Build Simul (2008) 1: 336−355
DOI 10.1007/s12273-008-8430-3
RESEARCH ARTICLE

Simulation-Enhanced Prototyping of an Experimental Solar House

Ruchi Choudhary(✉), Godfried Augenbroe, Russell Gentry, Huafen Hu

College of Architecture, Georgia Institute of Technology, 247 Fourth Street NW, Atlanta, GA 30332-0155, USA

Received: 30 August 2008 / Revised: 10 November 2008 / Accepted: 17 November 2008

Abstract The subject of this paper is the design analysis process of an experimental solar house, driven by the overarching goal to obtain net-zero energy performance while being functionally optimal and architecturally ambitious. The house was commissioned to participate in an international solar home competition called the Solar Decathlon. The paper demonstrates the use of simulation to support design decisions at various stages of the design process. Through it, the paper highlights attributes of simulation tools that are needed for supporting the design process effectively. In addition, this paper shows a novel use of building simulation by extending it to also inform the final use and operation of the house during the competition period. Finally, the paper also contributes to the design of solar homes by showing how their performance assessment and evaluation criteria can be different from homes that are served by the grid.

Keywords energy analysis, solar house, design analysis process, building simulation

1 Introduction

Support of the building design process through its different evolutionary steps has been discussed by many authors. Relevant work has addressed generalized design theories (Tomiyama and Yoshikawa 1986), specific computational environments (Mahdavi 1999), case studies (Lam et al. 2001) and delivery to the profession (McElroy et al. 2001). There is no single tool that supports all design stages; indeed, it is generally accepted that building design is too complex to be encoded as a "predictable" process, or to be managed as a formalized and codified set of steps with logical dependencies and associated information flows between separate activities. An appealing suggestion then is to instead use an arsenal of different tools to support the design process on an as-needed basis and to perform increasingly more refined analyses of incremental design decisions. The US Department of Energy documents over 300 building analysis tools for evaluating building performance measures such as energy use, component and system efficiencies etc. (www.eere.energy.gov/buildings/tools_directory). They range from tools that can be used at different stages of the design and for a large range of performance aspects such as heat transfer, daylighting, ventilation, and moisture control. Given that these tools are effective insofar they can be used for supporting the design process, it can be said that our available palette of tools is adequate if it can be used to respond to queries associated with design choices. While a comprehensive comparison of most energy simulation tools can be found in (Crawley 2008), it is still difficult to confirm if our current list of analytic tools are in fact able to respond to the dynamic demands of design process. One of the ways to prove this would be to build enough evidence of "how" these tools are used. Most existing records of design analysis demonstrate use of simulations as defense mechanisms for design decisions, rather than as tools for process-support.

This paper presents incremental stages of analysis for supporting the design and construction process of an experimental solar house. It is an in vitro case study of design evolution driven by a unique set of objectives that necessitate detailed analysis at various stages. The paper outlines the major milestone decisions in the evolution of the project. It does so with emphasis on the use of simulation tools for supporting design decisions. The qualifiers "solar" and "experimental" are important to note because

E-mail: ruchi.choudhary@coa.gatech.edu

they allow additional insights into two more attributes often desired in simulation tools: (a) representation of non-standard building systems and their configurations, and (b) instrumentation of novel concepts of design or building use/implementation.

2 Design analysis context

2.1 Overview of the competition

The Solar Decathlon competition invites 20 student teams from international universities to design, build, and operate a 74m^2 (800ft^2) all electric solar powered house within a tight set of performance criteria. All participating teams are required to transport their house to Washington DC for a specified week (October 2007 in this case). During this week each house is judged based on a range of subjective and objective contests related to architecture, overall engineering strategy, energy balance, maintaining specified range of temperature and humidity, operating prescribed appliances within a specific schedule and range, domestic water heating at specific temperatures, lighting design, and powering an electric car (Fig. 1). The subjective scores are given by examining committees that judge the design, marketability, and engineering design strategies of the house. The objective scores test the house as it operates during the competition week through continuously monitored points and by tasks that are representative of common daily energy needs of a typical US home (Fig. 2). One point that should be noted here is that although the objective contests are seemingly designed to test how the house will operate under the typical energy load of a US single family residence, in reality they are stricter. As an example, Fig. 3

Contest	Points	
Architecture	200	675 subjective scores
Engineering	150	
Marketability	150	
Communications	100	
Lighting design	75	
Lighting measurement	25	525 monitored points
Comfort zone	100	
Appliances	100	
Hot water	100	
Energy balance	100	
Getting around	100	
Total	1200	

Fig. 1 Solar Decathlon competition score distribution

shows the typical thermal comfort range recommended by ASHRAE. The green overlay on the figure shows the range that must be maintained for getting full points in the comfort contest. Similar constraints apply for hot water temperature, use of electric lights, and running appliances. In sum, the house's design and operation are put to test under a set of measures that are higher than the typical occupant demand-profiles of residences.

