

METHODOLOGY AND DEVELOPMENT OF A SOLAR HOUSE DESIGN TOOL

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ABSTRACT

Building designers need design tools that enable them to rapidly explore the energy performance implications of early design decisions, when such decisions can be implemented inexpensively. 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 and implementation issues.

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. The tool should take the user through a systematic approach, while maximizing design flexibility and creativity. It 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 form and fabric (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 that uses ESP-r as a simulation engine, as shown in Figure 1.

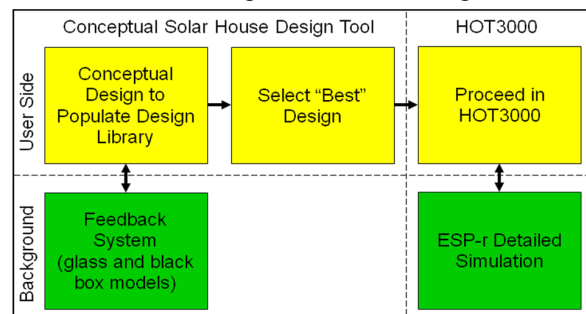


Figure 1: Block diagram of the design tool

In contrast to optimization, the tool will allow unquantifiable objectives to be considered, such as aesthetics and views to the outside. It is believed that designer input will actually be more efficient than formal optimization, at first, because much of the poor design space can be immediately eliminated using common sense.

One of the key practices to be promoted by the design tool is integrated design. That is, the act of considering the house as a complete system rather than several independent subsystems. “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 the fundamentals of designing a complex integrated system, with the application of a solar house. The paper is divided into two main parts. The first is an overview to the underlying methodology of the design tool, with emphasis on the interactions between parameters and subsystems. The second part explains how the methodology will be implemented, including the computational feasibility of real-time design feedback.

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 an overall high level of performance. 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 varying degrees.

Consider Figure 2, which shows all major subsystems intended for the design tool. 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.

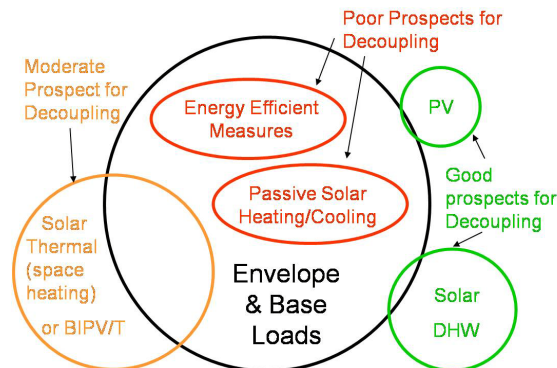


Figure 2: Venn diagram of the potential for decoupling the subsystems

Decoupling models not only offers computational advantages, but more importantly, it helps the designer, by breaking the problem into more manageable-sized pieces. To ensure, an integrated, holistic design process, the user should be informed of geometrical and practical 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. For instance, during the design of the house’s form, a high-level metric, such as annual incident solar energy on the roof, can be easily calculated and displayed. 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 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, at some point, no auxiliary heat is needed as a

result of passive solar gains, the system contributes nothing. Similarly collector performance may depend on the temperature of the storage medium, which is partly a function of the state of the house. While hourly simulations are ideal, comparing the predicted monthly heating demand with production can provide a sense of performance for preliminary sizing.

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 dynamic simulation.

Economic Considerations

While there are opportunities for decoupling the thermal model, it is important to manage the economic ramifications of all design decisions. Except for off-grid PV systems, most energy-conserving or energy-collecting upgrades to a house providing diminishing returns. That is to say that each additional RSI of insulation or m^2 of solar collector area reduces purchased energy by less than the previous increment. Thus, the design of low-energy solar houses typically involves a cost-effective combination of energy efficiency and energy collection.

