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DEVELOPMENT OF REQUIREMENTS FOR A SOLAR BUILDING CONCEPTUAL DESIGN TOOL

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ABSTRACT

This paper is focused on a discussion of the requirements and specifications for the development of a design tool that can be used for solar-optimized building design. The tool will initially be focused on single family houses and later on small commercial buildings. The solar optimization process refers to optimization of form so as to (i) capture as much solar radiation as possible on the two main surfaces facing near south – a façade and a suitably oriented roof section, and (ii) to utilize as much as possible of the captured solar energy as daylight and/or to be converted to electricity and heat. The first requirement refers to building form while the second refers to solar utilization systems such as building-integrated photovoltaics, solar thermal systems and fenestration systems, as well as energy storage systems. It is concluded that the developed design tool, in order to have as much impact on the design as possible should permit some degree of detailed analysis at the early design stage. Two approaches are possible – development of a customized simulation-design tool, or utilization of detailed simulation tool with a front end that defines most of the required inputs from standard requirements or rules of thumb.

INTRODUCTION AND REVIEW OF EXISTING TOOLS

The energy performance potential of small buildings (roughly less than 600 m^2 floor area) and single family dwellings is heavily influenced by form, massing and fenestration decisions made early in design. Conceptual designs are typically created by persons with only rudimentary knowledge of building energy systems, especially renewable energy systems. Development of software that could provide guidance during conceptual design has been a goal for a couple of decades. For instance, Lawrence Berkeley Laboratory began work on the Building Design Advisor (DOE 2006) for large buildings about 20 years ago. However, the user base is estimated at about 800 compared with more than 1000 users for the DOE2 simulation program, which requires specialized knowledge. One would expect that a successful simplified program would have a much larger user base than a program dedicated to specialists. Although simulation tools are not developed as design tools, they are often used as such by knowledgable users. However, they are often used outside their intended range of application.

A solar building design tool will facilitate optimal design of form so as to capture as much solar energy as possible while also efficiently using it to satisfy the needs for electricity, space and water heating, and lighting. Inevitably, in designing a building one must take into account practical considerations imposed by lot size and orientation, possible shading by adjacent buildings and user preferences regarding layouts.

Characteristics of the Prospective User Base. Discussions among the authors suggest that the conceptual design community for single family dwellings varies somewhat, with the largest volumes of designs being produced by architects in Quebec to architectural technologists in Alberta.

Early researchers on design methods in architecture characterized design as an analysis-synthesis sequence (Alexander 1964). During the 1980s, a hypothesis-test model of design became more widely accepted (Ledewitz 1985). That is, designers generate forms and then assess their performance relative to constraints and objectives. Design is then seen to begin with generation of form, and graphical representation plays a key role. Further, precedents play a very significant role in the formulation of new designs. Courses on precedent are common in architectural curricula.

The conceptual energy systems design software should have the following characteristics to reach a high adoption rate:

1. the interface should use the graphical-spatial language of designers,

2. it could be learned within a couple of hours or less if possible,
3. the results should be obtained within 5-15 minutes per scenario (including modeling and generation of results),
4. it could be used without specialized knowledge of building energy systems; however, a two stage process allowing easy use of the data in more detailed analysis would be useful, particularly for solar energy utilization options.

In terms of design support, building energy software may be classified into two categories: 1) open and 2) directive. "Open" means that the software provides results based on values entered by the user. The user has to interpret the results and can determine adjustments to the design by trial- and-error, experience, and some other means. This is time-consuming unless the user is very experienced. "Directive" means that software provides the user with guidance regarding promising design directions. A "directive" capability should enhance user productivity.

User productivity could also be enhanced by providing exemplars (precedents) as starting points for development of conceptual designs.

Energy modelling capabilities. Solar home design usually begins with passive solar design principles – particularly direct gain that is generally accepted to be cost effective. Passive solar envelope design techniques typically address the following basic requirements/principles (Athienitis and Santamouris, 2002):

• Transmission and/or absorption of the maximum possible quantity of solar radiation during winter.

• Utilization of integrated building envelope devices such as windows with photovoltaic panels as shading devices, or roofs with photovoltaic shingles; the dual role of these elements for electric power production and for exclusion of thermal gains increases their cost effectiveness.

• Utilization of received solar gains to cover instantaneous heating load and storage of the remainder in embodied thermal mass or specially built thermal storage devices. The thermal mass of the building causes delays in its response to heat sources such as solar gains - referred to as the thermal lag effect. This effect, if taken into account in the selection of thermal mass and appropriate control strategies, avoids thermal comfort problems such as overheating. It must also be addressed in heating/cooling system sizing.