The Solar Decathlon competition is run by the US Department of Energy for promoting the adoption of solar technologies by the US residential market. In the 2002 competition, the focus was on the market appeal of residential solar technologies, and most objective scores were directed towards how the house performed *off-grid* during the competition period. However, the US Department of Energy wants to target the growth of the photovoltaics (PV) market in grid-connected applications. Hence, since 2005, some percentages of the subjective competition

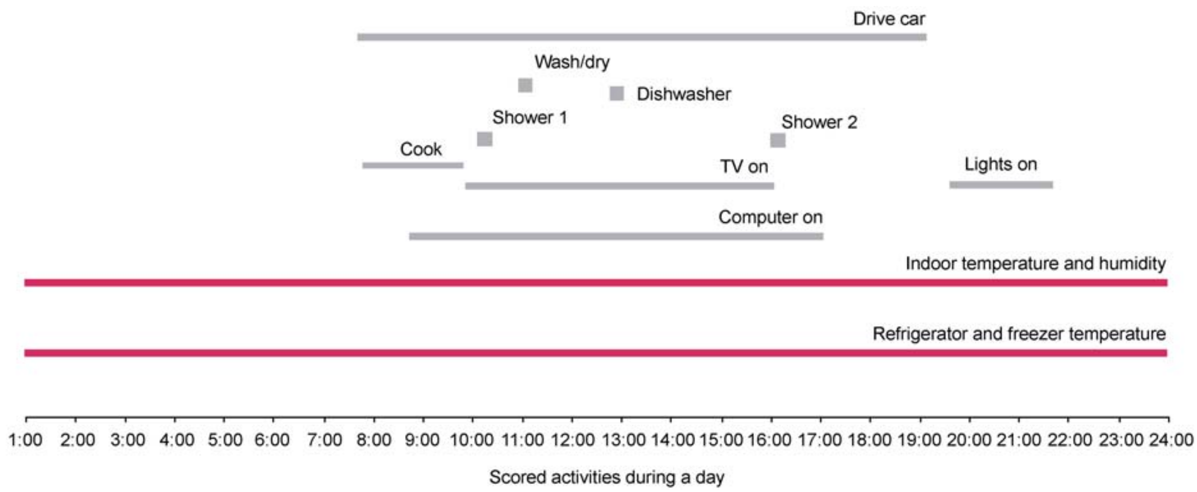

Fig. 2 Continuous and task-related objective contests during the Solar Decathlon competition week

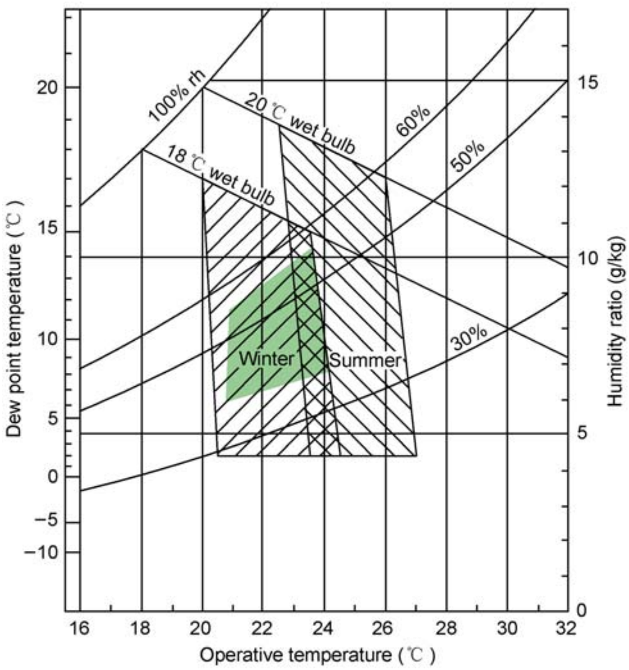

Fig. 3 Required thermal comfort range for the comfort zone contest

scores were allocated to the projected energy performance of the house, thus requiring all participating teams to demonstrate how the house would perform as a grid-connected house in a chosen location. This requirement was further stressed in 2007, requiring teams to compute levelized cost of energy projected over 30 years using the Building America Benchmark procedures (Hendron 2006) both for the schematic and final design of the house.

