SENSITIVITY ANALYSIS FOR A PASSIVE SOLAR HOUSE ENERGY MODEL

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ABSTRACT

A solar house design tool is being developed that will allow designers to efficiently design a house that performs in the optimal region. Detailed building energy simulation tools require a large number of inputs, many of which are simplifying assumptions that are assumed to remain constant throughout the simulation period. In order to study the effect of nine different parameters, which are particularly relevant for passive solar heating, a sensitivity analysis was performed. The metrics used in the study were both annual energy consumption for heating and cooling as well as the optimal glazing area associated with the assumptions. The analysis showed that both metrics are particularly sensitive to the mixing of indoor air, the rate of infiltration and ventilation, and magnitude of internal gains. The energy consumption of the house is particularly sensitive to infiltration and ventilation, HVAC setpoints, and external shading. This work will be used to assess the importance of characterizing critical user inputs for the design tool.

INTRODUCTION

The energy modeling of houses is a skill that requires strong understanding of thermal processes and building construction. During the input of model details, such as construction, operations, and geometry, many simplifying assumptions are available to shorten the input process at the cost of accuracy. There are also many qualities of a house that the designer cannot accurately predict. Perhaps the best example of this is the airtightness of the envelope, which is more a function of workmanship quality than design. Another example is occupant behaviours such as tolerance of overheating and appliance usage. This ability of the designer to predict these parameters is further inhibited if they do not have information about the eventual occupants. It is important to assess the level of accuracy of inputs required to obtain reasonable results.

A solar house design tool is being developed that will allow a designer to efficiently and systematically explore the design space, while being guided towards the optimal solution. In order to facilitate this, real-time feedback is being proposed, such that the effect of every design input is immediately displayed (O'Brien et al., 2008). There are two main outputs from the design tool. The first is annual energy performance. The second is the corresponding design parameters (e.g. construction and geometry) that enable that level of energy performance. The actual annual performance may be on the order of 10% different than the predicted annual performance because of unforeseeable occupant habits or weather patterns. Typically, the HVAC system is oversized to ensure that loads can be met. However, it is considered much more detrimental to guide the designer towards poor design decisions based on inappropriate assumptions. For example, if the design tool incorrectly assumed a high ground reflectance, but the house being designed was surrounded in asphalt with very low reflectance, the designer would be misled to use inappropriately large windows. Thus, the house would never be able to perform to its full potential.

For the design tool, for parameters that show little sensitivity, it may be most appropriate to hard-code the assumptions. This reduces the number of inputs and corresponding research or thought required. In contrast, the user should have the option to specify inputs for which the performance proves too sensitive.

A sensitivity analysis was performed for HOT3000 for a multitude of issues (Purdy and Beausoleil-Morrison, 2001). They found that energy consumption is particularly sensitive to sub-zoning, ground contact, thermal bridging, infiltration, and ground reflectance. However, the house that was modeled was not particularly suited to passive solar heating. In contrast, this study focuses on issues related to passive solar heating. Lomas et al (1992) performed sensitivity analysis on a comprehensive list of parameters on a very simple house model. They focused on the change in temperature profiles over a particular day. This paper takes sensitivity analysis one step further, by not only examining the magnitude of the change in performance but also the change in optimal glazing area. In this way, the degree to which faulty assumptions can mislead the user can be quantified. The glazing area was the focus because the optimum is probably the least obvious of the design parameters. In contrast, the addition of thermal mass and insulation nearly always improve performance (to a practical limit), although for mass there is a theoretical optimum based on frequency response techniques (Athienitis and Santamouris, 2002). The methodology used for this study can be repeated for any design parameters.

For most scenarios, plotting energy against glazing area shows a clear U-shaped curve. Increasing from zero south-facing glazing, there is a reduction in energy consumption (though with diminishing returns) until a certain point. At that point, the additional energy consumption due to nighttime heat losses in winter and excess solar gains in summer begins to outweigh the benefit of large glazing areas.

This paper first describes the house model being studied. It then describes the method used to perform the sensitivity analysis, followed by the results in graphical form. It is concluded with a discussion of how this work can be applied to the solar house design tool.

