New Paradigms

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The Efficacy of a Highly Insulated Building in KwaZulu-Natal

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Abstract

The CSIR undertook an energy and thermal performance research project in 2011 on a house constructed with the *Imison 3 Building System*.

The purpose was to analyse the energy and thermal performance of a highly insulated house in Pretoria.

The scope was to take actual temperature measurements inside the house and to model the energy and thermal performance for Pretoria.

Following the completion of the experiments the same house was modelled for the different climatic zones of South Africa, including KwaZulu Natal.

The results indicate that the house will require very little heating in winter but effective ventilation is required in summer to maintain a comfortable indoor environment.

The research has demonstrated that a highly insulated house improves thermal performance but that an appropriate design approach is required for each climatic zone in South Africa.

The research also demonstrates that reducing heating loads results in significant financial savings to the occupier, and significant reductions in carbon dioxide emissions and water usage at a national scale.

Background to the Study

CSIR and BASF entered into a Memorandum of Understanding (MoU) in 2011 in terms of which the CSIR and BASF would collaborate in the following areas:

i) Construction materials
ii) Construction methods
iii) Residential buildings
iv) Non-residential buildings
v) Industry intelligence

This study was executed in terms of the MoU.

The Study

This study reports on the findings of an energy and thermal performance research project undertaken in 2011 on a house constructed on the CSIR Innovation Site in Pretoria by BASF using the *Imison 3 Building System* as described more fully in this study.

Purpose of the Study

The purpose of the study is to analyse the energy and thermal performance of a highly insulated house (the BASF House) through actual data collection and thermal modeling.

Scope of the Study

The scope of the study was to take actual temperature measurements inside the house and to model the energy and thermal performance with a view to establishing the thermal comfort and energy efficiency of a highly insulated building system.

Indoor temperature measurements were taken from the 13th December 2011 to the 12th December 2012 on 30 minute cycles in the Pretoria house.

The same house was modelled for the various climatic zones in South Africa, including Durban.

Limitations

The study is subject to the following limitations.

1) The study is only valid for this house as more fully described in the section below.
2) The study is only valid for the climatic area of Pretoria Central and Durban.
3) The study assumes that heating is more prevalent than cooling in the residential market in South Africa.

Definition of Terms

Heating load: The amount of energy required to raise the indoor air temperature from a temperature lower than the lower limit temperature of a defined comfort band to the lower acceptable limit of a defined comfort band.

Cooling load: The amount of energy required to lower the indoor air temperature from a temperature higher than the upper limit temperature of a defined comfort band to an acceptable upper limit of a defined comfort band.

Study Methodology

To accomplish the purpose of the research, the following tasks were performed:

Stage one: Field studies were conducted on the Pretoria house involving measurements of outdoor and indoor air temperature.

The field studies were done:

