THE DEVELOPMENT OF A SOLAR HOUSE DESIGN TOOL

William O'Brien[1], Andreas Athienitis[1], Ted Kesik[2]
[1]Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada
[2]Faculty of Architecture, Landscape, and Design, University of Toronto, Toronto, Canada

ABSTRACT

Building designers need design tools that enable them to rapidly explore the energy performance implication of early design decisions. The tools should enable them to use their experience, along with performance feedback, to find near-optimal solutions, according to their criteria. This paper presents a methodology for a solar house design, followed by a description of how it will be implemented in a design tool. The design tool will use three methods to aid the designer, including: a reduction of the number of parameters, decomposition of certain subsystems, and instantaneous performance feedback. The focus of the paper is on some of the fundamental design issues. Two innovative means for feedback are presented. The final part of the paper explains the computational feasibility of providing the feedback in real-time.

INTRODUCTION

There is a trend towards low-energy or net-zero energy homes using a combination of efficiency measures and on-site solar energy collection. Currently, common design practice of such homes involves the expertise of multiple practitioners and at least as many building energy simulation programs – some of which may be custom-built or modified. However, the savings potential (energy and cost) for small residential buildings on an individual basis does not justify this type of investment for mainstream deployment. Thus, there is a niche for a streamlined procedure that reduces the level of expertise, design time, and number of distinct information sources (CAD programs, textbooks, design guides, etc.). The absence of such a tool has hindered the widespread adoption of systematic passive solar design in residential buildings. This gap was identified by Athienitis et al (2006) and in the design of several of Canada Mortgage and Housing Corporation's EQuilibrium demonstration homes. In order to widely deploy the proposed design methodology being proposed, a conceptual solar house design tool is being developed.

The objective of the conceptual solar house design tool (the "design tool") is to allow the user to discover the path of least resistance (e.g., cost, complexity) to their performance goals within their particular set of constraints or preferences. It should take the user through a systematic approach, while maximizing design flexibility and creativity. The tool should manage issues such as appropriate parameter interactions, design resolution, and modeling assumptions to ensure good results from inexperienced energy modelers.

The tool will focus on the house's envelope and form (including passive solar heating features), solar thermal, PV, and photovoltaic/thermal (PV/T) collectors, as discussed by Kesik and Stern (2008). Once the user establishes a good solution with the design tool, the selected parameters will be mapped to HOT3000, a detailed household energy modeling program, which uses ESP-r as a simulation engine.

As an introduction to the methodology, it is worthwhile to compare and contrast design and optimization. Put simply, optimization tools output the optimal design based on an objective function and a set of constraints, offering little insight to what makes a good design. Design tools provide the facilities to a designer to explore different concepts and reach the near-optimal design space using their experience and preferences. Unlike optimization, design permits valuation of unquantifiable design traits such as aesthetics and views to the outside. The solar house design tool will replicate what only the most patient of designers would do naturally: support concept generation with a series of proper calculations or simulations through many different design options.

For low-energy homes, most design upgrades provide diminishing returns, meaning that some quantification of performance – even if it is relative – is very valuable to the designer. This is particularly important at the beginning of the design process when design elements are being synthesized. If design is approached as a linear path in which upgrades are applied one at a time, then little thought is given to the interactions between elements. The product of such a design process tends to be expensive. In reality, "green buildings" do not have to be significantly more expensive than conventional buildings, because as the building envelope is improved, the equipment capacity can be reduced (Reed and Gordon, 2000).

This paper focuses on issues related to the form and fabric of a house, but the methodology is intended to be applied to active solar systems as well. The paper is divided into three parts. The first is an overview to the underlying methodology of the design tool. The second provides the proposed implementation of the design tool features through a user interface. The last part explains how these features will be achieved, computationally.

