International Journal of Structural and Civil Engineering Research

ISSN 2319 – 6009 www.ijscer.com
Vol. 2, No. 1, February 2013

Research Paper

THERMAL COMFORT AND ENERGY USE IN UK SCHOOL BUILDINGS

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This paper presents the results of an investigation on the effects of making changes to the design parameters of a generic school building. The design options are evaluated in order to study the performance of the building in terms of thermal comfort and energy use using two interventions under different climatic conditions (London and Stockholm). The building simulation is carried out using the IES software package and the thermal comfort metrics as defined in CIBSE Guide A. The summertime comfort and overheating have been evaluated on the basis of Building Bulletin - BB101. The findings demonstrate that combination of various design parameters can help in reducing the effects of overheating in both the climates

Keywords: Thermal comfort, consumption, building simulation, overheating

INTRODUCTION

The use of building simulation tools are very common now-a-days while designing any newconstruction. The use of simulation tools not only helpthe users to evaluate the energy consumption, thermalcomfort and indoor air quality of the buildings, but also enable them in analysing the designoptions to ensure optimum performance throughout theirservice life.Number of new buildings is now being constructed in UK under the Government's Building Schools for the Future (BSF) programme. There are various criteria which these buildings should fulfil (Griffiths and Eftekhari, 2008). One of the criteria is that the buildings should provide good thermal comfort along with the provisions for the supply of suitable quantities of fresh air. Building simulation tools can be used to optimise the design options to ensure that the buildings meet these criteria. However, school buildings are different from many non-domestic buildings in their occupancy. This is because the school buildings are occupied only for a short period (9.00 to 15.00 hours) during the school days in term time. Furthermore, overheating may cause summer time discomfort, and the building designers must consider this in the simulation.

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Jenkins *et al.* (2009) evaluated the performance of a school building using a building simulation tool (ESPr). The overheating in two proposed school designs was calculated for current and future (2030s) climate. A possible solution for evading overheating in school buildings has been proposed which is based on designing the building with proper ventilation and shading summer peak heat load. As per CIBSE Guide A (CIBSE, 2006), in the case of school buildings, when internal operative temperatures are greater than 28°C for a period more than 1% of annual occupied hours, the overheating occurs. However, the CIBSE overheating guidelines do not take into account the absolute temperatures. Therefore, a building having a very high maximum internal air temperature (for example above 32°C) may meet these criteria even though the thermal conditions are unacceptable.

A study on the ventilation rates in schools of UK by Clements-Croome *et al*. (2008) demonstrates the effect of minimum acceptable ventilation rate for the health of the occupants to ensure Indoor Air Quality (IAQ) guidelines and pupil's performance. Conceicaoand Lucio (2008)predicted thethermal comfort level in school buildingsin South Portugal using numerical and simulation tools, andtwo solutions were investigated to heat up the uncomfortable spaces during the winter. From both these studies, it is clear that to obtain the optimum ventilation rate for school buildings maintaining indoor air quality, the heating systems require a temperature setting from 18-21°C with minimum average background ventilation rate of 3 l/s per person of fresh air.

Holmes and Hacker (2007) carried out a study to evaluate the performance of a school building using simulation tools. The simulations were carried out for two cases viz. a base case and a case withfitted external shades. The external shades were used to reduce the level of solar radiation falling upon the windows. It was found that the conditions on the ground floor easily satisfy the design requirements. The conditions on the top floor were found to be inferior to those on the lower floors. This is similar to what is observed in manyother naturally ventilated buildings. According to the authors this is due to the materials used in the roof construction, which had little ability to store heat. The building was then simulated with a 200 mm cast concrete ceiling replacing the existing low mass ceiling tiles. The simulation results showed a clear improvement in the conditions in the top floor. Using subjective and experimental measurements, Conceicao *et al*. (2012) developed an adaptive model in a Kinder-garten. In the study, the ventilation of classrooms wasdone by natural airflow, while the indoor playground was ventilated by forced airflow. Good levels of thermal comfort were observed in winter, while in summer the indoor air quality was acceptable having CO_2 level below 1500 mg/m^3. In this study the building simulation is carried out using the IES software package and the thermal comfort metrics as defined in CIBSE Guide A (CIBSE, 2006). The summertime comfort and overheating have been evaluated on the basis of Building Bulletin - BB101 (BB101, 2006).

BUILDING DESCRIPTION AND PLAUSIBILITY CHECKING

Building Overview and Geometry

The base case building is a two-storey school buildingconsisting of 14 classrooms surrounding a central core teaching space (Figure 1). The building has rectangular shaped class rooms each with an area of 60.375m^2 and one core teaching space with an area of 234.60m^2. Each room has single sided windows for lighting and ventilation. The classrooms in the first floorare also ventilated with stacks. The core teaching space is lighted and ventilated by roof lights thus making it less exposed to the external environment than the classrooms.

Construction Details

The Overall U-values (Table 1) for external components of the base case building were reasonably low. Moreover, these are relatively lightweight, and this will create internal temperature swings and overheating. Thermal mass in the form of cast concrete was included