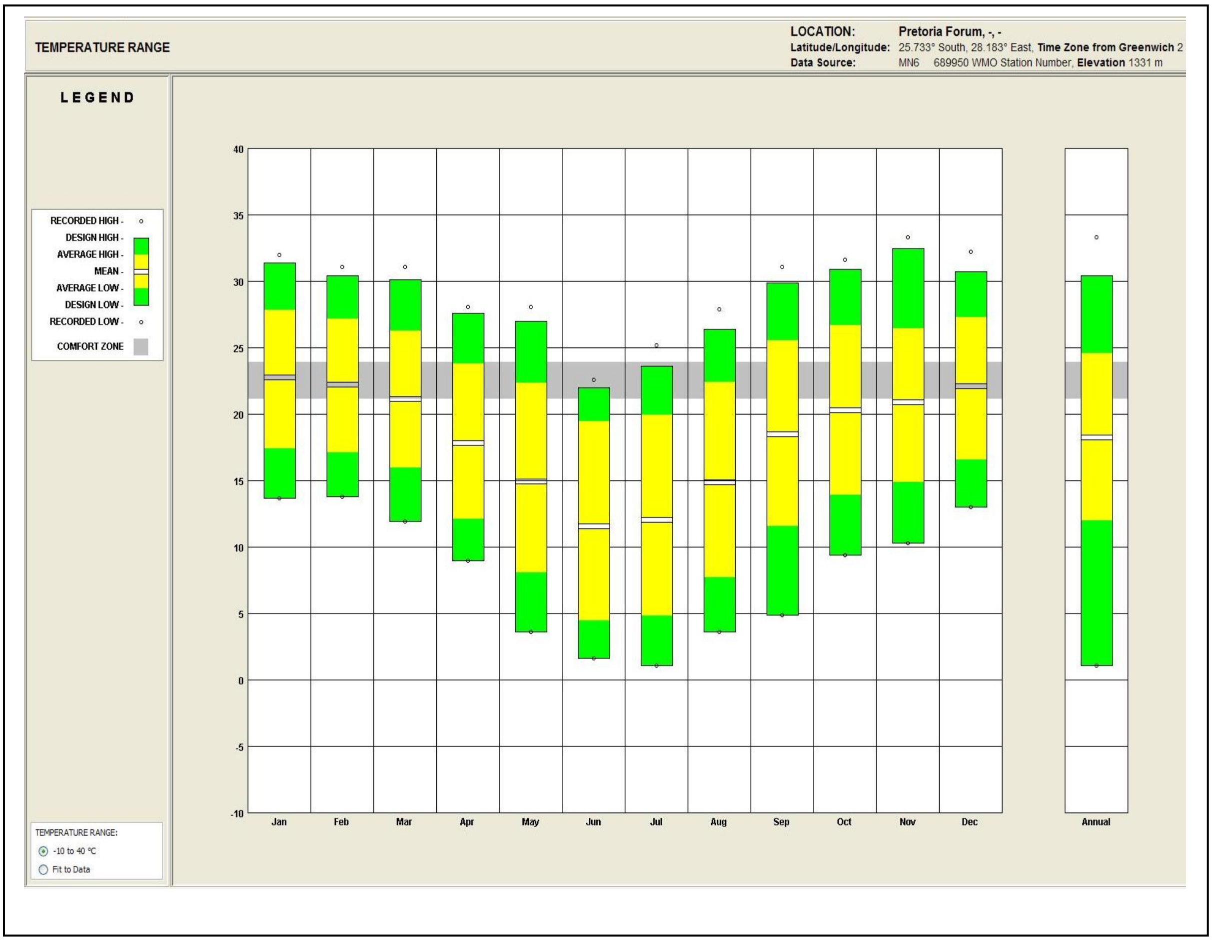
i. To assess performance of the building envelope in regulating internal climatic conditions against external climatic variations.
ii. To obtain data for the calibration of an *Ecotect™* Building Thermal Model.

Stage two: A thermal model of the house was modeled and calibrated in *Ecotect* analysis software. The calibration process compared the results of the thermal model with measured data. Calibration of building thermal simulation models is necessary for ensuring accuracy in analysis results (Yiqun et al., 2007).

Data Collection

For purposes of verifying the simulation software temperature measurements in the living room were conducted for the period 28 August 2012, 3 PM, to 11 September 2012, 7 AM. This period provides a representative spread of temperatures typical of average temperatures for Pretoria Central.

Figure 1: Average temperature for Pretoria



TEMPERATURE RANGE:
● -10 to 40 °C
○ Fit to Data

As can be seen from Figure 1 above the average annual temperature for Pretoria is 17.3 °C with the warmest average/high temperature being 28 °C in December and the coolest average minimum/low temperature being 3 °C in June/July.

A temperature measuring instrument (hobo™) was suspended at the centre (1.6 m vertical height above FFL) of the living room. Readings were taken every 30 minutes for the full period. A full range of external measurements, including rain, temperature and humidity, was also taken from a mini, localised 'weather station' that has been placed at an appropriate location at the CSIR. These constant measurements were also logged to create an actual weather file that was used in the software simulation.

All readings were taken with the doors and windows permanently closed. The building was only opened to retrieve the data.

Building Technology

The house as shown in Figure 2 below was constructed on the CSIR Innovation Site in Pretoria.

Figure 2: View of the BASF House from the North East

The system employed is the *Imison 3 Building System* (Agrèment Certificate 2008/342) which comprises of the following:

- Under slab insulation at ground level
- Prefabricated load-bearing wall frame panels using galvanized, light-gauge, cold-rolled steel components with insulating core, erected on site and finished with a proprietary fibre reinforced plaster coating, and the anchorages to foundations

- Prefabricated, light gauge, cold-rolled steel roof construction and the anchorage of the roof to the walls.

Energy and Thermal Performance

Measurement Results from the Pretoria House

An observation of the general trend of the recordings as described above shows that the indoor temperature stayed within the comfort range of 18.5-28 °C for most of the period under review. While the external temperature range for the period was from a high of 29 °C to a low of 6 °C indicating a variation of 23 °C, the indoor temperature range was from a high of 28 °C to a low of 15 °C, a variation of 13 °C.