THE MODEL

All energy performance analysis was simulated using ESP-r, a detailed, hourly time step building energy simulation program (Clarke, 2001). ESP-r is particularly accurate for passive solar houses, in which the behaviour of thermal mass is modeled using the finite difference method. ESP-r is also the simulation engine being used for HOT3000 – a residential energy program that the design tool will be integrated with (Purdy, 2004). The model house is designed for high passive solar heating performance and to fully demonstrate the sensitivity of the explored parameters. Thus, the sensitivity analysis results only apply to houses of similar design and would likely show less sensitivity for houses that are not designed with passive solar heating in mind. All simulations were based on the Toronto climate, which is typical of southern Canada. The base case model is described below and shown in Fig. 1.

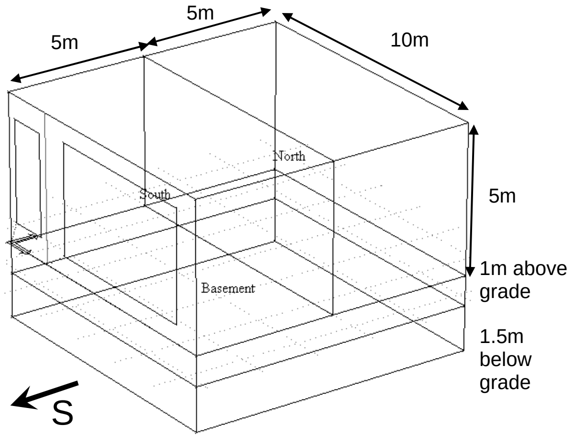

Fig. 1: The model house

The properties of the base case house model area as follows.

- Only 1D conduction was modeled – a common assumption in building energy analysis;
- Air was circulated continuously at a rate of 200 L/s from the south zone → basement zone → north zone. This is to simulate the combined house air circulation rate of a typical furnace/heat pump fan and natural flow;
- Ideal control was assumed and HVAC equipment was not explicitly modeled;
- The heating and cooling setpoints were set at 22°C and 27°C, respectively;
- Free cooling (ventilation of outdoor air) was assumed if the outdoor air was 10°C or less (or 12°C below the heating set-point for other setpoints) (DOE, 2001);
- The insulation level for all cases was kept constant and is summarized in Tab. 1. These values were found to be near-optimal for cold climates (O'Brien et al., 2008);
- An equivalent of 0.1 air change per hour (ach) ventilation and infiltration was assumed for each zone;
- No internal gains were considered;
- The house was considered to be completely unshaded; and,
- The South zone floor and the wall separating the North and South zones were made of 20 centimeters of exposed concrete (acting as thermal mass).

Tab. 1: Model house envelope insulation levels.

Wall type	RSI-Value, Km^2/W (R-Value, $°Fft^2h/Btu$)
Exterior walls	5.4 (30.7)
Roof	11.9 (67.6)
Basement walls	5.2 (29.3)
Basement floor	1.4 (8)

The windows were lumped as a single glazed area. Purdy and Beausoleil-Morrison (2001) found that this assumption changed heating loads by only about 0.2%. They were modeled as double-glazed, low-e (hard-coated), and argon-filled (based on Window5 software). The frame of all windows was modeled similarly as one lumped area with an equivalent U-value (1.70 W/m^2K). The window (including glazing and frame) had an equivalent U-value of 1.77 W/m^2K. The glazing had a solar gain heat coefficient (SGHC) of 0.603. This window type was found to be particularly effective for passive solar heating (O'Brien et al., 2008).

METHOD

A Matlab program was written to modify the model as needed and to perform batch ESP-r simulations. A large number of design assumptions was explored, as outlined in the Results section. For each item, a simulation was performed for glazing areas between 15 and 75% (in 15% increments) of the south-facing wall. These limits are based on minimum and maximum practical values. The results are plotted and a third-degree polynomial was fit to the simulated data points to estimate the optimal glazing areas.

To quantify energy consumption with a single metric, heating and cooling loads were summed. This is the value shown on the vertical axes of the graphs in the Results section. It should be noted that the relative cost of injecting and extracting heat from a building depends on the equipment and energy source. For this study, heating and cooling were assumed to have equal costs.