To visualize this concept, consider Figure 3. The graph shows the annual cost (or energy) savings versus the present value of the capital and maintenance costs of building upgrades. The horizontal axis represents the path from a standard house to a net-zero energy house. Curves for the possible energy efficiency upgrades, solar thermal systems, and PV systems are superimposed on the graph (shown as dotted lines). The curves for energy efficiency measures and solar thermal systems are asymptotic, indicating their contributions have limitations. For instance, solar thermal collectors cannot displace more purchased energy than the heat required by the house on an annual basis. Grid-tied PV systems do not exhibit this characteristic because they are not demand-dependent, since excess electricity can be sold. However, geometry is a limitation. As each surface becomes covered in PV modules, a surface with an inferior orientation must be used. The actual upgrades in the graph are labeled and shown as vectors. The slope of each vector indicates the payback period (i.e. economic efficiency). A flat slope corresponds to instantaneous payback; a vertical vector indicates an infinite payback period. Therefore, it is desirable to achieve the goal level of net-energy by following a path with the minimum slope.

Starting at a standard house (the origin), the path of least cost should be selected. The shallowest slope of the energy efficiency upgrades indicates that it should be the first category of improvements. However, as we follow the dotted line from the origin, it eventually becomes steeper, indicating that each upgrade becomes marginally less lucrative. At some point, adding an energy efficiency upgrade, say an additional inch of insulation, becomes less economically efficient than a solar thermal system. Similarly, there is a cross-over point between solar thermal and PV systems.

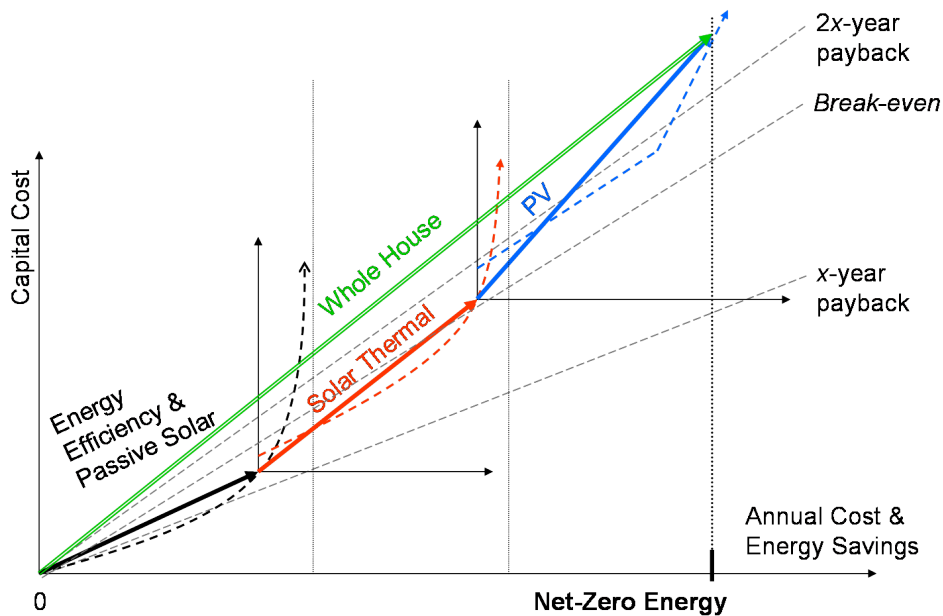


Figure 3: Visualization of the path of least resistance to low-energy homes

The performance of the whole house is indicated as the sum of the subsystem vectors. This graph proves that integrated design is required to yield the optimal solution and that a less integrated approach would yield an inferior design. The optimal level of upgrade of each subsystem depends on that of the other subsystems.

Parameter Interactions

A table of 26 independent parameters to describe the house's form and fabric that are intended to be implemented as inputs in the design tool is shown below (Figure 4). 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 4). Though, the methodology could be applied to simpler or more complex buildings. The purpose of having two above-grade zones is 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.

