# EFFECT OF ENVELOPE PROPERTIES AND THERMAL ADAPTATION ON ENERGY CONSUMPTION AND COMFORT CONDITIONS THROUGH SIMULATION OF VARIOUS ECMs

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## ABSTRACT

The study, conducted in composite climate of India, exhibits improvement in energy efficiency of a conditioned building block with the use of energy conservation measures (ECMs) recommended by National Energy Conservation Building Code (ECBC). In first part of it, subject building model was individually applied with five ECMs and two combinations of these ECMs by using constant thermostat settings. Similarly in second part of the study the same was done with adaptive thermostat settings. Sensitivity analysis showed that the effect of ECMs get reduced with increase in building footprint and internal loads. Analysis of thermal comfort in an unconditioned building using same set of ECMs was also carried out to see improvement in comfort hours.

## INTRODUCTION

In most countries, contribution of building's total energy consumption is one of the largest among all major sectors. Synnefa et al., (2007) demonstrated that energy in building sector is also high in rest of the countries; in 2003 nearly 60% of the net electricity consumption in the OECD (Organisation for Economic Co-operation and Development) economies was from the building sector covering both residential and commercial buildings, each representing about half of this electricity consumption. Therefore, most countries have already developed or are developing standards and codes to improve energy efficiency of buildings. India has also developed Energy Conservation Building code (ECBC) in year 2007. Estimates based on computer simulation models indicate that ECBC compliant buildings are expected to use about 40% less energy than conventional buildings. It is estimated that the nationwide enforcement of ECBC will yield annual saving of around 1.7billon kWh (USAID, 2009). This study was conducted to evaluate energy saving in a building block by implementing measures of ECBC related to specifications of building envelope such as: U-values of walls, roof, and windows, solar heat gain coefficient of glazing, roof reflectivity and some combination of these measures (BEE, 2007). Envelope measures were used first for fixed set point conditions and then for adaptive set point conditions.

It is revealed that increasing roofs reflectance from 0.08 to 0.3 and 0.5 decreases the energy consumption up to 15% to 30% respectively. Bhatia et al., (2011) showed that, with use of cool roof in place of gray roof; 8.75% annual cooling energy could be saved in composite climate (India) which is approximately 5.05% of total building energy. Akbari et al., (1999) conducted field tests of 11 Florida homes, daily air-conditioning electricity savings of 2–43% and utility coincident peak power savings of 11–30% were demonstrated with reflective roof coatings.

Thermal adaptation also comprises energy saving in residential and commercial buildings. Mui et al., (2003) conducted a survey in humid subtropical climate of Hong Kong published that with the integration of adaptive thermal comfort temperature (ACT) model, the total percentage of energy saving is about 7%. Similarly, a study conducted by Yamtraipat et al., (2005) concluded that preference of set point differs from person to person and 1$^{o}$C increase of cooling set point (from 22 to 23$^{o}$C, 23 to 24$^{o}$C and so on up to 28$^{o}$C) gives a mean energy saving of about 6.14%. Thus, from various studies it is clear that people are adaptive in nature and could feel comfortable at elevated temperatures. Dear et al., (2002) suggested comfort temperature preferred by occupants. Yao et al., (2009) state that perception of comfort is not a fixed condition according to the point of view of adaptive thermal comfort, whereas it depends on physiological and non-physiological factors, in particular in free-running buildings. Thus, study has been focused to evaluate the effect of ECBC measure in different warm climates to improve energy efficiency and thermal comfort conditions of a hostel building block. Effect of adaptation is also considered for further improvement in both areas.

## DESCRIPTION OF BUILDING BLOCK

The study was carried out through conducting measurements at a hostel building of an educational institute located in the city of Hyderabad, composite climate of India. The investigated part of building (fourth floor, single occupancy) is six year old, naturally ventilated and has room size of 3.6x2.4m, Window openings are of size 1.34×0.65m, window shade size is 0.91x0.6m, opaque door size is 1.98x1.0m and a corridor of 1.35m in front side of hostel rooms used for walkways to neighbour hostel rooms. Table 1 illustrates the construction details of subject building model.