• Reduction of heat losses to the environment through the use of the appropriate amount of insulation and windows with high thermal resistance (and high solar transmittance between SE and SW).

• Shading control devices to exclude unwanted summer solar gains which would create additional cooling loads, while admitting adequate daylight.

• Utilization of natural ventilation to transfer heat from hot zones to cool zones in winter and for natural cooling in the summer.

• Ground cooling/heating to transfer heat to or from the deep underground which is at a more or less constant temperature.

• Utilization of solar radiation for daylighting.

• Integration of passive solar systems with the active heating/cooling air-conditioning systems both in the design and operation stages of the building.

The last requirement is perhaps the most important for the successful design and operation of a building that utilizes solar design principles. However, it is usually overlooked because of the absence of adequate collaboration for the integration of building design between architects and engineers. Thus, the architect may design the building envelope based on qualitative passive solar principles while the engineer designs the HVAC system based on extreme conditions, often ignoring the benefits due to solar gains and natural cooling. A preferred design approach is based on the principle that the building and its HVAC system are one energy system and they must be designed together based on dynamic operation, taking into account energy storage, and control strategies. Thus, passive solar gains and dynamic building behavior must be estimated quantitatively under various control strategies to properly design both the building envelope and the HVAC system for optimized operation. Depending on the climatic conditions and building function, certain HVAC systems are more appropriate than others and more compatible with passive systems. For example, floor thermal mass may be used to store both direct solar gains and also for a floor heating system; however, this poses a control challenge that must be studied to achieve acceptable thermal comfort (Athienitis, 1997) and which still requires further research.

There has been much work in the building simulation field on the modelling of whole-building performance. Previous work on solar systems has addressed the modelling of individual components and systems (e.g., PV, solar domestic hot water, solar air pre-heating, daylighting, etc.) but building-integrated systems have not been adequately considered. Fundamental work is still required to create models of the appropriate resolution and to integrate the various modeling domains (envelope, equipment (HVAC), landscape, energy). This paper and a planned workshop will review currently available tools and discuss their strengths and weaknesses. The production of tools that enable the assessment of building form and fabric at the early design stages is critical in the effective exploitation of solar technologies. Without following this step first, subsequent simulation of design options is often done to justify decisions made on a subjective basis. Therefore, there is a need for the development of methodologies for systematic analysis of design options at the early design stage so that form is optimized to maximize collection of solar energy. Because of the numerous design parameters such as window area, thermal and optical properties of glazing systems (e.g., R-value and transmittance), photovoltaic array area, solar thermal variables, thermal storage, HVAC system variables, control strategies and comfort range, the number of possible design combinations, even with 4-6 allowable discrete values for each variable, is of the order of billions. In view of this complexity, methodologies are required for systematic simulation by exploiting design synthesis and optimization methods in order to guide the designer towards optimized solutions to maximize the collection and utilization of solar energy while minimizing costs. An optimization approach is followed in the BEopt software (Christensen et al. 2005), a computer program that determines optimal building designs using detailed simulation software.

Discussion on other design tools. Representative currently available simple software that might be suitable for conceptual design support is listed in Table 1. Inclusion in the table was based mainly on the audience being home designers as defined at the Building Energy Software Tools Directory (DOE 2006). Energy Scheming was also included, because it uses a graphical interface and is limited to small buildings. The CBIP Screening Tool was included, because discussion with architects and engineers revealed that professionals who are not energy specialists use it for early stage design assessment.

A review of the programs shows that none of the existing packages has all of the performance attributes described above. Energy-10 (Balcomb 1997) is an early design stage building energy simulation program that integrates daylighting, passive solar, low-energy cooling strategies and energy-efficient envelope design and mechanical equipment. It is used for small commercial and residential buildings. Other than the two-day training requirement, Energy-10 seems to be the strongest offering, and this is reflected in one of the largest user bases. Energy-10 also handles many of the issues of interest: passive solar heating, daylighting, insulation, solar water heating, glazing, and thermal mass.

Another system recently developed in Europe is IES virtual environment which provides design-oriented building analysis. A 3-D geometric representation of the building is the core of the model and application data is attached to that concerning specific tasks. It uses Apachesim for detailed thermal simulation and Macroflo for natural ventilation and infiltration analysis. The program offers a holistic approach and allows optimization of building and system designs with regard to comfort criteria and energy use (www.iesve.com).