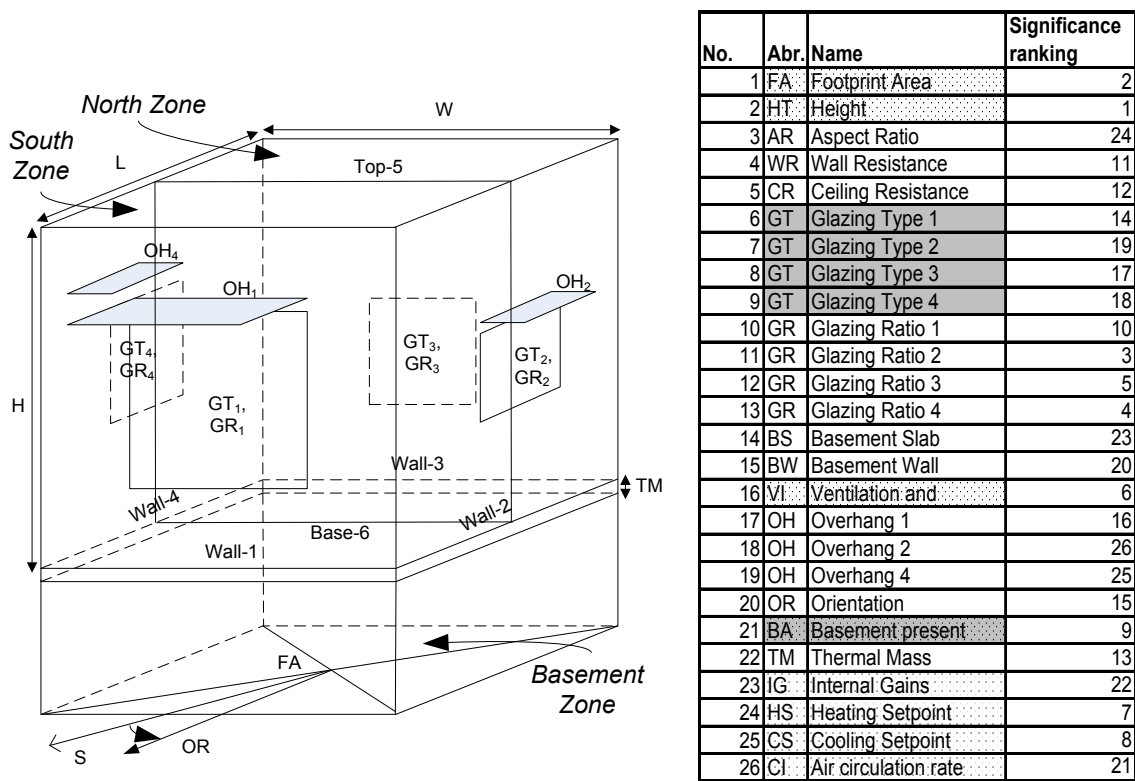


Figure 4: Major geometrical features of the house energy model; 26 key form and fabric parameter. Discrete parameters are gray; non-design parameters are shaded.

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 Figure 1.

The parameters were selected to be designer-friendly. For example, instead of defining the major dimensions as length and width, floorspace and aspect ratio are used. The reason for this is that the floorspace 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 southeast to southwest. This ensures that the “south zone” is more southward than eastward or westward. Since windows are allowed on all walls, this range of orientations is effectively the same as allowing any orientation. 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 input parameters can, in fact, be mapped to fewer mathematically significant parameters. The greatest opportunity for reduction of parameters was to combine all above-grade thermal conductances to a single value. Ventilation and infiltration, assuming a constant value for simplification, can be added to this, as it has the same boundary conditions as the above grade envelope components: outdoor air and indoor air temperatures. 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 m^2 , 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.

The mapping of parameters 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 (except for “BA”). 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 independent design decisions can be reduced.