*Table 1*
*Construction details of building block*

| Material (Outer to inner layer) | Roof Thickness (m) | Wall thickness (m) | Floor thickness (m) |
|---|---|---|---|
| Gypsum Plastering | 0.0127 | 0.0127 | 0.0127 |
| Sand and Gravel | 0.0254 | - | 0.0254 |
| Concrete slab | 0.1016 | - | 0.1016 |
| Brick | - | 0.2032 | - |
| Gypsum Plastering | 0.0127 | 0.0127 | 0.0127 |
| Cork tiles | - | - | 0.06 |
| Assembly U-value ($W/m^2$-$^oC$) | 3.760 | 1.782 | 3.057 |

Same construction materials composed external and internal walls. Roof constructed with Cement mortar having coarse surface finish result in high heat gain during daytime. Each room was equipped with a fluorescent light of 'T12' type and a ceiling fan without power backup; equipment load was not much significant in the occupied rooms. Mostly hostel students resided in the night except holidays and some of them used their personal computers.

## METHODOLOGY

Simulation model of the building block was developed in EnergyPlus V4, and was calibrated based on dry bulb temperature of room air through varying the subject building model conductivity of roof and wall materials, roof reflectivity; till the simulated room air temperature comes within the acceptable range of measured temperature. This model was then converted into conditioned by inserting HVAC related details. Thus, developed model was used as a base model for examination of effect of various ECMs, thermal adaptation on energy consumption. Seven ECMs as suggested by the ECBC of India considered in this study to improve energy efficiency and thermal comfort conditions of subject building model. Figure 1 shows the methodology of study.

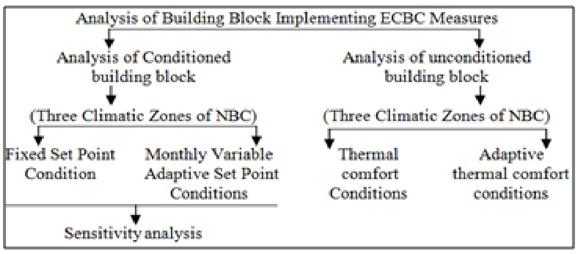


*Figure 1 Methodology of work flow process*

Conditioned and unconditioned building blocks were investigated to evaluate the energy consumption of individual ECMs and then adaptive phenomenon was considered to assess further energy conservation and improvement in thermal comfort conditions.

Analysis was done for three out of five different climatic zones of India namely hot and dry zone, warm and humid zone, and composite zone, other two climatic zones cold and moderate (temperate) were out of scope of this study because of average low temperature. Table 2 exhibits the details of recommended ECMs by ECBC-2007.

*Table 2*
*Energy Conservation Measures for envelope as by ECBC*

| Cool Roof reflectance | Wall U-value (W/m2-oC) | Roof U-value (W/m2-oC) | Glass U-value (W/m2-oC) | SHGC |
|---|---|---|---|---|
| 0.70 | 0.440 | 0.261 | 3.30 | 0.25 |

*all three climates have same values for U-value of wall assembly, roof assembly, Glass and SHGC of glass.
Table 3 shows envelope measures and their combinations, final ECM is termed as ECBC building.

*Table 3*
*Envelope energy conservation measures*

| Measures | Name | As is case-Actual Room |
|---|---|---|
| ECM_1 | C R | Cool Roof |
| ECM_2 | W | ECBC wall |
| ECM_3 | R | ECBC Roof |
| ECM_4 | G S | ECBC Glass SHGC |
| ECM_5 | G U | ECBC Glass U-value |
| ECM_6 | R S | ECBC Glass SHGC + ECBC |
| ECM_7 | ECBC | all cases (1+2+3+4+5) |

First, all seven ECMs were applied to the subject building model which was operating for package air conditioner unit of COP 3.1 and 24$^o$C cooling set point. In the second part of study, same methodology was used to compare the energy consumption of each measure using monthly variable adaptive set point (neutral temperature) conditions. Neutral temperature was calculated from $T_n$=17.6 + 0.31$T_o$ {1} (Wijewardane et al., 2008), by putting mean monthly outdoor dry bulb temperature ($T_o$) throughout all months one by another for all three analyzed locations. Neutral temperature tabulated in the following Table 4, was used as cooling set points in adaptive methodology. The maximum outdoor dry bulb temperature ($T_{mmo}$) was recorded in May month, which result in high neutral temperature ($T_n$) also.

