

## IMPLEMENTATION OF A MANAGEMENT SYSTEM FOR MULTIPLE DESIGN CONCEPTS AND THEIR PERFORMANCE IN A SOLAR HOUSE DESIGN TOOL

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### ABSTRACT

Building performance simulation provides a platform with which building designers can inexpensively explore many design options. The use of parametric studies is commonplace in practice for understanding the design space and how performance can be improved. Despite this, most existing design tools do not offer any functions to support this activity, and force users to manually manage the vast amounts of data. This paper starts with a review of existing tools and concepts that provide some form of data management and performance visualization. It then proposes a solution that provides a platform for both storing multiple designs and visualizing their relative performance. Both the data structure and graphical user interface are described for the implementation into a solar house design tool. Finally, the methodology is demonstrated through a simple design exercise for a solar house, in which its predicted energy use is reduced by 56%.

### INTRODUCTION

Building performance simulation allows designers to answer a lot of “what if” questions at a relatively low cost compared to the cost of discovering poor design choices only after a building is built. In the early stage design, building energy simulation is best used to determine relative performance of different design options (Hayter et al., 2001). At this stage, there are often many unknowns, such as the envelope’s thermophysical properties, thermal storage, geometry, and air tightness; all of which should be explored for their affect on energy performance and thermal comfort. However, it becomes immediately apparent that the design space is exceedingly large as the designer increases the thoroughness of the exploratory design process. Many documented building design case studies manually perform at least several parametric analyses (see e.g., Chen et al, 2007; Pollock et al., 2009; Struck et al., 2007; Tavares and Martins,

2007). Typically, one parameter is explored at a time and the optimal value of each parameter is selected, if economics permit. This provides information about the sensitivity of each individual parameter as well as the relative sensitivity of the parameters with respect to each other (for example, see Figure 1). This process has been shown to be quite effective at understanding the design space and improving performance, despite the fact that it cannot be considered formal mathematical optimization, since interactions between parameters are neglected. For instance, the benefit of thermal mass is not fully appreciated unless there are substantial solar gains (O'Brien et al., 2009).

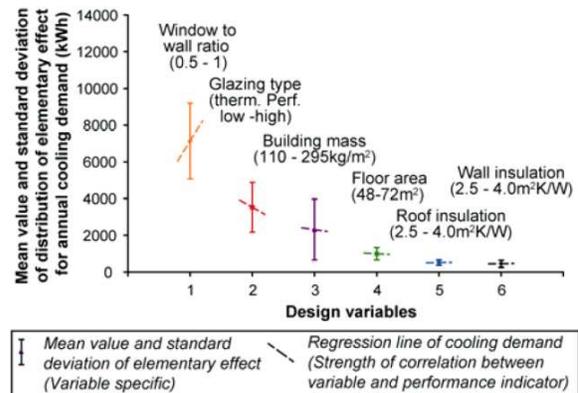


Figure 1: Example results from sensitivity analysis to support design (taken from Struck et al., 2007)

A solar house design tool (“the design tool”) is being developed to facilitate the early stage design of solar houses (houses that offset much of their energy use with on-site solar energy collection) as described by Athienitis et al. (2006) and O'Brien et al. (2009). The tool is aimed at architects, designers, and researchers, with moderate knowledge of passive solar design, who want to perform high-level exploratory design before using detailed simulation tools. The two main features that have been implemented are: lines of influence (LoI) and solar design days (SDDs). The former is

used to illustrate the sensitivity of all design parameters. The latter is used to display performance of key performance metrics (energy and comfort) for the duration of several design days, in an attempt to provide understanding to the house's thermal behaviour. Yet, both of these are entirely focused on the current design and possible directions for improved performance. Thus, the major gap is a feature that allows the user consider many different designs. It is this gap that is addressed here. The synthesis of these simple feedback mechanisms, backed by a comprehensive building performance model make this work unique.

This paper begins with a review of existing tools that have elements that address the aforementioned facilities. Following that, a solar house design tool and the implementation of a design management system are described, and finally, the implementation of a fully-functional design management system is explained in detail.