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. All parameters were kept at their mean value except for the parameter of interest, which was simulated for both extremes in the range. The resulting slopes were ranked in descending order for all of the parameters in the last column of Figure 4. To some extent, the ranking depends on the range of each parameter; however, an attempt was made to make the ranges practical.

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. It would be possible to remove the least significant parameters without adverse effects.

To assess the significance of parameter interactions, all two-way interactions were studied using MATLAB to drive ESP-r simulations. For a population of 26 parameters, there are 325 two-way interactions ($26 \text{ choose } 2$). High-order interactions (three-way and above) are unusual (Shah et al., 2000). To determine strength of interaction, the four combinations of the extremes of each pair of parameters was simulated, while the remaining parameters were kept at their mean values. 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 5. 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.

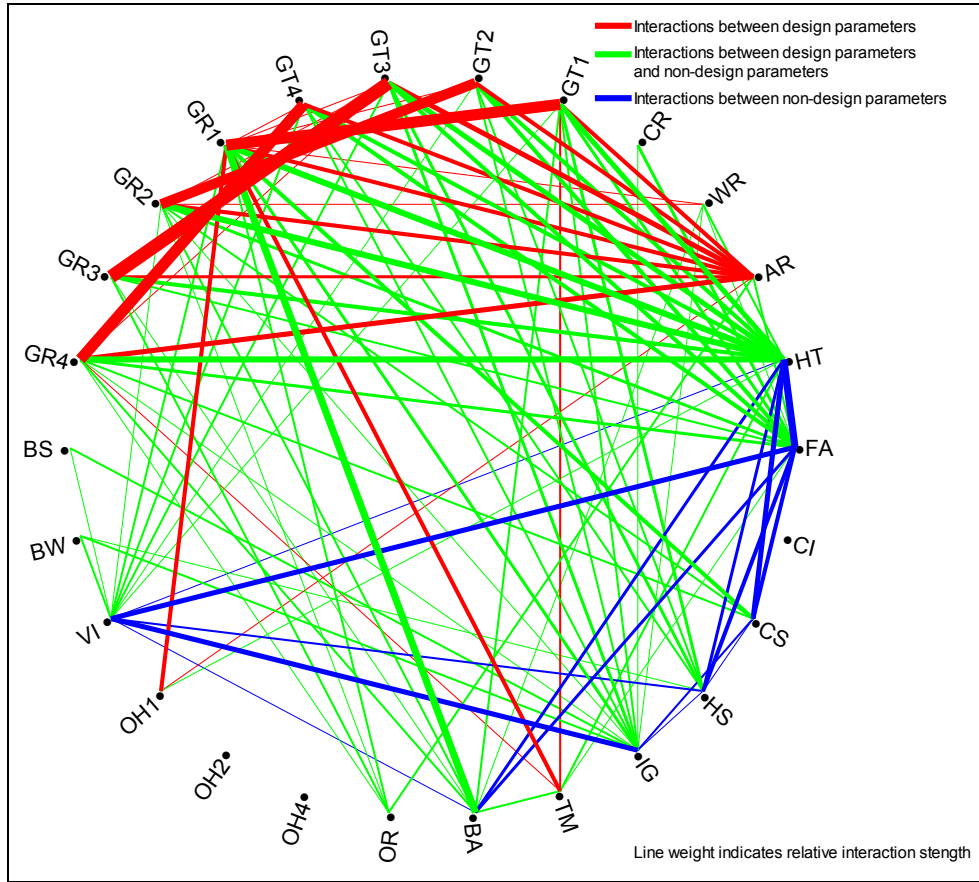
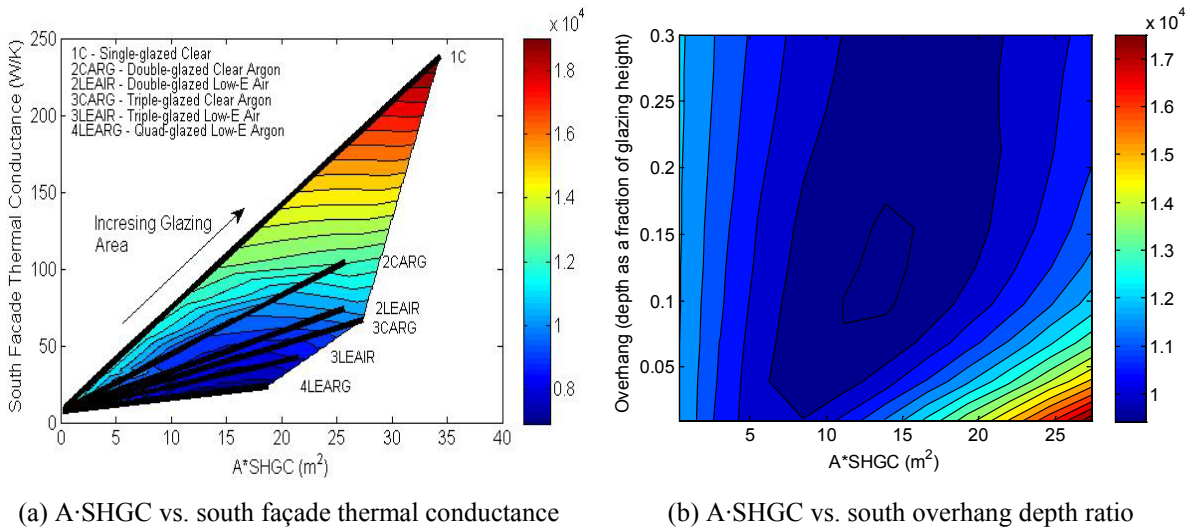