METHODOLOGY

The biggest challenge in designing a low-energy house, as with any engineering system, is that multiple design decisions must be made simultaneously with the goal of achieving a high level of performance, overall. The process is not as simple as merely selecting the best choice for multiple subsystems and assuming that this will yield the best integrated system. In reality, each subsystem interacts with the others, to some degree. For example, the optimal south-facing glazing area on a passive solar house depends on many other design decisions, including the level of thermal mass and insulation, as well as control of solar gains and space heating strategy. Thus, the design of a low-energy house can be equated to exploring a multi-dimensional design space, where the number of dimensions is equal to the number of independent design parameters. A table of 26 independent parameters intended to be implemented as inputs in the design tool is shown below (Table 1). While these parameters are not all design parameters, per se, it is beneficial to consider them to maintain model flexibility.

The underlying model that the parameters correspond to is a rectangular, three-zone house (Figure 1). Though, the methodology could be applied to simpler or more complex buildings. The purpose of having two above-grade zones it to characterize the possibility of overheating in the direct gain (south) zone. The model was selected to maximize design flexibility, even if some of the parameters and their ranges differ from traditional rules of thumb for passive solar heating (though not building code). It is the intention of the tool to demonstrate the performance of good designs, as well as bad ones, for contrast.

Table 1: List of parameters, their significance, and the mapping of input parameters to statistical model and display parameters. Gray parameters are discrete; shaded cells are non-design parameters.

No.	Abr.	Name	Significance ranking
1	FA	Footprint Area	2
2	HT	Height	1
3	AR	Aspect Ratio	24
4	WR	Wall Resistance	11
5	CR	Ceiling Resistance	12
6	GT	Glazing Type 1	14
7	GT	Glazing Type 2	19
8	GT	Glazing Type 3	17
9	GT	Glazing Type 4	18
10	GR	Glazing Ratio 1	10
11	GR	Glazing Ratio 2	3
12	GR	Glazing Ratio 3	5
13	GR	Glazing Ratio 4	4
14	BS	Basement Slab	23
15	BW	Basement Wall	20
16	VI	Ventilation and	6
17	OH	Overhang 1	16
18	OH	Overhang 2	26
19	OH	Overhang 4	25
20	OR	Orientation	15
21	BA	Basement present	9
22	TM	Thermal Mass	13
23	IG	Internal Gains	22
24	HS	Heating Setpoint	7
25	CS	Cooling Setpoint	8
26	CI	Air circulation rate	21

Each parameter can be classified as design or non-design and continuous or discrete. Here, non-design parameters are defined as those that affect the service that the building provides, namely, shelter, space, and protection from the elements. Put differently, they are likely to be fixed at the beginning of the design process. Design parameters are defined as those that affect energy performance, but not the service to the occupants.

Continuous parameters can be set to any value within the permissible range (though they may not all be convenient with regards to available building materials). Moreover, they can be modeled in ESP-r with a single value. Discrete parameters can take on one of several values. For instance the simplest way to deal with different glazing types is to explicitly model them, rather than having variable optical and thermal properties; some combinations of which would not be possible (e.g., high transmissivity and low U-value). The parameters are categorized in Table 1.

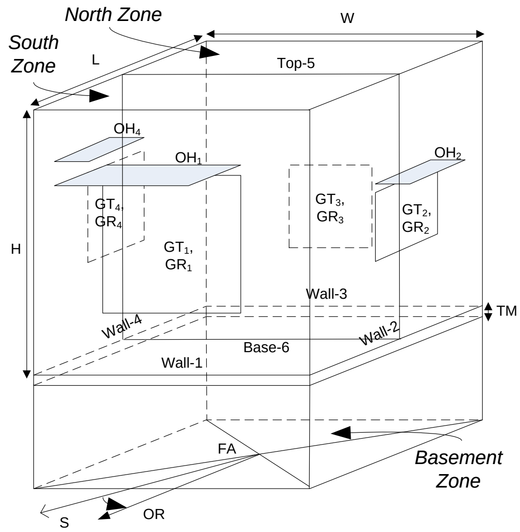


Figure 1: Major geometrical features of the house energy model

The parameters were selected to be designer-friendly. For example, instead of defining the major dimensions as length and width, floor space and aspect ratio are used. The reason for this is that the floor space is likely to be fixed (to suit the needs of the occupants). There are three parameters that are not particularly designer-friendly, including internal gains, ventilation and infiltration, air circulation rate. These parameters have been shown to be significant and will require the assistance of a brief wizard that allows the user to apply practical values.