## REVIEW OF EXISTING TOOLS

HEED (Home Energy Efficient Design) (Crawley et al., 2008; HEED, 2009), based on the Solar-5 simulation engine, is a design tool with a considerable number of inputs that allows up to ten different designs to be compared simultaneously. The cases can be compared to each other and several metrics can be compared in bar chart from (Figure 2). The visualization of certain climatic and performance metrics on an annual timeframe is excellent, through the use of surface plots. However, the tool does not enable renewable energy systems and is feature-heavy, making it slightly tedious for rapid exploratory design. Furthermore, it is restricted to a single zone and is therefore, not optimal for modeling passive solar houses (O'Brien et al., 2008).

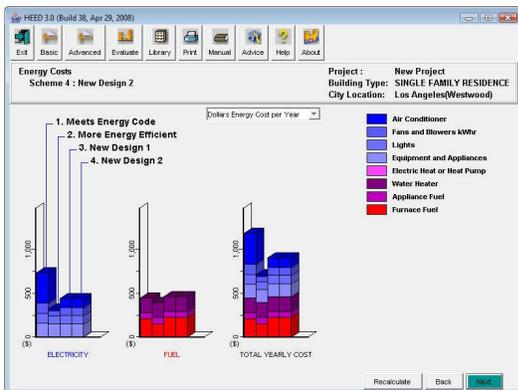


Figure 2: Screenshot of HEED

Building Design Advisor (BDA) (Papamichael, 1999) is intended for detailed design and has an AutoCAD-

like geometry input; though it has ceased to be supported. It allows multiple designs and their performance (e.g., daylighting and energy consumption) to be compared against each other using the "Decision Desktop" (Figure 3). I<sup>2</sup>PV (Interactive Integrated Performance View) (Prazeres, 2006) uses a very similar matrix-like approach, but interfaces with a single simulation engine – ESP-r – which makes the approach potentially more robust. Both BDA and I<sup>2</sup>PV require substantial building detail, and are therefore limited to detailed design.

Energy-10 is a comprehensive energy analysis tool for buildings under 10,000 square feet (930 m<sup>2</sup>), and that is certainly suitable for typical houses (Crawley et al., 2008; Sustainable Buildings Industry Council, 2008). While it only allows the management of two designs simultaneously, it has a unique feature that allows up to 14 different upgrades (e.g., better insulation, PV, etc.) to be applied to the building, one at a time. The upgrades are then individually simulated and ranked as a function of net present worth. This provides a sense of relative performance, but does not allow interactions between upgrades to be explored; nor does it allow continuous parameters.

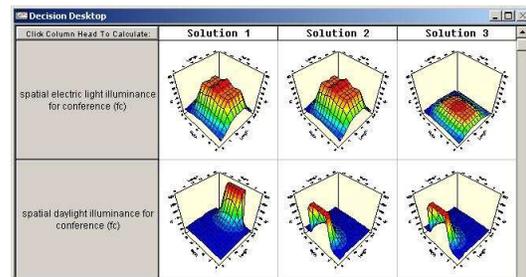


Figure 3: Screenshot of Building Design Advisor

Indeed, many innovative features in existing tools provide some means for managing multiple design concepts. However, none of those reviewed by the author were found combine ease of use with strong modeling capabilities appropriate for solar houses.

## DESIGN TOOL OVERVIEW

A solar house design tool is being developed, not as a mathematical optimization tool, but as a platform in which designers are provided with concise performance data in near real-time to allow them to make quick and informed decisions. Its motivation is to act an enabler for widespread adoption of solar houses. Each of its major components is shown in Figure 4 and described in the following subsections.

### Inputs

Simulation tools have inputs ranging in number from a handful (see e.g., RETScreen International, 2005) to an infinite number (any of the simulation engines). The design tool uses a relatively small set of “macro” inputs. That is, inputs that describe a high-level characteristic of the house. For instance, aspect ratio, orientation, footprint area, and height are used instead of all surfaces and vertices that define their limits. Clearly this has the trade-off of being limited to simple rectangular geometry. All of the house’s form and fabric inputs are listed in Table 1. Some of the inputs are catered to passive solar design, though they can be applied to lightweight, solar-neutral houses (houses that have similar glazing areas in all orientations) as well.