Figure 1: Model Schematic of Simulated School Building

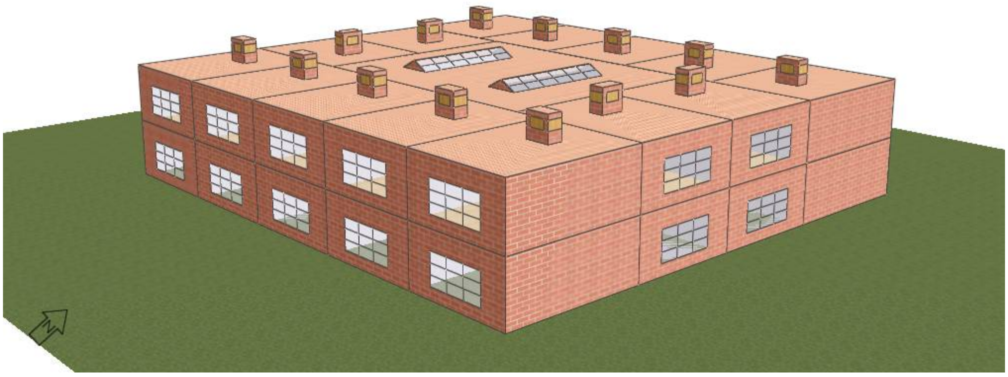


Table 1: Main Construction Details

Type	Material (Outer to Inner Layer)	Overall U-Value (W/m^{2}K)
External wall	Render (10mm), insulation (130mm), blockwork (100mm), gypsum plasterboard (13mm)	0.239
Internal wall	Gypsum plasterboard (13mm), cavity (72mm), gypsumplasterboard (13mm)	1.660
External window	Glass (6mm), cavity (12mm), glass (6mm)	1.977
Ground floor	Clay (750mm), cast concrete (150mm), insulation (120mm), screed (50mm), carpet (10mm)	0.219
Internal ceiling/floor	Carpet (10mm), cast concrete (100mm),ceiling tiles (10mm)	1.622
Roof	Aluminium (10mm), insulation (150mm),ceiling tiles (10mm)	0.217

in the ground floor and internal ceiling/floor of the building. However, their heat storage capacity was reduced due to the use of insulation, carpet and ceiling tiles.Insulation in the roof and walls also helps to reduce this solar gain, but will also reduce the ability of the excess heat to escape from the space.

Internal Heat Gains

Internal heat gains arise from the heat generated by occupants, lighting and electrical equipment. In the case of school buildings these gains are usually high (Table 2). This is because of the high occupant density levels and increased use of IT in theclassrooms. It is assumed that the spaces are fully occupied between 09:00 to 15:30 Monday to Friday every week and no occupants during the weekend and public holidays. The occupancy numbers are 30 for classroom and 60 for core teaching space. Lighting profile assumes 12 W/m^2 of sensible gain with fluorescent lighting for both classroom and the core teaching space. Therefore, the total lighting energy for classroom is 20286 W and 2815.20 W for the core teaching space. The base case model assumes that the light is on for the occupied hours throughout the year. Computers and equipment will consume 2100 W for each classroom and 4200 W for the core teaching space.

Heating Profile

The classrooms and the core teaching space are using weekly heating profile from 9:00 AM to 3:30 PM Monday to Friday for the winter months only whereas there is no heating profile from May toSeptember. The weekly profile of the school is using the daily profile from Monday to Friday 9:00 AM to 3:30 PM.

Ventilation Profile

The simulated classroom spaces are using single sided ventilation and cross ventilation with outlet stack. The bottom and top row of windows are controlled and openable. The cross-ventilation with an outlet stack is making use of the buoyancy effect of the heated classroom air to draw in cool air from the window openings and to expel the hotter classroom air. The stack opening on top of the classroom is using 50% openable area, which has been modelled as door for not allowing solar gain into the simulation calculation.

Table 2: Summary of Internal Heat Gains (Base Case Building)

Space	Type	Description	Max Sensible gain	Max latent gain	Radiant fraction	Total sensible gain (W)
Classroom	Lighting	Fluorescentlighting	12W/m^2	-	0.45	725
	Equipment	IT equipment etc.	60W/person	-	0.22	1800
	People	30 occupants	80W/person	60W/person	-	2400
Core	Lighting	Fluorescentlighting	12W/m^2	-	0.45	2815
Teaching	Equipment	IT equipment etc.	60W/person	-	0.22	3000
Space	People	60 occupants	80W/person	60W/person	-	4000

During occupied periods, window opening is proportional to the internal temperature and the CO_2 concentration within the space guided by a ramp function based on a temperature range of 20°C to 24°C and a CO_2 range of 800ppm to 2000ppm. During unoccupied periods, night cooling(only for summer season) is employed to purge the hot air from the space and replace it with cool night air which is achieved by opening the windows to their maximum setting during unoccupied periods. The core teaching space is ventilated using concrete ducts and the air enters the centre of the building through floor vents and is exhausted from the space using openable lantern lights incorporated into the roof.

SIMULATION RESULTS FOR BASE CASE BUILDING

Thermal Comfort Data

Based on the initial simulation of the school using London Heathrow weather file in IES VE for thewhole year, it is seen that on 29 December all the rooms experienced the minimum airtemperature in °C and on 14 May the maximum air temperature. Based on BB101 (BB101, 2006) Thermal Comfort Criteria, the rooms have been assessed which can be seen from Table 3. The rooms have been numbered as per the plans (Figures 2a and 2b). Although none of the rooms satisfy the thermal comfort criteria, three worst performing rooms namely GF13, FF09 and the core teaching space have been selected for improvement.

Energy consumption

A total of 161.83 MWh of electricity is consumed by the whole building which includes consumption from equipment, lights, system & DHW/Solar pump. Total natural gas consumption is 29.97 MWh, thus the total energy consumption of the building is 191.80 MWh. This means that the building is consuming 84.06 kWh/m^2 of electrical energy and 15.56 kWh/m^2 of fossil fuel. According to good practice guide (Carbon Trust UK, 2005)heating energy required by typical primary school of UK is 157kWh/m^2/year. It seems that the base case building meets the benchmark, but it is using too much of electricity which is three times more carbon intensive. Total CO_2 emission of the building is 99.30 tonnes which is equivalent to 51.58 kgCO_2/m^2. Figure 3 shows that the electricity consumption in winter month is slightly higher than the summer month, because of appliances auxiliary system and DHW pump in winter month using electricity in addition to the same monthly lighting energy consumption which is plausible. The outdoor temperature drop is reflective on winter season energy demand due to heating.

