A comparative analysis using multiple thermal analysis tools

Dr. Andrew Marsh
Welsh School of Architecture

Fahad Al-Oraier
Welsh School of Architecture

ABSTRACT

Recent work has been undertaken to determine the most effective passive cooling strategies to be adopted in the refurbishment of large numbers of traditional adobe dwellings in Riyadh City, Saudi Arabia. To do this, thermal simulation was used to first determine the sensitivity of each building to different design parameters and then assess the potential effectiveness of a range of different passive cooling strategies.

In virtually all aspects of simulation no single algorithm or methodology is perfectly suited to every modelling condition. All have their applications, but some will usually be more appropriate than others under certain circumstances. Given the ramifications of this work in terms of cost, a high level of confidence in the analysis results was very important. Thus, simulations were carried out using multiple thermal analysis tools and their results compared.

This paper outlines the issues associated with creating a base computer model that is fully compatible with multiple tools. It also presents the results of a series of comparative parametric sensitivity studies carried out between the tools and concludes with a summary of the results.

1. INTRODUCTION

The usefulness of thermal simulation and analysis software as both a research tool and as part of the building design process has been demonstrated many times. However, no single simulation method or implementation is entirely suitable for every condition, climate or building type. The results of the BESTEST (ANSI/ ASHRAE 2001) comparison clearly show wide variation in the results from different analysis tools, and even between different operators of the same tool.

To reduce levels of uncertainty in the analysis of any particular model, it is possible to compare the results of several different simulation tools. This usually requires the operator to generate the same model in each tool separately, or at least undertake extensive editing of a common input base, using each tool's native interface or file format.

Apart from the effort and time this takes, it introduces significant potential for data entry and interpretation errors. Also, very few users have a high level of proficiency in multiple analysis tools and the process and nomenclature can sometimes by very different between them. With the increasing move towards standardisation within the AEC industry, and the availability of hybrid analysis tools that can export their model data in a range of formats compatible with several different analysis engines, there is greater opportunity to use such a comparative approach.

This paper describes the process of generating and comparing the results of three different thermal analysis engines as part of research into the thermal comfort potential of refurbished adobe dwellings in Riyadh, Saudi Arabia. The overall aim of this work was to determine the most appropriate modifications required to maximise occupant comfort in these buildings using only passive design elements to encourage their adaptive re-use on environmental grounds. Simulation was used to predict the potential effect of each passive design element and rank them in order of effectiveness. This required an understanding of the relative accuracy and parametric sensitivity of each simulation tool in this particular situation.

2. ANALYSIS PROCESS

The analysis process involved first establishing confidence in the ability of each tool to effectively model the situation being studied. For this, on-site temperature recordings were taken in different rooms within three sample buildings. These buildings were then modelled and simulated over the same time period in each tool and the results compared directly with the measurements.

The generation of thermal models for the example buildings to be used for analysis was undertaken in the Ecotect software (Marsh, 1996). The primary reason for this was its visual user interface, in-built geometry editor and ability to export model data in the native file formats of a range of other analysis tools, including EnergyPlus, HTB2 and ESP-r.

Figure 1 Examples of the buildings being modelled.

Maintaining model data in one tool meant that changes need only be made once, and then propagated to each analysis tool automatically. This made the comparative analysis much easier as there was no requirement to manually edit the files for each tool - the modified model was simply re-exported and the new analysis run. This also meant that units conversion and the translation of different parameters were always consistent.

The software also included its own thermal analysis engine, which encouraged continual testing and checking for errors as the model was developing. In this case it meant that simple mistakes were picked up very early and, after some trial-and-error and consultation with the help files, allowed the rest of the models to be created faster and more accurately.

The software also incorporates a script interpreter which allowed the process of generating input data and batch files for the parametric analysis to be almost completely automated. Whilst some scripting was used to summarise output data, the majority of the output processing was still manual.

