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VERIFICATION OF A LOW ENERGY SOLAR HOME MODEL TO BE USED WITH A GA OPTIMISATION TOOL

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ABSTRACT

The application of computerised optimisation techniques for the design of low and net-zero energy buildings will provide building designers with a powerful design tool. This paper presents the results of the verification of a low energy solar home model that will be implemented as the main energy simulation engine for a GA Optimisation Tool that is under development. Results from the low energy solar home model are compared with monitored data of an energy efficient house based in Saskatoon. The results from the model were found to correlate well with the monitored data after adjusting the effective thermal capacitance of the zone and the control strategy used for the window coverings. The next step will be to demonstrate that the GA Optimisation Tool can systematically find optimal low and net-zero energy solar home design configurations.

INTRODUCTION

Homes that utilise solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net-zero energy solar homes. Over the years, there have been many demonstration projects and international initiatives that have promoted the development of low and net-zero energy homes (Charron, 2005). More recently, as countries are starting to implement measures to reduce greenhouse gas emissions to address global warming, interest in net-zero energy solar homes has increased. Traditional design tools were not developed to facilitate the design and optimisation of these high performance houses, and thus a new GA Optimisation Tool, introduced in (Charron and Athienitis, 2006), is being developed to help address this issue.

The GA Optimisation Tool is based in Fortran and uses an open source GA program (Carroll, 2005) that is being linked to a generic low energy solar home model based in TRNSYS (Beckman, 2000). Before proceeding with the development of the GA Optimisation Tool, a verification of both the GA program and the low energy solar home model needed to be made in order to ensure that they were properly implemented. Verifying the GA program was straightforward as the code comes with a test function with a known solution that can be used for verification purposes. When the program is run with the sample subroutine, an optimal function value of 1.0000 should be reached at generation 187 with the specified inputs. The problem is an N-dimensional version of a multimodal function with decreasing peaks presented in (Goldberg and Richardson 1987). In N dimensions, the function has $(\text{nvalley-1})^{\text{nparam}}$ peaks, but only one global maximum. This is a reasonably challenging problem for a GA, especially for higher dimensions and larger values of nvalley. The given subroutine was used and the expected results were obtained. This check confirms that the initial installation of the code was done correctly.

The verification is not as simple when it comes to ensuring that the low energy solar home model was properly developed within the TRNSYS environment. In order to accomplish this, results obtained with the model were compared with data obtained from monitoring an energy efficient house built in Saskatoon, Canada. This paper presents the results of this analysis.

MODEL VERIFICATION

Test house description

One of the reasons for selecting TRNSYS as the energy simulation engine was that there has been a considerable amount of work done validating its different components and systems (Crawley, et al., 2005). The objective of this analysis is not to validate TRNSYS itself, but more as verification as to whether the component models were correctly implemented such that the results obtained are comparable to what happens in reality. Due to the large number of different heating and cooling systems and other parameters with varying setpoints that are being implemented in the GA Optimisation Tool, it is impossible to validate the entire model including all the various different combination of parameters that are possible. Instead, the analysis will focus on the results obtained for one specific situation.

In order to verify that the model is sufficiently accurate at predicting the energy consumption and zone temperatures of a house, a highly efficient house built according to the Advanced House standard (NRCan, 1993) in Saskatoon, Canada, in 1992 was monitored for a one-year period in order to compare actual zone temperatures and energy consumption with results obtained with the low energy solar home model. Data for the test house was monitored starting March 6, 2005, with results from a full year of monitoring presented in Table 1. The house (Figures 1 and 2) features very high levels of insulation along with passive solar heating, an active solar thermal system, energy efficient lighting (mostly compact fluorescent lamps) and relatively efficient appliances (vintage 1992). The house, which also features double-thick 2 x 4 constructed walls with blown-in cellulose insulation in a 16 inch cavity, was reported as the best-insulated house on earth in Home Energy magazine (Dumont, 2000). Whether such a claim is true or not, the house is super-insulated with a ceiling R-value of R-80, walls (including basement) at R-60, windows at R-5, and the basement floor at R-35. The house is also very airtight with blower door tests showing only 0.47 ach at 50 Pa.