Several parameters deserve an extended explanation. Glazing ratio is essentially the window to wall ratio. The orientation of the house is restricted from southwest to southeast. This ensures that the "south zone" is more southward than eastward or westward. For the time being ventilation and infiltration and internal gains are assumed to be constant for modeling simplicity; though more complex regimes, such as those used in HOT3000, could be used in the future (Purdy and Beausoleil-Morrison, 2001). Air circulation is defined as the constant rate that air is exchanged between the three zones. Unlike typical homes, this parameter has a great effect on performance of passive solar homes because it assists in the distribution of heat from the direct gain zone, thus minimizing diurnal temperature swings. More complex temperature and mass flow controls may be added in the future.

The 26 parameters can, in fact, be mapped to fewer mathematically significant parameters. This serves three important purposes. First, it reduces the number of parameters, allowing for a significant reduction in effort required to predict performance using statistical means. Second, it nearly eliminates the discrete variables. Discrete variables are a nuisance for statistical methods and also introduce complexity to decision-making. Third, relationships between design parameters and performance can be more easily displayed, since the number of design decisions can be reduced.

The greatest opportunity for reduction of parameters was to combine all above-grade thermal conductances to a single value. Since the basement model to be used (BASESIMP) has two different boundary conditions for the below-grade portion of the basement, the conductance of the basement slab and basement walls must be distinguished (Beausoleil-Morrison and Mitalas, 1997). Glazing area and type are combined to yield a single numerical value equal to the area times the solar heat gain coefficient (SHGC), with units of m2, for each wall orientation. The meaning of this value is the equivalent area of a fictional window that transmits all solar energy to the indoors but that has some thermal resistance.

Significance of parameters

To quantify the relative significance of the parameters, a main effects plot was created. This has the purpose of identifying the effect of each parameter on energy consumption. Essentially, all parameters were kept at their mean value except for the parameter of interest, which was simulated in ESP-r for both extremes in the range. The resulting slopes were ranked in descending order for all of the parameters in the last column of Table 1.

The most significant parameters are those that define the surface area and volume of the house, followed by those that define the glazing area of non-south facing windows. Interestingly, the next three most significant parameters define operational details. The two least signficant paramters were found to be the overhangs on the non-south facing windows. This results from the fact that the, usually, detrimental summertime solar gains are difficult to control with overhangs alone. This suggests that these two parameters could be eliminated and replaced with sidefins or an accurate controlled blinds model – though, this is currently being developed for ESP-r. However, it should be noted that the range in orientations would allow the two overhangs to have a greater influence. The third last ranked parameter, in terms of significance, is the aspect ratio of the house. This fact is partly symptomatic of current model being used, which only uses thermal mass on the floor. A model with a thermally massive partition wall would benefit from a higher aspect ratio, since that geometry would lead to greater incident solar radiation on the mass wall.

Parameter Interactions

As mentioned, it would be unwise to merely optimize each parameter independently, since they all interact to some level. For instance, O'Brien et al (2008a) showed that the optimal south-facing glazing area for house with high internal gains was a third of the size of the optimal size with minimal internal gains. Therefore, it is concluded that parameters should be manipulated in subsets of the entire population of parameters. Obviously, manipulating more than several parameters simultaneously is tedious and yields an exponentially expanding design space. The proposed method to solve this problem is to identify the most significant interactions between parameters.