Figure 3: Temperature readings for the period under review

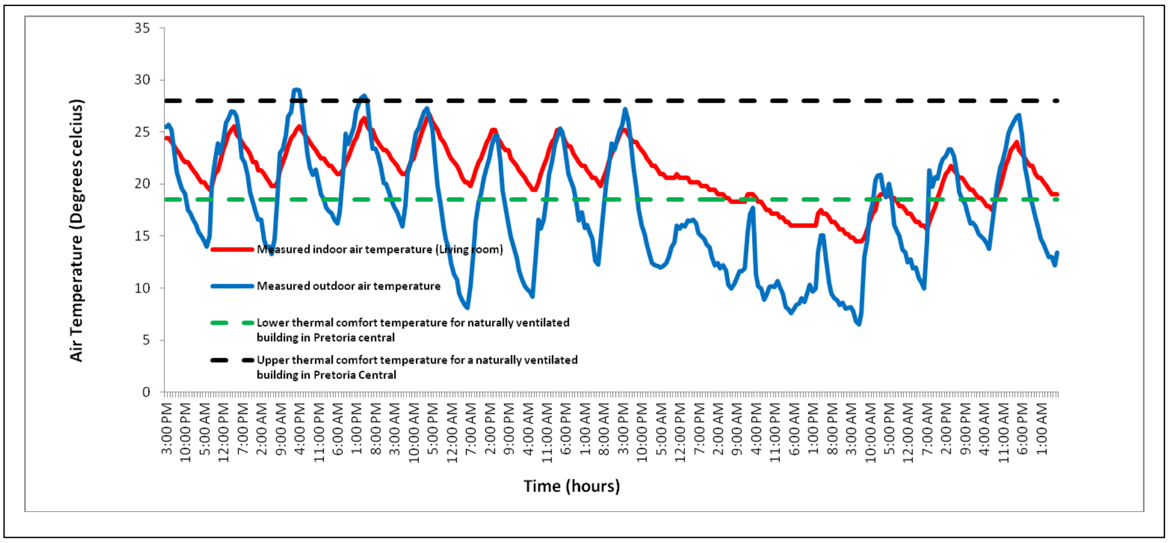


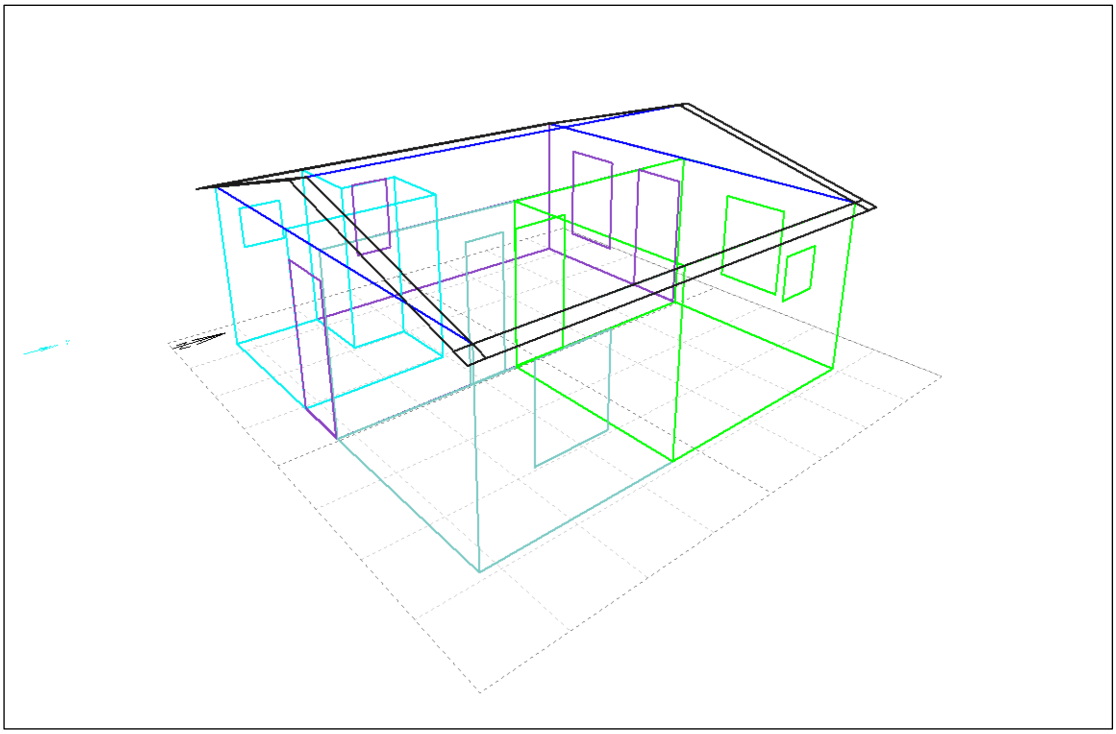
Figure 3 indicates that the house has steady thermal response maintaining comfortable indoor thermal conditions. The graph shows that the house retains heat even when the outdoor temperature drops below the comfort levels for short spells. The house does eventually lose heat when outdoor temperatures drop for an extended period, but recovers quickly when outdoor temperatures rise.