Table 1. Characteristics of several simple software that might be considered for general conceptual building energy design support.

Program/ Users/ Reference	**Primary Audience**	**D** [1]	**G** [2]	**P** [3]	**Notes**
[1] software is "directive" versus "open"; [2] graphical interface; [3] precedent-based					
Energy Scheming / 600+/ DOE 2006	Architectural professionals, students, and building designers		X		For small buildings. Entirely graphical input; 8 to 10 hours to learn; Analysis for 24 hours for each of 4 seasonal evaluation days; v3.0 available.
Builderguide / 1000/ DOE 2006	House designers, especially builders, architects, and do-it-yourselfers				Input: four one-page worksheets
CBIP Screening Tool/unknown/ NRCan 2006	Architects, engineers				Immediate use – about 5 minutes to enter data per run; massing and orientation ignored; based on data base of hundreds of DOE2 simulations.
ECOTECT (Marsch, 1996)	Architects, engineers	X	X		Interactive building design analysis tool that links a 3D modeler with a wide range of performance analysis functions covering thermal, daylighting, acoustics etc. Its main advantage is a focus on feedback at the conceptual building design stages.
Energy-10/3200+/ DOE 2006	Building designers, especially architects	X	X		Two days of training advised. Fast, easy-to-use, accurate. Automatic generation of base cases and energy-efficient

					alternate building descriptions.
HEED/ 6000+ downloads/ DOE 2006	Homeowners, ratepayers, designers		X		Simple-user friendly interface; specific to California conditions.
HOT2000/1400 / DOE 2006	Builders, design evaluators, engineers, architects				Two days of training.

Finally, as mentionned, some experts are using more detailed simulation tools in the conceptual design stages. One such tool is ESP-r, which offers a multi-domain (building thermal, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow) simulation environment. Users have the option to increase the complexity of models according to the requirements of particular projects (Crawley et al, 2005). Some of its capabilities include: climate display and analysis, shading/insolation calculations, 2D-3D conduction grid definitions, CFD, electric power flow modelling (PV hybrid), links with third party tools (RADIANCE, AUTOCAD and TRNSYS).

An extensive joint report on building simulation programs (Crawley, Hand, Kummert, Griffith, 2005) compares the different capabilites and approches followed by different detailed simulation and design tools.

DEVELOPING REQUIREMENTS FOR THE DESIGN TOOL

The focus of this paper is on the development of a conceptual design tool that aids the designer in enhancing solar energy utilization as opposed to automatically generating one optimum design. The optimization of solar utilization can be considered as a multi-attribute optimization problem that seeks to cost effectively maximize the utilization of solar energy by buildings without adversely affecting health, safety or the environment. However, in the present context, solar optimization is considered more an approach rather than the seeking of a specific absolute optimum. This approach partly overcomes the difficulty of assigning numerical values to important performance aspects such as daylighting quality, thermal comfort and views, while taking into account user and designer preferences.

As solar technologies evolve and achieve economies of scale through mass production, a solar optimized building may actually produce more energy than it consumes, but it is important to recognize that this relationship will change over time, hence optimal energy targets cannot be arbitrarily set. Instead, the current state-of-the-art must be assessed so that it is possible to project future potential and the research needed to achieve optimal success.

The design of single family detached homes usually starts with selection of the single storey, two-storey or split design options. The most common option, which also needs less land, is the two-storey option. A possible approach is as follows: given a certain lot size (e.g. 18 m wide by 25 m long) and city regulations (distance from neighbors etc), the designer will choose two or more plan layouts (variations of a basic design) based on passive solar design principles such as those recommended by CMHC (2005) for further analysis. Some of the basic principles provide guidelines for selection of window area on the main solar façade, location of the family room and kitchen adjacent to this façade and other useful suggestions. Generally, it is expected that the south or near-south facing façade will be wider (if possible) than the perpendicular dimension of the house so as to maximize passive solar gains in winter. With a two-storey design, usually the bedrooms are located on the second floor. Most houses include a basement but recently there has been some discussion of possible advantages of eliminating the basement. After a plan layout plus a variation of it are selected, the solar façade form is basically decided. However, there are several other questions that need to be addressed, the first one being that of roof form.