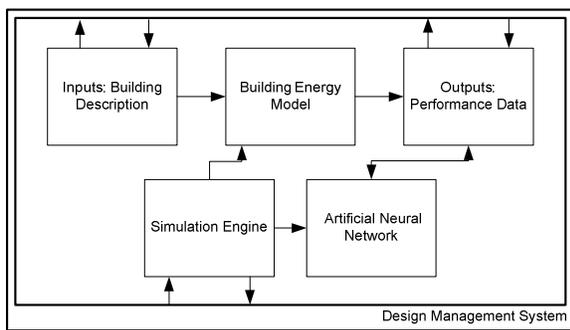


Figure 4: Overview of the Design Tool framework. The DMS encompasses the design tool by providing a facility for managing and visualizing multiple designs simultaneously.

The set of 32 parameters can be categorized as design or non-design. Non-design parameters are those that are fixed at the beginning of the design process because they are directly tied to the service that the house provides. In contrast, design parameters can be altered with the primary intention of improving energy performance and thermal comfort. While all design tools contain a selection of each of these, the design tool distinguishes them by grouping them in a different tab. Thus, the larger group can be somewhat lessened to create a more manageable design space. Unlike in most tools, the design tool uses sliders as the predominant user input for the design parameters, allowing rapid adjustment.

### Building Energy Model

The building energy model is constructed based on the values of parameters. The design tool automates the process of creating building description input files such that they can be simulated externally with a simulation engine. EnergyPlus (Crawley et al., 2008) was selected as the simulation engine because of its robustness and ease with which it can be scripted.

The model is specifically designed to characterize the performance of solar features – both passive and active. For instance, the above-grade living space is subdivided into two zones – a south and a north zone – to properly characterize the distribution of direct solar gains and potential overheating (O’Brien et al., 2008). This is in contrast to the majority of tools aimed at small buildings, such as those previously reviewed. Three active solar technologies will be included in the model, including building-integrated photovoltaics (BIPV), a solar domestic hot water system (SDHW), and a building-integrated PV/Thermal (BIPV/T) system to supplement heating energy.

### Outputs

There are two forms of graphical output provided by the design tool, including:

1. Solar design days (SDDs). Key performance metrics and weather conditions are displayed for the duration of a day for three weather types (cold sunny, cold cloudy, and warm sunny) to provide an understanding of the dynamic thermal behaviour of the house. The graphs are used to diagnose any undesirable occurrences, such as persistent overheating or high heating loads. SDDs not only minimize simulation time, but more importantly, they provide focus to the designer. A good correlation between SDD performance and whole-year performance was shown by O’Brien et al. (2008).
2. Lines of Influence (LoI). A subset of the design parameters is selected to be plotted on a graph of performance versus their value. This indicates the relative effectiveness of changing the value of one or more parameters. This automates the process that was previously cited as being a commonplace in design practice. LoI are generated from an artificial neural network (ANN) which is based on previously-run simulations (see O’Brien et al. (2009) for details).

Examples of both SDDs and LoI appear throughout the design exercise in a later section.

### DESIGN MANAGEMENT SYSTEM

The proposed design management system (DMS) is a standardized method for storing both characteristics of multiple house designs and their performance data and a method for following progress. For instance, multiple paths to net-zero energy or other goals can be followed.

This section begins with a technical description of the DMS implementation and is followed by a design exercise demonstrating its use. The DMS addresses three main needs within the design tool:

1. A visual method of comparing multiple designs for one or more performance metrics;
2. A method for monitoring progress and encouraging goal-setting; and,
3. A standardized method for storing multiple designs and allowing backtracking and retrieval of past designs.