In addition to these specifications, the competition precipitates a building project ridden with many other requirements. For one, a competition is the venue for pushing boundaries in current design and applications of solar homes and hence in principal must encourage non-standard solutions. Second, the house is designed and constructed by a team of students and relies heavily on donated materials and equipment by the industry. It hence defies the typical metrics and rules of construction and cost management and instead privileges teaching and learning. Each team is given one year during which they design and construct the house. Third, the house is built in the home location of the university, but then transported to Washington DC and operated there fully for a week. This poses severe constraints on weight and assembly of the house, thus affecting choice of materials and construction. Finally, the house has to comply not only with international building codes and local codes where the house is built, but also with a long list of regulations associated with the competition (www.solardecathlon/rules).

2.2 The design concept

In addition to the competition requirements, the Georgia Tech entry for the Solar Decathlon house began with another equally strong, albeit sometimes competing, objective of integrating solar technology within contemporary architectural practice through the following question:

> "Is the integration of solar design principles, and their allied technologies, within contemporary works of architecture environmentally and economical feasible given the increasing desire on the part of designers and consumers for spatial and architectural transparency?" (Trubiano 2007)

Hence, the development of the house proceeded under the fundamental design intent of exploring transparency via novel skin strategies within the single-family residential scale. This goal was translated into design primarily through a translucent roof and wall assembly and a clerestory window that runs across the entire perimeter of the house (Fig. 4; Trubiano 2008). The entire roof of the house is lightweight and translucent. The PV panels above the roof are part of an operable shading system that prevent or allow direct solar gains as needed. The clerestory window is conceived as an element that distinguishes the roof as different and independent from the walls, and thus runs all around the perimeter of the house. Although both the roof and the clerestory window are uniform throughout, the house is spatially divided into two distinct zones (Fig. 5). The main living space of the house is conceived to be a light-filled space offering abundant views at all sight angles: views of the sky through clerestory windows and exterior views at eye level and the ground through large uninterrupted glass doors. The large amounts of direct light coming into the space is complemented with diffused light coming in through the translucent roof and wall panels (also translucent) on the south and west. The second zone