Energy balance

Total heat gain from internal gain, solar gain and space conditioning sensible in the core teaching space is equal to 32.74MWh and heat loss due to external conduction gain, internal conduction gain and natural ventilation is equivalent to 32.79 MWh. Similarly in the case of all the classroom spaces, heat gain is equal to heat loss. This shows the balance of energy and hence the base case model is plausible.

Internal-External temperature

Figure 4 shows the internal and external temperature variation from May to September

Table 3: Thermal Comfort Data for Base Case Building

Room	No. of Hours (air temp > 28°C)	Avg internal to external air temp difference (°C)	Max air temp (°C)
Core teaching space	176	7.9	38.0
GF01	262	10.0	34.3
GF02	307	10.4	35.4
GF03	307	10.4	35.6
GF04	309	10.5	35.5
GF05	268	10.1	35.5
GF06	323	10.5	36.2
GF07	371	11.1	36.5
GF08	329	10.6	36.3
GF09	376	11.1	36.6
GF10	312	10.5	35.8
GF11	360	10.9	37.1
GF12	358	10.9	37.2
GF13	363	10.9	37.1
GF14	319	10.6	35.9
FF01	70	7.4	33.2
FF02	104	7.8	34.3
FF03	107	7.9	34.4
FF04	107	7.8	34.3
FF05	76	7.5	33.3
FF06	65	7.3	34.9
FF07	126	8.5	35.0
FF08	65	7.3	34.9
FF09	129	8.5	35.1
FF10	57	7.2	33.3
FF11	89	7.6	34.3
FF12	95	7.6	34.3
FF13	90	7.6	34.2
FF14	60	7.3	33.1