2.1 Analysis tools

It was originally planned to use three different thermal analysis tools as well as the analysis in Ecotect itself. EnergyPlus, based on the ASHRAE calculation method (heat balance), is developed by Lawrence Berkeley National Laboratories in San Francisco and is widely used internationally (Crawley, et.al., 2001). ESP-r is a highly regarded response factor-based analysis tool from the University of Strathclyde (Clark, 1996) whilst HTB2 is a finite different model developed at Cardiff University (Alexander, 1997).

However, the parametric analysis required more than a thousand separate runs to be performed and the output data collated. Whilst it was possible to batch run all of the tools using either DOS batch files or shell scripts generated using Ecotect, ESP-r appeared to use a format for its output data that was only accessible from within ESP-r itself. As a result, data extraction could not be easily automated, requiring significant manual navigation of menu items to generate text-based reports from each output file separately, for which there simply was not time in this study. It is understood that there are ways of doing this more effectively in ESP-r, however this was beyond the author's expertise - so unfortunately ESP-r was not included in the end.

2.2 The Geometric Model

As each of the simulation engines have their own specific requirements and limitations on the geometry they will accept, the base model had to be constructed carefully in order to be equally suitable for each.

EnergyPlus proved the most demanding tool in terms of model generation. Whilst it is understood that the latest release allows for a greater number of vertexes, the version used in this analysis was limited to a maximum of four vertexes to describe each surface. This required the subdivision of complex polygonal surfaces into much simpler surfaces.

Similarly each surface in EnergyPlus can only have one internal and one external condition, which means that surfaces cannot partially overlap surfaces on other zones. In Ecotect any surface can overlap any number of other surfaces, with the process of determining inter-zonal relationships based on the detection of these overlapping areas. To accommodate EnergyPlus, each area of overlap is simply created as a new surface in each zone, using the principle shown in Figure 2.

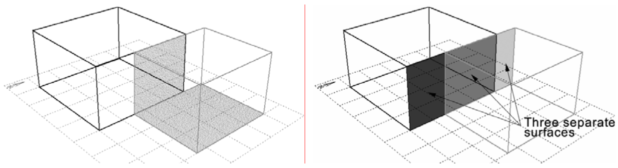
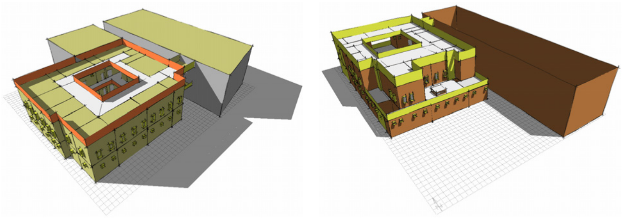


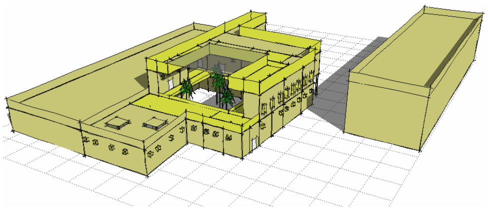
Figure 2 The process of separating overlapping surfaces into multiple simple polygons.

Unfortunately this issue was discovered only after the models were generated and the first export to EnergyPlus was attempted, so applying this retrospectively was somewhat more complex and time consuming than if they had been constructed this way in the first place. Those tools that did allow complex multi-vertex surfaces had no problems assimilating the segmented 4-vertex model. The resulting models used in the analysis are shown in Figure 3.

The effect of wall thickness was another issue in EnergyPlus. As the window reveals in the case study buildings provide significant self-shading, this needed to be accounted for during the simulation. As all the thermal analysis tools in this study use infinitely thin planar descriptions of zone surfaces, it was necessary to model the effects of wall thickness separately. This was done by simply extruding the sides of each window by an amount equal to the thickness of the surrounding walls. The shading effect of these extruded surfaces on the window itself is equivalent to the effect of the walls. However, in doing it this way, these extruded surfaces also have a shading effect on the walls that really isn't there, as shown in Figure 4 below.



Building 1 *Building 2*



Building 3

Figure 3 The three geometric models used in the comparative thermal analysis.