Fig. 4 Early model of the house demonstrating the main architectural concept

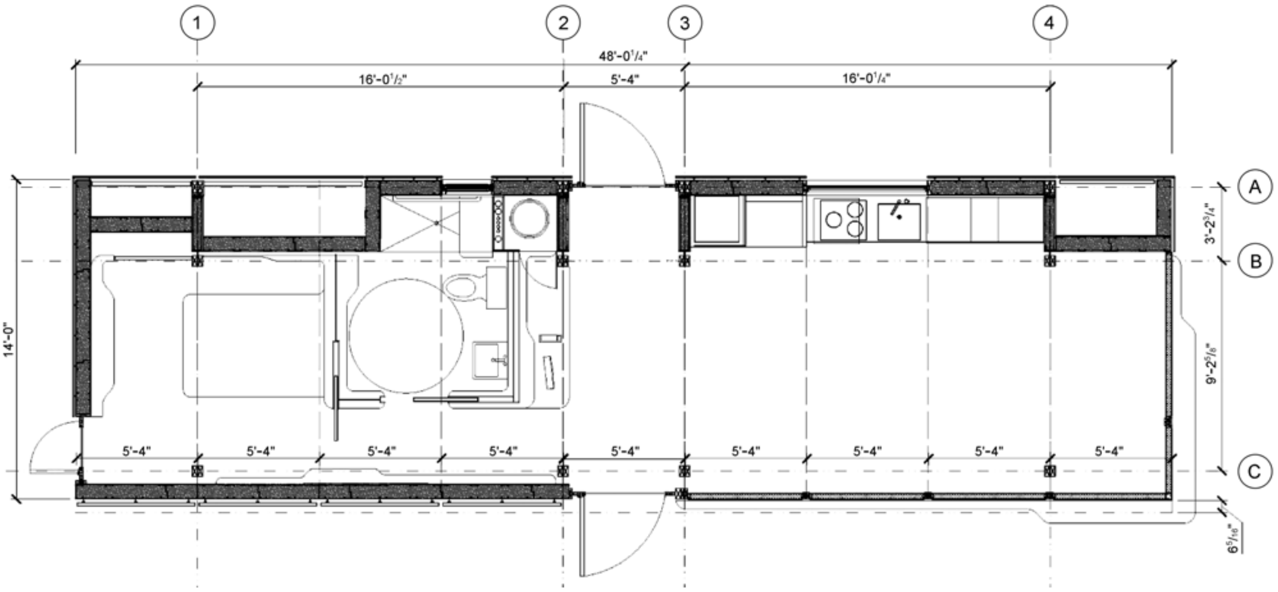

Fig. 5 Floor plan of the house

(the bedroom) is relatively less open, enclosed with structurally insulated wall panels.

3 Design analysis process

3.1 Analysis needs

Although the subject of analysis is a relatively small solar house, the combined set of competition requirements and design intents yield a complex analysis problem in many ways. For one, since this is an all-electric solar house, it is important that energy supply is synchronous with the demands. The house and its systems (lighting, heating, ventilation and air-conditioning (HVAC), PV, domestic hot water (DHW)) have to be thus designed and sized carefully so as to avoid mismatch between design and projected performance. Second, section 2.2 shows that like most experiments in design, this project encompassed a broader logic of development than a derivative solution that met all the competition requirements. The fundamental commitment of the design towards exploring transparency at the residential scale can be challenging even for base requirements of performance efficiency, let alone stricter mandates such as net-zero energy consumption. It hence became critical that design development is backed and informed by analysis that can guide it towards feasibility and trouble-shoot where necessary. Finally, this is a case where the analysis must not only support the design process, but also its optimal operation targeted towards maximizing competition points. This implied that the analysis process has to extend beyond the design stage to predict and provide feedback on how to best control the house during the competition week.

The key objectives thus formulated for the analysis are:

a. to provide quick estimates of energy loads in response to concept-level design queries posed by the design team, when many design elements are still unresolved;
b. to guide appropriate selection of system components for controlling the indoor conditions of the house;
c. to support the incremental development and fine-tuning the design of the house's components;
d. to develop a simulation strategy that would be extendable to final testing and commissioning of building systems and components;
e. to develop a simulation-based optimal control strategy that would be used for achieving required operational conditions during the competition period.

The simulation strategy thus formulated is illustrated in Fig. 6. It shows the three distinct phases of design analysis. The first phase is based using a steady state thermal model to compute rough estimates of the house's energy demand to inform concept-level design and system choices. This model is replaced with a lumped finite element model in which the "lumps" and flows are replaced as needed when more detailed representations of components become available. In the third step, the simulated systems are calibrated with their real world counterparts. The calibration of simulated component with a real component is enabled via the control system of the house. The third step results in a full size calibrated simulation model of the house synchronized with a real-time control system that guides optimal operation of all house components.

