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REPRESENTATION OF PERFORMANCE INDICATORS FOR THE CONCEPTUAL DESIGN OF PASSIVE SOLAR HOUSES

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ABSTRACT

This paper is based on current research being conducted within the Solar Buildings Research Network. The design of advanced solar housing is a key objective of the network research activities. It has been recognized that most of the important considerations for obtaining the optimal utilization of solar energy in buildings take place at the conceptual design stage. Normally, designers attempt to optimize the passive solar efficiency of a building before integrating active systems. While rules of thumb and some heuristics for passive solar housing design are available, these are insufficient to provide useful design guidance for advanced technologies. A key functionality needed by simulation software is the representation of critical solar utilization indices while reflecting other performance attributes at the conceptual design stage. This paper examines the use of 'Processing' software to construct a visual representation interface to convey the relationship between overall building U-value, thermal mass, glazing ratio and thermal/optical characteristics, and aspect ratio of the building. The objective of the interface is to guide the user to an optimization of performance based on five key indicators: solar utilization, heating energy demand, cooling energy demand, minimum/maximum zonal temperatures, and daylight autonomy factor. The optimization reflects imposed constraints that are common to new housing design in the Canadian context.

INTRODUCTION

Successful precedents of solar buildings in cold climates that optimize the utilization of solar energy resources combine passive and active technologies. Most of these precedents are the result of research and demonstration programs for solar buildings.

There are several well established heuristics for solar building design in cold climates. These involve the following parameters, traditionally prioritized as listed below, but not necessarily hierarchical:

Passive Elements

- building layout/geometry/aspect ratio
- solar orientation, exposure
- fenestration (U-value, SHGC, area, shading devices)
- thermal mass, phase change
- U-value and airtightness of building envelope

Active Elements

- energy conservation (heat exchange, shutters, sensors, controls)
- energy conversion/production (PV, solar thermal, geothermal, bio-mass, etc.)

A number of efforts have been made to capture, quantify and convey these heuristics. In Canada there have been a series of publications aimed at comprehensively addressing solar building design (CMHC, 1998) and this effort continues but without sophisticated digital tools supporting conceptual design. Some aspects of solar building behaviour, such as passive solar utilization, were researched at a fundamental level, but for a limited range of glazing technologies (Sanders and Barakat, 1984). More recently, this approach was extended to consider contemporary glazing technologies (Kesik and Papp, 1998). Since then, various researchers have looked at the selection of appropriate passive solar strategies for building design (Fernandez-Gonzalez, 2007), and simplified tools have been developed but not specifically for solar buildings (Nielsen, 2005).

During the selection stage of Canada Mortgage and Housing Corporation's EQuilibrium Housing demonstration program, candidate designs submitted by competing entries incorporated features which were difficult to simulate.[1] These near net-zero energy houses incorporated sophisticated solar energy strategies whose performance assessment required the expertise of some of Canada's leading solar building designers and researchers. Federal government engineers and building scientists employed to audit the submissions also found the energy modeling presented numerous challenges. A large variety of software was available, including sophisticated applications like TRYNSYS, ESP-r, ECOTECT, EnergyPlus, etc., but these required advanced modeling skills. If the best designers and researchers experience challenges in solar building design, what kind of a tool is appropriate to the average builder and designer of Canadian housing?

1 Author served as Selection Committee Member for EQuilibrium Housing Design Competition sponsored by Canada Mortgage and Housing Corporation, coordinated by RAIC, January 21-24, 2007.