RESULTS

An explanation of each of the factors being explored along with the results of the study is listed below. Each graph shows the estimated energy consumption for each setting of the parameter as a function of glazing area. Also, the glazing area corresponding to the minimum energy consumption is shown. For cases where the optimal is beyond the range of practical glazing areas, it is shown at the limit.

Ground Reflectance

Ground reflectance or albedo (denoted "ρ") can vary from 10% to 82%, depending on the ground cover (Purdy and Beausoleil-Morrison, 2001). Most building simulation software only allows a single value to be described for the entire surrounding area and a constant value for the entire year. In reality, the ground is irregular – particularly for urban environments. Furthermore, albedo can change seasonally from the presence of snow or vegetation. Several different albedos are examined in addition to a case in which snow is simulated. It is assumed that snow is present and the corresponding albedo is 70% for months whose average temperature is -5°C or below, as done in

RETScreen renewable energy software (RETScreen, 2005). For the Toronto climate, this period is from January to February.

The results (Fig. 2) suggest that the performance is relatively insensitive to albedo. In general, higher albedo values correspond to a lower optimal glazing area. This is because the ground helps to concentrate solar radiation into the house; meaning that a smaller glazed area is required for the same level of solar gains. The most notable conclusion that can be drawn is that the presence of snow is very beneficial since it increases solar gains during the time that they are most useful. For the design tool, it seems reasonable to base ground reflectance on expected snow cover. This assumption appears to have little effect on energy performance or optimal glazing area.

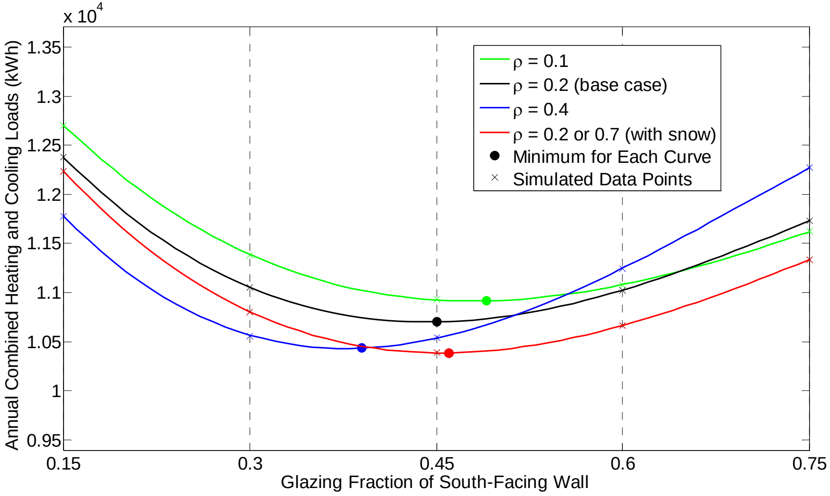

Fig. 2: Ground Reflectance

Infiltration and Ventilation

While ventilation can be quantified to some degree from the ventilation fan flow rate, infiltration is highly dependent on workmanship. The effective number of air changes per hour (ach) can range from 0.1 for an extremely airtight house that uses a heat recovery ventilator to 1.0 or more for a poorly built house (Hutcheon and Handegord, 1995). For this study, constant values of between 0.1 and 0.5 ach were examined. One can assume that a newly-built house, for which the designer or owner is energy-conscious will be better sealed than average. The results (Fig. 3) show that both performance and the optimal glazing area are extremely sensitive to infiltration. The optimal glazing area increases with higher infiltration because the solar gains become more usable (though most of this energy is lost to outdoor air). For less insulated houses, the heating and cooling loads due to the ventilation rate would become less significant.

