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THE USE OF SOLAR DESIGN DAYS IN A PASSIVE SOLAR HOUSE CONCEPTUAL DESIGN TOOL

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ABSTRACT

Traditional passive solar house design is cumbersome because of the effort required to vary the design parameters and interpret performance results. When this process is aided by building simulation software, the designer is not given adequate feedback on the relationships between key design parameters and their effects on passive solar performance. To improve the efficiency of the design process, the use of solar design days (SDDs) is explored. The days represent a cold sunny, cold cloudy, and warm sunny (shoulder season) day for the climate of interest. Unlike traditional equipment-sizing design days, the SDDs are used as performance indicators. Limiting the period that is studied can put the designer in touch with exactly how the window size, window type, thermal mass, and effective envelope U-value affect performance. While energy performance is a key metric, thermal comfort is also important. The warm sunny day will allow the user to prevent overheating and reduce cooling loads. Since there is a good correlation between cold sunny day performance and annual performance, it is adequate to design a house based on cold sunny day performance alone in the early design stages. This paper will explain how SDDs can be used as a tool to design passive solar houses and the associated methodology.

INTRODUCTION

It has been predicted that the next generation of building simulation software will not only provide performance data based on an inputted design, but also guide the designer during the design process (Clarke and Maver, 1991). In order to provide better guidance in a passive solar house design tool, this paper explores the use of solar design days (SDDs) to enable the designer to make key design decisions early in the design process. The motivation of this paper is to develop an efficient method to optimize passive solar house performance. This research will be used directly as part of a conceptual solar house design tool, which is being developed for the Solar Buildings Research Network (Theme 4.3). The objective is to optimize passive solar heat gains during the coldest part of the year. The use of solar design days has two main advantages over whole-year simulations. First, presenting the designer with only a few carefully selected days' worth of performance data allows them to make direct and real connections between the design and the corresponding performance (i.e. cause and effect). For example, they will observe how increasing the level of thermal mass can lower the peak temperature and reduce nighttime heating loads. A secondary factor is that computational time is reduced by about 95% versus whole-year simulations. While computing time is not a problem for single simulations, it becomes cumbersome if many designs are explored. This paper presents examples of each of these benefits of SDDs. It not only shows a good correlation between SDD performance and whole-year performance, but also demonstrates some general heuristics related to passive solar house design. While the SDD concept is expected to be effective for all types of solar house design (e.g. active thermal, electricity production), passive solar design is the focus of this paper because it is the most cost-effective means to harness solar power (Athienitis, 2007), and it is most critically affected by decisions made during the initial stages of the conceptual design process.

Since much of the literature on passive solar house design for a cold climate is several decades old, it is somewhat obsolete. Simulation methods of that time were often limited to statistically-based calculations, compared to the hourly time-step simulations that are routine today. Sanders and Barakat (1984) presented a graphical design approach for passive solar houses. However, their results are skewed by the poorer performing windows that were available at the time of publication. More recently, Kesik and Papp (1998) presented some general rules of thumb about good passive solar design practices through a parametric study. Perhaps the most significant conclusion was that the optimal solar aperture (south-facing glazing area to conditioned floor area ratio) for lower performance windows was around 6% while the optimal size for high-performance windows is substantially higher at 15% or more – a level that approaches the maximum practical value. Tap the Sun (1998) offers a wide variety of guidelines for passive solar design. The Athienitis house (Athienitis, 2007), among others, for which detailed analyses were performed, provide specific passive solar house designs and indicate that optimal south-facing glazing areas comprising 30% of the south façade is reasonable. Regarding saved computational time through part-year simulations, Degelman (1998) showed that using a typical week of weather data for each month of the year reduced simulation times by at least 50% while only introducing an error of ±10%. Athienitis et al. (2006) extensively examined issues related to developing a conceptual solar building design tool. They concluded that an effective conceptual design tool should allow some degree of detailed design up front.

METHODOLOGY

The three solar design days and their purpose are examined, as follows.