CONCEPTUAL DESIGN TOOL

The need for an effective and easy-to-use conceptual design tool for passive solar building design has long been recognized as an essential aid to architects and builders. Graphic methods were employed for this purpose before the advent of affordable computers and simulation software. These were followed by publications intended to educate readers about the potential of solar buildings, often bundled with various kinds of design aids and case studies. Despite these successive generations of solar building design tools, a regrettably small percentage of the annual housing starts reported in Canada deliberately deploy solar building design strategies. There are several reasons explaining this situation:

1. Until recently, solar buildings were a victim of a cultural amnesia arising from relatively low energy prices;
2. In the case of housing, the planning of subdivisions to maintain solar access rights for each dwelling was never addressed in federal, provincial or municipal legislation; and
3. Most solar building precedents are one-off buildings, typically designed by architects, often idiosyncratic, expensive, and not well suited to conventional subdivision home designs and market preferences.

With the advent of global warming, climate change and high energy prices, solar energy has been rediscovered. However, a lack of contemporary design tools and precedents makes solar buildings suspect as a throw back to another era. They appear to lack the cool factor of digital technologies and hybrid automobiles, even though they may be just as sophisticated.

The focus of the research in this paper is to eventually develop a conceptual design tool for solar houses that embody the following characteristics:

- Designers/builders should be able to employ the tool to determine a conceptual solar house design within less than 10 minutes, which delivers near optimum passive solar energy utilization performance for a selected building typology with a given location and orientation.
- The tool should provide feedback on energy performance of the building, operating cost, construction cost premium, and economic assessment metrics such as payback period, internal rate of return and life cycle cost. Reductions in environmental impacts versus a conventional building (compliant with minimum code requirements) should also be gauged.
- The tool must compare the energy performance of the building against one or more low-energy building standards. This permits the user to position the building in relation to the state-of-the-art. It is also recognized that in order to cost effectively implement renewable energy technologies such as photovoltaic and/or solar thermal panels, energy demands of the building must be relatively low.

***Figure 1** – Proposed structure of data supporting solar building design tools.*

PASSIVE SOLAR PERFORMANCE PARAMETERS AND INDICATORS

The work which follows focuses on passive solar performance parameters and indicators. The first in the research work was identifying critical parameters and the corresponding passive solar performance indicators they influence. These are summarized in Tables 1 and 2.

***Table 1** – Criticalperformance parameters.*

Parameter	Metric
Effective U-value of building (including airtightness)	$W/m^2.K$
Glazing Ratio defined as area of south facing glazing divided by gross south facing wall area	%
Glazing Characteristics based on window frame construction and optical properties of glass	$W/m^2.K$ and SHGC
Effective Thermal Mass based on interior elements capable of capturing and storing solar gains	MJ/K
Aspect Ratio defined as the gross south facing wall area divided by the gross exterior wall area	%
Note: Solar orientation is a given parameter, with the wall and window areas of interest being assigned a southern orientation.	

***Table 2** - Solar building performance indicators.*

Indicator	Metric
Annual space heating/cooling energy demand.	$MJ/m^2.K$
Useful solar gains	$MJ/m^2.K$
Thermal comfort	Min/Max Zonal Temperatures
Daylighting using the Daylight Autonomy Factor (DAF)*	%
*The percentage of electric lighting energy saved is the DAF.	

The parameters are intended for use within a simulation model to conduct a series of parametric analyses. Figure 2 indicates a base model for a normative Canadian house typology. Assuming the use of energy simulation software, such as ESP-r or HOT3000, and varying the dimensional base model parameters along with the critical parameters in Table 1, simulations would produce an extensive array of data. These data would be subsequently synthesized to produce values for the indicators. These tasks are ongoing outside of the research presented in this paper, which presents a mock-up. This component of research focuses exclusively on how the passive solar indicators could be represented to assist the conceptual design process.