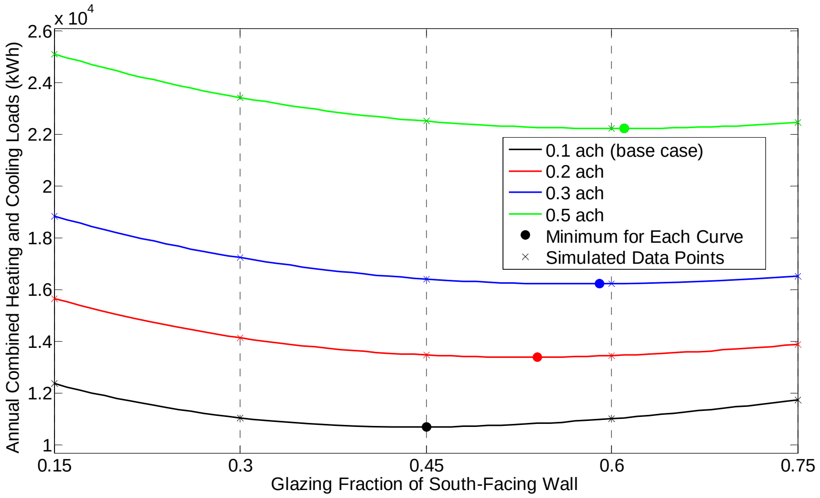

Fig. 3: Infiltration and Ventilation

Internal Gains

Internal gains represent the heat that is produced from appliances, lighting, or occupants. While the majority of houses have some base loads such as refrigerators and lights, the presence of occupants or the use patterns of appliances cannot be stated with complete certainty. Nor can the magnitude be considered constant on a daily or seasonal basis. However, it simply would not be practical to define internal gains on an hourly basis. The magnitude of internal gains can be on the same order of magnitude as heating loads on a cool day. Therefore, it is worthwhile to study the effect of the assumed value. Three different reasonable values were explored and compared to the base case. To justify the values that were explored, NRCan (2007) shows that the average detached house in Canada consumes an average of 1600 Watts. However, about 40% of this is for water heating; meaning that much of the heat is lost and does not contribute to internal gains. Human occupants that are sitting each produce about 100 W (Hutcheon and Handegord, 1995). It is expected that a new solar house would make use of energy efficiency appliances which consume considerably less energy than average. Hence the exploration of lower than average internal gains assumptions.

The results (Fig. 4) clearly show that higher internal gains decreases energy consumption (which is mostly made up of heating). The case with a constant 1500 Watts of internal gains shows that the glazing area should be minimized. This is because solar gains would merely contribute to overheating the house rather than significantly reducing heating loads. That is, the heating loads are met by internal gains alone. A house with higher heat losses (from infiltration or conduction) would be better able to handle significant internal gains. It follows that high-performance envelopes prevent heat transfer and thus, accurate internal gains should be reported during the design stage.

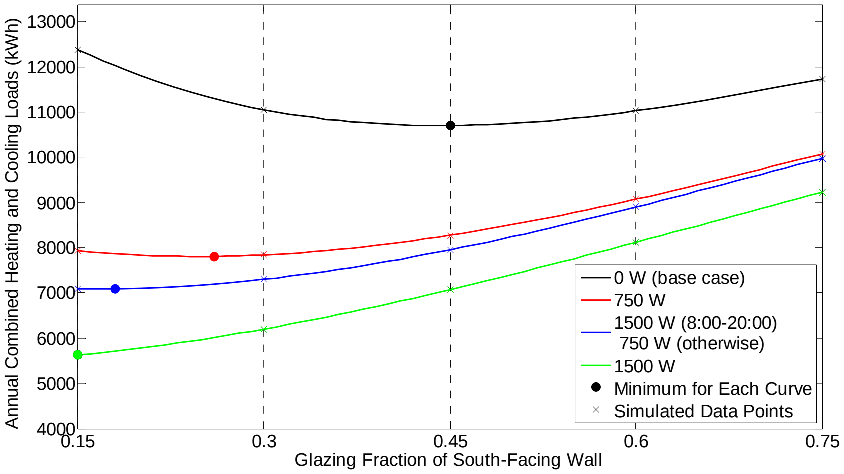

Fig. 4: Internal Gains

Air Circulation Rate

The base case model assumes that the house is divided into three thermal zones, for which the temperature is homogeneous in each. However, other than the conduction that occurs between zones, most houses would also allow airflow between all zones (or rooms) – particularly in houses that are relatively open. Airflow is also caused by central air-based heating systems. To model the combined effect of airflow, a constant circulation rate was assumed. The results (Fig. 5) show that if the air is stagnant, energy consumption is at its highest while the optimal glazing area is reduced. The reason for this is that the heat from solar gains is not properly distributed to the other zones, merely leading to overheating in the south zone. A high circulation rate translates to lower energy consumption and a higher optimal glazing area. The results of the four cases that were analyzed suggests that increasing the airflow rate leads to diminishing returns.