*Table 4*
*Mean monthly outdoor DBT and neutral temperature for analyzed cities*

| Month | Hot and dry | | Warm and humid | | Composite | |
|---|---|---|---|---|---|---|
| | Ahmedabad | | Chennai | | Hyderabad | |
| | $T_{mmo}$ | $T_n$ | $T_{mmo}$ | $T_n$ | $T_{mmo}$ | $T_n$ |
| Jan | 19.9 | 23.8 | 24.5 | 25.2 | 22.8 | 24.7 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Feb | 22.3 | 24.5 | 26.0 | 25.7 | 25.2 | 25.4 |
| Mar | 28.1 | 26.3 | 27.8 | 26.2 | 29.2 | 26.6 |
| Apr | 31.5 | 27.4 | 30.1 | 26.9 | 31.7 | 27.4 |
| May | 33.6 | 28.0 | 32.1 | 27.5 | 32.9 | 27.8 |
| Jun | 33.2 | 27.9 | 31.0 | 27.2 | 28.6 | 26.5 |
| Jul | 29.6 | 26.8 | 30.2 | 27.0 | 26.8 | 25.9 |
| Aug | 28.2 | 26.3 | 29.3 | 26.7 | 25.7 | 25.6 |
| Sep | 28.9 | 26.5 | 29.0 | 26.6 | 26.2 | 25.7 |
| Oct | 27.2 | 26.0 | 27.7 | 26.2 | 26.1 | 25.7 |
| Nov | 23.5 | 24.9 | 26.1 | 25.7 | 23.7 | 25.0 |
| Dec | 20.6 | 24.0 | 24.8 | 25.3 | 21.7 | 24.3 |

Likewise, energy efficiency of subject building model, thermal comfort conditions were evaluated with and without effect of adaptation for all above locations. Thermal comfort hours were calculated as per ASHRAE standard 55-2004 and effect of adaptation was evaluated using neutral temperature equation. Then De Dear and Bragger suggested ±3.5°C about the neutrality temperature, was added to the neutral temperature to get adaptive comfort limit (Wijewardane et al., 2008).
In above climates neutral temperature varies from 23.8 to 28°C, which shows high potential of energy savings as compared to 24°C cooling set point throughout in year.

## RESULTS

This study covers the three predominantly warm climatic zones namely: warm and humid zone, hot and dry zone, and composite zone as per National Building Code guidelines. Energy efficiency of building block was improved by about 40% in all three climatic conditions using ECBC envelope measures and savings were further improved by using adaptive concept. Following sub-sections explain the energy efficiency and thermal comfort conditions in different climates.

### Energy conservation in composite climate

Hyderabad has chosen as representative city for composite climate. While analyzing the effect of thermal adaptation, the cooling set point has been varied on monthly basis as per the neutral temperature that change from 26.6°C during March to 27.8°C during the month of May. Table 5 shows the annual energy consumption per unit area considering each ECM using fixed and adaptive set point for the given HVAC system. The following can be noted from the results:

- With ECM 7 (ECBC building), i.e. combination of all individual ECMs, 40% (around 72kWh/sqm/yr) energy could be saved over the common practice case i.e. the ‘as is’ case.
- Further, additional energy saving by about 15 to 19% could be achieved (or maximum of 30kWh/sqm/yr) by using adaptive set point conditions.
- The effect of ECMs with adaptive set point approach is similar as compared to the fixed set point approach. This is evident from comparison shown in Figure 2.
- From Figure 2, it can be observed that when all the ECMs are applied with the adaptive set point approach, the monthly variation of energy consumption reduces by a large extent, whereas in case of fixed set point conditions peak is very higher as compared to rest of the period.