As both Ecotect and HTB2 use shading masks for the calculation of incident solar radiation, it was simply a matter of first calculating the shading for the windows with the extruded shades on, and then later for the walls with the shades off. This resulted in the correct shading masks for the two different elements.

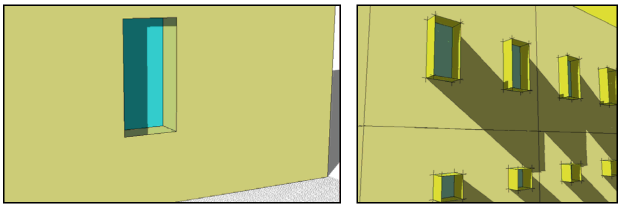


Figure 4 The effect of wall thickness on window shading, and how this was modeled in Ecotect.

However, EnergyPlus requires that all external shading devices be explicitly defined in the geometric model, from which it calculates its own shading factors. This presented a problem in that the extruded planes would also cast shadows on the walls containing the windows.

The option to avoid this was by using a much higher shading co-efficient for the windows and simply not including the extruded planes. However, some preliminary calculations showed that the shading effect of these surfaces on the walls was negligible in EnergyPlus as the shaded area was moving each hour and the additional sol-air temperature effects made very little difference to overall heat flows though these surfaces.

The decision was therefore made to include the extruded surfaces in order to more accurately model the shading on the windows, but accepting that there would still be some small effect on heat flows through the walls themselves.

2.3 Material properties

Obtaining accurate data for the materials used in these buildings was a significant problem. There appears to be real lack of detailed information on the properties of material used in adobe construction. Whilst there are some references to recommended U-values, data for the density, specific heat and conductivity of the different layers in each material had to found from a diverse range of sources or extrapolated from similar materials. Also, the thermal properties of earth roof buildings are not well known due to differences in types of construction and variations in the thermal properties of the different layers used in their construction.

In the references, a wide range of often conflicting values for each property are given. The decision was therefore made to generate and test three different wall and roof materials, using the extreme maximum referenced value for each property, one the extreme minimum and one the mean of the range of values for each property. In this way, the full potential range of material properties could be accommodated.

Table 1 The range in values found for some of the materials used in the model construction.

<table>
<tr><td>External Wall</td><td></td><td>U-Value</td><td colspan="2">Admittance</td><td colspan="2">Time lag</td></tr>
<tr><td><i>- 400 mm Adobe Sun Dried Brick.</i></td><td><i>Max</i></td><td>1.1</td><td colspan="2">5.167</td><td colspan="2">12</td></tr>
<tr><td><i>- 30mm Mud Plaster.</i></td><td><i>Ave</i></td><td>0.9</td><td colspan="2">4.8395</td><td colspan="2">11</td></tr>
<tr><td></td><td><i>Min</i></td><td>0.7</td><td colspan="2">4.512</td><td colspan="2">10</td></tr>
<tr><td>Internal wall</td><td></td><td>U-Value</td><td colspan="2">Admittance</td><td colspan="2">Time lag</td></tr>
<tr><td><i>- 400 mm Adobe Sun Dried Brick.</i></td><td><i>Max</i></td><td>1.1</td><td colspan="2">5.167</td><td colspan="2">12</td></tr>
<tr><td><i>- 30mm Mud Plaster.</i></td><td><i>Ave</i></td><td>0.9</td><td colspan="2">4.8395</td><td colspan="2">11</td></tr>
<tr><td></td><td><i>Min</i></td><td>0.7</td><td colspan="2">4.512</td><td colspan="2">10</td></tr>
<tr><td>Roof</td><td></td><td>U-Value</td><td colspan="2">Admittance</td><td colspan="2">Time lag</td></tr>
<tr><td></td><td>Max</td><td>1.205</td><td colspan="2">5.167</td><td colspan="2">11</td></tr>
<tr><td></td><td>Ave</td><td>1.182</td><td colspan="2">4.8395</td><td colspan="2">10</td></tr>
<tr><td></td><td>Min</td><td>1.141</td><td colspan="2">4.512</td><td colspan="2">9</td></tr>
<tr><td>Glazing for Windows and Skylight</td><td></td><td>U-Value</td><td>Admittanc</td><td>Shading</td><td>Transp.</td><td>R. idex.</td></tr>
<tr><td><i>- 6mm clear float glass + timber frame</i></td><td></td><td>5.1</td><td>5</td><td>0.94</td><td>0.92</td><td>1.74</td></tr>
<tr><td>Door</td><td></td><td>U-Value</td><td colspan="2">Admittance</td><td colspan="2">Time lag</td></tr>
<tr><td><i>- Solid timber slats</i></td><td></td><td>2.31</td><td colspan="2">3.54</td><td colspan="2">0.4</td></tr>
</table>

