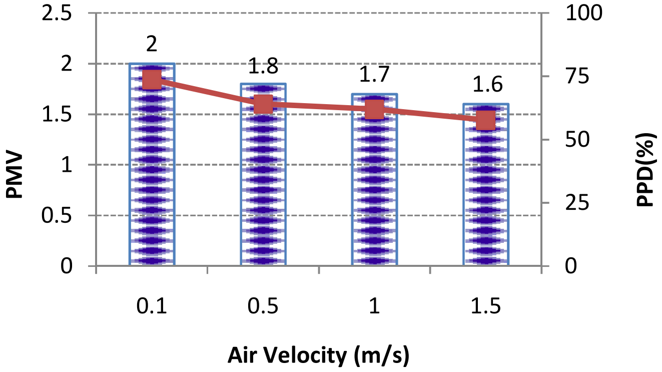

Fig. 13. PMV and PPD representation of the best ACH (10/10) for H.T. building

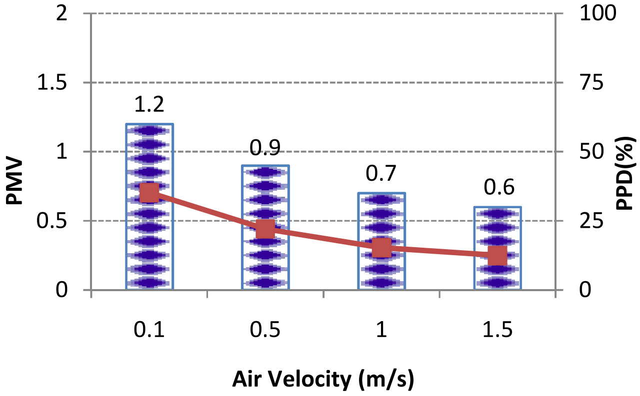

Fig. 14. PMV and PPD representation of the best ACH (1/0.5) for P.T. building

The H.T. building (rectangular block) oriented towards north-east and south-west had an original cooling load of 235.16 $kWh.m^2.a^{-1}$. Different glazing types were explored. Single glazed window with a solar heat gain coefficient of 0.18 and a u-value of 5.7 recorded a 25.4% reduction in cooling loads. The ten best scenarios out of the total of 40 did reduce the initial cooling loads between 30-35%. The effect of thermal mass in a hot humid climate as documented by [41] has not worked so well here. Perhaps, this observation is so because the case study buildings lack the heavy massing that is important for heat transfer in thermal mass [21]. Table 6 illustrates the 10 best out of the 40 scenarios that did reduce cooling loads by appreciable values. The curtain wall office building with inoperable windows also had the highest base case mean overheating of 5.6K when Tn was operating and 8.6K when C.T. was working (Figs. 9 and 13). This was due to the effect of solar radiation (improper orientation), since there was no shading on all sides of the building. The increase in radiation led to the higher conductive gains in the office spaces, which resulted in uncomfortable indoors [42].

The P.T. building (curtain wall) had an initial cooling load of 126.2 $KWh.m^{-2}.a^{-1}$. The alternative improvement of using an efficient glazing reduced the cooling loads by 17.7%. Other glazing types were also explored with different shading coefficient values. Cooling loads were reduced between 5 to 16%. An efficient lighting gain of $2W/m^2$ led to a decrease in the initial cooling loads by 10%. Table 5 demonstrates the 10 best cooling load reduction scenarios. At P.T., the base case mean-over heating value recorded was 1 K for C.T. (Figs. 10 and 14). The P.T. building shows better results for passive mode than the rest of the buildings. It does not record any overheating value for neutrality temperature. This indicates that the indoor temperatures simulated were all below the Tn but higher than the C.T. Comparatively, conditions in the P.T. are comfortable. Through the improvement scenario, the mean-overheating dropped to 0.7 K. The form, orientation of the

Table 4. Overview of the best 10 simulation scenarios for the W.T.C. Building out of 40 scenarios