*Table 5*
*Energy consumption details for both set points conditions in composite climate*

| Annual Energy Saving in Case of Hyderabad | | | | |
|---|---|---|---|---|
| cases | Energy consumption_F_Sp (kWh/m2/yr) | Energy consumption_A_Sp (kWh/m2/yr) | Energy Saving (kWh/m2/yr) | Saving (%) |
| As is | 177.9 | 149.3 | 28.5 | 16.0 |
| ECM_1 | 164.2 | 135.6 | 28.6 | 17.4 |
| ECM_2 | 142.5 | 117.1 | 25.4 | 17.8 |
| ECM_3 | 141.1 | 115.8 | 25.3 | 17.9 |
| ECM_4 | 156.0 | 126.0 | 30.0 | 19.2 |
| ECM_5 | 184.8 | 155.3 | 29.5 | 16.0 |
| ECM_6 | 141.4 | 116.4 | 25.0 | 17.7 |
| ECM_7 | 105.7 | 89.2 | 16.5 | 15.6 |

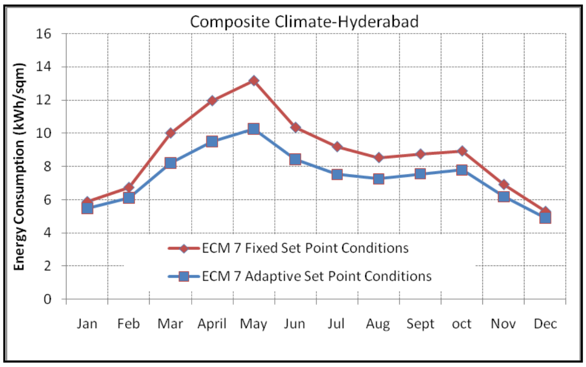


*Figure 2 Energy Consumption of ECBC building using fixed and adaptive set points*

### Energy conservation in hot and dry climate

For hot and dry climate, Ahmedabad was chosen as a representative city. While analyzing the effect of thermal adaptation, the cooling set point has been varied on the monthly basis as per neutral temperature that change from 26.3 during March to 28.0°C during the month of May. Neutral temperature varies little bit higher than composite climate due to good summer and winter conditions. Table 6 shows the annual energy consumption per unit area by considering each ECM using fixed and adaptive set point for the HVAC system. The following can be noted from the results:

- With ECM_7, i.e. ECBC building, 43.1% (84kWh/m2/yr) energy could be saved over the common practice case i.e. the ‘as is’ case.
- Further, additional energy saving by about 15 to 19% could be achieved (or maximum of

33kWh/sqm/yr) by using adaptive set point condition.

- Tphe effect of ECMs with adaptive set point approach is similar as compared to the fixed set point approach. This is evident from comparison shown in Figure 3.
- From Figure 3, it can be observed that when all the ECMs are applied with the adaptive approach, the monthly variation of energy consumption reduces by a large extent, whereas in case of fixed set point conditions peak is very higher as compared to rest of the period.

*Table 6*

*Energy consumption details for both set point conditions in Hot and Dry climate*

| Annual Energy Saving in case of Ahmedabad | | | | |
|---|---|---|---|---|
| Cases | Energy consumption_F_Sp (kWh /m2/yr) | Energy consumption_A_Sp (kWh/ m2/yr) | Energy Saving (kWh/ m2/yr) | Saving (%) |
| As is | 196.3 | 164.5 | 31.8 | 16.2 |
| ECM_1 | 181.5 | 149.8 | 31.7 | 17.5 |
| ECM_2 | 161.5 | 136.4 | 25.1 | 15.6 |
| ECM_3 | 156.5 | 129.2 | 27.4 | 17.5 |
| ECM_4 | 179.5 | 146.4 | 33.1 | 18.4 |
| ECM_5 | 201.0 | 168.2 | 32.7 | 16.3 |
| ECM_6 | 155.5 | 128.3 | 27.2 | 17.5 |
| ECM_7 | 111.7 | 93.2 | 18.4 | 16.5 |

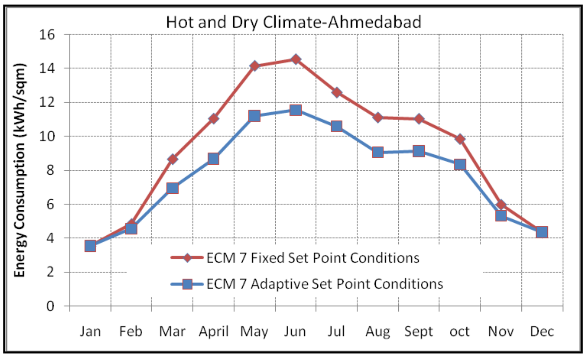


*Figure 3 Energy Consumption of ECBC building using fixed and adaptive set points*