Cold sunny day (CS): Represents the weather during which passive solar design is ideal. Solar gain is to be maximized, while being balanced with heat loss associated with large glazed areas. Thermal mass can be used to reduce daytime peak temperatures and store heat to be released at nighttime.

Cold cloudy day (CC): Represents the weather during which maximum heat loss is expected due to the cold temperatures and minimal solar gain. This design day allows the designer to balance the advantage of a large glazed area with the associated heat loss.

Warm sunny day (WS): Represents the weather during a shoulder season day. The temperature is warm, but the solar altitude is relatively low, causing significant solar gains. For typical passive solar design, with large south-facing windows, it is these conditions that cause peak annual indoor temperatures.

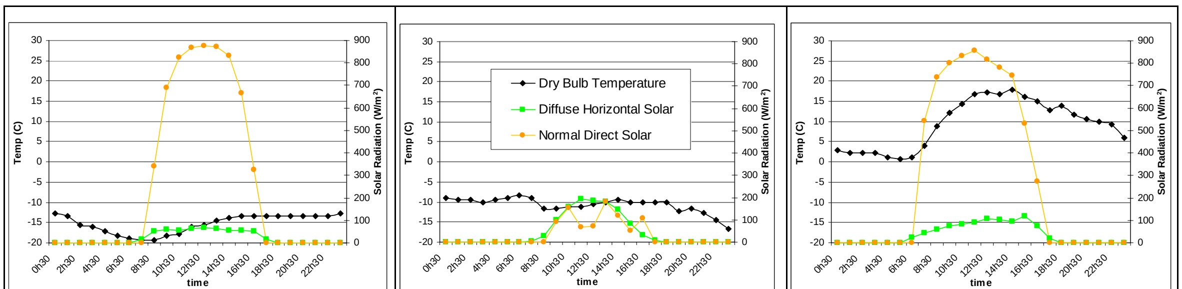
The selection of the design days was performed manually for this research, but will be performed automatically in the future by deselecting a day with the desired characteristics. For example, the CS day might exhibit the coldest average temperature and 95th percentile solar radiation. Automation will allow the solar house design tool to accommodate any location and maintain consistency. The selection process is not trivial. A typical passive solar house with large windows will suffer more from overheating in the fall when solar angles are low and temperatures are mild than in the summer when solar angles are high but temperatures are very warm. In contrast, typical Canadian houses with less south-facing glazing experience peak overheating during the warmest months of July and August, since their indoor temperature is less a function of solar gain and more of ambient temperature. In order to properly compare a number of design options, the solar design days must remain constant for a given locale. Thus, the solar design days were selected with the intention of being applied to a house design that resembles a passive solar house. The SDD weather for Toronto, shown in Figure 1, was obtained from a CWEC (Canadian Weather for Energy Calculations) weather file.

Proof of Concept

To show the correlation between SDDs and whole-year solar gains and purchased heating, a wide variety of houses were simulated. The metric that was used to measure performance was the purchased heating. That is, the total heating minus that provided by passive solar heating. The varied parameters were window size (5 levels), window type (2 types), and level of thermal mass in the form of different construction types (3 levels).

The Model

Energy performance simulations were performed using ESP-r. A Matlab program was written to create ESP-r input files, run the simulations, and analyze the results. The model used was a simple square house with a south zone and north zone, dividing the upper floors equally, and basement zone. The conditioned floor area was 300 m^2, with 2.5 meter room heights. Only glazing on the south wall of the south zone was explored.