Figure 5: Interactions wheel for 26 parameters for the top 100 (of 325 possible) interactions

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 6.



(a) A·SHGC vs. south façade thermal conductance

(b) A·SHGC vs. south overhang depth ratio

Figure 6: 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 m², two storey, well-insulated, south-facing house, unless otherwise specified. All A·SHGC values refer to the south-facing façade. Note: the SHGC values are based on glazing ratings, which is for normal solar incidence.

Figure 6a 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, to be considered. 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.

The very notion of interactions is that if one parameter is changed, the effect of changing another also changes. For example, Figure 6b shows that an overhang has little effect on performance for small window sizes, but that for very large windows, they can reduce energy use by about 40% - an astonishing amount.

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 manipulated simultaneously. 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.

Solar Design Days

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 the 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 such as:

- 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?
- 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 et al (2008). Its implementation in the design tool is shown in Figure 11. 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 et al (2008) 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. Figure 7 shows how user-input parameters are mapped to meaningful parameters so that several different models can be employed.

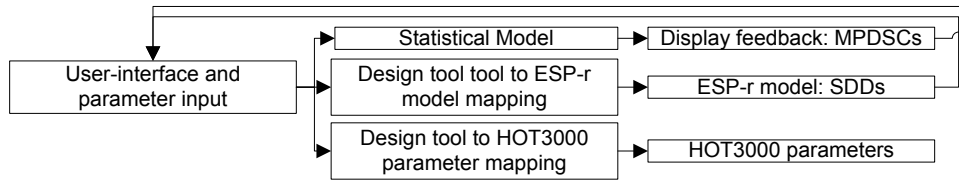


Figure 7: Data flow in the design tool

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.

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.

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. The process is shown in Figure 8.