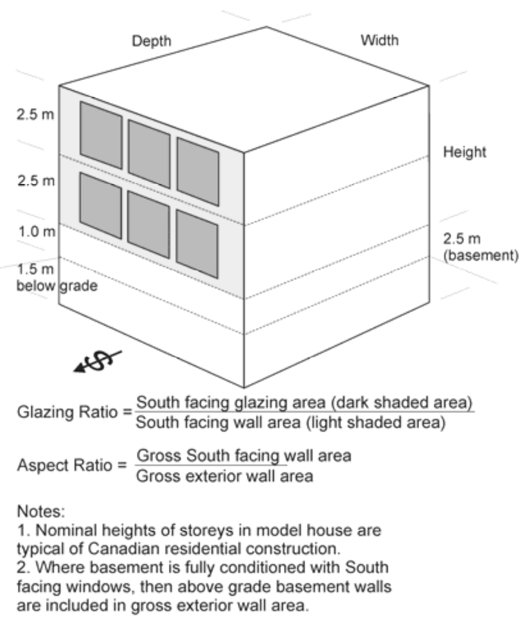

***Figure 2** – Example of base house model for generating parametric performance simulations.*

REPRESENTATION / VISUALIZATION

There is a large body of research and applications that has been conducted in the field of data representation and visualization. The conceptual design tool that is intended to emerge from the current research program borrows ideas from other fields (Shneiderman, 2002). The important contribution it attempts to make to solar buildings research is to provide a framework for visualizing conceptual design and performance evaluation (Blundell et al., 2006).

Conceptual design tools must support design decisions within a set of constraints. In practice, a particular home may not occupy an ideal site in terms of solar orientation. The intended occupants for the home may rule out a two-storey design for reasons of accessibility. Lot widths and by-law restrictions on maximum building height will further constrain permissible house typologies and aspect ratios. All of these constraints can be managed within parametric analyses, but a far more complex challenge is how to represent the resulting performance indicators of a candidate passive solar house.

This solar performance visualization tool was developed using in 'Processing' software, which is a free, open-source Java programming tool initiated by Ben Fry and Casey Reas (http://www.processing.org/). It evolved from ideas explored in the Aesthetics and Computation Group at the MIT Media Lab. Processing has gained popularity due to its adoption by artists and designers alike for its strong focus on visual output and interactivity built on top of trusted Java cross platform and web compatibility. There are two main challenges which must be confronted by visualizations which deal with high-dimensional datasets: one is how to effectively navigate through parameter space and secondly is how to represent a series of values in the context of a parameter space which resists conventional flattening or projection.

Ques were taken from the internal data storage structure within the program when the GUI navigational system was developed. Because the stored dataset was discretized rather than continuous, these discrete values were abstracted as nodes and then connected as a matrix employing a multi-pointer linked list structure. Each node contains internal indicator values, their address in parameter space, as well as the addresses (or pointers) of all of the immediately adjacent nodes. Using this data structure, one could step across the matrix by requesting the pointer of a node's immediate neighbour in the direction one chose to step along. This system suggested that all the user needed in order to navigate this matrix was a representation of the current node's address and those which were accessible from that address. The node address was represented as the intersection of each of the dimensions of the