Figure 2a: Ground Floor Plan

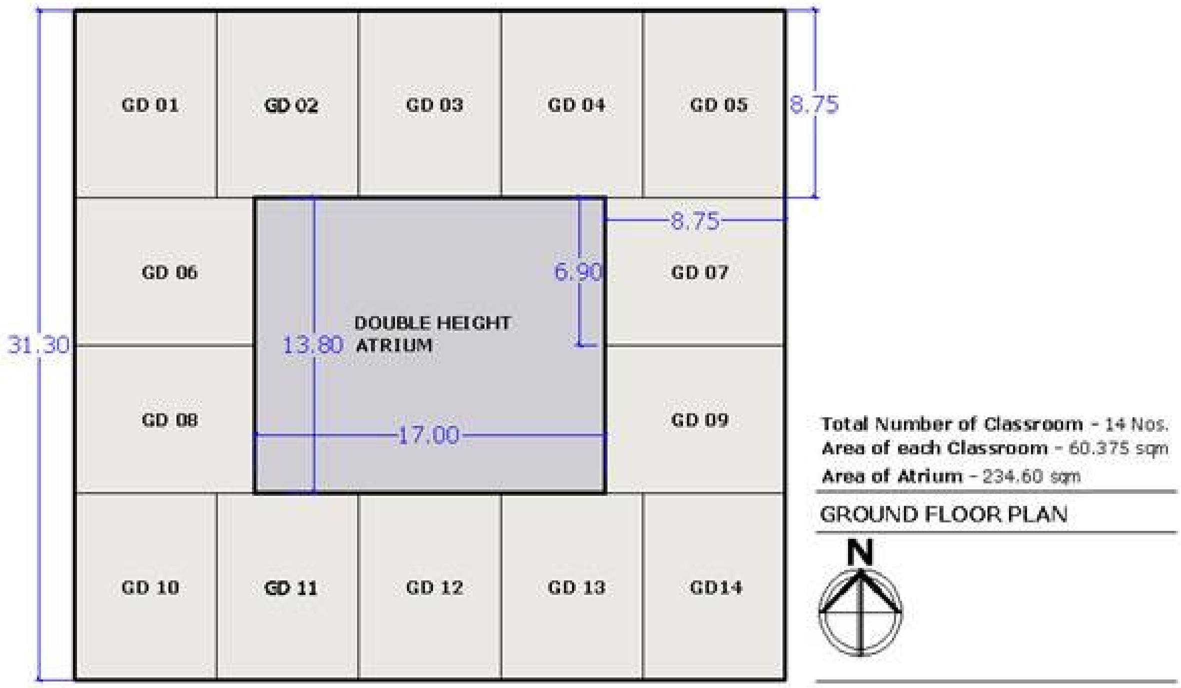


Figure 2b: First Floor Plan

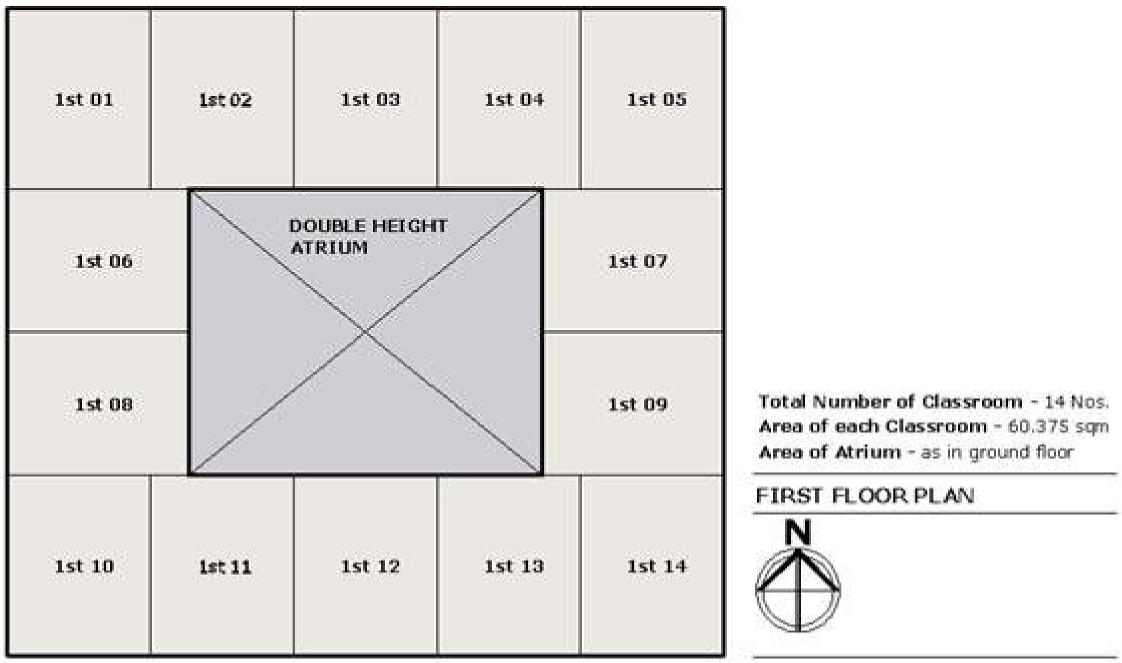


Figure 3: Energy Consumption Plot

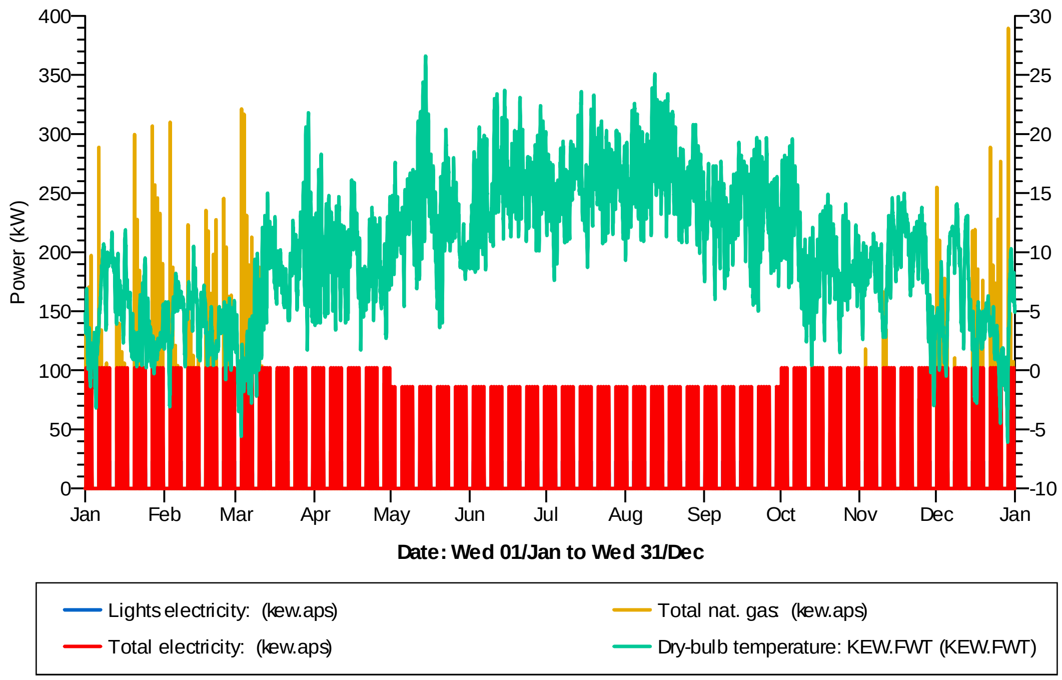
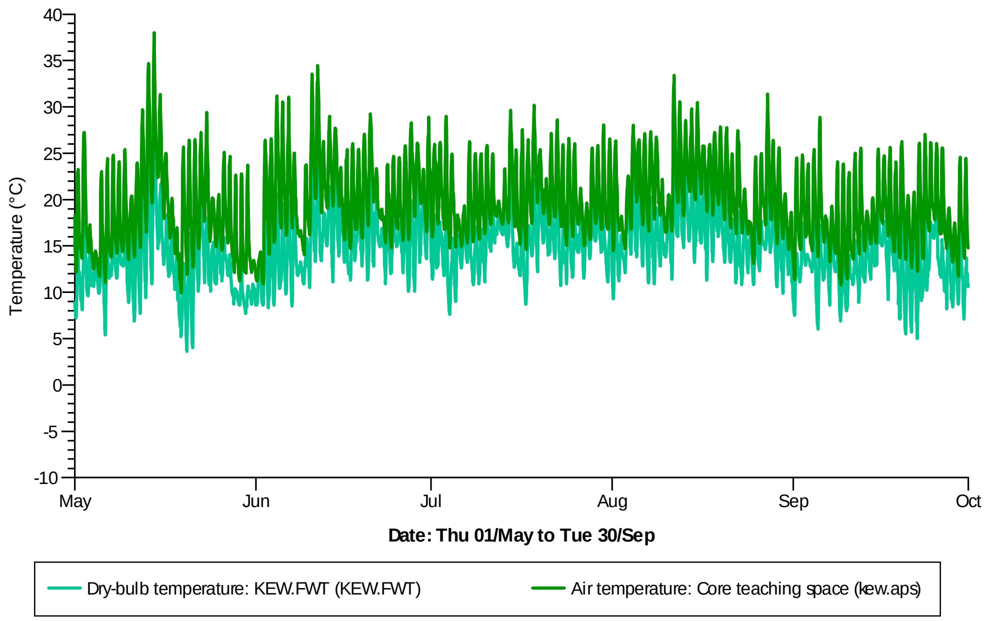


Figure 4: Internal-External Temperature Plot



for the core teaching space. It is evident from the graph that the internal temperature swings is high and hence causes overheating of the space with maximum temperature of 38 °C thus causing the space thermally uncomfortable. This is plausible for the base case model. Similarly, the same can be observed for the classroom spaces GF 13 and FF 09 (Figures 5 and 6).