### Data Structure

The data structure is shown in Figure 5. It is a dynamic array that stores all design parameters and performance data, depending on what has been obtained from the simulation engine. The minimum data for each new design is: the user-defined name and full set of parameter values. The rest of the data is only populated when the user requests it. Between designs, the user can make one or more parameter changes. This allows different strategies – which often involve multiple parameter changes – to be understood in a coupled fashion.

The DMS data is stored in comma separated value (CSV) format for easy porting to reports. Furthermore, the model input file is available if the user wishes to tweak the design using more advanced features that are not available from the design tool.

| Design 1                          | Design 2          | Design 3                        | Design 4          | Design 5 |                                  |
|-----------------------------------|-------------------|---------------------------------|-------------------|----------|----------------------------------|
|                                   |                   | Higher glazing and thermal mass | Controlled blinds | PV added | ← Name                           |
| Base Case                         | Better insulation |                                 |                   |          | ← User-defined name              |
| P(1)                              |                   |                                 |                   |          | ← Parameter values               |
| :                                 |                   |                                 |                   |          |                                  |
| P(n)                              |                   |                                 |                   |          |                                  |
| High-level performance metric (1) |                   |                                 |                   |          | ← High-level performance metrics |
| :                                 |                   |                                 |                   |          |                                  |
| High-level performance metric (n) |                   |                                 |                   |          |                                  |
| SDD performance(1)                |                   |                                 |                   |          | ← Solar design day performance   |
| :                                 |                   |                                 |                   |          |                                  |
| SDD performance (n)               |                   |                                 |                   |          |                                  |
| Whole year performance (1)        |                   |                                 |                   |          | ← Whole-year performance         |
| :                                 |                   |                                 |                   |          |                                  |
| Whole year performance (n)        |                   |                                 |                   |          |                                  |

Figure 5: Example of the data structure

### Graphical User Interface (GUI)

The GUI for the DMS (depicted in Figure 14) consists of a large graph with a column corresponding to each saved design. A list of user-selected metrics is plotted for straightforward comparison between designs. Once one or more entries into the DMS are saved, the user is able to step back and examine all aspects of a saved design, including performance and parameter settings, using the “back” and “forward” buttons. Designs can be overwritten, as well.

Only upon clicking on “simulate current” or “simulate all” are the simulations run and the performance

metrics plotted. The latter feature allows multiple designs to be set up and be run in batch. Upon retrieving a design, all GUI inputs (i.e. sliders and text fields) are set to the parameters corresponding with that design.

### DESIGN EXERCISE

This section contains a case study in which the design tool is used. Its purpose is to demonstrate the use of both LoI and SDDs, to draw conclusions about promising directions for advancing the design. The former are used to compare the effectiveness of multiple upgrade options or the optimal parameter setting. The latter are used for passive solar design; pushing energy use down while maintaining thermal comfort. Meanwhile the design management system is used to track the progress of the design process. The tool does not explicitly lead the user towards better designs, but rather provides the information with which they can progress. The process is iterative, though the return time of results is sufficiently short to minimize the consequence of poor initial design choices. Furthermore, the DMS ensures that backtracking to previous design concepts is straightforward.

The example house, to be located in Toronto, is rectangular, detached, and two storeys (plus basement); each floor is 80 m<sup>2</sup>. The building lot constrains the house to being aligned with the cardinal directions, and neighbouring houses constrain the aspect ratio to being 0.8 or less (with the narrow sides facing North and South). So as to maintain comfort, the non-design parameters, as previously defined, are fixed. The house starts at a level that just meets MNECB (for Southern Ontario) (NRC, 1997). We wish to reduce predicted energy consumption by at least 50% using envelope upgrades and BIPV. All starting parameter values are listed in Table 1. For simplicity, heating and cooling are assumed to be delivered with a COP of 3.0 each. Domestic hot water consumption is 200 L/day and electricity consumption for appliances and lighting averages 544 W, representing an energy-conscious family (Armstrong et al., 2009).

The design strategy applied is to first attempt to reduce energy use through a better envelope design and then resort to a BIPV array if necessary.