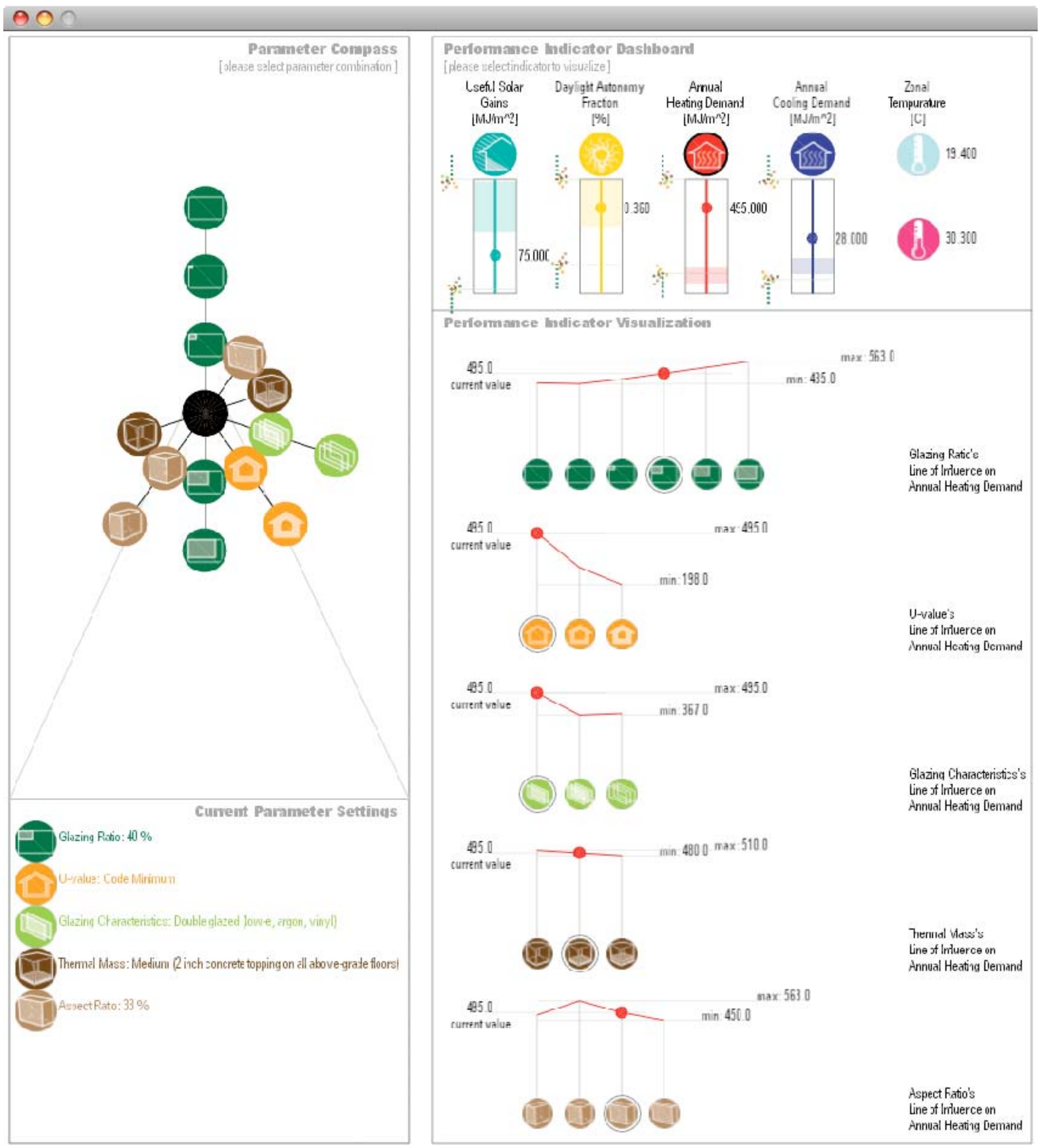

***Figure 3** – Application layout indicating the location of key features such as the Parameter Compass, Current Parameter Settings, Performance Indicator Dashboard, and Performance Indicator Visualization regions.*

parameter space at it's current address (as given by some combination of parameter values selected by the user). The value of the current parameter combination or address is shown in the Current Parameter Setting box (shown in lower left region of Figure 3). The intersection representation allows the user to orient themselves in the available range along each dimension which the user could travel during their optimization search. This intersection representation has been termed the Parameter Compass (shown in upper left region of Figure 3).

The basic indicator representational strategy employed is best understood through its 2D analogy (as shown in Figure 4). In this simplified example, the x and y axis represent the parameters (independent variables) and the tone field represents the value of the indicator (dependant variable). By searching the neighbouring parameter space for a local gradient in the indicator, the user is able to follow the topology towards an optimal solution. The intersection representation used in the navigation tool described above was used to define the neighbouring parameter space. The parameter space visible from a particular intersection (or address) is limited to only those directly adjacent parameter spaces along each dimension. The gradient visualization can be understood as a iso-contour where the local gradient is unwrapped along each dimension extending from the current intersection as if each of the other parameters (or dimensions) was kept constant. This unwrapped gradient has been termed the Line of Influence, one of which is displayed for each parameter (shown in lower right region of Figure 3).