Figure 5: Internal-External Temperature Plot for GF 13 (London)

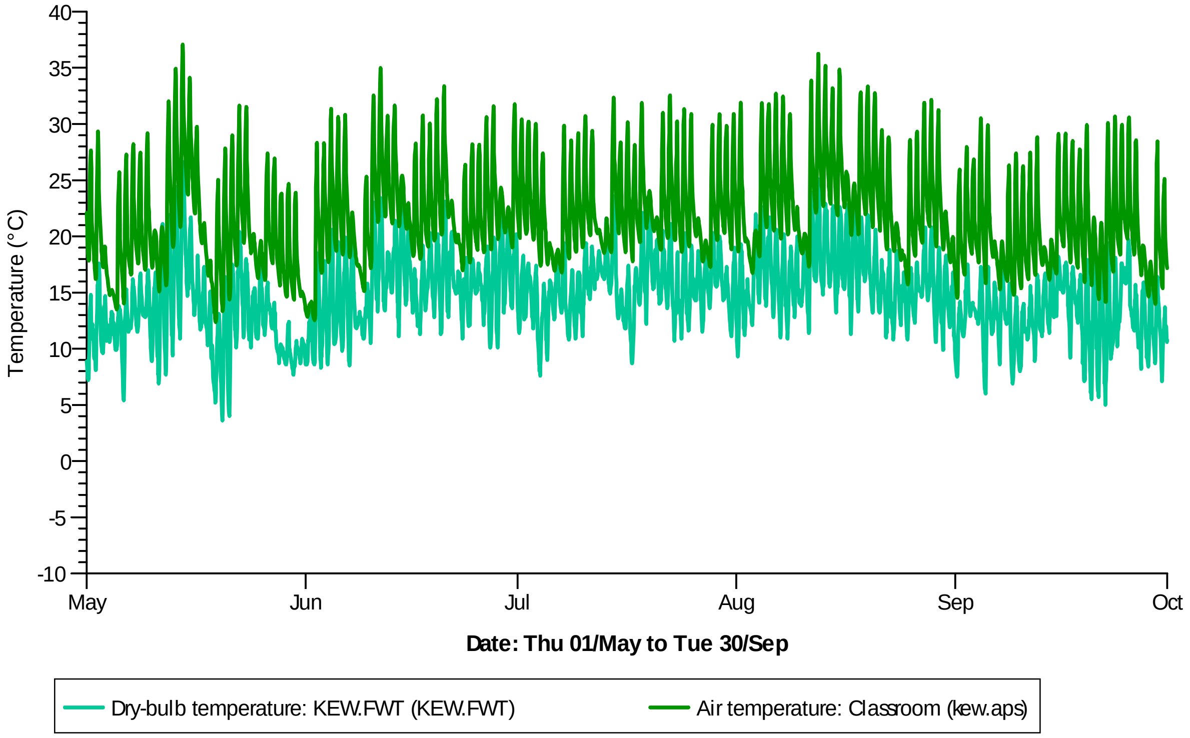
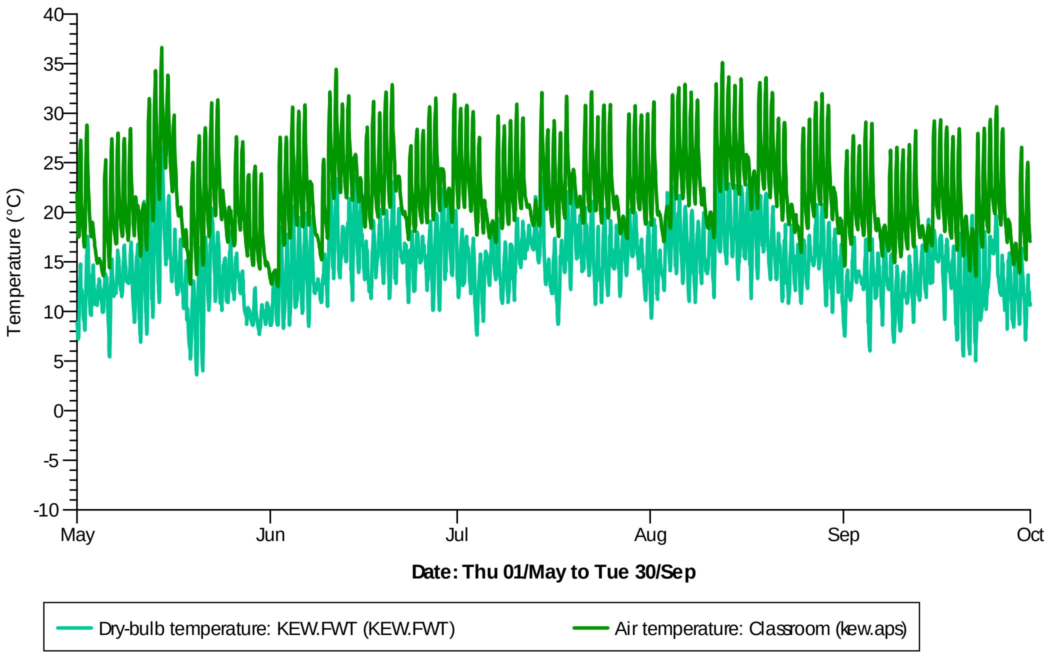


Figure 6: Internal-External Temperature Plot for FF 09 (London)



RESULTS AND DISCUSSION

On the basis of the analysis as per thermal comfort criteria, three spaces have been chosen for improvement viz. Room No 13 in Ground Floor, Room No 9 in First Floor and Core teaching space. Two interventions have been considered for adoption in the building. These are to analyse the effect on thermal comfort and energy use. Details of these interventions and their effects on the thermal comfort and energy use are discussed in the following sections.