Table 1: One-year electricity consumption breakdown of test house starting Mar 06, 05

Load	Electricity Consumption (kWh)
Electric heaters	8,349
Dryer	1,340
Electric water heater	1,114
*Monitoring equipment	1,086
Oven + range top	851
Freezer	499
*HRV	482
Refrigerator	323
*Computer + DSL modem	301
* 2 televisions	170
Microwave	112
Dishwasher	91
Misc. (lighting, outdoor use, garage, car block heaters, small plug-in appliances, doorbell, 6 smoke detectors, garage door openers, small plug-in loads)	1,609
TOTAL	**16,327**

* Estimated consumption based on spot monitoring of consumption and extrapolating over a year

Figure 1: North façade of the house in Winter

Figure 2: South façade of the house in Winter

During the monitoring period, the house was heated primarily with 3 electric baseboard heaters, including a 1000 W natural convection baseboard heater located in the hallway of the second floor of the house, a 1500 W fan forced convection heater located in the dining room of the house, and a 1500 W natural convection baseboard heater located in the family room of the house. The total electricity consumption monitored for the baseboard heaters for the year was 8,349 kWh. This consumption was higher than expected by the homeowner based on previous experiences in monitoring the heating consumption.

The reason the heating load was higher than expected was likely due to two reasons. The first being that one of the windows in the basement was improperly closed for the majority of the monitoring period; in August of 2005 a monitoring wire was passed through the window, and the window did not close properly afterwards. The second reason that the heating load would be higher than normal is due to the fact that the bird screen on the intake duct for the HRV was found to be blocked by debris in the spring of 2006 when the monitoring was completed and was likely blocked for most if not all of the monitoring period. Although air filters were cleaned regularly, the homeowner neglected the bird screens. Flow measurements at the exhaust of the HRV during the monitoring period indicated a flow of about 40 L/s. The ventilation system was likely acting as an exhaust only system with very little heat recovery.

Low Energy Solar Home Model Validation

In order to use the data from the advanced house in Saskatoon to compare with results obtained with the low energy solar home model, the portion of the loads attributed to the basement needed to be approximated. The house was modelled using Hot2000 version 9.31. The effects of the leaky window were not considered, but the HRV was modelled as an exhaust fan operating continuously at 40 L/s. It was assumed that the main floors would be heated to 20ºC and the basement to 15ºC based on the monitored data. The total consumption for heating was calculated at 9,552 kWh. This is 14.4% higher than the monitored value. Three likely factors in predicting a higher heating load are that the HRV duct may have been only partially blocked allowing for some heat recovery, the second is that some of the unoccupied rooms in the house were left unheated by closing the room doors, and finally HOT2000 used default weather data, which can play an important role in determining the heating load. Nonetheless, the data from HOT2000 will be useful in determining what portion of the monitored heating load was attributed to the basement, which is not included in the low energy solar home model.

The heat losses for the house were divided at 41.9% for the upper floor's envelope, 14.8% for the basement envelope and 43.2% due to infiltration and ventilation. Considering that the basement was unheated for the great majority of the year, that it has smaller windows and is partially underground restricting infiltration, it was assumed that only 15% of the ventilation load was due to the basement. The energy lost through the floor in the low energy solar home model, should be close to the heat lost in the basement floor modelled in HOT2000. Given that the floor represents 63% of the below grade foundation area, which itself represents 65.6% of the basement heat loss, the heat loss through the foundation floor should represent approximately 41.3% of the basement load, which represents 6.1% of the total heat loss. Therefore, a house without a basement would have a heating consumption of approximately 84.7% (41.9 + 36.7 + 6.1) of the heating energy of a house with a basement. Therefore, for the house in question, the monitored consumption would drop to 0.847 x 8,349 kWh, or 7,072 kWh, without a basement.

In order to compare results with the test house with results obtained with the low energy solar home model, the following modifications were made to the model to represent the actual house:

- the weather data file was changed to monitored data from the Saskatchewan Research Council;
- the hot water consumption pattern was changed to the measured data;
- the major and minor appliances loads were changed to the measured data with 40% of the miscellaneous loads assumed to take place outside the residence, releasing no heat inside the house;
- the form, window areas, floor area, wall composition, roof slope, south overhang length were changed to represent the as-built condition;
- heating control set-points were changed to closer represent actual conditions derived by examining the measured zone temperature data.

The heating system also needed to be modified, as none of the heating systems considered for the GA Optimisation Tool are electric baseboard heaters. Since there are multiple heaters in operation in the house, these can be working similarly to a multi-stage heating system. In order to represent the heating system, a heater of 2 kW was connected to the heating control. The heat released from the heater was input directly into the zone's input radiative and convective gains assuming a split of 20% radiative and 80% convective. A second stage 2 kW heater was added that started when the zone temperature dropped below 19ºC with a deadband of 1ºC.