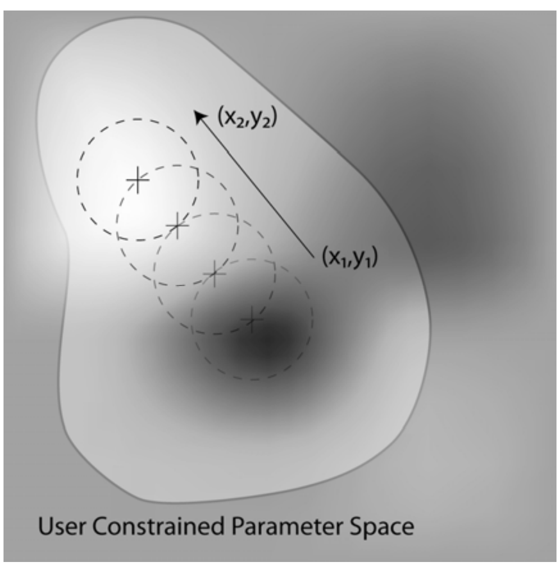

Figure 4 – 2D analogy for the application's parameter space searching method and indicator visualization strategies.

While this method focuses on finding local minima and maxima the indicator values are presented in the context of the global minima and maxima for the whole dataset. By keeping the current values in context, the user is shown that potentially there may be more optimization that can occur through a different combination of parameter values (assuming that parameters values are within the user-constrained search space). This global referencing takes place in the Performance Indicator Dashboard along side the presentation of the simultaneous meters of all applicable indicators (shown in upper right region of Figure 3). It is here on the Dashboard that the user is able to select the indicators to prioritize and optimize. Once an optimal solution has been found for one indicator by stepping through the parameter space along the gradients shown through the Lines of Influence, the user can save this address for further consideration This saved address becomes important as the user then goes on to optimize other indicators and will eventually be able to compare how their new set of optimization actions effected their original one. Further, the user can compare their indicator values to a target range that is achieved by high performance buildings in order to get a sense of where their optimal solution fits in a spectrum of solutions (these target regions are shown by a shaded region overlaid on the indicator meters in the Dashboard).

An example of a typical optimization using this visualization tool is shown in Figure 5. In this example the Dashboard has been used to select the Useful Solar Gains (USG) Indicator as the one to optimize. Starting from the default parameter address (Glazing Ratio = 5%, U-Value = code minimum, Glazing Character = Double glazed, low-E, Thermal Mass = Light, and Aspect Ratio = 17%) the USG value is given as 9.0 MJ/m^2 (Step 1 in Figure 5). By reviewing the presented Lines of Influence, it is visually apparent that the Glazing Ratio parameter has the greatest effect on the USG indicator. By choosing Glazing Ratio = 80%, the USG value will raise to 101.0 MJ/m^2 which the user can see is the highest possible value along the visible Lines of Influence indicated by the maximum values floating to the right of each iso-contour. Once the user uses the Parameter Compass to enact this step along the Glazing Ratio dimension (Step 2 in Figure 5), they will see that all the other parameter Lines of Influence will alter to reflect the new parameter intersection. Further refinements can be made through additional steps along the Thermal Mass and Aspect Ratio dimensions eventually increasing the value of USG to 202.0 MJ/m^2 (Step 3 and 4 in Figure 5) leaving one final step of increase along the Glazing Characteristic dimension to the final global maximum of 225.0 MJ/m^2.