For a population of 26 parameters, there are 325 two-way interactions (26 choose 2). The focus is on two-way interactions since, as high-order interactions are unusual (Shah et al., 2000). One commonly used method to understand interactions, in the field of design of experiments, is to create interactions plots. In all, 325 plots were created by using MATLAB to drive ESP-r simulations. To create the plots, all parameter settings were set to the mean value of the range, except for the pair of parameters being examined. For those two parameters, the extreme values were combined, to yield four (2^2) different parameter combinations and corresponding performance values. The strength of interaction was quantified as the angle between two lines in each interactions plot. To display the results, an "interactions wheel" was created to demonstrate the type and strength of the interactions between all parameters, as shown in Figure 2. The lines in the graph are colour-coded to indicate whether the interaction is between two design parameters, one design parameter and one non-design parameter, or two non-design parameters. Arguably the most important category, is the first, as these parameters are flexible, and do not affect the service provided by the house. The second and third categories, while perhaps not being of immediate interest to designers, underpin the importance of properly defining non-design parameter values before proceeding with design.

Not surprisingly, the strongest interactions are between each corresponding pair of glazing types and glazing ratios. Other strong interactions occur between both of those glazing properties and the house geometry. Two other notable interactions between design parameters are between glazing ratio 1 (south-facing) and each of: thermal mass and overhang size.

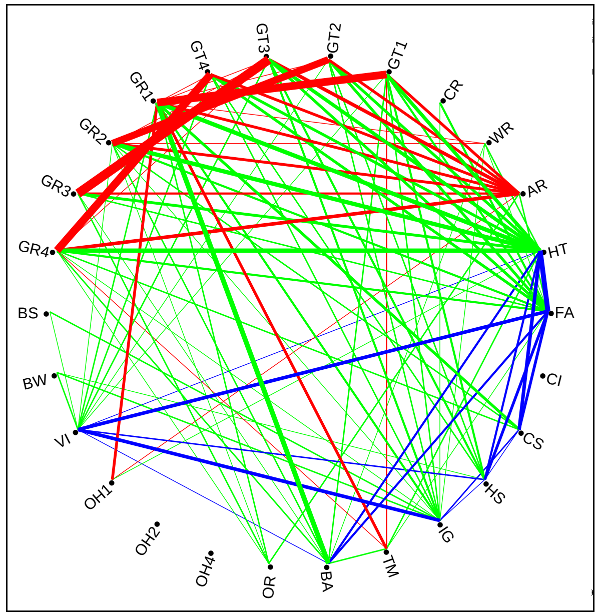


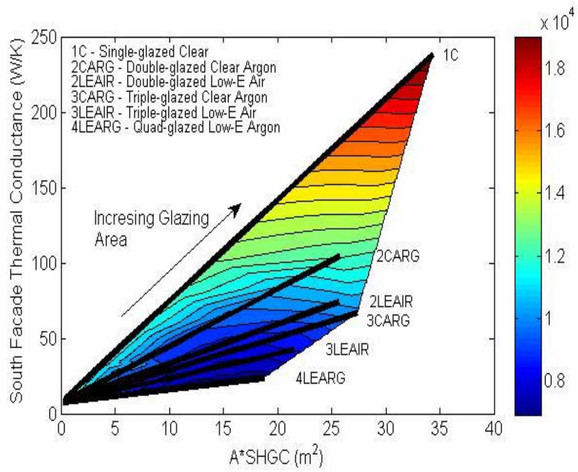
Figure 2: Interactions wheel for 26 parameters for the top 100 (of 325 possible) interaction. Line weight corresponds to interaction strength. Red lines are between design parameters; blue between non-design parameters; and green between design and non-design parameters.

With these relationships established, the most valuable subsets of the 26 parameter design space have been identified. These subsets can be visualized as a slice of the multidimensional design space, much like a two-dimensional image of a brain scan. The corresponding performance charts are being termed "multi-parameter design support charts" (MPDSC). To illustrate their value, two significant MPDSCs are shown in Figure 3.