1. Roof forms. One of the major questions to be addressed in this paper is the following: how many different roof forms and designs will be considered by the design tool and how? Given a certain lot size, once a few optional floor plans are selected based on user needs and passive solar design principles, there are many possible roof shapes that can fit the plans. Obviously, in a solar optimization process, the designer should select the form that will accommodate the building-integrated photovoltaics and solar thermal systems while resulting in an overall cost-effective system. Consider, for example two possible roof forms for the same floor plan often used with some variations in Canadian housing. Roof A may have more south-facing roof area (shaded) than roof B but uses more material (both can be considered as instances of one design with different angles a and b). If the attic space is partly useful space then this fact has to be also considered. The question of which shape is more appropriate from a solar energy utilization point of view is complex and depends on a number of factors such as:

▪ If building integration requires that the whole surface is covered by one material to avoid water penetration and have a robust water shedding surface, then it would be desirable to cover the surface with BIPV or integrated thermal collectors. However, if the surface is too large then the solar system may be too costly if it were to cover the whole shaded surface. Then option B starts becoming attractive from a cost effectiveness point of view.

- The price of the PV system per unit area and the area required to achieve a certain desired capacity. By using a higher efficiency BIPV system, one could potentially generate the same quantity of electricity as A with option B.
- The price of the solar thermal system and the area required to achieve a certain desired capacity.

Depending on the goals set for the design, the above three considerations may have different priority. Some designers may prefer to set energy performance goals and cover only part of the surface.

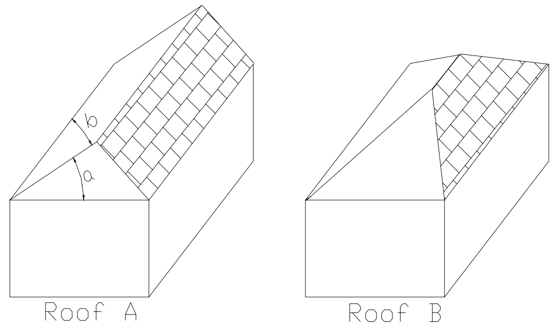

Figure 1. Two common roof shapes used in Canadian housing (soffits not shown). Shaded area is close to south facing (roofs A and B may be considered as instances of one design for specific angles *a* and *b*).

Another possibility is that all or part of the shaded roof area may be semitransparent, that is, it may cover an attic-solarium with semitransparent PV. This option may possibly be considered as a sub-option of one of the layouts. The slope of the roof is another major design variable. The optimal slope for maximization of yearly collected solar energy is a slope approximately equal to latitude. The roof form/shape problem may be considered as a mathematical optimization problem about maximization of solar energy use with major variables the angles a and b. However, the roof form/shape problem can not be simply one of maximization of solar energy collection and utilization because other practical considerations have to be taken into account such as construction cost, aesthetics, snow accumulation and melting (which affect performance of solar systems in winter significantly).

In some cases, practical considerations such as avoiding rain penetration and shedding snow may override small differences in solar energy collection such as the difference in solar energy incident on a roof for two slope angles that differ by 10 degrees (e.g. see Fig. 2).

Thermal mass and/or isolated storage. A second question is that of thermal mass, its impact on type of construction and type of heating system. This decision needs to be made at the early design stage as it impacts on structural design of the building. For example, a floor heating system with 5 cm or more of concrete has a major impact on building response, peak loads and the type of structure that is needed. Slab-on-grade construction, i.e. elimination of the basement, makes a floor heating system more cost-effective and provides thermal mass for storage of passive solar gains. A mix of radiant and convective heating/cooling also has a major impact on the envelope decisions.

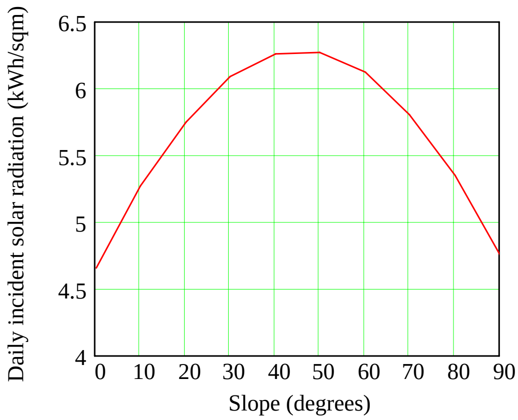

Figure 2. Total solar radiation (kWh/sq.m.) incident on a clear day on an inclined south-facing surface as a function of tilt angle for latitude 45 degrees (for September 21).