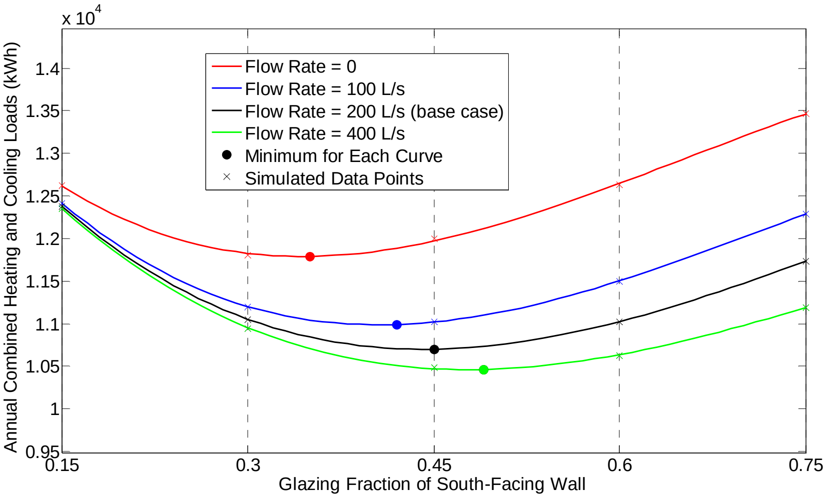

Fig. 5: Airflow rate between zones

HVAC Setpoints

The HVAC setpoints represent the threshold temperatures at which heat is added or extracted to the house. The setpoints used in a particular house are based on occupant preferences and cannot be assumed with complete certainty. Therefore, a variety of reasonable values were explored. The results (Fig. 6) show that having a lower heating setpoint results in lower overall energy. Having a higher cooling set-point shifts the optimum glazing area higher because the solar gains are more useful and more heat can be absorbed before cooling sets in. If the occupants are tolerant to large temperature fluctuations, energy savings can be achieved; particularly for large glazing areas. Having a nighttime setback results in significantly lower energy consumption but has little impact on optimal glazing area for the cases considered.

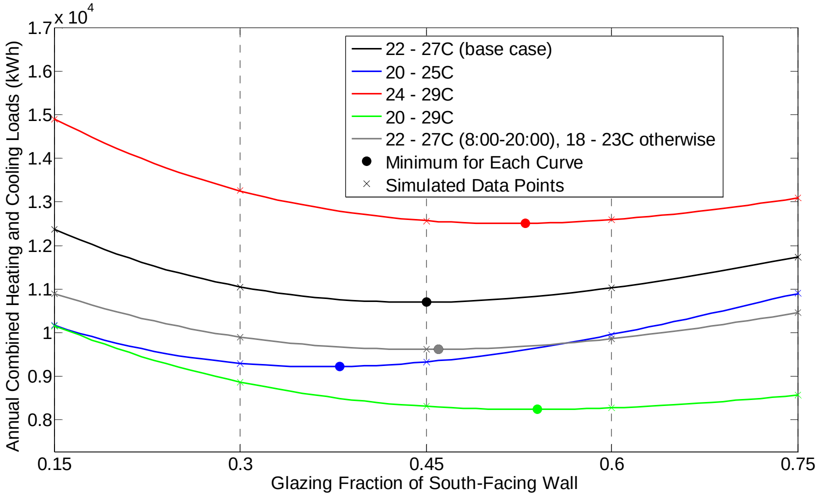

Fig. 6: HVAC setpoints

Thermal Mass Control Volume Discretization

By default, ESP-r treats a single homogeneous construction material (e.g. concrete slab) as being at a single temperature. This is a relatively inconsequential assumption for most construction materials. However, accuracy is increased by discretizing a construction into layers; particularly if it has a high heat capacity. For the analysis, the two main thermal masses in the direct gain zone where divided into four control volumes (CVs) – depth-wise. The results (Fig. 7) show that modeling concrete slabs with a single CV slightly underestimates energy consumption. A single CV also leads to a slightly higher optimal glazing area. However, the simulation with 4 CVs took approximately three times longer to process and did not offer substantial improvements. For the design tool, the user would not have access to the number of CVs since it is not a design issue. The results suggest that using a single CV to represent a 20 centimeter slab is adequate. Alternatively, a follow-up sensitivity analysis could determine the thickness at which the additional computations associated with a greater number of CVs would be justified. However, for studies of more complex control algorithms and radiant heating more CVs may be required.