Intervention one

The base case model is experiencing high internal gains of 80 W per person (Table 4). According to CIBSE Guide A (CIBSE, 2006) sensible heat gains from teaching staff is 75 W, while Jenkins *et al.* (2009) suggested that the heat gain from students shall be counted as 60 W/per student. Therefore, in this intervention an attempt has been made to reduce the internal gains, and a heat gain of 60per person is considered.In Base Case total internal gains from computer for each class room is 2100W, which means that there are nearly 17 computers considering 125W of heat gain per computers. According to BB87 (BB 87, 2003) "Up to five desktop PCs with CRT screens, a laser printer and an OHP/computer projector will constitute the ICT equipment in a 'typical' classroom". Therefore, in a classroom a total of 5 computers and other ICT equipment shall not cross 900 W gains and this has been used in this intervention to limit the internal gains. The core teaching space is considered to be equivalent to two classrooms and, hence, a total of 1800W heat gain is considered.Solar heat gains transmitted through glazing is another factor for over-heating buildings.Although the glazing U-value of base case model is 1.9773 W/m^{2}k, which is reasonable, but nowadays low E double glazed windows have U-value as low as 1.5 W/m^{2}k which has been adopted for both external windows and roof lights in this intervention.

The thermal comfort data after intervention one was summarised in Table 5. It is clear from this Table that the implementation of intervention 1 satisfies the 1st thermal comfort criteria for all the three spaces in London case. Reduction of internal heat gain in Stockholm case could not meet the 1st criteria for the south facing GF13 due to high solar gains compared to London climate during summer. In both the climate cases, maximum air temperature was above 32°C and the average internal to external temperature difference is higher than 5°C for all the three spaces.Although the maximuminternal temperature for core teaching space is almost same for both cases,

Table 4: Internal Gains for Assumed Spaces (Base Case Building)

Room	Area (m^2)	Internal gains (kW)	Internal gains (W/m^2)
Ground Floor 13	60.38	5.22	86.53
First Floor 9	60.38	5.22	86.53
Core Teaching Space	234.6	11.82	50.38

Table 5: Thermal Comfort Data After Intervention One

Room	No. of hours (air temp > 28°C)[1]		Avg internal to external air temp difference (°C)[2]		Max air temp (°C)[3]	
	London climate	Stockholm climate	London climate	Stockholm climate	London climate	Stockholm climate
Core Teaching Space	42 (P)	86 (P)	6.6 (F)	6.8 (F)	35.5 (F)	35.0 (F)
Ground Floor 13	112 (P)	225(F)	8.8 (F)	8.4 (F)	33.8 (F)	36.7 (F)
First Floor 9	67 (P)	161(F)	7.6 (F)	9.0 (F)	33.5 (F)	36.3 (F)

Note: P-Pass, F-Fail; [1]BB101 Criteria 1: There should be no more than 120 hours when the air temperature in the classroom rises above 28°C (for occupied hours); [2]BB101 Criteria 2: Average internal to external temperature difference should not exceed 5°C (for occupied hours); [3]BB101 Criteria 3: Internal air temperature when the space is occupied should not exceed 32°C (for occupied hours)

the maximum internal temperature for both the classroom spaces in Stockholm case is much higher than London. This is becauseof longerday light period during summer in Stockholm than Londonand, hence, more solar radiation is being transmitted in case of Stockholm. The total yearly energy consumption for modified building in Stockholm is 239.35 MWh which is higher than 153.25 MWh in London. This is due to the fact that winter is much colder in Stockholm than in London and, hence, increased boiler load for the former case. Therefore, the energy consumption is reduced compared to the base case in London and increased in case of Stockholm due to the intervention (Table 6). Heat gain in the core teaching space is 27.68MWh and heat loss is 27.72MWh for London case after intervention one which fulfils the energy balance. This has been validated for all classroom spaces for both climates. Figure 7 shows the internal-external temperature variation for Stockholm case from May to September after intervention one. From this figure it was evident that although the internal gains reduced, the maximum internal temperature rises above 32°C for a number of hours during the summer which is due to high solar gains.

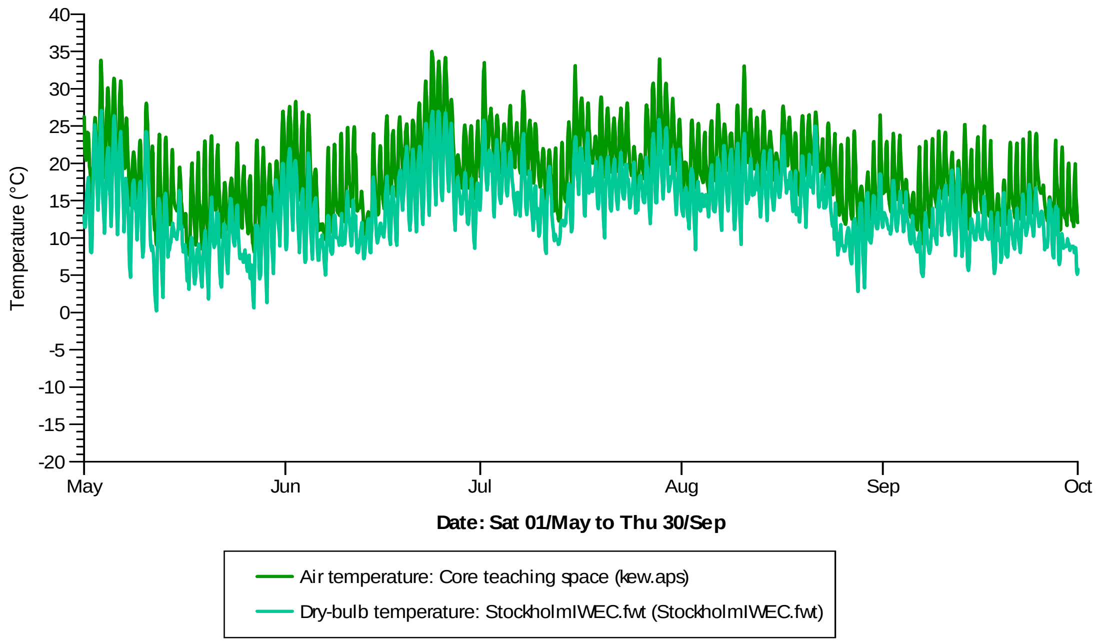
Intervention two

An undesirable rise in temperature during the summer period can be caused by the solar gains. To reduce excessive solar gains, the use of a simple soleil shading device (0.5m)