The following steps assume that the design tool user has moderate knowledge of passive solar design and building energy modeling. Since it would be impractical to show a screenshot of at each stage of the design, the key outputs are displayed along with an interpretation.

**A) Initialization:** The starting parameters (Table 1) are entered and the design is saved using the DMS as

“1-Base”, and simulated. The results (see Figure 14) indicate that the heating energy represents about half of the total energy use.

*Table 1: Starting parameter values for the design exercise. Grey values represent fixed (non-design parameters). The blind control thresholds are initially set to values that will trigger the blinds to close; effectively eliminating the presence of blinds. All units are in SI, where applicable (e.g., thermal resistance in  $m^2K/W$ )*

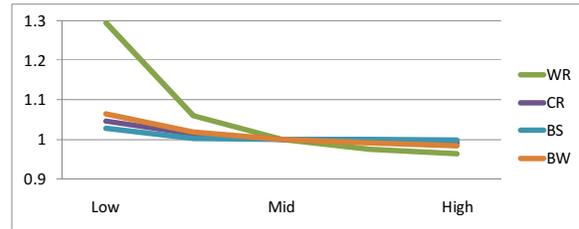
| Abr. | Name  | 1-Base                           |
|------|---|----------------------------------|
| FA   | Footprint Area                              | 80 m <sup>2</sup>                |
| HT   | Height (above grade)                        | 5m                               |
| AR   | Aspect Ratio                                | 0.8                              |
| OR   | Orientation                                 | 0                                |
| WR   | Wall Resistance                             | 4.4                              |
| CR   | Ceiling Resistance                          | 8.8                              |
| BS   | Basement Slab Resistance                    | 1.6                              |
| BW   | Basement Wall Resistance                    | 3.1                              |
| WT1  | Window Type 1                               | Double-glazed, clear, air-filled |
| WT2  | Window Type 2                               |                                  |
| WT3  | Window Type 3                               |                                  |
| WT4  | Window Type 4                               |                                  |
| WWR1 | Window-to-Wall Ratio 1                      | 0.05                             |
| WWR2 | Window-to-Wall Ratio 2                      | 0.05                             |
| WWR3 | Window-to-Wall Ratio 3                      | 0.05                             |
| WWR4 | Window-to-Wall Ratio 4                      | 0.05                             |
| IV   | Effective infiltration and ventilation rate | 0.3 ach                          |
| CI   | Air circulation rate                        | 0                                |
| OH   | Overhang Depth:Window 1 height ratio        | 0                                |
| BLS  | Blinds close solar threshold                | 2000                             |
| BLT  | Blinds close temperature threshold          | 50                               |
| BA   | Basement present                            | 1                                |
| TMS  | Thermal Mass on South zone floor            | 0                                |
| TMV  | Thermal Mass vertical wall                  | 0                                |
| IG   | Internal Gains Regime (low,med,high)        | low                              |
| HS   | Heating Setpoint                            | 20                               |
| HSN  | Nighttime Heating Setpoint                  | 18                               |
| CS   | Cooling Setpoint                            | 26                               |
| RT   | Roof Type                                   | Gable                            |
| SL   | Roof Slope                                  | 30 deg                           |
| RH2  | Attached house against Wall 2?              | No                               |
| RH4  | Attached house against Wall 4?              | No                               |

**B) 1-Base to 2-Insulation added:** The first approach is to attempt to reduce the high heating load by increasing the overall thermal resistance of the envelope. By referring to the pertinent LoI, the relative benefit of changing parameters is determined (see Figure ). They indicate that the best opportunity for improvement is to increase the insulation level in the walls, while some improvement can be yielded through increasing basement wall insulation. Wall resistance (WR) and basement wall resistance (BW) are increased to 8 and 5  $m^2K/W$ , respectively.

There is little sense in analyzing the SDDs because the windows are so small at this point, that little dynamic behaviour is present. For the same reason, there is little point in changing the window types.

At this point, the design is saved as “2-Insulation added” and a whole year simulation in performed

because we want to determine the predicted energy savings from adding the insulation.