A final modification was done to the specified infiltration in the low energy solar home model. In the current model, infiltration is calculated based on the following equation:

$$\dot{m}_{\inf il} = \rho_{OA} \cdot V_{zone} \cdot (K_1 + K_2 \cdot (T_{OA} - T_{Zone}) + K_3 \cdot V_W)$$

where K1, K2, and K3 are empirical constants. The test house in question has a very tight envelope. Given that the HRV was essentially acting as a constant exhaust of 40 L/s during the monitored period, there wouldn't be much more air infiltrated above the air needed to replace the exhausted air. Based on measured infiltration properties and exhaust fan, HOT2000 calculated the total ventilation and infiltration at 0.192 air changes per hour. Using the same infiltration rate and a constant air density of 1.21 kg/m^3, this translates to a continuous introduction of outdoor air into the space of 138.1 kg/hr. Therefore, the infiltration constants were all set to 0, and a fan was added to the zone that would introduce a continuous flow of 138.1 kg/hr of outdoor air.

A one-year simulation starting March 6th, 2005, was done with the above modifications. The heating consumption was calculated as 6,619 kWh, or 6.4% less then the adjusted monitored heating. The calculated temperature fluctuated more then measured temperatures with the temperature difference being more pronounced in the shoulder season when there is little heating and no natural ventilation for cooling as seen in Figure 3. One of the reasons for the difference between the measured and calculated data might have to do with how the blinds are modelled, which are assumed to only be down in the model when the room temperature is getting too hot based on a temperature setpoint. In reality, people close blinds due to glare, privacy, or other reasons and may not actively use them to help with heating or cooling. If you look at Figures 1 and 2, you will see that on a cold winter day that half of the blinds in the house are down, reducing the impact of solar gains. The blinds are also a mix of Venetian blinds and Silhouette^{TM} type blinds that would have different properties.

In order to verify the impact of blinds, the control strategy was modified such that blinds would be considered for the same temperature conditions as before, but would also be lowered when solar radiation incident on a given window (by orientation) was higher than 150 W/m^2. For this new blind control strategy, the yearly heating energy was increased to 8,917 kWh and the temperature profile for May is as shown in Figure 4. The calculated temperature profile is now closer to what was measured, but the heating energy is now 26% higher than monitored. As seen from the pictures of the house, not all the blinds are down, which would affect the results. The current modelled blind properties have a transmissivity of 10% and absorptance of 30%. If we assume that only half the blinds are down at any given time, this would increase the effective transmissivity to 0.55 and decrease the absorptance to 0.15. At these conditions, the calculated heating load is 7,695 kWh, which is closer to the monitored value, but now the temperature profiles are again closer to those seen in Figure 3. These results seem to indicate that the blind properties and control strategy used in the modelling can have a significant impact to the heating load and temperature profiles.

Figure 5 shows the calculated and measured temperatures from November 1, 2005 to February 28, 2006 using the new blind control strategy with blind properties of 0.1 transmittance and 0.3 absorptance. As can be seen from the figure, the temperature calculated with low energy solar home model is in between the temperature measured on the first and second floor, which is what you would expect for the one zone model. In fact, over the course of the year, the calculated zone temperature is on average 0.5ºC cooler than what was measured on the main floor, and 0.2ºC hotter than the 2nd floor zone, and 0.1ºC cooler than the average of the two zones together.