Table 6: Energy Consumption and CO_2 Emissions Data After Intervention One

Building	Boiler MWh	Aux./ DHW MWh	Nat. Gas MWh	System Elect. MWh	Lighting MWh	Elect. Equip. MWh	Total Elect. MWh	Total Energy MWh	CO_2 Emission ton/yr
Base Case Building	29.97	15.76	29.97	15.76	39.19	106.88	161.84	191.80	99.30
Modified Building London	52.49	15.76	52.49	15.76	39.19	45.80	100.76	153.25	52.70
Modified Building Stockholm	138.59	15.76	138.59	15.76	39.19	45.80	100.76	239.35	69.41

Figure 7: Internal-External Temperature Variation (Stockholm)



on top of external windows is considered for this intervention (Figure 8). Solar shading can help in reducing the internal temperature swings that can occur during the sunny days. The effect of solar shading only on the base case is not significantreducing the internal temperature swings in the base case building (Table 7). Therefore, in this intervention, solar shading is introduced keeping all the changes in the first intervention. Also, the classroom stack openable area was increased to 60% to allow the ventilation to occur at an increased rate.

The thermal comfort data after intervention two is summarised in Table 8. From this table, it was observed that due to the increased

Figure 8: Schematic Diagram of Building After Intervention 2

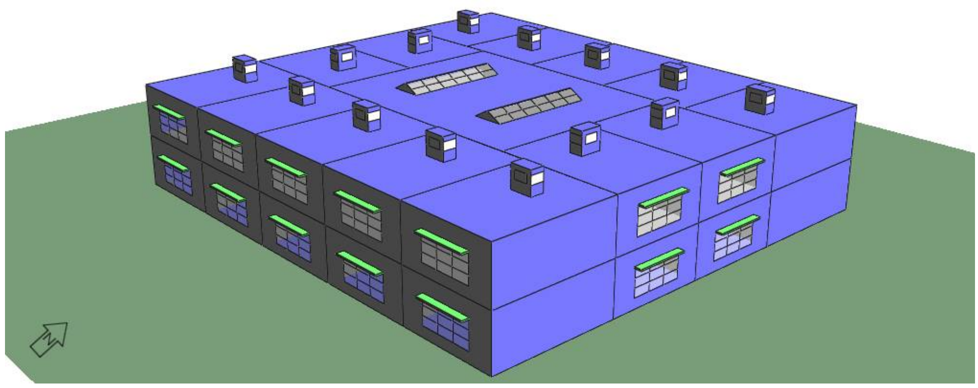


Table 7: Thermal Comfort Data due to Solar Shading for London

Room	No. of hours (air temp > 28°C)	Avg internal to external air temp difference (°C)	Max air temp (°C)
Core Teaching Space	80 (P)	8.5 (F)	32.6 (F)
Ground Floor 13	353 (F)	11.5 (F)	33.0 (F)
First Floor 9	163 (F)	9.5 (F)	31.7 (F)

Note: P-Pass, F-Fail.

Table 8: Thermal Comfort Data After Intervention Two

Room	No. of hours (air temp > 28°C)		Avg internal to external air temp difference (°C)		Max air temp (°C)	
	London climate	Stockholm climate	London climate	Stockholm climate	London climate	Stockholm climate
Core Teaching Space	28 (P)	78 (P)	4.4 (P)	6.8 (F)	34.3 (F)	34.8 (F)
Ground Floor 13	43 (P)	182 (F)	6.6 (F)	8.1 (F)	31.8 (P)	35.4 (F)
First Floor 9	14 (P)	83 (P)	5.0 (P)	6.5 (F)	31.7 (P)	33.7 (F)

Note: P-Pass, F-Fail.

openable area, internal temperature swings reduced as a result of the increased pressure drop across the openings and increased ventilation rate. The average solar gain reduction is significant for both the climatic conditions due to the effect of shading which can be seen from Figure 9. It can be seen that solar gain in the core teaching space has not changed for London case which is logical as shading has no effect on the space. For both London and Stockholm cases, solar gain has been reduced considerably due to external shading on south-facing GF 13 and east-facing FF 09. Heat gain in the core teaching space is 56.38MWh and heat loss is 56.40MWh for London case after intervention two which fulfils the energy balance. This has been checked for all classroom spaces for both climatic conditions. As a result of intervention two thermal comfort criteria is satisfied for all three spaces for London case. On the other hand, in case of Stockholm case, although the solar gains reduced, the stack openable area was not effective in reducing the internal temperature swings as compared to London. This could be due to the intense solar radiation during the summer season in Stockholm.

Figure 10 shows the internal-external temperature variation from May to September for classroom GF 13 for London case. It can be seen that there is a significant reduction in the internal temperature swings with the maximum temperature rising to 34.3°C compared to 37.1°C in the base case. It is interesting to note that the annual energy