Cold Sunny Day: Jan. 27 | Cold Cloudy Day: Jan. 10 | Warm Sunny Day: Oct. 9

Figure 1: Climate graphs for the three SDDs for Toronto

Model Assumptions

- The windows are lumped as a single glazed area. However, equivalent U-values were used assuming 2 m^2 windows with vinyl frames (based on WINDOW5 software). The 2 m^2 size was selected to properly determine reasonable frame sizes. Thus, fractions of a window were allowed. The frame of all windows was modeled similarly as one combined area with an equivalent U-value (1.7 W/m^2K). Window types and sizes are summarized in Tables 1 and 2.
- Only 1D conduction was modeled – a common assumption in building energy analysis.
- Air is circulated at a rate of 200 L/s from the south zone → basement zone → north zone. This is to simulate the house air circulation rate of a typical furnace fan.
- Ideal control is assumed and HVAC equipment was not explicitly modeled.
- The heating set point is 22^{o}C.
- No cooling set point was used, as cooling was only explored qualitatively in this study.
- The insulation level for all cases was kept constant and is summarized in Table 3.
- An equivalent of 0.1 ach ventilation and infiltration was assumed for each zone.
- No internal gains were considered.
- The house was considered to be completely unshaded.

Light Construction (L): Standard house construction with the only insulated thermal mass being the concrete basement floor and 12.7 mm gypsum on all walls.
Medium Construction (M): Same as light construction but with the addition of a 5.1 cm concrete on the south zone floor.
Heavy Construction (H): Same as medium construction, but south floor concrete slab was 20.3 cm and the interior partition wall between the south and north zones was replaced by a 20.3 cm concrete wall.

Table 1: Window types investigated

Type	Glass U-value (W/m^2K)	Total U-value (W/m^2K)	SHGC
Double-glazed, Argon, hard coat low-e (D)	1.610	1.774	0.603
Triple-glazed, Argon, hard coat low-e (T)	1.143	1.431	0.537

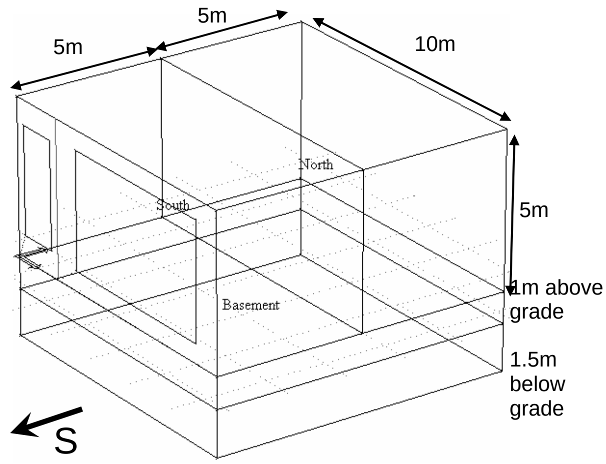


Figure 2: The house model used to test proof of concept.

Table 2: Solar apertures investigated.

Glazing % of S. Façade	Solar Aperture	Number of 2 m^2 windows	Glazed Area
15 %	2.5 %	3.75	7.5 m^2
30 %	5 %	7.5	15 m^2
45 %	7.5 %	11.25	22.5 m^2
60 %	10 %	15	30 m^2
75 %	12.5 %	18.75	37.5 m^2

Table 3: Model house envelope insulation levels.

Wall type	RSI-Value (R-Value)
Exterior walls	5.4 (30.7)
Roof	11.9 (67.6)
Basement walls	5.2 (29.3)
Basement floor	1.4 (8)
Note: Envelope insulation levels represent near optimal values for passive solar houses located in cold climates, hence these were not varied.	

SIMULATION

Performance on SDDs was isolated by examining a how a particular house behaves when it is exposed to quasi-steady state weather conditions. Thus, the standard weather file (for Toronto) was modified by repeating the weather data on the SDD on the four days leading up to the SDD. This is important because nature of passive solar heating it that it is not only felt on that day but also part of the next day (depending on the house's thermal capacity). While the weather file used was 365 days long, processing time was saved by only running the 15 days of interest (five consecutive days for each SDD). The SDDs could not simply be run consecutively for the first 15 days of the weather file because each SDD had to occur at the proper time of year so that ESP-r would apply the appropriate solar angles.

Simulation Results

The correlation between the CS day purchased heating and whole-year purchased heating is shown in Figure 3. There is a clear correlation between CS day and annual heating loads. Rather than to predict annual performance, the intention of the SDDs is to demonstrate the trends to the designer. It is evident that the SDD concept accomplishes this quite well. Some general conclusions can also be made from this data: Passive solar design alone can reduce annual purchased heating by about 30% for the cases considered.