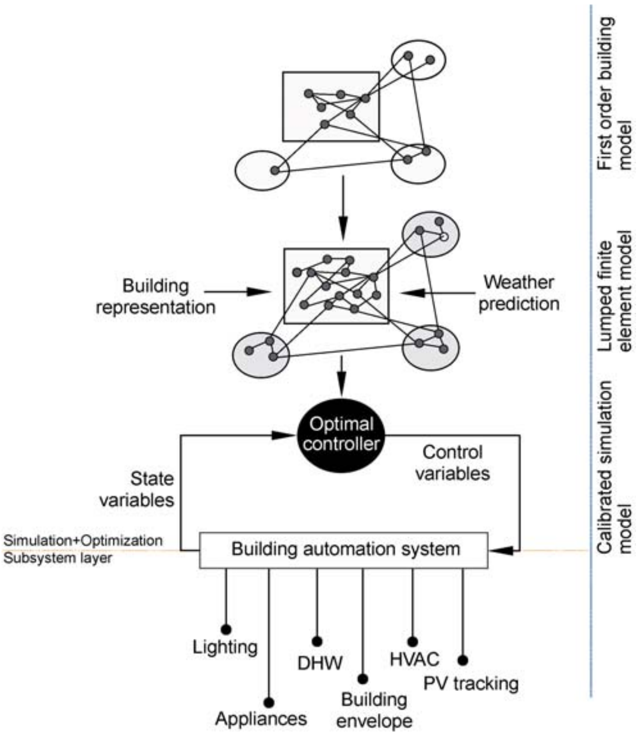

Fig. 6 Three step simulation strategy

3.2 Simulation requirements

Steps (a) to (b) are generally expected from any design analysis process. If the design context is typical these steps can be well supported by using existing set of simulation tools to support or endorse expectations of the building's performance. Yet, our arsenal of simulation tools becomes progressively weaker as design solutions become more innovative—both in being able to represent the design problems and offering credible feedback. The Georgia Tech Solar Decathlon house incorporates many innovative materials, equipment, and control strategies in addition to its solar electric and hot water system. Available simulation models could not be used because they do now allow "short" representation of all the house's systems in one model, as required for early stages in design, without heavy implicit assumptions. In addition, steps (d) and (e) imply a high level of interaction between the predicted and actual behaviour of the system in real time. These require analysis models which can be used to explicitly represent and observe the dynamic behaviour of all of the house's components, systems, as well as their control strategies.

3.3 Simulation tool development

This section describes two main tools that were developed solely for the purpose of supporting the design analysis process of the Georgia Tech Solar Decathlon house. These tools formed the basis of most of the analysis process, supported as and when needed by other existing tools.

A quick energy estimate spreadsheet called *HandCalculator* was created in the very beginning of Solar Decathlon project. *HandCalculator* was used to offer quick estimates of annual heating/cooling load as a function of design changes and to visualize the resulting differences in the annual energy production and consumption curves of the house. This tool served steps (a) and (b) of the process—to estimate the extent to which any design decision would influence the difference between average energy production and consumption for each month.

HandCalculator estimates heating load based on steady state heat transfer for heating loads shown in Eqs. (1)–(4) and cooling loads in Eqs. (5)–(6) (SI units have been used for all parameters). The calculations follow closely the normative calculation schemes as defined in current standards (NEN 1999; ISO 2008). Although these standards focus on non-residential buildings, the part that defines the calculation scheme for the heating and cooling demand is equally valid for residential buildings.

$$Q_{heating} = Q_{loss} - \eta_h \times Q_{gain} \tag{1}$$

$$Q_{loss} = \Sigma U_i A_i \Delta T_i + V_{air} \rho C_{air} \Delta T \zeta \tag{2}$$

$$Q_{gain} = Q_{int} + Q_{solgain} \tag{3}$$

$$Q_{solgain} = Q_{facade} \times A_{opaque} \times U_{opaque}/h_{total} \times \varepsilon_{sol} + Q_{facade} \times A_{transparent} \times \text{SHGC} \tag{4}$$

where,

$Q_{heating}$: heating load;
Q_{loss}: heat loss from the house;
Q_{gain}: heat gain of the house;
U_i: conductivity of each house component;
A_i: area of each house component;
V_{air}: volume air flow rate;
ρ: air density;
C_{air}: air thermal capacity;
ΔT: the temperature difference between ambient air and indoor air ($T_{amb} - T_{air}$);
Q_{int}: internal gains;
$Q_{solgain}$: solar gains;
η_h: heat utilization factor;
ζ: side effect coefficient of ventilation;
Q_{facade}: solar radiation falling on a facade;
A_{opaque}: opaque envelope area;
U_{opaque}: the U-value of a piece of opaque envelope;
h_{total}: the effective heat transfer coefficient over exterior surfaces;
ε_{sol}: solar absorptance of the opaque surface;

$A_{transparent}$: transparent envelope area;
SHGC: solar heat gain coefficient of transparent envelope.

$$Q_{cooling} = Q_{gain} - \eta_c \times Q_{loss} \quad (5)$$

$$Q_{gain} = \Sigma U_i A_i \Delta T_i + V_{air} \rho C_{air} \Delta T \cdot \zeta + Q_{int} + Q_{solgain} \quad (6)$$

where,
η_c: cooling utilization factor.

Both utilization factors have significant impacts to space load and more details on how to estimate them are addressed in (NEN 1999).