This allowed the thermal property data to be used at the earliest possible stage in the simulation process when uncertainties are greatest. After several runs for the three groups in each tool, it was found that the three models showed virtually no detectable difference. Therefore, the decision was made to use the materials with average properties.

2.4 Weather data

To compare temperature values, the same external conditions as experienced by actual building must also be used in the simulation. However, only on-site outdoor temperature and the relative humidity values were recorded. Thus, the generation of a weather data set for the analysis required combining this recorded data with additional solar radiation and wind speed/direction data from the local meteorological office.

This was considered valid as solar radiation during the recorded period in Riyadh City is very consistent with invariably clear sky conditions and almost imperceptible levels of cloud. Thus, incident solar radiation levels closely approximate the maximum available and therefore are unlikely to have varied significantly between the actual site and the local meteorological office.

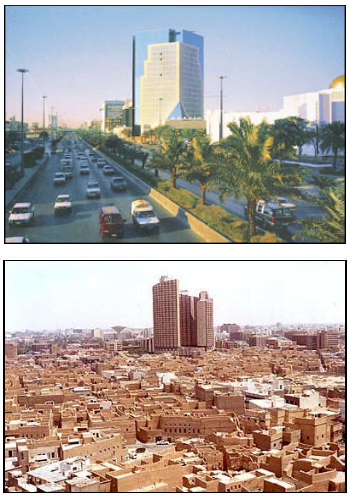


Figure 5 Images of Riyadh City showing a typical clear blue sky and the densely packed nature of the buildings being studied.

In terms of wind speed and direction, the adobe buildings being studied are located in dense, tightly packed groups. As a result, wind conditions are dominated by localised micro-climate effects which are unlikely to be consistent between different buildings and different sites. Thus it is just as valid to use data recorded at the local meteorological office as to use data recorded at any one of the test sites.

3. ANALYSIS RESULTS

3.1 Temperature comparison

It is well understood that a direct comparison of measured and modelled temperature data is not entirely valid. Temperature sensors give a very localised spatial value that will usually have some radiant component whilst simulation tools typically provide spatially averaged temperatures. Thus some disparity between the two sets of results is to be expected.

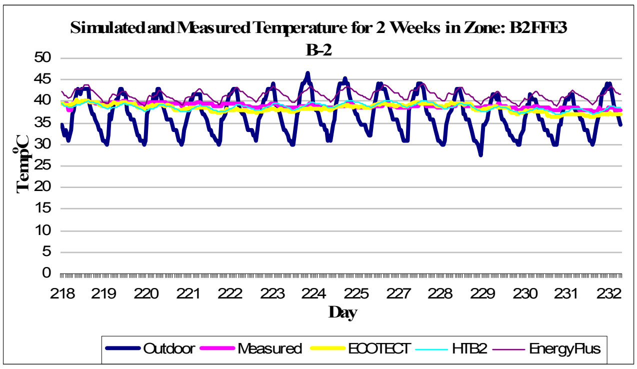


Figure 6: An example comparison of simulated and measured temperature in a room of the test building.

Overall, this preliminary comparison showed that predicted temperatures showed close agreement with recorded data. What was apparent from the analysis was that some of the tools exhibited diurnal temperature fluctuations that were not present in the measured data. As the same base values were used in each tool, this suggested variation in their sensitivity to different parameters.