Figure 3 show that the house has a small rate of heat transfer to outdoors during the night. The BASF house is capable of keeping the heat that accumulates inside the structure for a long time despite very low outdoor night temperatures. This conclusion is evidenced by the big difference in temperatures (approximately 6 ^{0}C) of the troughs for the red line (measured indoor air temperature) and the blue line (measured outdoor air temperature).

Simulation Results for the Pretoria House

The building thermal analysis simulation software *Ecotect v 5.6* was used in this study. *Ecotect* simulates thermal performance (building thermal loads and human thermal comfort) of buildings. The *Ecotect* 3-dimensional thermal model of the BASF house is shown in Figure 5.

Figure 4: Ecotect model



Thermal Zones

A thermal zone is defined in the *Ecotect* model as a homogenous enclosed volume of air. In most cases this will be a single room, assuming that the air within it is able to mix freely. Living room and passage and passage were considered as one thermal zone; bedroom one and two and the toilet were considered as different thermal zones (See Figure 5). The attic (ceiling void) was also considered a separate thermal zone. This was done to account for inter-zonal thermal exchanges.

Building Material Thermal Properties

The software relies on the thermal properties of the materials used in the building to be inputted: the data used is shown in Table below.

Table 1: Building element thermal properties

Building element	Values
Windows	uPVC double clear glazing, U=3.8 w/m^{2}K, SHGC= 0.68
External doors	uPVC double clear glazing, U=3.8 w/m^{2}K, SHGC= 0.68
External and internal walls	22mm fibre glass reinforced[1] cement, 100mm Neopor, 22mm fibre glass reinforced cement. U=0.27 w/m^{2}K, T.L=3.96 hrs, Solar absorption= 0.6
Ceiling	6.4mm rhino board U=4.91 w/m^{2}K, Thermal lag=0.07hrs, Solar absorption= 0.9

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[1] Order of material layers is from outside to inside

Roof	0.5mm galvanised steel, 38mm Neopor, U=0.73 w/m^{2}K, Solar absorption= 0.65, Thermal lag=0.08hrs
Floor	200mm Soil, 100mm Neopor, 85mm Concrete, U= 0.27 w/m^{2}K, Thermal lag= 11.37hrs

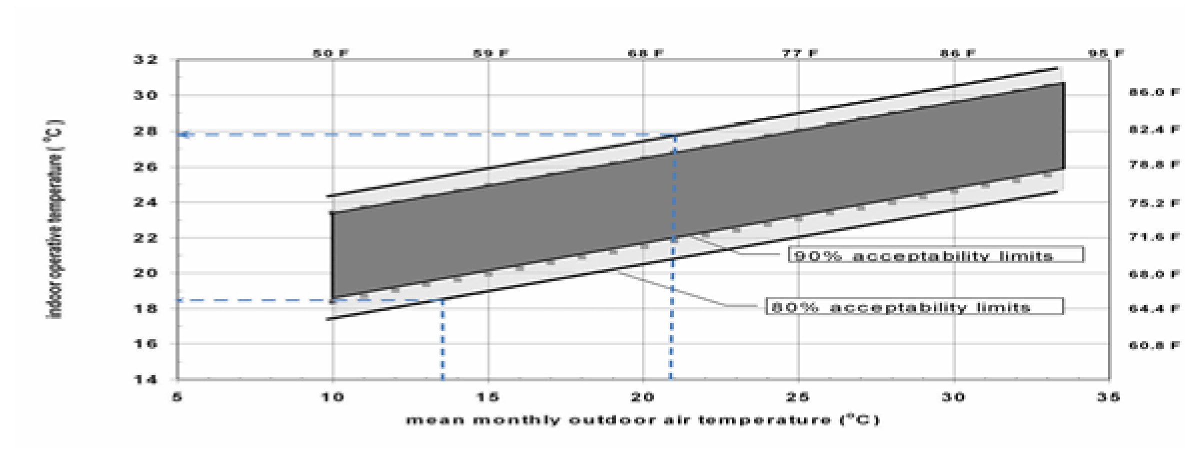
Human Thermal Comfort for Naturally Ventilated Spaces