*Figure 6: LoI for envelope insulation. The vertical axis indicates the normalized combined heating and cooling energy. For instance, having WR at the lowest value is associated with 30% more energy use than the mid-range value. The horizontal scale is based on the minima and maxima of the parameter ranges.*

**C) 2-Insulation-added to 3-Passive solar:** For the second set of design changes, we want to improve passive solar performance. First, the south-facing glazing area is increased to a window to wall ratio (WWR1) of 0.5, as an aggressive measure to maximize useful solar gains. The best tool to determine the impact of this is the cold sunny SDD, because it allows the behaviour of the house with the large window area to be understood and any overheating to be rectified.

Figure 7 indicates that daytime purchased heating is nearly zero but that the South zone reaches a temperature of 40°C, which is clearly unacceptable. However, the other zones remain at comfortable temperatures, suggesting that mixing the air would be beneficial. Furthermore, the indoor temperature curves indicate that minimal thermal storage occurs, since they quickly descend.

To address the issues of passive solar gains distribution and storage, the air circulation rate (CI) and thermal mass (TMS and TMV) (on both the South zone floor and the partition wall) are simultaneously increased to 400 L/s and 10 cm of concrete and, respectively. These moderate values were selected based on the fact that the LoI indicate diminishing returns for all three parameters (Figure 8).

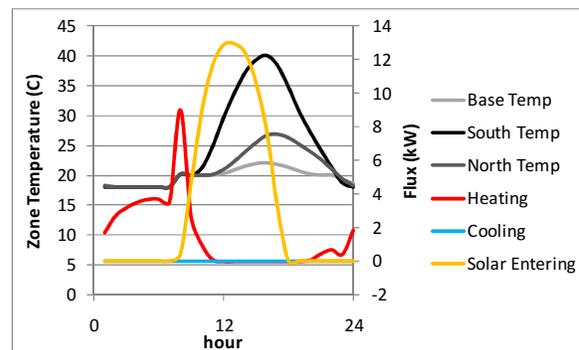


Figure 7: Cold Sunny Day for case with large south-facing window

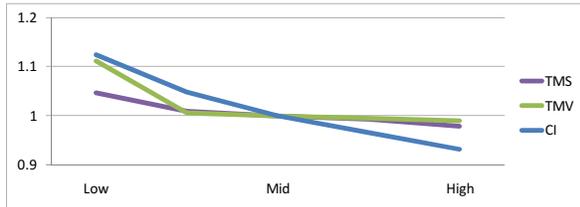


Figure 8: LoI for thermal mass and air circulation

Again, the cold sunny day is simulated and plotted (Figure 9). It indicates that the parameter changes now provide a comfortable indoor temperature (peak of 27°C). The change also reduces the heating load.

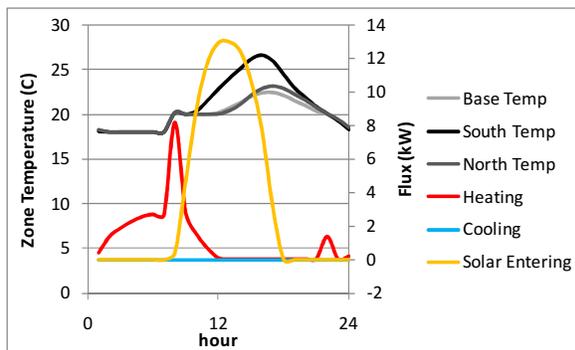


Figure 9: Cold sunny day after thermal mass and air circulation were increased.

A LoI for the window type was created to determine if energy savings can be achieved, now that the glazing area is significant and is likely responsible for a large portion of heat loss. The LoI (Figure 10) indicates that switching to triple-glazed, low-e, argon-filled glazing is beneficial, and thus, the upgrade is made.



Figure 10: LoI for south-facing window type

The last thing to ensure for this stage is that overheating on the warm sunny solar design day is not severe (passive solar houses are most susceptible overheating in spring and autumn because of low solar angles and mild temperatures). The warm sunny SDD is used for this purpose, as shown in Figure 11. It clearly indicates overheating, with a peak temperature of nearly 30°C. However, the mean outdoor temperature for the warm sunny day is 12°C and the

solar gains are comparable to those on the cold sunny day.