3.2 Parametric analysis

To be sure that specific values used for materials, occupancy, internal gains and ventilation were not skewing the comparison or producing unrealistic results, a parametric analysis was conducted to determine the relative effect of changes in a wide range of these values. If any model was highly sensitive to a particular parameter, then more care would need to be taken in establishing its base value. If the models were relatively insensitive, then that parameter can be assumed not to be significantly affecting results.

Additionally, the results of the parametric analysis can provide a clear guide as to which modifications are likely to have the greatest effect on internal conditions. This in turn will be used to help prioritise the application of passive design elements within the refurbishment process - based on their potential effectiveness.

Table 2 lists the parameters included in the analysis and the range over which they were varied. A full set of parametric results for Building 2 is included at the end of this paper.

Table 2 Parameters and value ranges used.

Parameter	Minimum Value	Maximum Value
Infiltration/Ventilation Rate	*0.1 ac/h*	*4 ac/h*
Internal Gains	*1 W/m²*	*40 W/m²*
Window Shading	*0.1*	*1.0*
Wall and Roof Reflectance	*0.1*	*0.9*
Wall and Roof Insulation	*0.1 W/m²K*	*4.0 W/m²K*
Orientation	*0deg*	*360deg*
Evaporative Cooling	*-1W/m²*	*-40W/m²*

3.3 Parameters with greatest effect

As a summary of the results, Table 3 shows the average diurnal temperature variation and the percentage variation between maximum and minimum heat loss rates for the same building. This is shown for each tool over the whole year, as well as for summer and winter. The summer period was assumed to be the three months from 1st of June to 31st of August whilst the winter period was taken from 1st of December to the end of February.

Table 3 The relative effect of each parameters.

TEMPERATURE	**ECOTECT**			**HTB2**			**ENERGYPLUS**		
PARAM.	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**
Internal Gain	14.0	14.0	16.0	7.0	6.0	8.0	8.0	6.0	7.0
Ventilation	2.0	4.0	2.0	2.0	2.0	1.0	4.0	4.0	4.0
Insulation	1.5	1.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Colour	0.5	0.7	0.5	1.8	3.0	2.1	2.2	3.4	1.6
Orientation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shading	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SPACE LOADS	**ECOTECT**			**HTB2**			**ENERGYPLUS**		
PARAM.	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**
Internal Gain	468.46%	420.40%	279.40%	1526.44%	1535.61%	1760.87%	535.75%	435.94%	597.64%
Ventilation	128.13%	130.28%	129.69%	225.68%	232.43%	231.60%	227.00%	224.02%	260.96%
Insulation	100.00%	115.50%	112.82%	0.0	0.0	0.0	0.0	0.0	0.0
Shading	100.02%	100.00%	100.01%	100.09%	100.12%	100.09%	0.0	0.0	0.0
Colour	100.56%	100.26%	100.41%	117.98%	118.42%	123.09%	107.78%	103.09%	104.07%
Orientation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

From these results it is clear that internal gains and ventilation rates have by far the greatest potential effect on both temperatures and space loads. The application of insulation and highly reflective external surface treatments have a small effect whilst orientation and shading were negligible.

3.4 Potential effects on temperature

The results of the parametric analysis showed that internal gains were a significant factor influencing internal temperatures. Taken literally, this means reducing appliance and lighting loads in each space, but it has more important ramifications than this. Cooling is essentially a negative internal gain. Thus, despite the levels of thermal mass in the building, spaces are still sensitive to the application of cooling which, if done passively using evaporative and transpirative cooling, can create reasonably comfortable internal conditions with little or no energy cost.

This emphasizes the importance of the central courtyard as a potential source of passively cooled air. By including misting systems, shading and vegetation, a controlled environment can be created in which evaporatively cooled air pools at the base and can be ducted towards required spaces. A series of air flow studies were then conducted to determine the extent of cooling possible, however a detailed analysis of these results is beyond the scope of this paper.