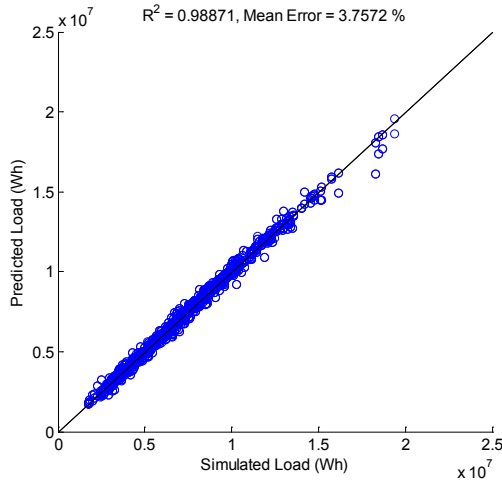
Figure 8: Method for obtaining SDD simulation data

While simplified models or the results of pre-run simulations could be used to display SDD performance, the use of run-time ESP-r simulations provides flexibility and accuracy. Overall, the approach is relatively easy to implement, but presents some lag at run-time. The option to prevent automatic SDD graph updates will be available.

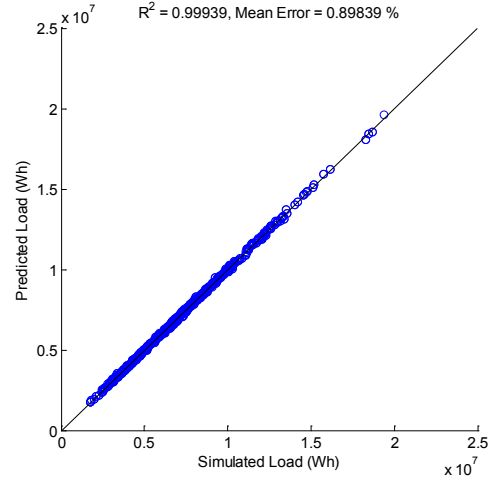
Implementation of black box model

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 parameter is being adjusted. The sample MPDSCs shown used the results of 121 whole-year ESP-r simulations. Thus, 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.

Two regression models were considered: non-linear multivariate regression analysis (MRA) and a feed-forward back propagation artificial neural network (ANN). Randomized sampling was used to run simulations and create a database of 10,000 whole year results, based on the 11 most significant parameters that were previously listed. These simulations represent about 10 days of processing time on a standard desktop computer. Regression model architectures were determined by trial and error. The MRA is second-order and therefore includes two-way interactions. The ANN uses two hidden layers of 30 nodes each. The output of each model is the combined annual heating and cooling load. To compare models for accuracy, MATLAB was used to create the models and validate them against 1000 separate randomized samples. The results are shown in Figure 9. They show that the ANN performs significantly better, in terms of accuracy. It should be noted that the ANN was also run for all 26 parameters and was able to predict performance with a mean error of 4.1%. This is not shown in the comparison because the MRA was too computationally intense. The results highly favour the ANN approach for this application.



(a) Nonlinear Multivariate Regression Analysis



(b) Artificial Neural Network

Figure 9: Results of the MRA and ANN models

It has been suggested that a design tool based on pre-run simulations is limited to those designs envisioned by the developer and that they may not apply to reality. However, the large number of parameters allows an immense number of house designs. While they are limited to rectangular houses, at the present, the methodology presented could easily be extended to other common forms.

User Interface

The two types of feedback models should be used in conjunction to approach the optimal design range, as shown in Figure 10. 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.

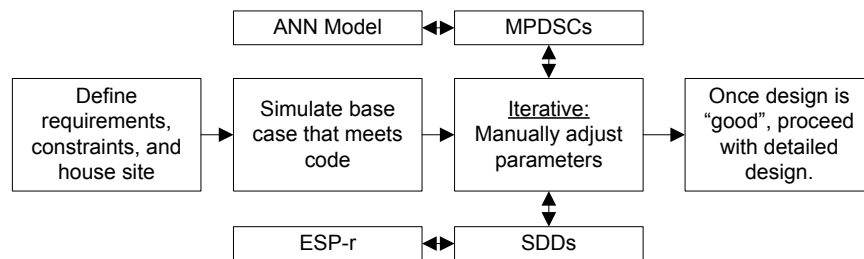


Figure 10: High-level design methodology using SDDs and MPDSCs

A mock-up graphical user interface (GUI) is shown in Figure 11. 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 using a combination of shortened simulation periods and an artificial neural network. The design tool will enable designers to use their common sense and observations to design cost-effective, low-energy houses.