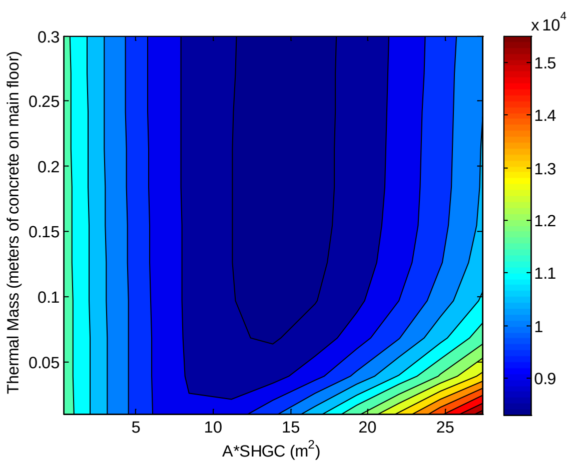
Figure 3a explores the trade-off between solar gains and envelope conductance. This MPDSC should be considered the most important of all, as it allows the implication of all glazing choices, including type and size. These are fundamental aspects of passive solar heating. Without such a graph, the designer must juggle with selecting appropriate glazing type and size, simultaneously. One of the key trade-offs is between high SHGC and low thermal conductance. Six different glazing types are plotted for glazing ratios of 0 to 80%, represented by the black lines.

Given that two extreme glazing types are explored, the filled-in area can be considered to cover the entire design space. The gradient indicates energy performance in the form of combined annual heating and cooling loads.

It should be noted that this MPDSC, like the others, cannot be considered static, but rather, dependent on all other parameters to varying extents, as identified by the interactions wheel. Otherwise, these results could be merely published in a book and there would be no need for a design tool. In Figure 3b, which compares solar heat gain and thermal mass, an increase in envelope thermal resistance would push the optimal range of thermal mass higher. This is because higher envelope thermal resistance would cause a higher fraction of the solar gains to be trapped in the house and translate to a higher temperature swing unless additional thermal mass were added. In the current graph, little improvement is seen beyond 15 cm of concrete, as found by (Athienitis and Santamouris, 2002). This is an important observation for the cost-conscious designer.



(a) A•SHGC vs. South facade thermal conductance



(b) A•SHGC vs. thermal mass

*Figure 3: Two significant MPDSCs the contour lines correspond to combined annual heating and cooling loads in kWh. The data for each graph are nominally based on 121 ESP-r simulations of a square, 300 m^2, three storey, well-insulated, south-facing house, unless otherwise specified. All A*SHGC values refer to the south-facing façade.*

While the MPDSCs shown focus on energy performance, the methodology could be applied to thermal comfort, costs, peak loads, or a weighted average of multiple performance metrics.

To expand the interactions concept to the entire house (including active solar collectors), consider Figure 4. It demonstrates the degree of interaction between major subsystems in a solar house. Subsystems that do not interact at all can be designed independently. Subsystems with moderate interactions can be developed somewhat independently. Subsystems with substantial interactions must be designed in an integrated manner because the change of a design parameter for one subsystem is likely to have a significant effect on the other subsystem.

The best prospects for decoupling from the envelope and base loads are PV and solar DHW systems. PV's performance is not dependent on energy demands of the house (for grid-tied systems). Solar DHW systems' performance is dependent on demand. But, demand is not tied to the design of the house, per se, but rather the DHW demand, which is only a function of occupant behaviour. Both systems do share a geometric relationship with the house, but these relationships can be managed externally to the thermal models. While PV performance is a function of its operating temperature, this is unlikely to vary significantly between different house designs.

Solar thermal systems for space heating have some traits in common with the other types of solar collector. However, their performance is tied to demand from the house. If no heat is demanded because of passive solar gains, the system contributes nothing at that time. Similarly collector performance may depend on the temperature of the storage medium. Thus, while hourly simulations are ideal, comparing the predicted monthly heating demand with production can provide a sense of performance for preliminary sizing.