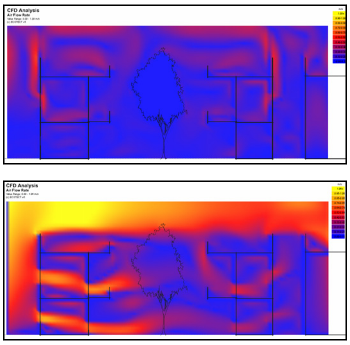


Figure 7 CFD analysis of a traditional courtyard house showing air flow rates under still conditions (left) and a 2.5m/s breeze from left to right (right).

As a way of summarizing and testing the strategies recommended by the parametric analysis as most effective, it is possible to apply all of them to one of the example models and then compare the internal temperatures in each zone of interest with those in the same zones of the base case model. The suggested strategies to maximize comfort included:

- Reducing internal gains to as low as 2.5W/m² floor area within each zone.
- Applying a night-time ventilation schedule in which air change increase from 0.25ach during the day (7am-8pm) to 5ach at over night (8pm-6am) to simulate relatively still conditions.
- White-washing external surfaces to achieve an external surface reflectance of around 0.85.
- Utilizing evaporative cooling effects, applied as a negative heat load to simulate the effect of vegetation and mist spraying within the courtyard. As this effect is likely to vary significantly, calculations were run assuming a range of evaporation rates. Using air flow rates and cell temperatures calculated using simple CFD analysis, and dividing the overall cooling potential by the floor areas of each zone, average cooling values ranging between *-10 W/m²* and *-25W/m²* were calculated.

Figure 8 shows the potential change in temperature on the hottest day of the year in Riyadh, assuming the lowest potential evaporative cooling rate. It compares temperatures in four zones in Building 2 before and after the application of these modifications. This clearly shows that an average instantaneous temperature reduction of almost 4°C is possible, a significant reduction given the thermal mass of the building.

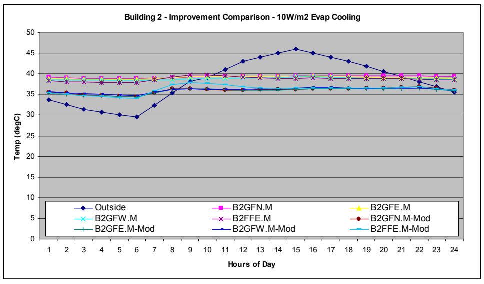


Figure 8 Comparison of internal temperatures before and after(-Mod) application of passive techniques, assuming -10W/m2 evaporative cooling effect.

If the effectiveness of the evaporative cooling is increased to -25W/m², possible on a relatively still day with both misting and large amounts of vegetation in the courtyard, then a temperature reduction of around 6°C is possible.

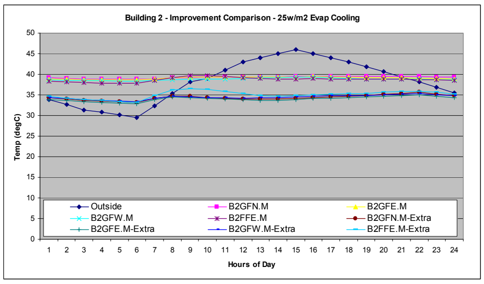


Figure 9 Comparison of internal temperatures before and after(-Mod) application of passive techniques, assuming -25W/m² evaporative cooling effect.

Of most significance is the fact that, even with the lesser evaporative cooling effect, maximum daytime internal temperatures are close to 10°C below maximum outdoor temperatures. With the more effective evaporative cooling, this is closer to 12°C. Peak temperatures are still quite high, around 34-35°C, however the real benefit is at night where 28°C is actually reasonably pleasant.

4. CONCLUSION

The initial comparative analysis in all cases showed reasonably close agreement between the simulated results and the measured data. In some cases there was variation between the tools and the measured data and sometimes between the tools themselves. This is to be expected and the magnitude of differences was not disproportionate given the location of sensors and variations in material properties.