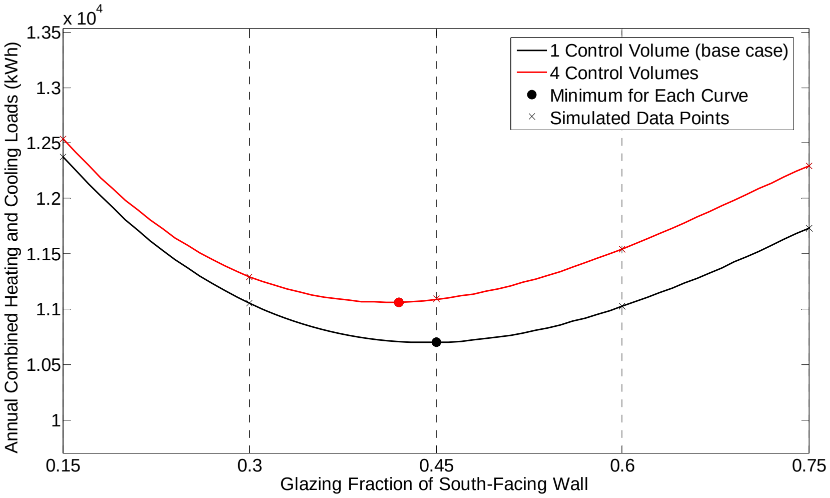

Fig. 7: Discretization of thermal mass

Thermal Zones

The base case model is divided into three zones – one basement zone and two upper zones, each extending from the ground floor to the second floor. The reason for dividing the upper floors into two zones was to properly quantify the degree of overheating that can occur. If only one zone were modeled, air would be assumed to be completely mixed, thus reducing the maximum temperature reached on sunny days. This effect is similar to having a high airflow rate, as previously studied. For the case with five zones, the two upper zones were subdivided horizontally; with the glazing also distributed equally. One of the downsides to increasing the number of zones is that simulation time increases approximately with the cube of the number of zones. The results (Fig. 8) show that having three or five zones makes little difference, while removing all divisions in the house leads to substantially lower energy consumption. It follows that having fewer zones translates to larger optimal glazing areas. Again, this is because solar gains are properly distributed instead of merely overheating the direct gain zone. The base case assumption of three zones appears to be reasonable since some internal walls that impede airflow are usually present. Little change was observed when five zones replaced three. Thus for the design tool, modeling three zones appears to be a reasonable compromise between accuracy and processing time.

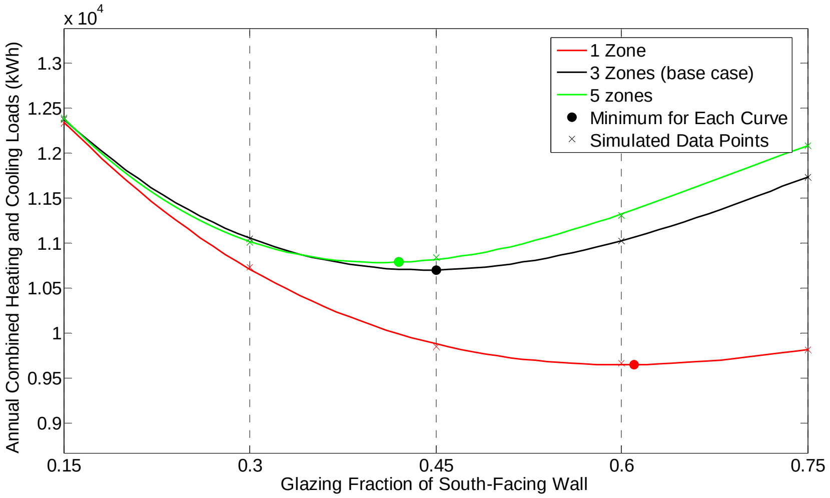

Fig. 8: Number of thermal zones

Shading

By default, most building simulation software assumes that the building is completely unobstructed from solar radiation. In reality, at least some shading will occur; particularly for urban or suburban locales. For this analysis, a house of the exact same size was assumed to be south of, and at different distances from, the modeled house. The results (Fig. 9) show that a house that is 10 meters away has very little effect. The house that is 5 meters away increased energy consumption by an average of 9%. Meanwhile, the case for which the glazing is completely blocked, though unrealistic, illustrates the benefit that passive solar heating provides. For the other cases, the optimal remains nearly unchanged at about 45%. Certainly shading is an important parameter for the design tool. However, these results suggest that only large nearby obstructions are worthy of modeling.