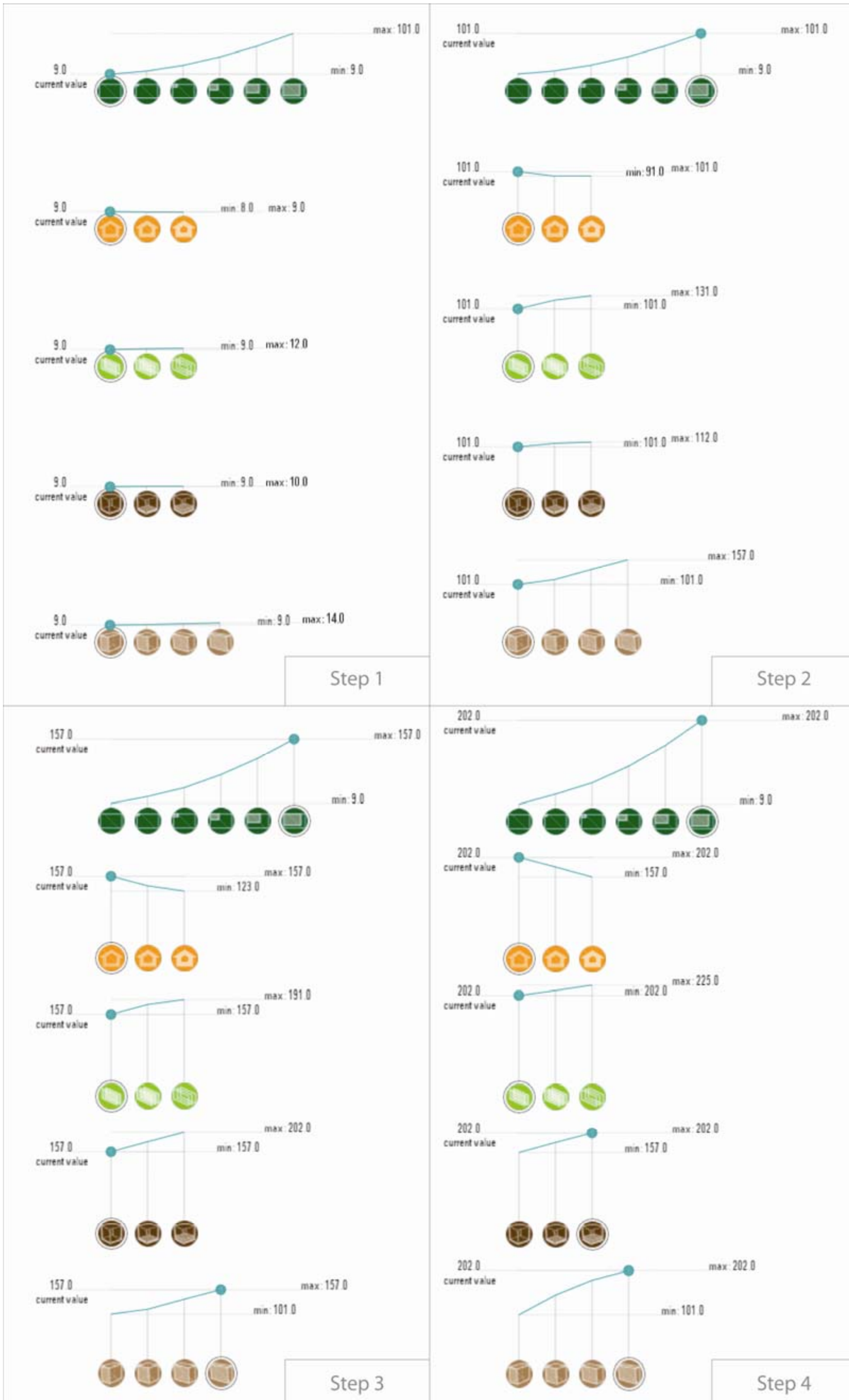

Figure 5 – A typical example of an optimization sequence for Userful Solar Gains(USG). This maximization involves navigating through parameter space first along the Glazing Ratio, Aspect Ratio, and finally Thermal Mass dimensions.

PRACTICAL CONSIDERATIONS

A passive solar building performance visualization tool has the potential to reduce the complexities of energy and daylighting simulations into a coherent set of inter-relationships that can guide the user towards an optimal design strategy.