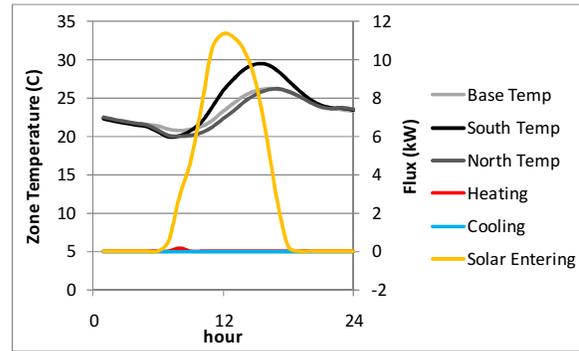


Figure 11: Warm sunny day performance indicating overheating.

When blind control is implemented such that the blinds close when both the outdoor temperature is above 10°C and the solar radiation on the exterior of the south-facing window exceeds 300 W/m<sup>2</sup>. These values were selected using the corresponding LoI (not shown). This reduced the average peak temperature on the warm sunny day to 28°C (not shown), but is arguably too high. Thus, the air circulation rate was set to be doubled during times of discomfort. The result is that the peak zone temperature only briefly exceeds 27°C in the late afternoon and that purchased heating is only needed very briefly when the heating setpoint increases at 7AM (the default time to switch from nighttime to daytime heating setpoint). This clearly shows that SDDs can be used to fine-tune performance and to help make a compromise between energy performance and thermal comfort.

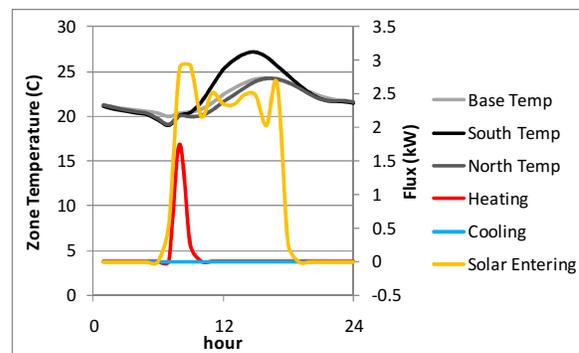


Figure 12: Warm sunny day with the addition of blind control and increased air circulation. The jagged “solar entering” curve indicates active blind control

This design is saved in the DMS as “3-Passive solar”. Upon whole-year simulation, it is evident that savings in heating and cooling energy are about 26%. The thermal comfort, if measured by the number of zone-

hours above 27°C is relatively constant for all of the considered designs.

**D) 3-Passive solar to 4-PV added:** Given that the passive solar potential has been pushed to a practical limit, the use of BIPV will be used to reduce net energy use. While one of the roof surfaces is currently south-facing, the slope has not been optimized for BIPV orientation. To determine the optimal slope, a LoI was created (Figure 13). The mid-value is clearly near optimal, which is equal to about 35°, so a 7/12 pitch was selected. PV modules of 10% nominal efficiency are added.

If a more complex solar collector system were implemented, such as BIPV/T (BIPV with heat recovery from the PV), temporal consideration generation would also be of concern. But for a grid-tied system, the goal is merely maximizing generation.

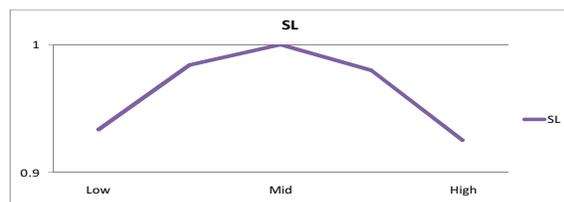


Figure 13: LoI for annual incident solar radiation on south-facing roof as a function of roof slope.