The second model, *GTSim*, is a finite element based simulation model programmed in MATLAB (www.mathworks.com) in which the house's solid components are discretized in a finite element mesh, whereas other heat and mass flows are represented by lumped elements (e.g., ventilation flows, boundary convective flows, radiation exchange). The model is deliberately kept "lightweight", e.g., all solid components (such as walls, windows, ground mass) are modelled with only one-dimensional elements. Figure 7 shows a schematic representation of the model mesh. The space discretization shown in the figure leads to the well-known formulation when the finite element technique is used:

$$\boldsymbol{M}(\boldsymbol{\theta}, t)\mathrm{d}\boldsymbol{\theta}/\mathrm{d}t + \boldsymbol{S}(\boldsymbol{\theta}, t)\boldsymbol{\theta} = \boldsymbol{f}(\boldsymbol{\theta}, t) \quad (7)$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{S}$ is the stiffness (or conductivity) matrix and $\boldsymbol{f}$ is the load vector (solar loads). The state vector $\boldsymbol{\theta}$ represents, depending on type of node, the unknown state variables—temperature, stored energy level, and humidity. As some of the equations have a zero mass matrix, it should be noted that the system in Eq. (1) is a differential algebraic system. The system is time variant and nonlinear as a result of the terms that reflect time and/or temperature dependency, such as results of time varying ventilation flows, movable insulation panels, and temperature dependent heat transfer coefficients. At each time step *GTSim* uses instant weather information from a weather file, updates all three matrixes ($\boldsymbol{M}, \boldsymbol{S}, \boldsymbol{f}$) and solves the updated set of DAEs, returning temperature values at each node. Space heating/cooling load are estimated based on user-supplied heating/cooling set-points. The model has been validated with other equivalent energy simulation models such as EnergyPlus (www.eere.energy.gov/buildings/energyplus).

GTSim is completely transparent and not limited by preset simulation skins/interfaces. New elements, systems, and control strategies can be added and implemented whenever needed. This was an important advantage because in this project neither the architectural design nor the building control were typical in the traditional sense that most existing simulation tools are designed to be based on. *GTSim* was used for two main purposes during the design process: (1) the study of behaviour under peak loads, in

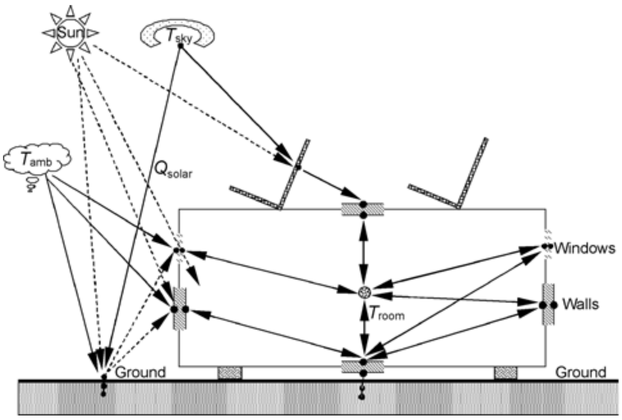

Fig. 7 Schematic representation of the house's dynamic simulation model

relation to equipment sizing, comfort and consumption patterns, (2) fine tuning and verification of dynamic control strategies. Additionally, *GTSim* was also used for implementing a simulation-based control and optimization model to guide the operation of the house during the competition period, for which, its base model was extended by adding the control vector $\boldsymbol{u}$ explicitly to the system equations:

$$\boldsymbol{M}(\boldsymbol{\theta}, t)\mathrm{d}\boldsymbol{\theta}/\mathrm{d}t + \boldsymbol{S}(\boldsymbol{\theta}, t; \boldsymbol{u})\boldsymbol{\theta} = \boldsymbol{f}(\boldsymbol{\theta}, t; \boldsymbol{u}) \quad (8)$$

Each control variable u_i in the vector $\boldsymbol{u}$ represents a particular device action (e.g., by an actuator) or occupant intervention in the system behaviour. It should be mentioned upfront that the details of the optimal control model were trickier to implement, and depended a lot on first calibrating the simulation model to actual system behaviours. Still, later sections of the paper show how the actual performance of the house during the competition week gives insights for further development of this model, and it in fact represents research in progress.

4 The simulation storybook

This section is a documented record of selected parts of the design analysis process that spanned the design, construction, and operation of the Georgia Tech Solar Decathlon house. The parts shown in the paper highlight those instances where design analysis was particularly important. For example, in synchronizing the energy supply and demand of the house, in the development of the translucent roof, and designing control strategies for the house. The sectional divisions do not suggest a sequential design process, rather, they reflect different resolutions of the process from the time meta-level design decisions were being made to the final operation of the house during the competition.