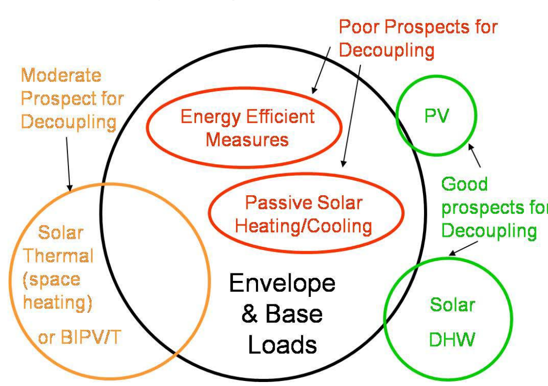


Figure 4: Venn diagram of the potential for decoupling the subsystems

At the other end of the spectrum, energy efficiency measures or passive solar features are intimately linked to the house envelope. For instance, the benefit of added insulation or windows cannot be accurately predicted without considering the existing envelope through simulation.

Decoupling models not only offers computational advantages, but more importantly, it helps the designer, by breaking the problem into more manageably-sized pieces. To ensure, an integrated, holistic design process, the user will be informed of geometrical compatibility and system-level performance during the design of each subsystem. That is to say, the user can focus on the task at hand, while keeping an eye on the big picture. The advantage of the design tool's immediate feedback approach, described in the next section, is that no matter what order the user chooses to design subsystems, the penalty for pursuing the wrong route is inconsequential.

The usefulness of MPDSCs is evident; they provide a visualization of high performing combinations of design parameters based on the values of non-design parameters. This allows designers to be sure they are within the optimal region. However, MPDSCs provide little information about why the trends are they way they are.

The designer should be provided with a means to gain an intimate understanding of the thermal behaviour of the house, as well as, diagnose problems. It is useful to provide answers to questions like:

- What is the indoor temperature swing on a typical cold sunny day and how does adding thermal mass or increasing the air circulation rate affect it?
- How effective is an overhang on reducing peak cooling loads?
- How much glazing is required to eliminate daytime heating loads on a cold sunny day?
- If the glazing area is optimized for a cold sunny day, how is heat loss affected on a cold cloudy day?

The proposed solution is to display key metrics, including zone air temperatures, heating and cooling loads, and solar gains, for solar design days (SDD) in the form of a line graph, as explained by O'Brien el al (2008b). Three days are selected as providing good indication of passive solar performance, including a cold sunny, cold cloudy, and warm sunny day. The cold sunny day is considered an ideal day for exemplifying passive solar heating. The cold cloudy day is assessed for heat loss and the downside of having a large solar aperture. The warm sunny day, which is selected as a shoulder day, when the solar altitude is low at solar noon, is used to assess the risk of overheating caused by high levels of solar gains. As expected, it was found that the overheating of passive solar houses is actually more problematic in the shoulder seasons – particularly autumn - than mid-summer because the sun penetrates much deeper at low solar altitudes (Athienitis and Santamouris, 2002). Conventional passive shading measures, such as overhangs, are not effective in the shoulder seasons. O'Brien el al (2008b) provide a design methodology using solar design days to design a high-performance passive solar house.

IMPLEMENTATION & FEASIBILITY

With the underlying principles established, we now progress to how the design tool will work. It will use three main principles to enable the designer to efficiently navigate the design space, including:

1. Reduction to the key independent design parameters. The thousands of parameters that could be used to define the house's fabric and form has been reduced to 26. An flow chart of the flow of parameter data and parameter mapping is explained below.