- Larger south-facing glazing areas greatly reduce annual heating loads.
- The double glazed windows perform slightly better than the triple glazed windows, indicating that the higher transmittance outweighs the poorer U-value for Toronto. However, this optimum may change as different properties of the fenestration are modified.
- Heavier constructions nearly always outperformed lighter constructions. The benefit is much more pronounced for larger glazing areas where much of the solar gains contribute to future heating rather than merely increasing the air temperature.
- The CS day accurately represents the annual performance for heat loss when solar gains are not experienced. Thus, this confirms that the CC and WS days are only needed to perform checks, as described in the next section.

The use of cold cloudy & warm sunny design days

Figure 3 clearly shows a positive trend between larger south-facing glazing areas and a reduction in purchased heat. However this ignores the two possible downsides of large glazing areas. The first is a greater chance of overheating and thus increased cooling loads, if thermal comfort is to be maintained. The second is greater heating loads on cold cloudy days when conduction heat loss through the window is substantially greater than solar gains. The designer can use the WS day to explore the affects of different overheating prevention strategies and the CC day to weigh the benefits of larger glazing areas with the consequential heat loss. The CC day may also be used to decrease the heating equipment capacity.

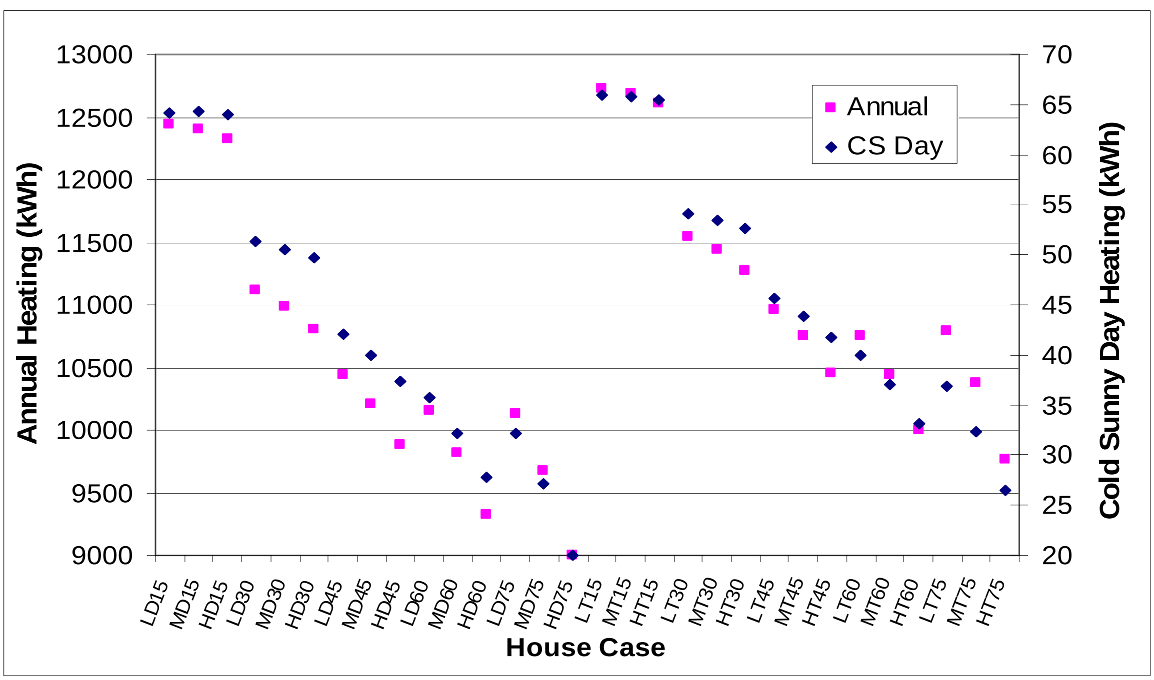


Figure 3: Comparison between CS day and annual heating loads. The first letter of the house case refers to construction type; the second letter refers to glazing type; and the number refers to glazing area as a percentage of the south façade. For example, LD15 is light, double-glazed, and its south façade is 15 glazing.