The result is saved as “4-PV added“, which is predicted to consume 56% less net electricity than the first design, thus exceeding the goal (see Figure 14). While the frequency of overheating is increased in the later designs, the overheating is not severe, as indicated by the top graph in Figure 14. The annual number of zone-hours that exceeds 27°C for the last two designs is only 77. The number of hours in which the zone temperatures exceed 25, 27, 29°C is shown to provide information about the frequency distribution.

If, upon realizing the potential PV generation is inadequate or too expensive, the user would be able to backtrack to the third design option, for instance, and attempt to decrease heating and cooling loads through more aggressive passive solar design or higher insulation levels. Decreasing the electrical loads from appliances, lighting, and DHW was beyond the scope of this example, but clearly becomes increasingly important and envelope loads are minimized.

## CONCLUSIONS

Despite the fact that parametric analyses involving one or more simultaneous parameter changes are commonplace in design, few tools have attempted to implement a feature to facilitate them. While the proposed tool already had several useful graphical

feedback mechanisms to guide the user towards better designs, a major weakness was found: there was no method for indicating whether the designer was making progress. To solve this, a design management system was implemented into the tool and discussed. The DMS has the purposes of comparing multiple designs, tracking design process progress, and backtracking. Furthermore, it facilitates the subjective weighting of multiple objectives, such as energy use and thermal comfort. The features are currently being developed in a design tool to enable widespread adoption of solar homes.

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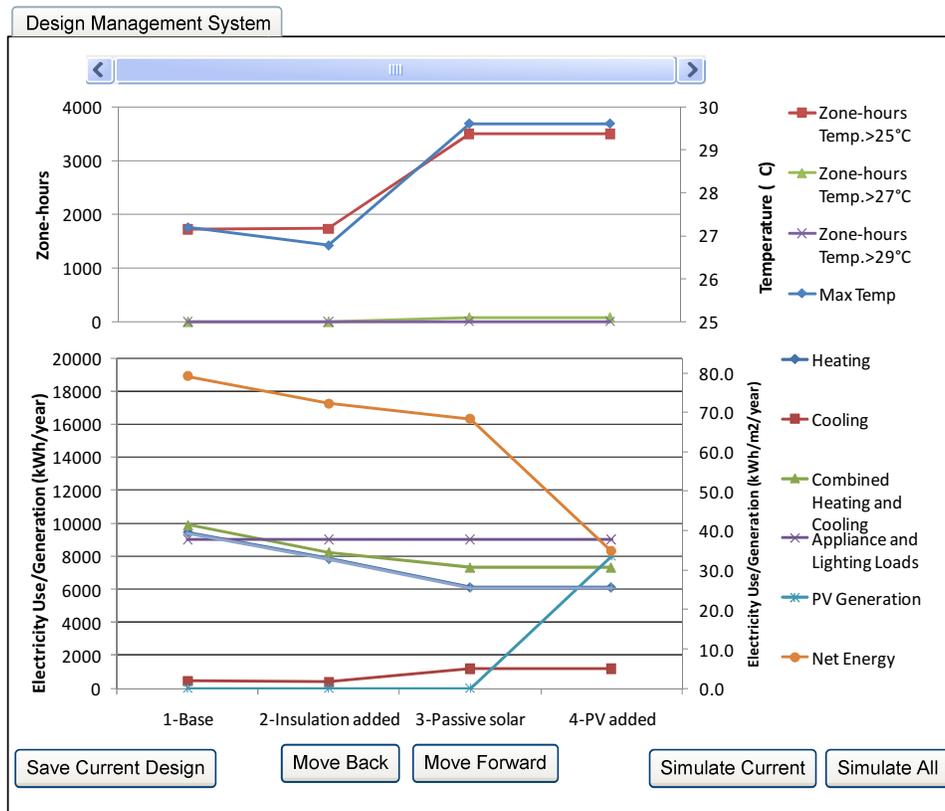


Figure 14: Screenshot of DMS as it appears after the design exercise is complete. The shaded region of the graph indicates the current design, the buttons at the bottom are used to save a design, navigate through the designs, to perform whole-year simulations for the current design, and for all designs (from left to right).