## Energy conservation in warm and humid climate

Chennai was chosen as a representative city for warm and humid climate. While analysing the effect of thermal adaptation, the cooling set point has been varied on monthly basis as per the neutral temperature that change form 26.2$^{o}$C during March to 27.5$^{o}$C during the month of May. Table 7 demonstrates the annual energy consumption per unit area considering each ECM using fixed and adaptive set point for the HVAC system. Following can be noted down from the followings results:

- With ECM_7, i.e. combination of all individual ECMs as per ECBC, 39% energy could be saved over the common practice case i.e. the 'as is' case.
- Further, additional energy saving by about 15 to 19% could be achieved (or maximum of 36.6kWh/sqm/yr) by using adaptive set point condition.
- The effect of ECMs with adaptive set point approach is similar as compared to the fixed set point approach. This is evident from comparison shown in Figure 4.
- From Figure 4, it can be observed that when all the ECMs are applied with the adaptive approach, the monthly variation of energy consumption reduces by a large extent, whereas in case of fixed set point conditions peak is very higher as compared pto rest of the period.

*Table 7*

*Energy consumption details for both set points conditions in warm and humid climate*

| Annual Energy Saving in case of Chennai | | | | |
|---|---|---|---|---|
| Cases | Energy consumption_F_Sp (kWh/ sqm/yr) | Energy consumption_A_Sp (kWh/ sqm/yr) | Energy Saving (kWh/ m2/yr) | Saving (%)pp |
| As is | 212.4 | 177.6 | 34.7 | 16.4 |
| ECM_1 | 197.5 | 162.5 | 35.0 | 17.7 |
| ECM_2 | 179.6 | 151.6 | 28.0 | 15.6 |
| ECM_3 | 172.1 | 141.8 | 30.3 | 17.6 |
| ECM_4 | 195.3 | 158.7 | 36.6 | 18.8 |
| ECM_5 | 218.0 | 182.0 | 36.0 | 16.5 |
| ECM_6 | 171.5 | 141.2 | 30.3 | 17.7 |
| ECM_7 | 128.8 | 108.1 | 20.7 | 16.0 |

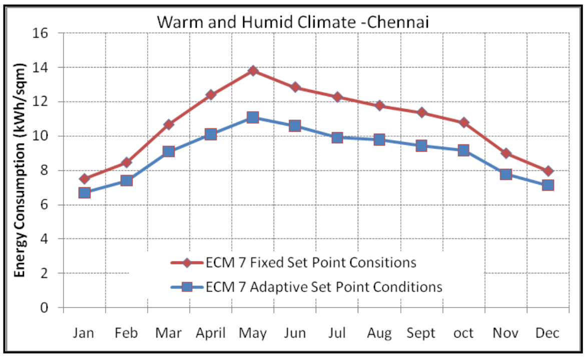


*Figure 4 Energy Consumption of ECBC building using fixed and adaptive set points*

Thus from energy efficiency point of view, the envelope must take into consideration.

**Improvements in thermal comfort conditions-** Thermal comfort conditions were evaluated in the unconditioned mode of operation of the building block, based on ASHRAE thermal comfort chart and then it was followed by adaptation approach. ASHRAE 55., (2004) defines, "Thermal comfort is the condition of mind which expresses satisfaction with the thermal environment and assessed by subjective evaluation". Many field studies conducted in different climates shows that people become adaptive to the particular type of climate after some period. Humphreys., (1978), Nicol., (2004) and Indraganti., (2009) showed through field studies that preferred temperatu res are variable, responding to the monthly mean ambient temperature and it also varies from climate to climate.

**Thermal comfort conditions in the building block of the analyzed cities**

Environmental conditions at which occupants feel thermally comfortable are not fixed and dependents on the outdoor weather conditions, therefore, the range of thermal comfort conditions are variable. It is revealed from the above that mean monthly dry bulb temperature in summer varies from about 27 to 45$^{o}$C is a good indication for thermal adaptability. From Figure 5 & 6, it is observed that an ECBC envelope measure improves thermal comfort conditions in all three analyzed cities. Hyderabad, which comes under composite climate, has 1067 comfortable hours, whereas Ahmedabad (hot and dry), Chennai (warm and humid climate) has 1276 and 500 comfortable hours based on ASHRAE comfort chart. Calculation of comfortable conditions mentioned in the Appendix, Table A2 & Table A3.