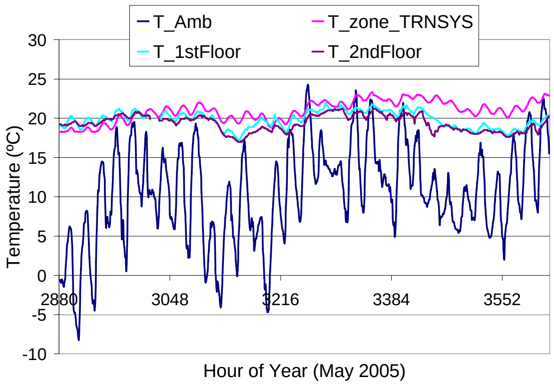

Figure 3: Comparison of simulated temperature versus monitored for May 2005

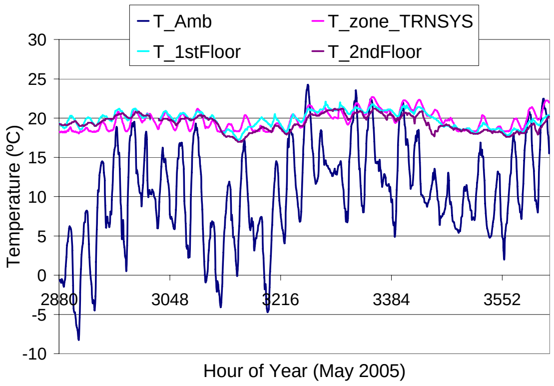

Figure 4: Temperature comparison for May 2005 with new blind control strategy

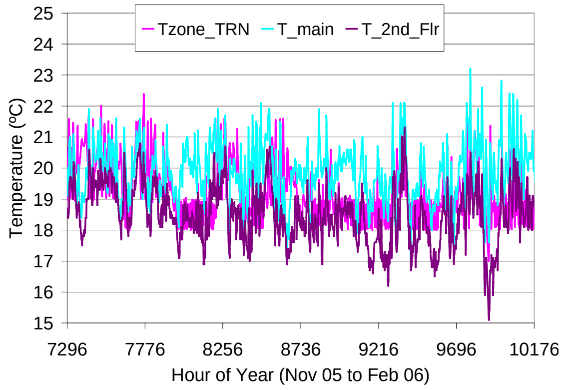

Figure 5: Measured and calculated temperatures for winter 2005-06

The effect of changing the split between radiation and convection for the baseboard heaters was verified and seems to have little effect on the overall results. When the split is 10% radiative the heating is 8,838 kWh, at 20% it is 8,917 kWh, and at 30% it is 8990 kWh. Therefore, tripling the radiative fraction increases the heating consumption by only 1.7%.

The current model assumed that all the ventilation going into the house came directly from outside due to an exhaust fan. If instead we assume that all the outdoor air was first going through an HRV at 75% efficiency, assuming no infiltration, then the heating for the year would go down to 5,664 kWh from 8,917 kWh. Even if the HRV was working, there would still be some infiltration going into the house. It is quite possible that the HRV duct was not blocked during the whole monitoring period, or that a fraction of the air did manage to go through the HRV intake resulting in a consumption that would be between the two calculated values as was monitored.

Another parameter that might be contributing to differences between monitored and simulated results is the modelled effective thermal capacitance. TRNSYS Type 19 zone model uses an effective thermal capacitance of the room air and furnishings plus any mass not considered in the building envelope. The capacitance value that was initially recommended by the TRNSYS software providers was to use a capacitance equal to 12 times the room air capacitance, which is what was implemented. However, Jeff Thorton, the president of Thermal Energy System Specialists (TESS) answered the following questions related to setting the thermal capacitance on the TRNSYS user group on March 4th, 2006 (University of Wisconsin, 2006):

Q: *Is there any basic criteria for selecting capacitance?*

A: It depends entirely on the type of zone that you are modelling. For residential and commercial zones I usually multiply the volume by 10 to 50 times the default value (1.2 x Zone Volume) to account for non-wall capacitance.

Q: *Will it make major changes in inside temperature or heat transfer calculation?*

A: Heat transfer calculation - no. Inside temperature - yes. The higher the capacitance the slower the building will respond to changes. Try different values until the building behaves like you think it should to a step-change in temperature.

Therefore, the effective zone air capacitance that was used for the verification, despite being the recommended value, was on the low end of the range of values used by TRNSYS experts. In order to test the effect of the effective air capacitance, simulations were done using a fictitious 150 m^2 house located in Montreal comparing the use of a capacitance that is 50 times zone air capacitance versus 12. The capacitance did have an effect on calculated heating electricity consumption with the heating load dropping by approximately 13% when radiant heating systems are used. Using higher air capacitance, the frequency of zone temperature oscillation decreased, in addition there was less variation in the calculated zone air temperature using different time-steps with the higher capacitance. Another attribute of the higher effective capacitance is that calculation time decreased by approximately 30% with the higher capacitance. Calculation run-time savings are due to the program requiring less iteration per time step for the solution to converge since there is less fluctuation in the air temperature from one time-step to the next.

In order to determine what capacitance value to use, the results from the test-house were used. It is likely that the difference between calculated and measured temperature was due to a combination of blind control and the zone air capacitance values that were used. Various air capacitance values were modelled with the new blind control strategy in order to get closer correlations in the zone air temperature between measured and calculated values. The value that seemed to offer the best results over the whole year had the capacitance multiplied by 40 times zone air capacitance. The calculated heating electricity consumption was 7,534 kWh, which is 6.5% higher then the modified measured results but still within the range of uncertainty associated with the accounting of the basement in the real situation. Therefore, the effective air capacitance in the low energy solar home model was changed to 40 times zone air capacitance.