The parametric analysis does show noticeable variation between tools in their sensitivity to individual parameters. However, the overall shape of the sensitivity curves were all very similar, with differences only in magnitude.

The analysis of these abode buildings has shown that the application of a range of relatively simple passive design modifications can have a significant effect on internal comfort levels. The most important single modification is the control of ventilation - which has two critical aspects. The first requires night-purge effects to cool the thermal mass overnight. The second involves conditioning any inlet air during the day using natural evaporative cooling effects and transpiration from vegetation in the courtyard.

REFERENCES

Alexander, D. (1997). HTB2 user manual 2.0c.: a model for the thermal environment of buildings in operation, Welsh School of Architecture, University of Wales, College of Cardiff, Cardiff.

ANSI/ASHRAE Standard 140-2001, (2001). Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Clarke J.A. (1996). The ESP-r System: Advances in Simulation Modelling' Building Services Journal pp27-9, May 1996.

Crawley, D.B., Lawrie, L.K., Pedersen, C.O., Winkelmann, F.C. (2004). EnergyPlus: New, Capable and Linked, Proceedings of the World Renewable Energy Congress VIII, 2004, Denver, Colorado.

Judkoff, R., Neymark J. (1995). "Home Energy Rating System Building Energy Simulation Test (HERS BESTEST)," Vol. 1 and 2, Report No. NREL/TP-472-7332. National Renewable Energy Laboratory, Golden, Colorado 80401-3393. <URL: http://www.nrel.gov/publications/>

Marsh, A.J. (1996). Performance Modelling and Conceptual Design, International IBPSA Conference, The University of New South Wales, Sydney, Australia.