*Table 8*

*Adaptive comfort temperature range for three climatic conditions*

| Month | Hyderabad (Composite) | (Ahmedabad) Hot and Dry | Chennai Warm and Humid |
|---|---|---|---|
| | ACT Range | ACT Range | ACT Range |
| Jan | 21.2-28.2 | 20.3-27.3 | 21.7-28.7 |
| Feb | 21.9-28.9 | 21.0-28.0 | 22.2-29.2 |
| Mar | 23.1-30.1 | 22.8-29.8 | 22.7-29.7 |
| Apr | 23.9-30.9 | 23.9-30.9 | 23.4-30.4 |
| May | 24.3-31.3 | 24.5-31.5 | 24.0-31.0 |
| Jun | 22.9-29.9 | 24.4-31.4 | 23.7-30.7 |
| Jul | 22.4-29.4 | 23.3-30.3 | 23.5-30.5 |
| Aug | 22.1-29.1 | 22.8-29.8 | 23.2-30.2 |
| Sep | 22.2-29.2 | 23.0-30.0 | 23.1-30.1 |
| Oct | 22.2-29.2 | 22.5-29.5 | 22.7-29.7 |
| Nov | 21.4-28.4 | 21.4-28.4 | 22.1-29.2 |
| Dec | 20.8-27.8 | 20.5-27.5 | 21.8-28.8 |

Adaptive thermal comfort temperatures also vary due to change in mean monthly outdoor dry bulb temperature. Figure 5 showed comfortable hours for all seven measures in their respective climates. Hot and dry climate is more comfortable as compare to composite, and warm and humid climate. The most comfortable conditions achieved in the glass ECM (ECBC Glass SHGC) case; they were comparatively a bit in the case of ECBC building (ECM 7). Table 9 shows comparison in thermal comfort conditions.

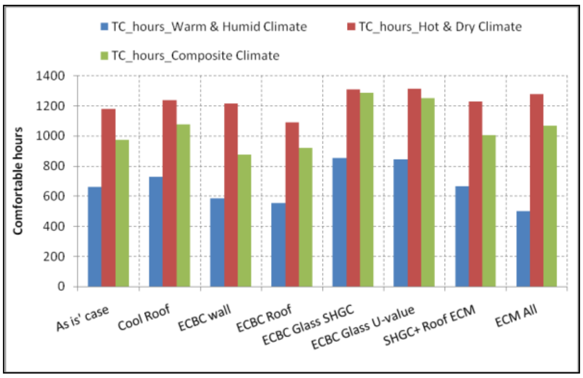


*Figure 5 Comparison of thermal comfort conditions in three analyzed cities*

Figure 6 shows that effect of adaptation is observed to a great extent in composite climate and comparatively less in warm and humid climate.

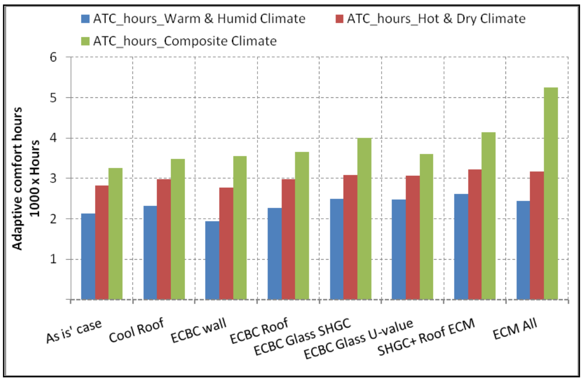


*Figure 6 Comparison of adaptive thermal comfort conditions in three analyzed cities*

Table 9 shows thermal comfort conditions and effect of adaptation in analyzed climatic zones.