DISCUSSION

The verification of the low energy solar home model focused on comparing modelled results with monitored data. For the GA Optimisation Tool, no existing house will be available to help set inputs and parameters, which will present more unknowns introducing more uncertainty as more assumptions will need to be made.

For example, the analysis on the effects of the effective capacitance showed that the value that is used has an effect on the air temperature profile, the calculated heating and cooling load, and the program computational time. Using values in the recommended range of 10 to 50 times the zone air capacitance results in a range of possible different solutions. Using the suggested strategy of trying different values until the building behaves like you think it should to a step-change in temperature is far from ideal, especially in this situation where a fixed value will be used for a wide variety of design configurations. The capacitance value will change on a case by case basis depending on the amount of capacitance that is in the furniture and interior walls that are not included in the model. Therefore, in later stages of design more detailed modelling that considers this parameter need to be carried out.

Another area that can affect the accuracy of a simulation model occurs in the modelling of infiltration. In super-insulated houses, infiltration can account for a larger percentage of the overall heating load. However, without having a measured infiltration value it is difficult to know how much infiltration you could expect since typical infiltration values can vary significantly from one house to the next. For tightly constructed houses, the seasonal average air exchange rates are in the range of about 0.2 air changes per hour (ach), whereas loosely constructed houses can have air exchange rates as high as 2.0 ach (ASHRAE, 2001). Various studies have been done to evaluate the air exchange rates of a number of houses. One such study looked at two groups of houses: the first comprising of 292 energy efficient houses that were built incorporating measures to reduce air infiltration, and the second comprised of 331 control houses. Tests showed that the first group of houses had average air exchange rates of about 0.25 ach, whereas the second was at 0.49 ach (range: 0.05 to 1.63 ach) (ASHRAE, 2001). ASHRAE Fundamentals 2001 goes on to list various studies done to test the accuracy of models used to predict air exchange rates due to infiltration and found that the models exhibited average errors on the order of 40% for many measurements on groups of houses and were sometimes off by 100%. Therefore, the predicted infiltration value introduces inaccuracies to the overall building model.

Another area that becomes more critical in modelling low energy houses relates to the occupant loads, which are dependent on occupant behaviour. A given energy efficient house might be able to reach the net-zero energy target for a specific family of four that is more aware of their energy consumption, whereas it may be short by as much as 50% for a different family of four that pays no attention to the amount of energy they consume. Studies in the US, the Neatherlands, and the UK estimate that 26-36% of in-home energy use is due to resident behaviour (Wood and Newborough, 2003).

In the verification analysis, real weather data was used. However, when using the tool to make predictions about future consumption, one does not have that luxury. With our climate changing due to global warming, using weather from old databases may tend to overestimate heating energy consumption, and underestimate cooling energy. (Christenson, et al., 2006) looked at the climate trends in Switzerland to see how heating degree days (HDD) and cooling degree days (CDD) have changed. Their results indicated that during 1901 to 2003, HDD have decreased by 11–18%, depending on the threshold temperature (8, 10 or 12ºC) and location. Looking ahead to 2085, the scenario calculations suggested a further decrease between 13% and 87%. For CDD, a significant increase in cooling potential was found to have occurred between 1901 and 2003 (between 50% and 170% based on CDD based on a threshold of 18.3ºC). Looking ahead to 2085, the CDD was projected to increase by up to 2100%! The results of the study indicate that weather used in energy simulation programs should be updated regularly. In addition, it seems to indicate that one should consider the rising cooling loads in the coming years. If simulation data shows that no cooling technologies are needed, but that in 5 years the occupants find the space uncomfortable, they may opt to purchase an inefficient window AC unit, which could have a considerable impact on yearly energy consumption.

CONCLUSION

The low energy solar home model was found to be able to produce realistic results that correlate well with measured data. The accuracy of the modelling will be more limited by other assumptions that need to be made when modelling buildings in the early design stages. However, when used with the GA Optimisation Tool, designs will be compared on a relative basis, which will reduce the impact of any modelling inaccuracies. The next stage of the research will demonstrate that the GA Optimisation Tool can in fact find optimal configurations of low and net-zero energy solar homes. Once that is established, the Tool will be used to demonstrate the advantages of using this new design optimisation approach.

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