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 55:2004 defines an occupant-controlled naturally conditioned space as spaces where the thermal conditions are regulated primarily by the occupants through opening and closing of windows. ASHRAE 2004 presented a method for determining thermal comfort temperatures for naturally ventilated spaces (See Figure 6). In order for this method to apply, the following conditions must be met:

i. The indoor space in question must be equipped with operable windows that open to the outdoors and that can be readily opened and adjusted by the occupants of the space.
ii. It applies only to spaces where the occupants are engaged in near sedentary physical activities, with metabolic rates ranging from 1.0 MET to 1.3 MET.

An 80% acceptability limit criteria (See Figure 6) was used in determining the thermal comfort band for a naturally ventilated building in Pretoria Central. *Climate Advisor*™ was used to calculate the approximate winter average and summer average temperatures for Pretoria central and these were mapped on to Figure 6. From the mapping on Figure 6, the thermal comfort band for naturally ventilated building in Pretoria Central is 18.5°C-28°C.

Figure 5: Acceptable operative temperature ranges for naturally conditioned spaces (adapted from ASHRAE 2004)



Weather File

The CSIR has developed a Köppen-Geiger bioclimatic region map based on a high resolution grid of (1 km x 1 km), using 20 years of monthly temperature and precipitation data. The source data ranges from 1985 to 2005[2]. The map attempts to formalise the process of recognising climatic similarity. The map indicates that the CSIR Innovation Site is located in the Köppen region Cwa. The Pretoria Forum weather file, being the closest weather station of Köppen classification Cwa was selected for the building simulations. In order to minimise errors in simulated indoor air temperatures, on-site outdoor temperature and relative humidity were recorded and then input into the Pretoria Forum weather file. This was an attempt to get a closer correlation between observed and predicted values.

The climate map also indicates that Durban falls into the Köppen region Cfa.

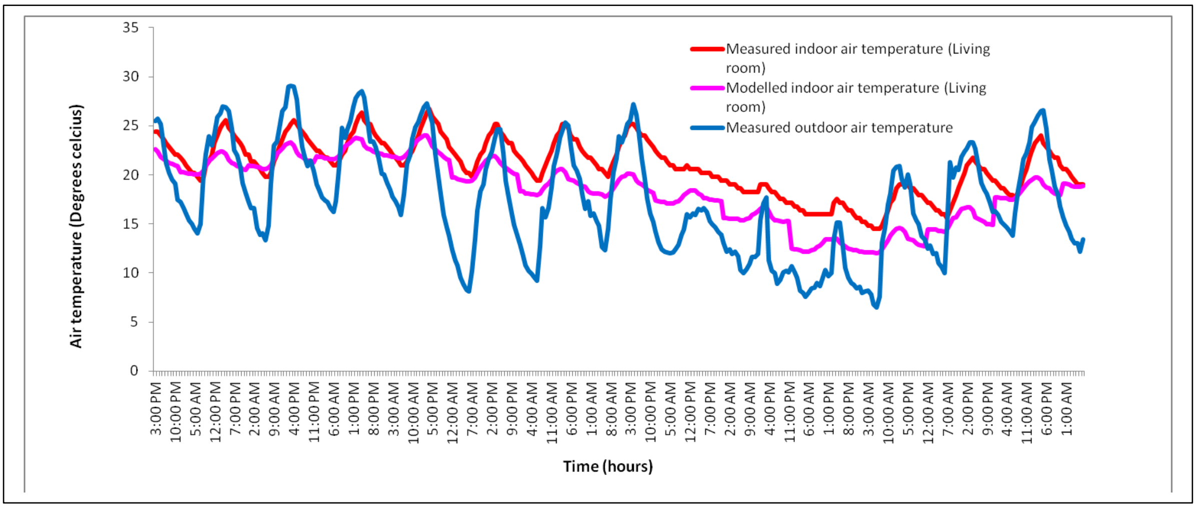
Infiltration

Infiltration rate is measured in air changes per hour (ACH) and specifies air leakage within the zone through cracks and gaps. This rate ranges from 0.25 ACH for airtight buildings to 2.0 for leaky ones (based on the Ecotect software database). In this case an Infiltration value of 0.25 ACH was used for all thermal zones of BASF test house as air leakage for the BASF house is minimised by double glazed windows and doors.