*Table 9*

*Thermal comfort and adaptive thermal comfort conditions in three warm climatic zones*

| **Composite climate (Hyderabad)** | | |
|---|---|---|
| Case | TCC (hrs) | ATC (hrs) |
| As is case | 974 | 3260 |
| Best ECM | 1287 | 5245 |
| Improvement in comfort hours | 313 | 1985 |
| **Hot and Dry climate (Ahmedabad)** | | |
| Case | TCC (hrs) | ATC (hrs) |
| As is case | 1179 | 2830 |
| Best ECM | 1312 | 3213 |
| Improvement in comfort hours | 133 | 383 |
| **Warm and Humid climate (Chennai)** | | |
| Case | TCC (hrs) | ATC (hrs) |
| As is case | 661 | 2135 |
| Best ECM | 853 | 2621 |
| Improvement in comfort hours | 192 | 486 |

In composite climate, more than 2000 hours were felt comfortable considering effect of adaptation which was uncomfortable as per ASHRAE thermal comfort conditions.

## SENSITIVITY ANALYSIS

Sensitivity analysis was carried out to evaluate the energy consumption of ECBC building model. It has been divided into two parts; in the first part, only the building size was changed to observe its impact of change in the exposed surface area of building with respect to its volume. Subject building model was increased from 3.6x2.4m (8.6sqm) to 40x40m (1600sqm). As next variation, higher values of LPD and EPD have been considered. The LPD was increased from 4W/sqm to 10W/sqm (as suggested by ECBC for office buildings). The EPD was increased from 5W/sqm to 20W/sqm (as is found in IT offices).

Analysis of variation of building size revealed that with the increase in building size, keeping the intensities of internal loads same, the energy savings due to ECBC measures reduce from 43% to 6.6% (8.2kWh/sqm/yr) in Ahmedabad, from 40% to 6.3% (7.98kWh/sqm/yr) in Hyderabad, and from 39% to 10.5% (15.35) in Chennai (Appendix: A, Table A1).

Similarly, analysis of change in internal load with increased subject building model reveals that the effect of adaptation gets reduced further from 10.5 to 3.4% (9.01kWh/sqm/yr) in Chennai, 6.6 to 2% (5.0kWh/sqm/yr) in Ahmedabad and from 6.3 to 2.5% (6.0kWh/sqm/yr) in Hyderabad. Study concluded that the effect of thermal adaptation reduces in large buildings with increased internal loads.

## DISCCUSSION

It is revealed that energy efficiency of hostel building block was improved largely using ECBC envelope measures and adaptive approach could achieve further energy savings. It is observed from results that, with use of Recommendations of ECBC for cool roof, roof insulation, wall insulation, glass U-value, glass solar heat gain coefficient (SHGC), the building becomes comfortable for additional 313 hours in Composite, 133 hours in Hot and Dry, and 192 hours in Warm and Humid climate. However, it has been found that adopting all the ECMs does not always produce best results for thermal comfort in unconditioned buildings. Therefore, careful use of ECMs is recommended in conditioned and unconditioned buildings for improving energy efficiency and thermal comfort conditions.

## CONCLUSION

Energy saving potential varies from building to building but strongly depends upon the building area, envelope, operation and design features. It is possible to operate buildings at efficient mode by applying various ECBC measure and by integrating the adaptive set point concept. For small buildings, ECBC compliant buildings could save up to about 40% of energy and adaptation gives additional saving of about 16% in all warm climatic zones of India.

Percentage energy saving get reduced by increasing building footprint and by varying internal loads. From sensitivity analysis, it is clear that energy saving reduces to about 6% in first part, whereas it is again reduces to 2% in case of increased footprint and internal load.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| ECBC | Energy Conservation Building Code | ECM | Energy Conservation Measure |
| LPD | Lighting Power Density | EPD | Equipment Power Density |
| TCC | Thermal Comfort Conditions | ATC | Adaptive Thermal Comfort |
| F Sp | Fixed Set Point | A Sp | Adaptive Set Point |
| $T_{mmo}$ | Mean Monthly Outdoor Dry Bulb Temperate | $T_n$ | Neutral Temperature |
| NBC | | National Building Code | |

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## APPENDIX: A Sample of Calculations