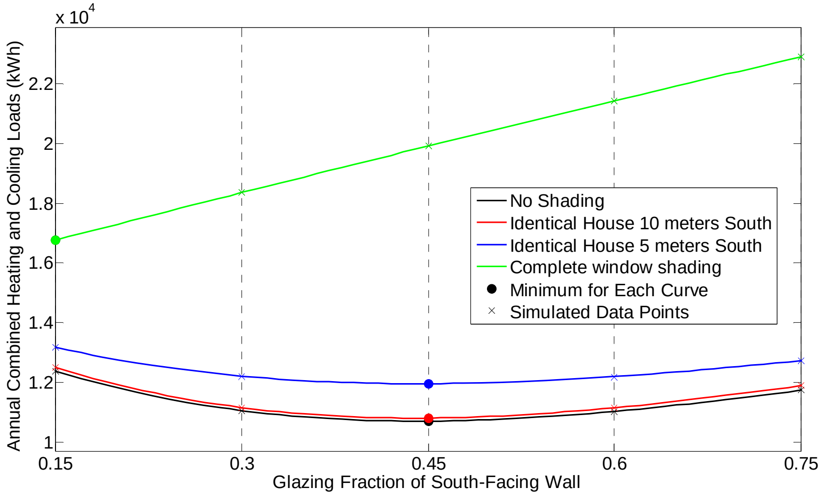

Fig. 9: External shading

Reduced Glazing Transmittance

After being installed, windows begin to accumulate residue that reduces their transmittance. Additionally, insect screens may be installed, further reducing their transmittance. The effect of reducing transmittance by 10 and 20% was explored. A modest change in both energy consumption and optimal glazing area were observed. Thus, while it may be beneficial to assume transmittance is modestly (1 to 2%) lower than the window manufacturer’s specifications, such assumptions appear to have little impact on energy performance or the optimal glazing area.

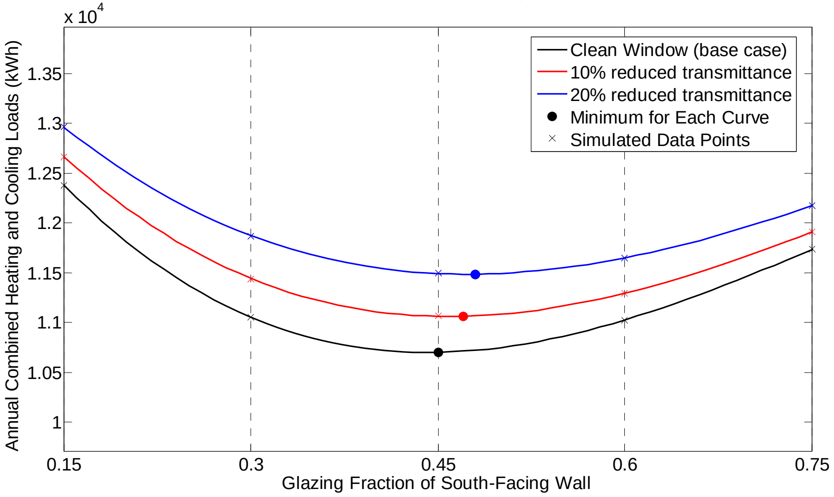

Fig. 10: Reduced window transmittance

DISCUSSION & FUTURE WORK

Of the parameters that were examined, the energy consumption was the most sensitive to the rate of infiltration. The maximum infiltration rate studied led to a 103% increase in annual energy consumption. The optimal glazing area was also very sensitive to infiltration. Energy consumption was also shown to be quite sensitive to the number of zones, the HVAC setpoints, the internal flow rate, and internal gains. Perhaps the most difficult of these issues to define are the interaction between, and subdivision of, thermal zones. Purdy and Beausoleil-Morrison (2001) also concluded that these issues need to be well characterized and remain a challenge. The relative magnitude of the sensitivity of each parameter is summarized in Tab. 2.