Calibration of Thermal Model

The calibration process, used here, compares the results of the simulation with real-world measured data. An alternative calibration method involves comparing results of the same thermal model from two different thermal modeling software packages (inter-model comparison). A limitation of inter-model comparisons is that there is no known “right answer” against which to measure the absolute accuracy of the predictions. Calibration of simulation models is necessary for accuracy and usability of building analysis simulation software.

Figure 6: Comparison of measured and modelled temperature, Pretoria (28 August to 11 September 2013)



Discussion of Calibration Results

The average variance between measured living room temperature and modeled living room temperature is 2.5^{0}C resulting in a percentage error of 12%.

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[2] Conradie D. 2011. *Designing for South African Climate and weather*. The Green Building Handbook South Africa Volume 4: The Essential Guide, Cape Town. ISBN 9780620452403.

Generally the thermal model under-estimates living room indoor air temperatures when compared with the measurements for the same period. The reason for the differences between the measured and the modeled data is highly likely as a result of

i. **Unaccounted heat transfers into and out of the house due to thermal bridging in the roof void**. The *Ecotect* thermal model for the BASF test house in this study did not consider any thermal bridging in the structure; however, inspections carried out by the research team reviewed gaps between roof purlins and roof insulation. These gaps expose the highly thermal conductive galvanised steel sheets to the interior of the house thus causing thermal bridging through the roof. The big disparity between modeled ceiling void temperature and measured ceiling void temperature is more evidence of thermal bridging through the roof. Good detailing and workmanship will ensure that thermal bridging can be eliminated thus further improving thermal performance.
i. **Measurement errors**. Temperature sensors provide a very localized spatial value that will usually have some radiant component, while simulation tools typically provide spatially averaged temperatures. Thus, some disparity between the two sets of results is to be expected. The model accurately predicted the measured indoor temperature trends. The peaks and troughs for the measured indoor temperature occurred the same time as the ones predicted by the model. The performance of this thermal model therefore to replicate data and thus make predictions can be considered adequate.

Findings

The following findings can be made from the results obtained. All the experiments are based on an occupation of four (4) sedentary people.

Thermal Comfort

The results indicated in Figure 6 and Table 2 were obtained from *Ecotect* and were calculated with the following considerations:

i. No natural ventilation coming in through open windows and doors;
ii. Occupancy of four sedentary people.

From the predicted results of Figure 7 and Table 2, no heating of the house is required during the winter period; the house remains thermally comfortable during winter months given closed doors and windows in terms of heating loads, indoor temperature and thermal comfort since the winter sun will quickly heat up the indoor air in the house consequently requiring less or no artificial heating energy during winter. It also indicates that the house will remain thermally comfortable for a long time after any heating system is switched off.

The results also indicate that summer indoor temperatures will be uncomfortable with the doors and windows closed. Table 2 below provides the number of hours per month when the indoor temperature will be uncomfortable under a no ventilation circumstance.