Cooling Methods
While it is recognized that certain designs may incur overheating, this paper only examines measures to prevent overheating qualitatively, with the exception of the use of thermal mass. There are a number of methods to prevent overheating, including the use of controlled motorized blinds, external shading devices (e.g. overhangs), nighttime cooling, and natural ventilation. Of the shading (or solar gain rejection) methods, controlled motorized blinds are expected to be among the more effective means because overheating actually tends to be worst in the shoulder seasons – particularly the fall. That is, for passive solar houses that have large glazed areas, overheating is more severe where there are mild ambient temperatures and high solar gains than where there are hot temperatures and lower solar gains. In contrast to fixed shading devices, motorized blinds can be actively controlled and used regardless of solar altitude. Mechanical cooling is the least desirable and most energy intensive means to prevent overheating.

METHODOLOGY
The suggested methodology for approaching the design is outlined in Figure 4. In general, the performance on the CS day should be optimized while the CC and WS days are used to check the downsides of large glazing areas.

This section shows how the SDDs are to be used in practice through an example. A typical house was modeled first and the performance is displayed by means of a graph of the key performance metrics during the CS day. Based on these initial results, the designer can adjust the key design parameters: glazed area, glazing type, and thermal mass accordingly. All model details are the same as the previously defined three-zone model unless otherwise noted. Operational modes are also examined. Five iterations are shown and analyzed. Only one modification is made in each step, although the advanced designer could make multiple modifications. The descriptions and corresponding performance graphs are shown below in Figure 5. The temperature is shown for the south zone only, as this is the zone that experiences the greatest temperature range. Once the design achieves reasonably good performance, the CC and WS days are examined.

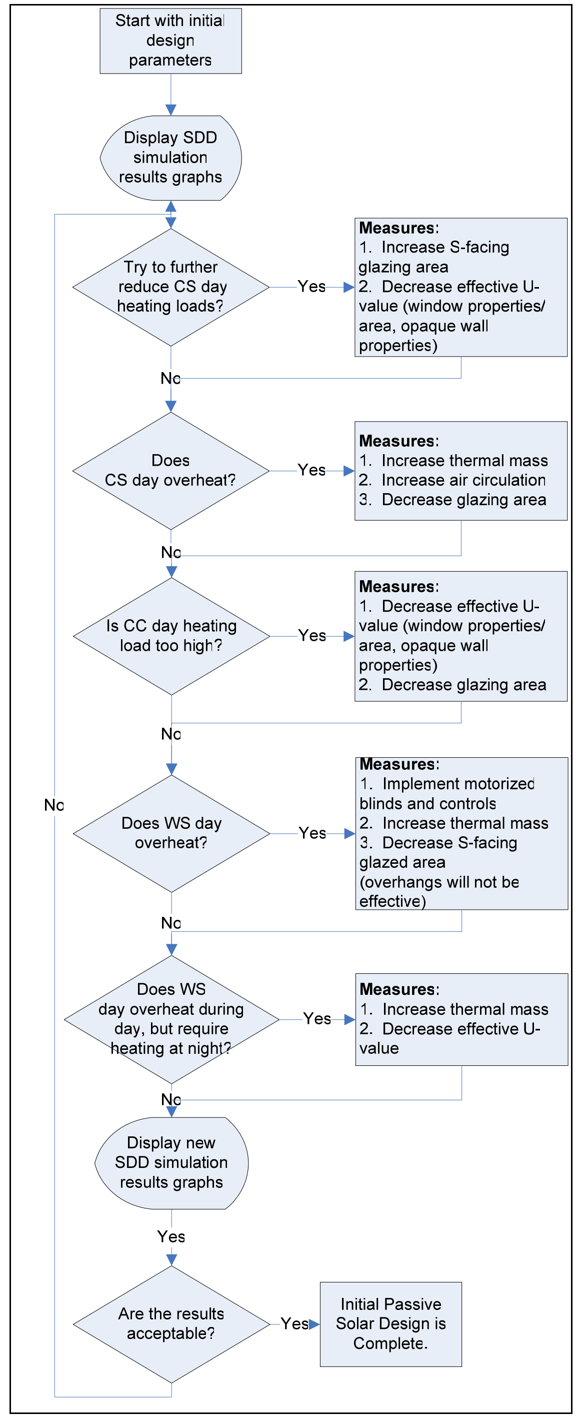
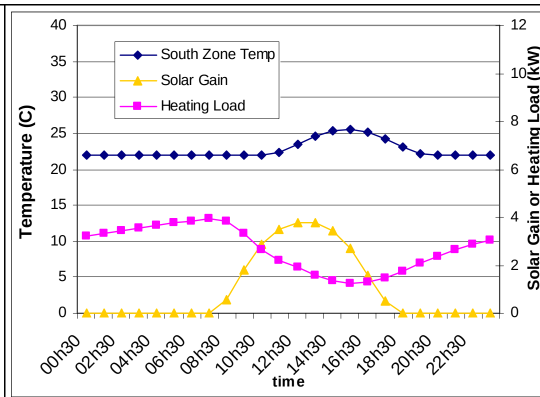