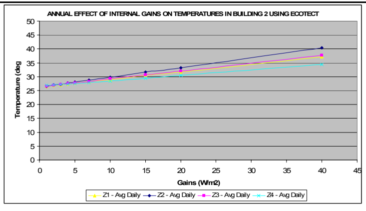
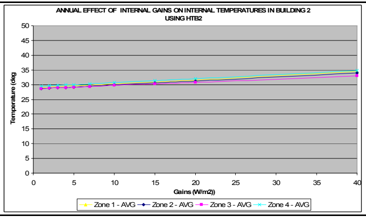
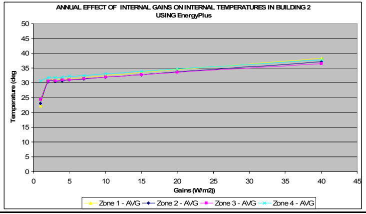
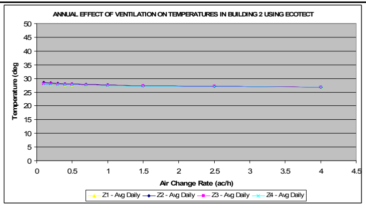
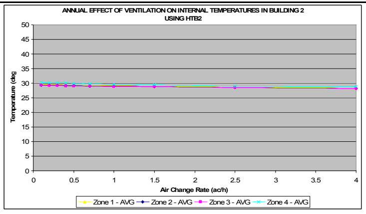
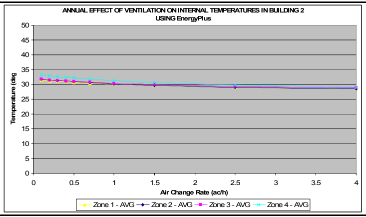
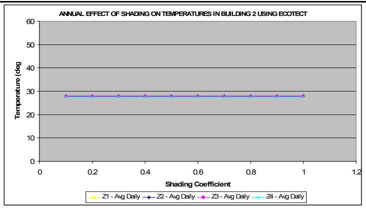
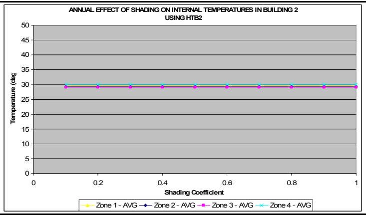
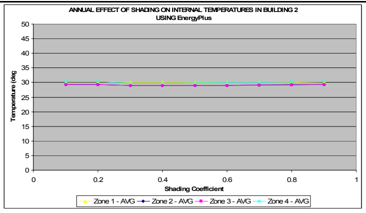
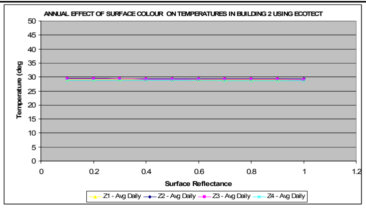
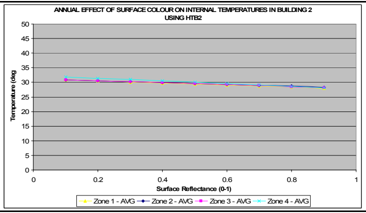
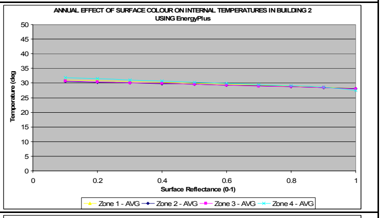
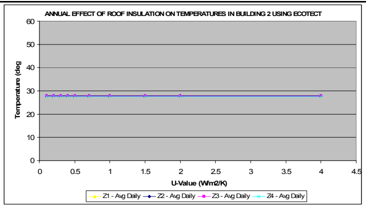
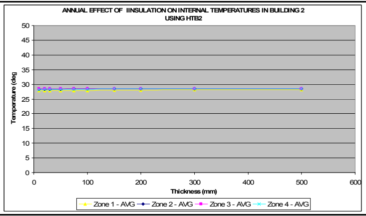
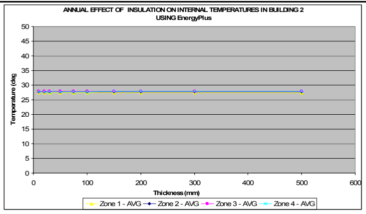
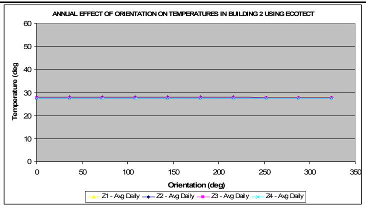
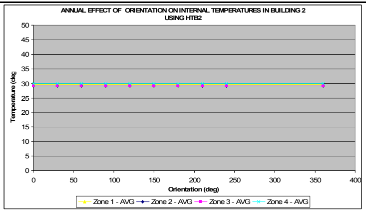
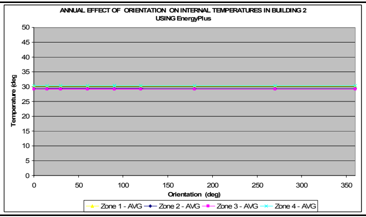
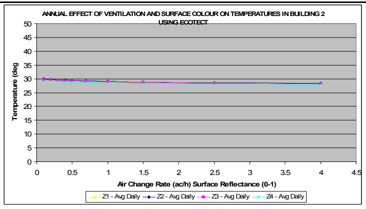
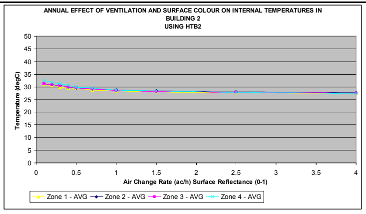
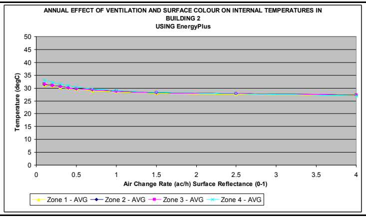
Parameter	**Annual Temperature for Building 2**		
	ECOTECT	**HTB2**	**EnergyPlus**
IntGain			
Vent.			
Shad			
Colour			
Ins			
Orient			
Vent. & Colr			

Figure 10 Full results of the annual parametric sensitivity analysis for Building 2.