Modeling detail and thermal zones at the early design stage. A third major question is that of modeling detail. During the early design stages of a building, when the geometry is not finalized, the designer or software should make assumptions about basic thermal zones, their interaction and dynamic building response. In sizing windows for passive solar design, a decision needs to be made about how much thermal mass to include, as well as on solar gain control (active or passive). Obviously, some degree of dynamic analysis (at least for design days) is needed at the early design stage. This paper will also partly examine some of the possible approaches that can address this need, including the feasibility of guiding the design tool through heuristics.

Two approaches are possible – development of a customized simulation-design tool, or utilization of a detailed simulation tool with a front end that hides most of the required inputs such as window dimensions, generating them – for example, from a specified percentage façade area. If a detailed simulation tool is utilized with an "expert system" front end, it will also allow mappings of thermal storage options (such as high mass, medium, low). The issue of positioning windows on facades considering both thermal and daylighting aspects- starting from an optimal percentage of window area on each façade- is considered a detailed design issue.

A promising possibility for a customized design tool involves developing a graphical design interface with HOT3000 to take advantage of the sophisticated ESP-r simulation engine. The user would have the option of generating an original layout, or selecting among a population of solar optimized typologies that would be previously developed by extensive parametric analysis. A solar scoreboard window would interactively reflect the status of various key performance parameters (daylighting quality, solar heating fraction, power generation, cost, etc.) as the conceptual design is manipulated. The user would be able to assess, for example, the trade-off between larger north-facing window areas for view versus a more thermally efficient and opaque building envelope. As well, user generated values for key parameters could be compared to performance statistics from an online database, so that the performance of the proposed design could be assessed in relation to highly optimized, state-of-the-art precedents for a particular climatic location. A fully innovative approach would be to develop the application to behave as a gaming/design tool so that conceptual design files could be downloaded to a Web site and the scores automatically posted to a database. Thus, solar building performance simulation statistics would be self-generating by the user community and provide an insight to what is potentially achievable for a given mix of solar building technologies.

An increasingly popular component of Canadian homes is a **3-season or 4-season solarium** connected through a patio door to a kitchen or family room. Generally, the 3-season solarium has single glazing while the 4-season one is double glazed conditioned space suitable for all seasons, although still somewhat cool at night in winter. A 3-season solarium may experience indoor temperatures in the range 10-30 C even in winter and be designed to store and release thermal energy in this range. In such a case, it needs to be considered as a special thermal zone with this temperature variation.

The question of modeling detail at the early design stage needs to be considered further. Generally if we were to represent dynamic thermal effects with the minimum level of detail in a custom-developed conceptual design tool, the thermal mass in each zone should be represented by one lumped thermal capacity, and all the windows areas on one façade added together as an equivalent large window for each zone. For example, in the case of the two-storey home in Figure 3, one would need a fourth-order thermal network (four capacitances), plus interconnecting resistances. The conceptual design tool does not have to be extremely accurate in terms of performance prediction. It should however show the impact of important design parameters (thermal mass, window area, etc) in the simplest way, in order to guide the designers.

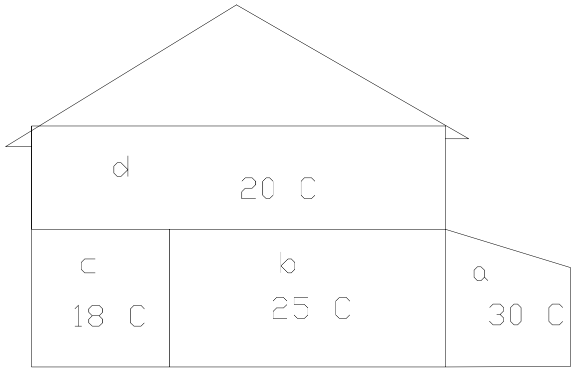

Figure 3. A likely distribution of interior temperatures in a two-storey passive solar home in February on a clear day. Zone a is an attached solarium, zone b is a direct gain zone, while c and d are zones with low solar gains.

A DESIGN AND SIMULATION WORKSHOP TO FURTHER DEVELOP REQUIREMENTS FOR THE DESIGN TOOL

This paper has outlined some of the requirements and considerations in the development of a design tool suitable for dynamic analysis and solar optimization at the early design stage. A design and simulation workshop is planned at the Network meeting in August 2006 to complete this exercise.