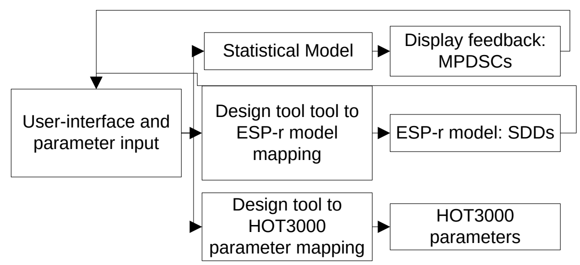


Figure 5: Data flow diagram

2. Decomposition of the system into subsystems or parameter subsets, as previously explained.
3. Real-time feedback to guide user towards a better design region. Both a "glass box" and "black box" model will be used, as explained in the next section. Glass box models are typically transparent to the user, allowing them to understand the inner workings of the system. Black box models, in contrast, do not reveal the underlying model. They merely take in inputs and provide corresponding outputs. Each type of model has an important role in the design tool. In the following section, they are discussed in the context of design of the house form and envelope, but will be applied to the design of each subsystem in the design tool, including PV, solar thermal, and PV/thermal systems. A block diagram of how the design tool will be integrated with HOT3000 and the interactions with feedback or simulation engines is shown in Figure 6. The trend to note is that as the design progresses in detail, both the accuracy of the feedback and the associated processing time increase.

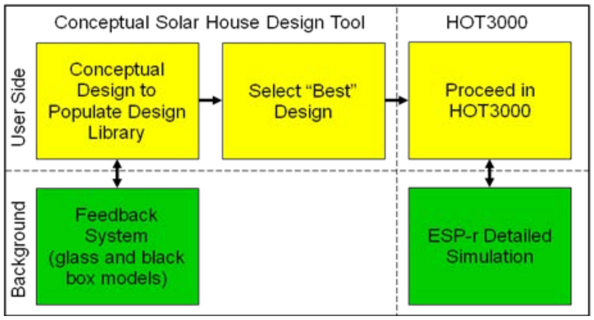


Figure 6: Block diagram of the design tool

Implementation of the glass box model

The glass box model that will be used will provide designers with an understanding of the behaviour of the system. The implementation that will be used is to display key solar design day performance metrics on a line graph, as previously explained. See Figure 7 for the implementation.

A simple prototype showed that ESP-r can be called at run-time and return a day's simulation data with an acceptably small lag of about half a second, on a typical desktop computer. Naturally, this lag will decrease with the advance of computers. Each time the user adjusts a parameter, the following occurs: (1) the appropriate ESP-r input files are modified, (2) an ESP-r building simulation is run for the appropriate day(s), (3) the output file is scanned for the information of interest and (4) that information is then displayed on the graph. While simplified models or pre-run simulations could be used to display SDD performance, the use of run-time simulations provides flexibility and accuracy. Overall, the approach is relatively easy to implement, but presents some lag at run-time. The option to not update the display at every design change will be provided for users who find this lag too long.

Implementation of black box model

The black box model to be used will guide the designer to the optimal range. The proposed method is to show display the most relevant MPDSC(s) when a given parameter is being adjusted. MPDSCs provide two main forms of feedback. First, they offer a sensitivity analysis. If the gradient for particular parameter is steep, this indicates that there is a significant opportunity. Second, they provide information about the interactions between parameters. Thus the user is informed of what sets of parameters should be designed together. As mentioned, MPDSCs can be adapted to other objectives such as thermal comfort and economics, as the tool advanced in development.

Since the results of multiple whole-year simulations are required to display trends, performing simulations at run-time has been deemed to be ineffective. Two main options to achieve this remain: a database of pre-run simulations or a simplified (computationally fast) model. Given the power and validation of existing simulation engines, such as ESP-r, in conjunction with the desire for software responsiveness, the first option was selected as the most appropriate. The proposed solution is an artificial neural network (ANN) that is trained using ESP-r simulation data. Preliminary results, using the 11 most significant parameters, suggest that the house's performance can be predicted very accurately by an ANN. 1000 training samples were able to predict 1000 validation samples with a mean error of 2.4%. 1000 whole year, hourly ESP-r simulations represents a day's worth of processing time. This is a small fraction of the time that would be required to conduct full factorial design. The use of these predictions will allow the display of any MPDSC. The tool will allow whole-year simulations, once the user arrived at their desired design.

The two types of feedback models should be used in conjunction to approach the optimal design range. MPDSC allow the user to quickly enter the optimal range of parameters while SDDs allow fine tuning of parameters to maximize useful solar gains, prevent discomfort, and visualize the effect of thermal mass, overhangs, and insulation.