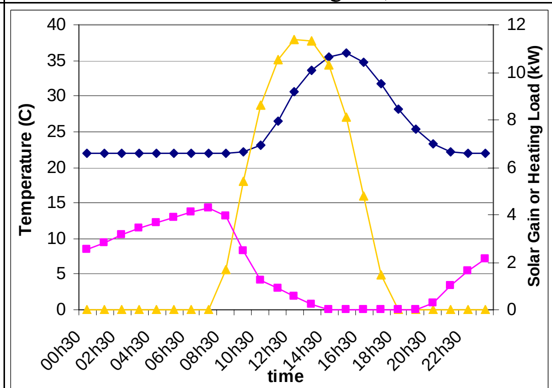
Figure 4: Methodology for incorporation of SDDs in passive solar design

Design 1:
Construction: Light (as previously defined)
Windows: 15% of S. façade, double-glazed
Interpretation: The purchased heating savings from solar gains are modest. A tolerable temperature rise occurs on cold sunny days.
Next Step: Increase glazing area to 45% and leave everything else intact to attempt to decrease purchased energy.



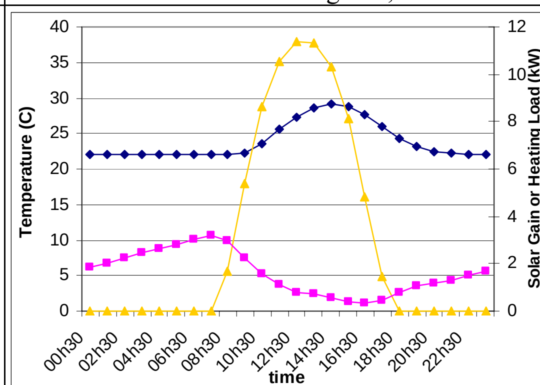
Peak Indoor Temperature: 25.6°C
Purchased Heating: 64.24 kWh
Annual Purchased Heating: 12,441 kWh

Design 2:
Construction: Light (as in Design #1)
Windows: 45% of S. façade, double-glazed
Interpretation: The heating load is completely covered by solar gains during about 5 hours of the late afternoon. However, the savings are at the cost of thermal comfort, as south zone temperature reaches 35ºC. Also, heating is required only an hour after sunset, indicating that little of the capture heat is stored. Furthermore, the peak heating load (which occurs at night) is actually higher than Design 1, resulting from the larger window area.
Next Step: Leave glazing area at 45% but increase thermal mass to reduce peak temperatures and store some heat for post sunset hours.