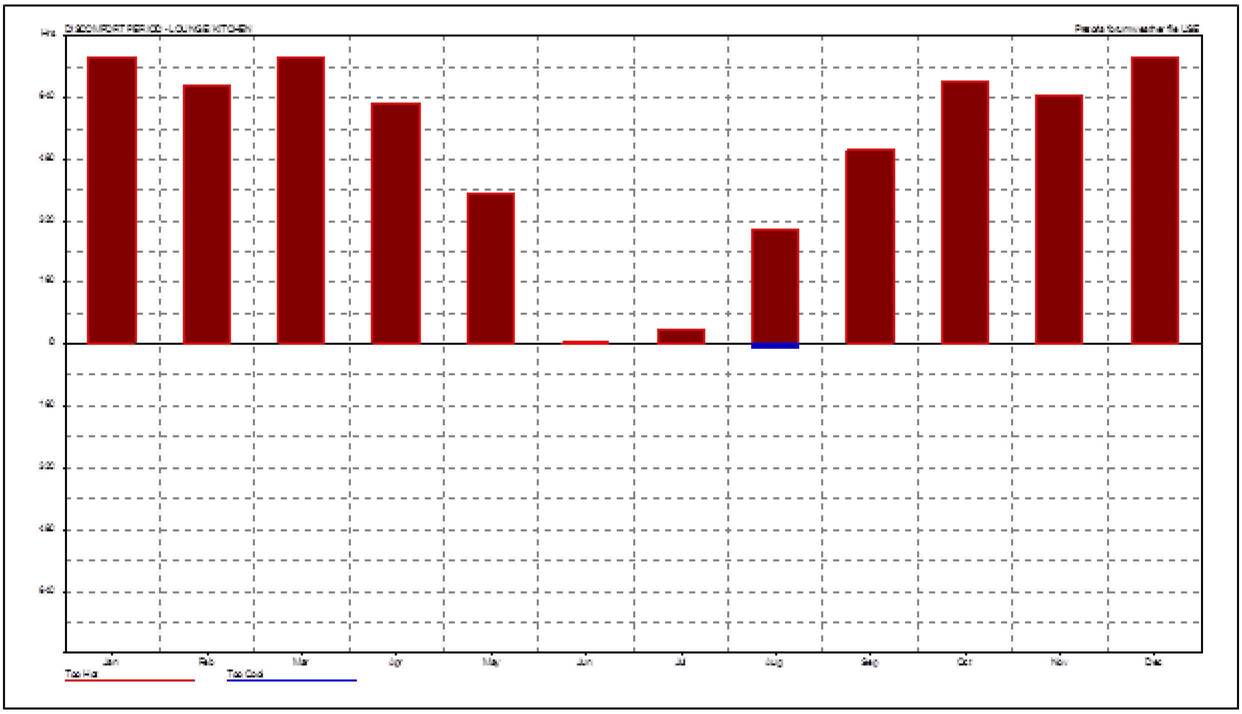
Table 2: Predicted thermal comfort chart (no ventilation)

	TOO HOT	**TOO COOL**	**TOTAL**
MONTH	**(Hrs)**	**(Hrs)**	**(Hrs)**
Jan	744	0	744
Feb	672	0	672

Mar	744	0	744
Apr	625	0	625
May	392	0	392
Jun	4	0	4
Jul	38	0	38
Aug	298	14	312
Sep	503	0	503
Oct	683	0	683
Nov	644	0	644
Dec	744	0	744
TOTAL	6091	14	6105

The results as shown in Table 2 are shown graphically in Figure 8 below. As clearly indicated the number of hours when the indoor environment is too cold is minimal, while the number of hours when it is too hot is fairly high. This is to be expected when doors and windows are kept closed in summer.

Figure 7: Predicted thermal comfort chart (no ventilation)



Impact of Ventilation

The results of Table 3 are from *Ecotect;* they were calculated with the following considerations:

i. Type of system is switched to natural ventilation.
ii. The opening and closing of windows is controlled by a ventilation schedule (See Figure 10); the schedule assumes fully open windows in summer from 0600 to 2100 hrs.

NB: The natural ventilation rates in Table 3 were not determined experimentally; these values were varied to evaluate the impact of natural ventilation on summer thermal comfort. Natural ventilation rates in buildings depend on:

i. The ambient wind speed (the higher the ambient wind speed the higher the ventilation rate)
ii. Ratio of openable area to floor area (the higher the ratio, the higher the ventilation rate and area of window openings)
iii. Configuration of the openable areas (openings on opposite walls promote cross ventilation and cross ventilation achieves higher ventilation rates when compared to single sided ventilation openings adjacent to each other on the same wall).

The results of Table 3 show dramatic improvement in comfort hours with increase of natural ventilation rate.

Table 3: Impact of increased ventilation on indoor comfort

Ventilation rate (ACH)	**Too hot hours**
5	1501
6	1215
7	994
8	873
9	806
10	743
15	582

Impact of Underfloor Insulation

As stated earlier, the house has insulation under the ground floor slab, in the walls, and under the roof sheets. Given the temperature range in Pretoria, there would appear to be little gain to be had from under-slab insulation in winter and a negative contribution in summer as it restricts the ground under the slab from acting as a heat sink. The same applies to Durban.