Tab. 2: Summary of Results

Factor	Average Change in Energy (%)			Maximum Change in Optimal Glazing Area (percentage points)		
	0-9	10-19	20+	0-9	10-19	20+
Ground Reflectance	✓			✓		
Infiltration and Ventilation			✓			✓
Internal Gains			✓			✓
Airflow Between Zones		✓			✓	
HVAC Set-points			✓	✓		
Thermal Mass Discretization	✓			✓		
Number of Thermal Zones	✓				✓	
Window Trasmittance	✓			✓		
External Shading	✓			✓		

The following generalizations can be concluded from the results (for the assumptions that were explored):

- The removal of heat from the south zone results in higher optimal glazing areas. However, only cases in which this heat is transferred to the other zones (as opposed to outside) result in lower energy consumption.
- The reduction of solar gains increases the optimal glazing area but also increases energy consumption.
- Higher cooling setpoints result in higher optimal glazing area. Higher heating setpoints results in higher annual energy consumption.
- Higher internal gains assumptions reduce the optimal glazing area and reduce the energy consumption to maintain thermal comfort.
- Except for the case of HVAC setpoints and the number of thermal zones, the level of sensitivity to energy consumption corresponds to the sensitivity of the optimal glazing area, in magnitude.

For the design tool, it is evident that the most important input from the user (other than design inputs) is the estimated rate of internal gains. While infiltration and setpoints also exhibited high sensitivity, it is probably most appropriate to use typical values as defaults, since the values are hard to characterize until the house is built (in the case of infiltration). Likewise, for all other parameters, it appears to be most appropriate to suggest default values that the experienced designer can modify.

This study focused on the modeling assumptions that are most relevant to passive solar heating. However, there are issues that remain to be studied, such as the modeling of windows and controlled shading devices. Furthermore, the issues were examined on an individual basis and interactions were not studied.

CONCLUSION

The effects of nine different modeling/parameter assumptions that pertain to passive solar heating for a house were explored. Both the annual energy consumption and optimal glazing area were used as metrics. The analysis showed that the optimal glazing area is particularly sensitive to the mixing of indoor air, the rate of infiltration and ventilation, and magnitude of internal gains. The energy consumption of the house is particularly sensitive to infiltration and ventilation, HVAC setpoints, and external shading. It was concluded that of these factors, the magnitude of internal gains should be input by the user of the solar house design tool, while the other parameters should be set to average or expected values by default with the option to modify them. This work enables the determination of the parameters for which the most effort should be focused on in the solar house design tool.

REFERENCES

Athienitis, A. and Santamouris, M., 2002. Thermal Analysis and Design of Passive Solar Buildings. James & James, London, 288 pp.

Clarke, J., 2001. Energy Simulation in Building Design. Butterworth-Heinemann, Oxford, 384 pp.

DOE, 2001. Cooling Your Home with Fans and Ventilation.

Hutcheon, N.B. and Handegord, G.O.P., 1995. Building Science for a Cold Climate. Institute for Research in Construction, Canada.

Lomas, K.J. and Eppel, H., 1992. Sensitivity Analysis Techniques for Building Thermal Simulation Programs. Energy and Buildings, 19(1): 21-44.

NRCan, 2007. Residential Single Detached Secondary Energy Use by Energy Source and End-Use. In: O.o.E. Efficiency (Editor).

O'Brien, W., Kesik, T. and Athienitis, A., 2008. The Use of Solar Design Days in a Passive Solar House Conceptual Design Tool, Solar Buildings Conference, Fredericton.

Purdy, J., 2004. The Development of a Dynamic On-line Whole-Building Energy Analysis Tool for Homeowners, eSim 2004 Conference, pp. 8.

Purdy, J. and Beausoleil-Morrison, I., 2001. The Significant Factors in Modeling Residential Buildings, 7th International IBPSA Conference, Rio de Janeiro, Brazil.

RETScreen, 2005. Clean Energy Project Analysis. Ministry of Natural Resources Canada.