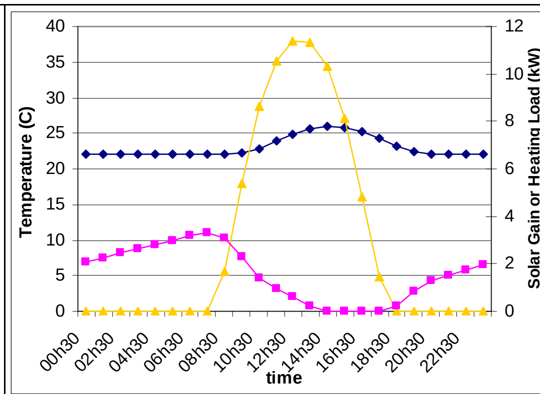
Peak Indoor Temperature: 36.0°C
Purchased Heating: 42.3 kWh
Annual Purchased Heating: 10,437 kWh

Design 3:
Construction: Heavy (as previously defined)
Windows: 45% of S. façade, double-glazed
Interpretation: The heating load is mostly covered by solar gains while the sun is up and is vastly reduced for many hours following. Also, the peak temperature may be slightly uncomfortable at 29ºC, but only lasts at this level for a few hours in the mid-afternoon. The troubling part is that is that the additional thermal mass hampered heat transfer from the south zone to the other zones. Thus, while the south zone is overheating, the north zone is still being heated through purchased energy (not shown on graph).
Next Step: Leave unchanged, but increase airflow to distribute solar heat better.



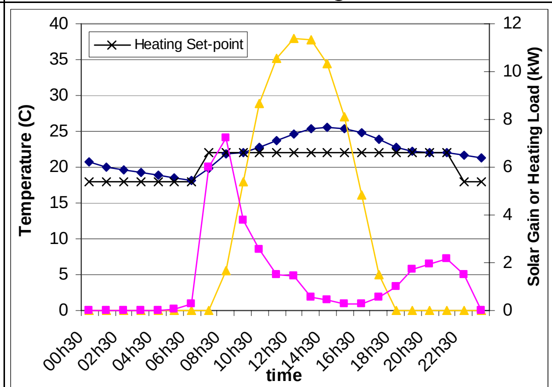
Peak Indoor Temperature: 29.4°C
Purchased Heating: 38.8 kWh
Annual Purchased Heating: 9,882 kWh

Design 4:
Construction: Heavy (as previously defined)
Windows: 45% of S. façade, double-glazed
Airflow: Tripled from 200 L/s to 600 L/s (note: this could be achieved through open-concept design, but is assumed to be mechanical here, for modeling simplicity)
Interpretation: The increased airflow shows considerable improvement over the previous design. Purchased heating is reduced, such that there are four hours where no purchased heating is required throughout the house. Furthermore, the peak temperature is a comfortable 26ºC.
Next Step: Now that overheating is under control, it may be possible to reduce heating loads and improve thermal comfort by modifying the heating set-points.



Peak Indoor Temperature: 25.6°C
Purchased Heating: 38.0 kWh
Annual Purchased Heating: 9,804 kWh

Design 5:
Construction: Heavy (as previously defined)
Windows: 45% of S. façade, double-glazed
Airflow: 600 L/s
Operations: Nighttime (10pm to 7am) heating set point is lowered to 18°C.
Interpretation: The lower nighttime set point means that heating is not needed until about 7am. However, because the set-point after 7am, before solar gains are experienced, is 22ºC, substantial purchased heating is required in the morning.
Next Step: There may be an opportunity to decrease heating loads further by increasing the glazing area. Another option would be to experiment with changing the glazing type. If we suppose that we are satisfied with the design at this point, then it would be worthwhile exploring performance on the CC and WS days.