Achieving an optimal design in practice, however, is an ideal that rarely if ever occurs. It is important to appreciate the reasons for this, as much of today's energy simulation software development continues to incorporate optimization algorithms that obscure fundamental relationships in building design.

Looking at the problem of housing design, especially within the context of existing neighbouhoods, or typical new development subdivisions, the solar orientation of the house may not be ideal. Usually there is a south-facing façade, not necessarily direct south, but within 30 to 45 degrees of south. This south-facing façade may form the exterior envelope of rooms or spaces that are not ideally suited to passive solar strategies, such as bathrooms, hallways, closets, etc., because these will generally not afford a sufficient glazed area to capture direct solar gains.

Even in the situation where the solar orientation of the building is ideal, the owner of the dwelling may not wish to elect the optimal glazing ratio for aesthetic reasons. Passive solar houses tend to have much larger south-facing glazed areas than conventional houses, and in some cases the larger windows pose problems such as the placement of furniture, or simply visual privacy.

To further complicate the situation, lot sizes and setbacks may rule out certain aspect ratios for the building. Mobility problems may rule out a multi-storey design. In many cases, for the sake of preserving market value, homeowners and prospective home buyers want to "fit in" with the other homes in terms of style, layout and features. In reality, the vast majority of new homes in Canada are designed by developers who construct thousands of homes with no thought to solar energy utilization.

Given these circumstances, there are essentially two approaches to the passive solar house design problem. One is to use simulation software to determine the best performing (optimal) set of parameters for a given geographic location and to offer this as a prescriptive formula for house design. The second is to recognize that this optimal solution can seldom be realized, and to develop a passive solar performancevisualizationtoolthat indicates the best achievable performance under the given constraints. In reality, the first approach is used to perform parametric analyses that support the second approach for a conceptual design decision tool.

The prototype performance visualization tool presented in this paper is a simple mock-up and contains a number of important features that were explicitly developed for the conceptual design stage by an architectural users group. This segment of the design community has resisted the introduction of energy simulation into the everyday design process because it is an expensive and disruptive proposition.

As a gauge, the application presented in this paper is envisioned as residing online with all of the parametric analyses having been performed previously and the results made available to the conceptual design tool. A front-end, not shown in this paper, would obtain basic information from the user, such as the location of the house and the maximum width and height that would be considered and/or allowed.

Subsequently, the user would engage the application as indicated in Figure 3 and work through the various parameters to arrive at the best solution under the given set of constraints. This is really a crude form of optimization because issues of capital, operating and life cycle costs have not been considered, not to mention environmental impacts such as greenhouse gas emissions. However, the process could be very affordable, if sponsored by a government agency and/or energy utility, and it should take no longer than 10 or 15 minutes.

Finally, after the conceptual design process is complete, the user should have an option to view house designs with corresponding passive solar attributes contained in a database created by users. The application should also be able to launch a wizard that creates a detailed model of the conceptual design in a more sophisticated application that can then consider active solar technologies.

This entire process, as described herein, is aimed at providing convenient and affordable access to a reliable prediction of house energy performance at the conceptual design stage. Ideally, it would be as easy to operate as an ATM and useable by builders and consumers alike. The results should enable users to assess compliance with respect to energy targets that are reflective of advanced solar buildings around the world and across Canada so that policies and programs aimed at efforts such as greenhouse gas reductions are clearly reinforced.

This paper is not suggesting that the only barrier to the design and construction of solar buildings is a lack of suitable software. The existing design and analysis tools cannot be abandoned as they serve a vital research function. But there is a notable lack of software that can be easily adopted by the average builder or designer in daily practice. Given all of the research and development efforts since the 1970s energy crisis, assuming the most favourable scenario, less than 0.6% of new housing starts may be defined as solar buildings.2It is estimated that solar energy currently provides 8% of the averageCanadian home's heating requirements, and this proportion could be easily increased to 22%(David Suzuki Fdn., 2004).An effective conceptual design tool could potentially contribute to improving these statistic.