Figure 9: Solar Gain After Intervention Two

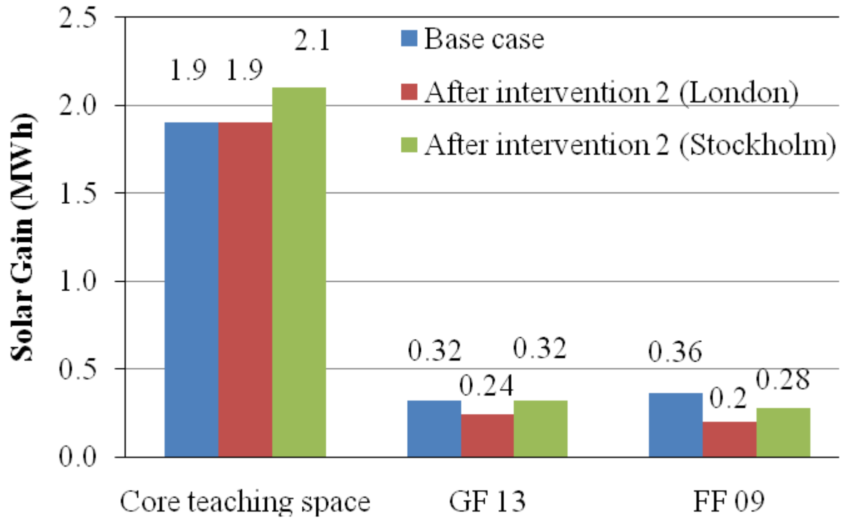
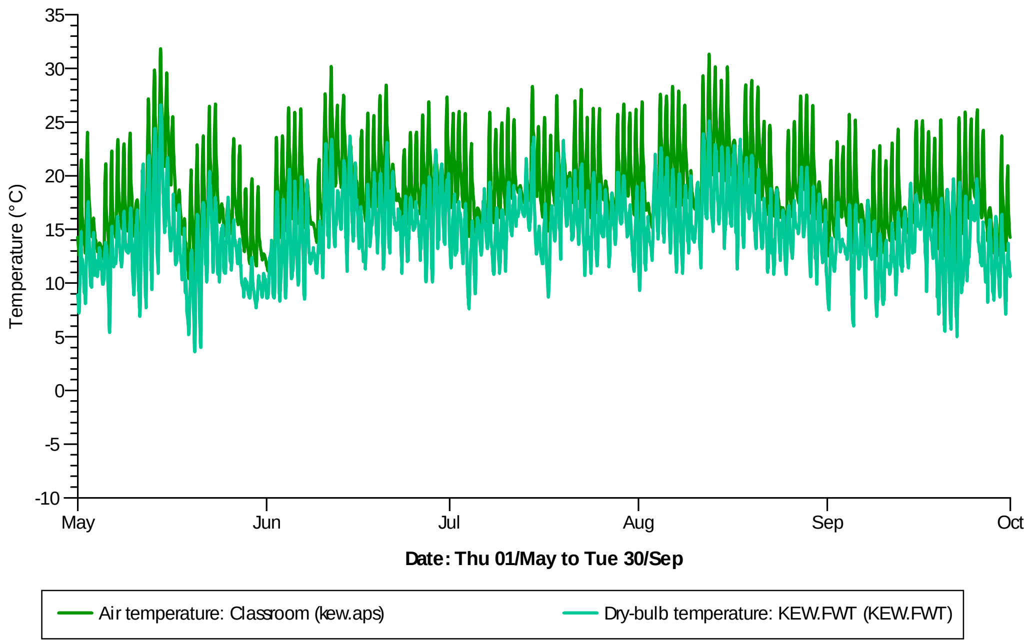


Figure 10: Internal-External Temperature Variation (London)



consumption in London case was almost double (372.78MWh) of the base case (191.80MWh). This is because of more heat loss due to the increased stack opening area in the classrooms. Similarly, the energy consumption increased in case of Stockholm, but this is not as significant as compared to the London Case. The CO_2 emissions for both the cases are lower than the base (Table 9).

Table 9: Energy Consumption and CO_2 Emissions Data After Intervention Two

Building	Boiler MWh	Aux./ DHW MWh	Nat. Gas MWh	System Elect. MWh	Light-ing MWh	Elect. Equip. MWh	Total Elect. MWh	Total Energy MWh	CO_2 Emission ton/yr
Base Case Building	29.97	15.76	29.97	15.76	39.19	106.88	161.84	191.80	99.30
Modified Building London	272.02	15.76	272.02	15.76	39.19	45.80	100.76	372.78	95.29
Modified Building Stockholm	148.07	15.76	148.07	15.76	39.19	45.80	100.76	248.83	71.25

CONCLUSION

In this paper an attempt has been made to study the effects of alteringvarious design parameters of a generic school building on its performance in terms of thermal comfort and energy use. Based on BB101 Thermal Comfort Criteria, the rooms of the building have been assessed. Although none of the rooms satisfy the thermal comfort criteria, three worst performing rooms namely GF13, FF09 and the core teaching space have been selected for improvement. Two interventions were adopted and evaluated for two climatic conditions namely London and Stockholm. In intervention one, internal gains and the glazing U-value of external window and rooflights were reduced. In intervention two, external shading was adopted on top of external windows and classroom stack openable area increased to 60% keeping all the changes of intervention one. On the basis of the results presented and discussed in this paper the following conclusions have been drawn:

(i) Due to the reduction in the internal gain in intervention one, the thermal comfort criteria of air temperature greater than 28°C not more than 120 hours was satisfied for all the three spaces in London climate.

(ii) The total yearly energy consumption after simulation in intervention one reduced in London, but this increased in the case of Stockholm. However, the CO_2 emissions reduced in both cases.

(iii) Solar gain was limited as a result of external shading as part of the intervention two, which provided sufficient cooling and reduced the maximum internal temperature significantly in both the climates compared to the base case. In particular, the two classroom spaces were successful in meeting the third comfort criteria of not exceeding the maximum temperature of 32°C.

(iv) Increasing the classroom stack openable area from 50 to 60% was found to reduce significantly the internal temperature swings due to the increased ventilation rate.

(v) As a result of intervention two, the energy consumption increased in both the climates; almost to double in the case of London climate compared to the base case due to the increased heat loss.

A wide range of other ventilator options now exist with combinations of secure louvres, acoustic vents and motorised control units. These should be considered with the aim of producing a quiet, controllable, draught-free supply of fresh air. Finally, the aim of this paper is to provide results which can be used broadly in the current design of school buildings and not to focus on the design of a particular individual building.

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