Peak Indoor Temperature: 25.5°C
Purchased Heating: 33.38 kWh
Annual Purchased Heating: 8,975 kWh

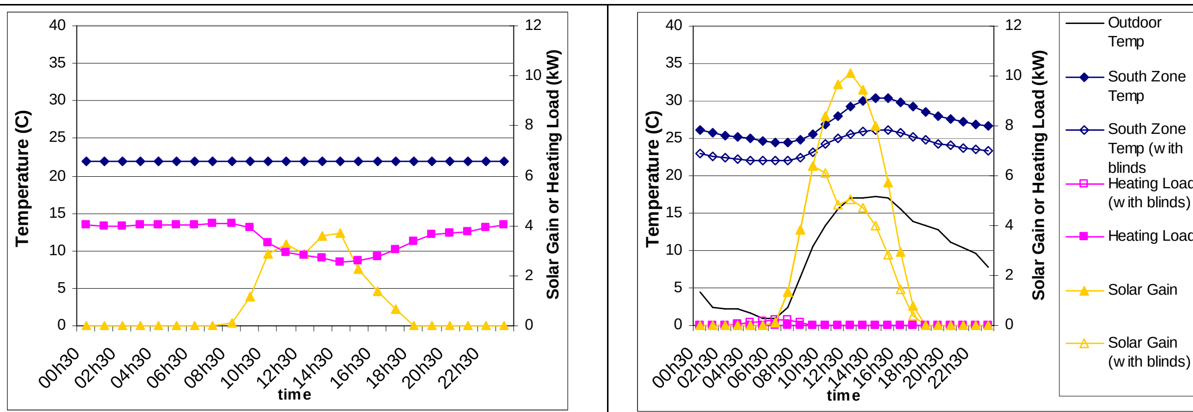
Figure 5: CS day performance corresponding to the five analyzed designs

The CC and WS day performance for Design 5 is shown in Figure 6. Based on a peak heating load of about 4 kW on the CC day, the designer may choose to take actions to reduce equipment sizes or improve the building envelope. Having seen that the house experiences a peak temperature of 30°C on the WS day, the designer may want to implement a shading device. Suppose a controlled Venetian blind is used, such that solar gain is reduced by 50% when the south zone air temperature exceeds 23°C. The performance graph corresponding to the impact of this addition is superimposed on the graph with no blinds. The result is that the peak temperature is reduced by 3°C. With blinds, a small amount of purchased heating is required before sunrise, but this could likely be eliminated by tweaking the blind control algorithm.

DISCUSSION

It was shown that a house's performance on the CS day is an excellent predictor of annual purchased heating. This assumes that heat can be properly rejected to prevent thermal discomfort during warm sunny weather. Future work will be needed to model different heat rejection strategies so that their use can be explored on the WS day. A more in-depth look into thermal mass and effective thermal mass must be explored. This paper simplified the situation by merely considering three different construction types without quantifying the effectiveness of the thermal mass. Also, while air temperature was used as the comfort metric, it would be worthwhile to examine operative temperature – particularly for houses with large windows where significant radiant exchange can occur with cold windows (Athienitis and Santamouris, 2002).

The design process shown is iterative in nature. The eventual implementation of the SDD concept for the design of passive solar houses will be more fluid and efficient. In context of the graphical user interface, it is hoped that the designer would be able to adjust various parameters using sliders and watch the graph of zone temperatures and other performance metrics change in real-time. The effects of various control strategies and heat rejection strategies will also be explored.



Design 5 CC
Purchased Heating: 85.4 kWh
Peak Indoor Temperature: 22.0°C

Design 5 WS: With and (without blind control)
Purchased Heating: 0 kWh (1.85 kWh)
Peak Indoor Temperature: 30.3°C (26.3°C)

Figure 6: CC and WS day performance for Design 4

CONCLUSIONS

This paper has explored the concept of solar design days and how they can be used to help design a house for optimal performance. By examining energy simulations for a variety of houses, it was shown that there is a good correlation between cold sunny design day performance and annual performance. Thus, it is worthwhile to continue pursuing this concept for other climates, envelope designs, and external factors such as shading. Based on these promising results, a method for using solar design days to design a passive solar house was proposed. This method was demonstrated using a simple house to show how a designer would advance a house design through five design iterations. The general conclusions about passive solar houses that can be made are that large south-facing glazing areas are beneficial, but must be accompanied by substantial thermal mass to prevent overheating and to store thermal energy. The ability to reject solar gains for large south-facing glazing areas is important. It was found that automatically controlled blinds were able to maintain comfort on the warm sunny design day.

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