CONCLUSIONS

The first step in the development of a design tool for solar buildings is to recognize that the complete tool embodies a two-stage process, where the first stage focuses on the passive solar design parameters to maximize the potential for passive solar energy utilization and reduce the annual energy demands of the building to a threshold where active solar technologies are feasible.

The second step is to develop a visual representation of the critical performance indicators that enable relatively straightforward and rapid assessment of energy performance at the conceptual design stage. This paper has presented one approach to advancing this objective. Based on the research conducted to date, several conclusions have been reached:

The use of any tool must assume an entry level of knowledge and provide sufficient support to users. This work remains to be completed for the prototype application presented in this paper.

The abstract nature of conceptual design requires that the parameters selected using such an application be correlated to actual building precedents so that users can visualize instances of buildings with similar parameters and energy performance.

Initial research in this regard indicates there are many house typologies that can embody such parameters and provide comparable energy performance, but this can only be confirmed by assembling a database of solar houses.

There are many other forms of visualization that can be developed using the same parameters and performance data and ideally, a conceptual design tool would offer a menu of representation types that best suit the comprehension of the users. For example, tabular data and bar charts are preferred by some individuals over graphic formats.

In general, conceptual design tools necessarily rely on a research level tool capable of performing a large number of parametric analyses and generating performance data that can be easily accessed by representation engines. This approach also has inherent limitations previously discussed in this paper, but at the conceptual design stage represents an encouraging alternative to outdated heuristics, narrowly prescriptive methods, and time intensive, real-time, first principles simulations and analyses.

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REFERENCES

Canada Mortgage and Housing Corporation, 1998. Tap the Sun: Passive Solar Techniques and Home Designs.

Kesik, T. and G. Papp. 1998.Utilization of High Performance Windows and Glazing for Passive Solar Heating of Houses.*1998 CSME Forum*, May 19-22, Ryerson Polytechnic University, Toronto ON, pp. 420-427.

Nielsen, T.R., 2005. Simple tool to evaluate energy demand and indoor environment in the early stages of building design. *Solar Energy* 78 (2005) 73–83.

Sander, D.M. and S.A. Barakat, 1984. Mass and Glass. How Much? How Little? *ASHRAE Journal*, Vol. 26, No. 11, 1984, pp. 26-31.

Fernandez-Gonzalez, A., 2007. Analysis of the Thermal Performance and Comfort ConditionsProduced by Five Different Passive Solar Heating Strategies in theUnited States Midwest. *Solar Energy* 81 (2007) 581–593.

Shneiderman, B., 2002. Inventing Discovery Tools: Combining Information Visualization with Data Mining. *Visualization* 1 (2002) 5-12.

Blundell, B.J., G. Ng and S. Pettifer, 2006. Visualization Framework for Design and Evaluation. SPIE-IS&T/ Vol. 6060 606008: 1-12.

Smart Generation. David Suzuki Foundation, 2004.

2 Assuming every R-2000 home is a solar home, in the period 1990 – 2004, there were 8,498 R-2000 homes constructed. From 1990 to 2004, CMHC estimated a total of 1,436,551 single housing starts. R-2000 housing starts over this same time period represent approximately 0.6% of total single housing starts.
[Sources: *Improving Energy Performance in Canada – Report to Parliament Under the Energy Efficiency Act For the Fiscal Year 2004-2005*. Office of Energy Efficiency, Natural Resources Canada. http://oee.nrcan.gc.ca/Publications/statistics/parliament04-05/index.cfm

Single Housing Starts, Canada, Provinces and Metropolitan Areas, 1990–2005 (units). Canadian Housing Observer, Canada Mortgage and Housing Corporation. http://www.cmhc-schl.gc.ca/en/corp/about/cahoob/data/data_002.cfm]