The Solar Buildings Design Tool Workshop forms part of a larger effort to develop a conceptual design tool that can account for available solar technologies. At this stage, the workshop seeks to achieve the following objectives:

- To identify gaps in knowledge, simulation software or design methodologies to more effectively direct future research and the development of suitable conceptual design tools;

- To compare the predicted performance of various solar building design technologies and strategies within the context of single-family detached housing;
- To examine critical solar building strategies and their corresponding assessment parameters (performance metrics) to better inform the design process;
- To determine which, if any, heuristics for the design of solar buildings are valid, applicable and programmable.

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 (this remains, in fact, to be determined from the workshop):

(a) 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

(b) Active Elements

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

The workshop participants will perform design and simulation of a two-storey home without a basement with different simulation tools before the workshop. At the workshop, they will present their designs and simulations, discuss the procedure that they followed, assumptions that they made and shortcomings/needs in the software used. The design tools will include ESPr, TRNSYS, eQuest, Mathcad custom developed thermal network models/software etc. It is expected that senior doctoral students, PDFs and other researchers will also participate in this exercise.

The lot to be considered (see Fig. 4) is 18 m wide by 25 m deep and is situated in Montreal. A 2-storey rectangular house with a total floor area of 180 m^2 is to be centered on the lot keeping a minimum of 2 m at the edges of the lot. The house will be built using exterior walls made of 2” x 6” studs with 2” exterior insulating sheathing for a total R-value of 30; the roof is R40. The windows are to be double glazed windows with a low-e coating and argon fill. The house is to include roof integrated photovoltaic panels and solar thermal collectors. The modeled heating and cooling load of the house will be reduced by changing different parameters, including: the depth to width ratio of the house, window size and location, roof shape, use of window shades and overhangs, and type, location and amount of thermal mass (floor mass only on bottom level, wall mass in lower and upper levels). Similar houses exist on both sides. The possibility of shading may be considered if appropriate. A suggested location of a one-car garage is shown (facing NE).

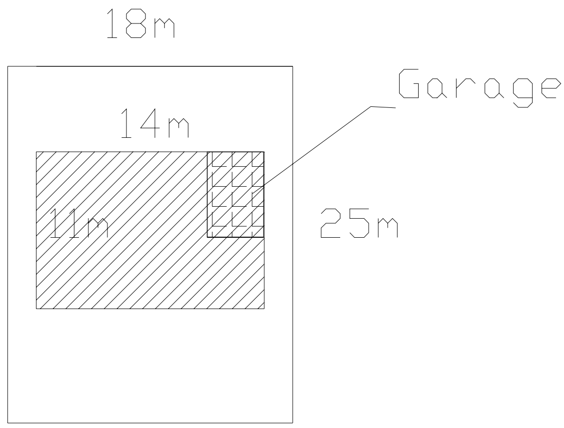

Figure 4. The lot (18 m x 25 m) to be considered in the design tool workshop. 2-storey, 180 m^2 rectangular house must be centered on lot with a minimum of 2 m on lot edges.

The participants will go through the modeling exercise and take note of assumptions and modeling approaches that were followed, as well the design process that they followed. Any limitations found with the modeling software being used will also be identified. The participants should take particular care on how the PV panels, solar thermal collectors and solar thermal storage tanks were integrated within the building design and how building thermal mass is represented. An explanation on the assumptions made for the zoning strategy used in the modeling will be given including recommendations on how zoning should be approached in the future. Finally, the participants will explain how shadowing effects from neighboring buildings were included in the modeling and how they affected the results. A discussion on how shadowing on the roof solar thermal and PV panels can be considered to include self shading from other building elements, and shading from trees will also be included. Shadowing effects from trees do not pose too big a risk in new neighborhoods, however, occupants should be aware of how far away they need to plant trees in order to avoid any shading of their PV panels in the future, which could result in considerably reducing the performance of the PV array.

CONCLUSION

This paper discussed the requirements and considerations for the development of a conceptual design tool that can be used for solar-optimized building design. The solar optimization process refers to optimization of form so as to (1) capture as much solar radiation as possible on the two main surfaces facing near south – a façade and a suitably oriented roof section, and (2) to utilize as much as possible of the captured solar energy as daylight, converted to electricity and/or converted to heat. It is concluded that the developed design tool, in order to have as much impact on the design as possible should permit some degree of detailed analysis at the early design stage. Two approaches are possible – development of a customized simulation-design tool, or utilization of detailed simulation tool with a front end that hides most of the required inputs. A design tool workshop to be held at the Solar Buildings Research Network Conference will provide further input to the development of the design tool.

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