*Table A1*

*Sensitivity analysis of **fixed and adaptive set point for ECM 7 only** in three warm climatic cities*

| **Energy saving -Fixed and Adaptive set point using ECBC building** | **Ahmedabad** | | **Saving %** | **Hyderabad** | | Saving % | **Chennai** | | **Saving %** |
|---|---|---|---|---|---|---|---|---|---|
| | Fixed (kWh/m2/yr) | Adaptive (kWh/m2/yr) | | Fixed (kWh/m2/yr) | Adaptive (kWh/m2/yr) | | Fixed (kWh/m2/yr) | Adaptive (kWh/m2/yr) | |
| Variation in size only | 132.1 | 123.9 | 6.2 | 127.4 | 119.4 | 6.3 | 146.9 | 131.5 | 10.5 |
| Variation in size and internal Load | 248.4 | 243.4 | 2.0 | 244.3 | 238.3 | 2.5 | 265.0 | 256.0 | 3.4 |

*Table A2*

*Calculation of Thermal Comfort hours in warm climatic zones*

| **Sr. No.** | **Analyzed case** | **Comfortable hours** Composite cliamte | **Comfortable hours** Hot and dry climate | **Comfortable hours** Warm and humid |
|---|---|---|---|---|
| 1 | As is case (Base case) | 974 | 1179 | 661 |
| 2 | Cool Roof | 1078 | 1238 | 729 |
| 3 | Roof U-value | 875 | 1216 | 586 |
| 4 | Wall U-value | 922 | 1091 | 553 |
| 5 | Glass SHGC (0.26) | 1287 | 1307 | 853 |
| 6 | Glass U-value | 1252 | 1312 | 843 |
| 7 | Case (3+5) Roof + Glass SHGC | 1005 | 1229 | 668 |
| 8 | Case (1+2+3+4+5+6) –ECM all | 1067 | 1276 | 500 |

*Table A3*

*Calculation of Adaptive Thermal Comfort hours in Composite climate*

| Months | Mean Monthly Outdoor DBT ($T_{mmo}$) | Neutral Temp ($T_n$) °C Hyderabad | Range of ATC hours ($T_n \pm 3.5$) | ATC hrs as is case | CR_ATC_hrs | W_ATC_hrs | R_ATC_hrs | GS_ATC_hrs | GU_ATC_hrs | RS_ATC_hrs | ECM All_ATC hrs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22.79 | 24.7 | 21.17-28.17 | 58 | 598 | 605 | 641 | 633 | 623 | 664 | 718 |
| 2 | 25.19 | 25.4 | 21.91-28.91 | 23 | 253 | 209 | 240 | 234 | 262 | 225 | 385 |
| 3 | 29.19 | 26.6 | 23.15-30.15 | 61 | 71 | 92 | 58 | 115 | 78 | 97 | 192 |
| 4 | 31.70 | 27.4 | 23.93-30.93 | 10 | 12 | 3 | 8 | 25 | 21 | 13 | 4 |
| 5 | 32.91 | 27.8 | 24.30-31.30 | 1 | 2 | 1 | 1 | 5 | 2 | 3 | 2 |
| 6 | 28.58 | 26.5 | 22.96-29.96 | 17 | 195 | 254 | 210 | 315 | 205 | 326 | 280 |
| 7 | 26.78 | 25.9 | 22.40-29.40 | 24 | 263 | 347 | 264 | 403 | 282 | 403 | 559 |
| 8 | 25.69 | 25.6 | 22.06-29.06 | 32 | 361 | 442 | 433 | 520 | 370 | 584 | 662 |
| 9 | 26.19 | 25.7 | 22.22-29.22 | 25 | 285 | 322 | 318 | 384 | 297 | 427 | 633 |
| 10 | 26.10 | 25.7 | 22.19-29.19 | 26 | 290 | 213 | 278 | 269 | 300 | 248 | 484 |
| 11 | 23.71 | 24.9 | 21.45-28.45 | 45 | 474 | 397 | 489 | 412 | 487 | 442 | 590 |
| 12 | 21.73 | 24.3 | 20.83-27.83 | 64 | 674 | 660 | 709 | 679 | 684 | 717 | 736 |
| Total thermal comfort hours due to adaptation | | | | 3260 | 3478 | 3545 | 3649 | 3994 | 3611 | 4149 | 5245 |