Scenario	Glazing	Efficient lighting	Night ventilation	Shading option	Blind deployment schedule	Thermal mass	Façade insulation
1	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a	I_5^1
2	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_1	TM_a	I_{10}^1
4	$G_{0.3}$	L_e	$NV_{m.4}$	SO_e	BS_{12}	TM_a	I_{10}^2
20	$G_{0.3}$	L_e	$NV_{m.4}$	SO_e	-	-	I_{10}^2
22	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	-	-	I_5^1
23	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{12}	-	I_5^2
30	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{12}	-	I_{10}^1
31	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	-	I_{10}^2
34	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	TM_a	I_{10}^1
39	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_1	TM_a	I_{10}^1

Table 5. Overview of the best 10 simulation scenarios for the P.T. building out of 40 scenarios

Scenario	Glazing	Efficient lighting	Night ventilation	Shading option	Blind deployment schedule	Façade insulation
1	$G_{0.3}$	L_e	$NV_{m.1}$	SO_e	BS_{12}	I_5^1
3	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_5^1
4	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{10}^1
9	$G_{PT0.4}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_{10}^1
14	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	I_5^1
19	$G_{PT0.4}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	I_{10}^1
23	$G_{0.3}$	L_e	-	SO_e	BS_{11}	I_5^1
28	$G_{PT0.4}$	L_e	-	SO_e	BS_{11}	I_5^1
31	$G_{0.3}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	-
36	$G_{0.3}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	-

Table 6. Overview of the best 10 simulation scenarios for the H.T. building out of 40 scenarios

Scenario	Glazing	Efficient lighting	Night ventilation	Shading option	Blind deployment schedule	Thermal mass
2	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
3	$G_{S0.18}$	L_e	$NV_{m.3}$	SO_e	BS_{11}	TM_a
10	$G_{0.2}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	TM_a
16	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	TM_a
17	$G_{S0.18}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
19	$G_{0.2}$	L_e	$NV_{m.2}$	SO_e	BS_{11}	-
20	$G_{0.2}$	L_e	$NV_{m.3}$	SO_e	BS_{HT11}	TM_a
21	$G_{0.2}$	L_e	$NV_{m.2}$	SO_e	BS_{HT11}	-
31	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_i	BS_{HT11}	TM_a
40	$G_{S0.18}$	L_e	$NV_{m.2}$	SO_i	BS_{12}	-

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

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

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

ii. The existence and deployment of external shade with proper opening schedules is a major factor of all the better performing scenarios. The top ten performing scenarios amongst the 40 scenarios considered, included external blinds (See Tables 3 and 4).

iii. There was a clear improvement in the initial cooling loads for all the buildings when glazing with higher shading effectiveness (specified via g-value) was considered. From the study, it's clear that the u-value does not play a decisive role in reducing the cooling loads. Glazing type $G_{0.3,}$ (See Table 2) with a low g-value and a high u-value was able to reduce cooling loads significantly (R.T, W.T.C. and P.T.). As in this case, the visual transmittance is not too low and therefore daylight usage potential (reduction in electric energy for lighting) is not compromised.

iv. Increased night time ventilation also led to a reduction in the initial cooling loads for all the buildings though the decreases were all below 10% except for the R.T. building. This 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.

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

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

5. CONCLUSION

The current paper has presented the results of an extensive simulation-based exploration of the thermal performance and improvement scenarios in 4 typical multi-storey office buildings in Ghana. It could be verified that through a combination of design features, (efficient glazing, external shading, thermal mass etc.) a significant reduction of the cooling loads (active building operation mode) and over-heating tendencies (free-running operation mode) can be achieved.

The study‘s repercussions for building design and architectural practice in Ghana are as follows:

Choosing the appropriate glazing type with a low solar heat gain co-efficient value will significantly reduce the cooling loads within the building. Efficient lighting of 2W/m^2 also leads to an appreciable decrease in the cooling loads. Through the combined effect of building features and a good responds to our localized climate, the total base case cooling loads for buildings will reduce significantly. Sealed inoperable glazed windows with inappropriate orientation do not work in the warm humid climate of Ghana and should be avoided.

The application of passive cooling techniques (thermal mass, natural ventilation [day/night], external shading, façade insulation) together with a fan induced air velocity, can reduce the PMV within the indoor spaces from 2 (warm) to 0.7 (slightly warm) and PPD from 75% to 20%.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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