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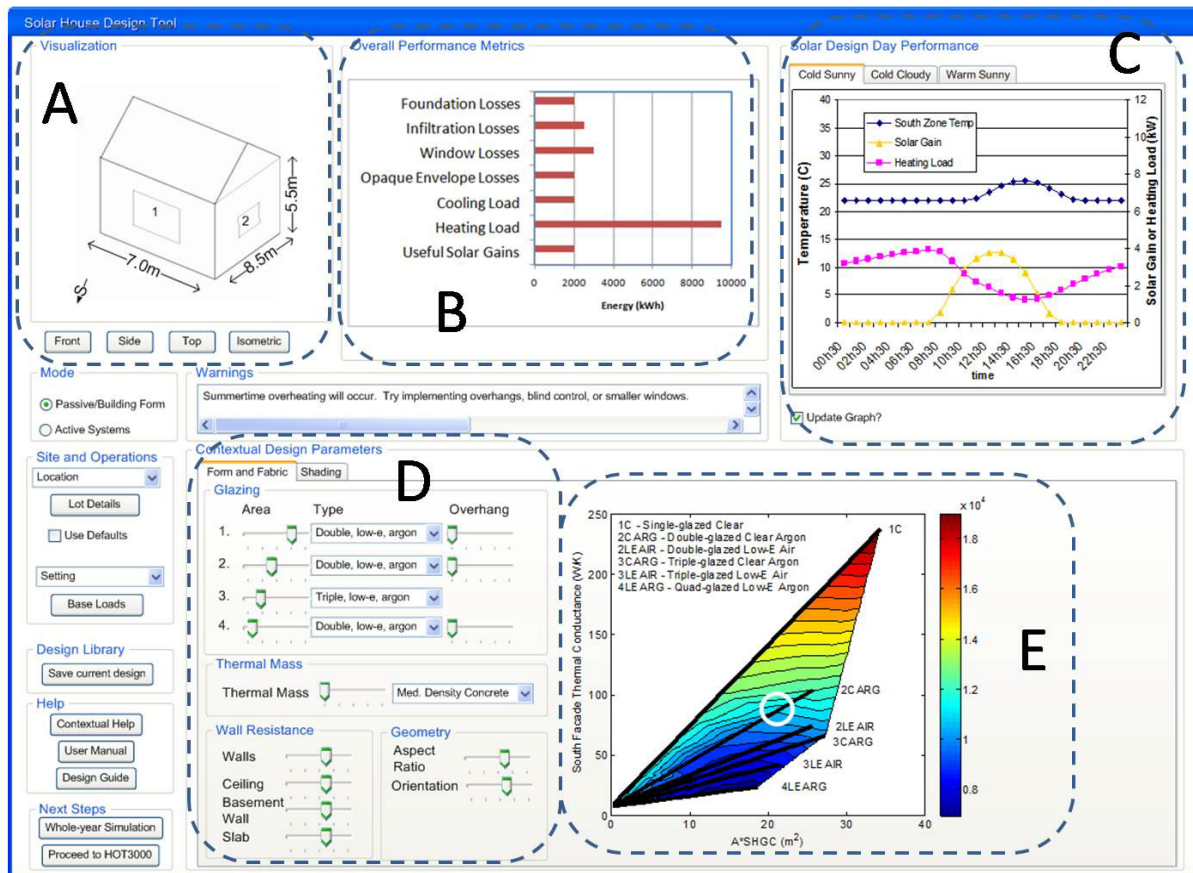


Figure 11: Mock-up GUI for the design tool. Labels are referred to by the text. (A) house geometry representation, (B) performance metrics, (C) solar design day performance, (D) slider inputs, and (E) MPDSC. The circle on the MPDSC indicates the current design parameter settings.

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