Energy Efficiency

The following considerations were taken into account for the calculation for the heating and cooling loads:

i. Total occupancy of four people in the house;
ii. Heat output per sedentary occupant = 70 watts;

iii. Sensible heat gains (heat output from stove and electrical appliances) = $\frac{470}{16} w/m^2 = 29 w/m^2$. The value of the sensible gain is based from ASHRAE Fundamentals (2001);
iv. All four people were assumed to occupy the living room from 08:00 am to 2100;
v. 2 people were assumed to occupy bedroom 1 from 2200 to 07:00 am;
vi. 2 people were assumed to occupy bedroom 2 from 2200 to 07:00 am;
vii. Electrical appliances (e.g. stove) is assumed switched on from 08:00 to 09:00 am, 12:00-1300 and from 1600- 17:00;
viii. The heating and cooling loads were calculated with the bathroom and ceiling void not being air conditioned; and
ix. No natural ventilation coming in from open windows and open doors.

Table 5: Heating and cooling loads for Pretoria house

HEATING (GJ)	**COOLING (GJ)**	**TOTAL (GJ)**
1.7	20	21.7

The results indicated in Table 5 show that the BASF house will require very little heating in winter to maintain a comfortable indoor environment. As can be expected from a highly insulted building in summer, the house will require cooling, but this can be achieved by opening windows and doors to allow natural ventilation as illustrated in Table 3.

Table 6: Heating and cooling loads for Durban house

HEATING (GJ)	**COOLING (GJ)**	**TOTAL (GJ)**
0	21.3	21.3

The results indicated in Table 6 show that the BASF house in Durban will require no heating in winter to maintain a comfortable indoor environment. As can be expected from a highly insulted building in summer, the house will require cooling, but this can be achieved by opening windows and doors to allow natural ventilation as illustrated in Table 3.

Heating Costs

The heating but not the cooling costs have been calculated since heating is generally the norm in South African residences while mechanical cooling is not. The study also has a bias toward the lower income household sector who cannot afford to heat a home and often rely on the burning of fossil fuels (biomass, coal or paraffin) for heating with its concomitant negative health impacts.

Using the conversion rate of 1 Gj equaling 277.77 kWh[3] and a kWh rate of R1.20, the Pretoria BASF house will have an annual heating cost of R566.66. For comparative purposes the conventional RDP house constructed on the CSIR Innovation site has a heating load of 12.28 Gj[4] or 3,401 kWh resulting

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[3] http://www.unitjuggler.com/convert-energy-from-GJ-to-kWh.html

[4] CSIR (2010). Energy Modeling Report, CSIR, Pretoria.

in an annual heating cost of R4,081.87, while a SANS 204 compliant house has a heating load of 7.66 Gj[5] or 2,127 kWh and an annual heating cost of R2,553.26.

The Durban house will have a zero heating cost in winter.

Carbon Dioxide Reductions

The reduction in heating loads impacts beyond the financial considerations: using ESKOM's emission rate of 0.96 $kgCO_2$/kWh of electricity produced, the Pretoria house will result in annual CO_2 emissions of 265 $kgCO_2$ equivalents compared to a conventional RDP house of 3,264 $kgCO_2$ equivalents.

The heating load of the Durban house will result in 0 $kgCO_2$ equivalents per annum.

Water Reductions

The reductions in heating loads also impacts on water usage due to the energy/water nexus: using ESKOM's rate of 1.34l/kWh SO (sent out), the heating load of the Pretoria house will result in a water consumption of 371l/annum compared to a standard RDP house of 4,557 l/annum.

The heating load of the Durban house will result in 0 l/annum.

Reductions Extrapolated to a National Scale

Using data obtained from Statistics South Africa[6], the projected area of all residential building for 2013 is 2,776,361 square meters. Using the same values for carbon dioxide and water reductions the total CO_2 reduction nationally would be 6.13m tonnes and 18.69m litres respectively if the residential buildings were built using this technology.

Conclusion

The results from the experiment indicate that the indoor environment remains comfortable in winter and will require very little heating in Pretoria and no heating in Durban.

The results indicate that the indoor environment will become uncomfortable in summer in both climatic zones if the doors and windows are kept closed, but that this improves significantly as ventilation rates increase. This is to be expected in summer.

The experiment demonstrates the efficacy of a highly insulated building with regard to indoor comfort and reduced heating and cooling loads. However the placement of insulation and effective ventilation is critical in terms of maximizing these efficiencies.

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[5] Ditto

[6] StatsSA (2013). *Selected building statistics of the private sector as reported by local government institutions*, May 2013, Statistical release P5041.1, Statistics South Africa, Pretoria.