User Interface

A mock-up graphical user interface (GUI) is shown in Figure 7. The intention is to minimize complexity and the number of screens. Input controls were selected to be mouse-operated such that the user can keep their eyes on the screen and watch the performance indicators morph in real-time.

CONCLUSIONS

This paper presented the methodology and implementation of conceptual solar house design tool. The design tool will enable the efficient conceptual design of a low-energy house and guide the designer towards the optimal design space. This paper makes the case that while holistic design is of the utmost importance, there are opportunities for decoupling the energy models of certain subsystems and parameter subsets.

It was shown how two methods of feedback can be used together to guide the designer towards the optimal range. Furthermore, it was shown how accurate real-time performance feedback is realistic. The design tool will enable designers to use their common sense and observations to design cost-effective, low-energy houses.

ACKNOWLEDGEMENTS

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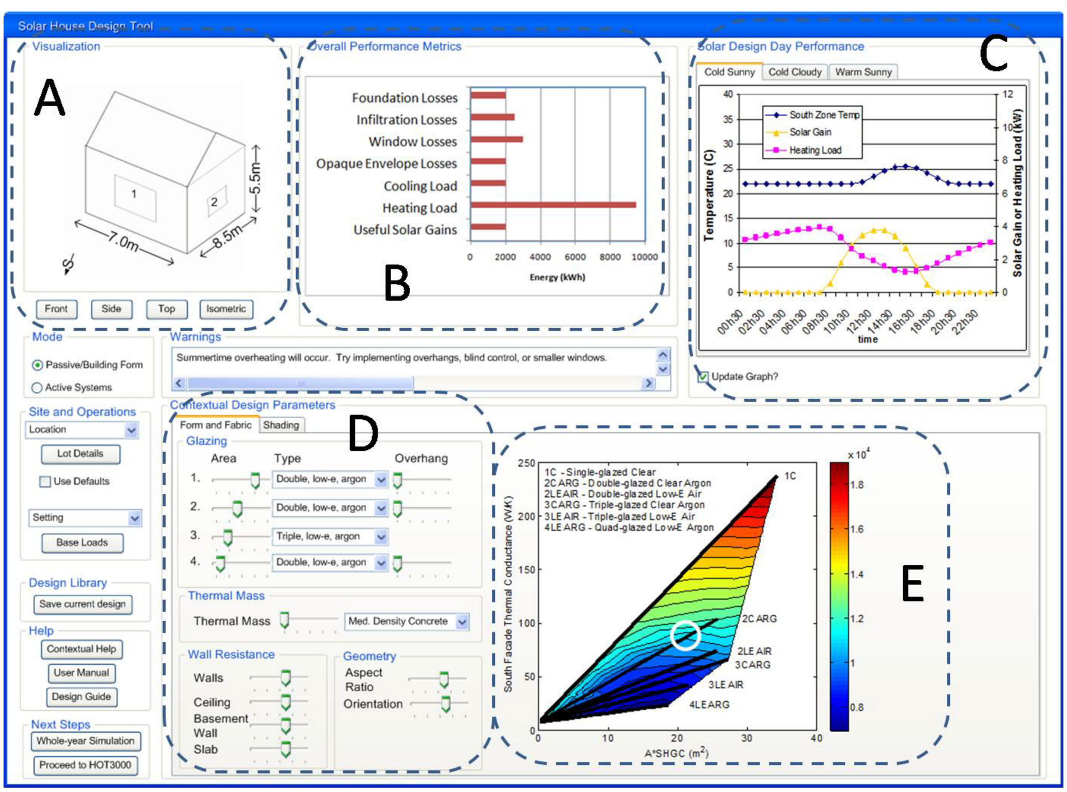

Figure 7: Mock-up GUI for the design tool. Labels are referred to by the text. (A) house geometry representation, (B) performance metrics, (C) solar design day performance, (D slider inputs, and (E) MPDSC. The circle on the MPDSC indicates the current design parameter settings