4.1 Preliminary design analysis

Purpose: to reduce the total energy consumption of the house and to size the total PV array.

Method: (a) evaluate alternative building-skin materials and their configurations for energy savings against a base-case house, (b) match energy supply and demand curves, and (c) select properties and location of key system components of the house.

Tools: *HandCalculator*, Ecotect (www.ecotect.com), PV Supply Hand Calculation.

4.1.1 Establishing the base-case design

The base-case house is the initial design proposed by the design team. The key design aspects of this house were manifested through three elements: (a) a translucent roof, (b) translucent south and east walls, and (c) a 0.762m (2ft6in) clerestory window running along the entire perimeter of the house. The base-case house is designed for the climate of Atlanta, GA since this is where the house will be located. However, since the same house is expected to operate in Washington DC for the competition, some of the analysis (especially for assessing aspects implicating competition strategy rather than long-term performance) is based on the Washington DC climate. This variation, when applied, is indicated in the results. The main specifications of the base-case house are summarized in Table 1.

An estimation of the expected household energy consumption is fundamental for the design and operation of a residential photovoltaic system and of the house's electrical system. However, accurate values of the expected power consumption of each system and appliance cannot be obtained until the specific equipment that is to be used is decided and is available. Therefore, reasonable estimates were assumed based on typical power consumption profiles of high performance systems and appliances. A typical average and peak daily electric demand profile was thus generated and translated into a preliminary total daily energy demand of the house at 18.66kW·h, based on information found in (Hendron 2006). Assuming three days autonomy, this resulted in estimating the PV array requirement to be approximately 6 – 8kW for an off-grid battery operated system (this range also accounts for optimum tilt versus no tilt of the PV panels).

The PV panels had to geometrically fit within the 4.3m× 14.6m (14ft× 48ft) roof and rotated to their optimal tilt angle with respect to the solar incidence. In addition, the PV rows had to be spaced within the 4.3m width so that the panels would not self-shade one another at any tilt angle. Combined with retractable shading devices, these panels also had to shade the roof completely when gains from direct solar radiation were undesirable. Values of solar insolation at all points on the roof surface were used for deriving sizes of the shading devices needed to fully protect the roof. A series of geometric shadow analysis (using Ecotect and hand calculations) were used to compute the shadow lengths cast by the PV panels at the minimum and maximum tilt angles and to therefore determine the optimum distance between each row.

4.1.2 Development of the roof assembly

Among all of the elements of the house, the roof was the most challenging to model. It was initially proposed as an ETFE pillow inflated with low pressure air. Several issues made it an infeasible component for the house:

- R-value: as shown Fig. 8, the R-value of the ETFE pillow is 1.7m^2·K/W (9.6h·ft^2·°F/Btu). This is much below the standard R-value of the roof (R-38), and had to be immediately addressed even before establishing an analysis of the base-case design. The key issue was that although ETFE pillows have a thermal advantage over double glazing, they needed to perform as a roof in this house.
- Noise levels: ETFE pillows are acoustically transparent with an extremely low coefficient of fading (8dB). This can be especially problematic for noise levels inside the house due to rain (Robinson 2005).

Table 1 Summary of the base-case house for energy analysis

Location	Atlanta, GA
Climate information	Monthly ambient temperatures, ground temperatures, and solar radiation
Building information	
Thermal zone description/geometry	Single floor rectangular building 14.6m× 4.6m (48ft× 15ft), flat roof shaded with PV panels; two exterior doors, with orientations of north and south respectively
Surface construction elements	North and west wall: structurally insulated panels; south wall: 50% structurally insulated panels and 50% polycarbonate panels with aerogel insulation; east wall: polycarbonate panels with aerogel insulation; roof: ethylene tetra fluoro ethylene (ETFE) foil pillows filled with air at low pressure shaded by integrated and operable PV panels & shading panels; windows and doors: triple-glazed, low-e
Internal gains and equipment loads	Typical values of US residences (with operational schedules for PV simulation) based on Building America Research Benchmark Definition (Hendron 2006)

- The pillows are fed via a two pumps that dehumidify the air inside the pillow and keep the pillow pressurized. The pump requires about 100W of power and needs to run for 2 – 3 hours in the day (information provided by manufacturers).

The main question at this point was how much would be the minimum R-value required for the house to be feasible in its given context? Analysis showed that it was critical that the roof should have an R-value of at least 3.54m^2·K/W (20h·ft^2·°F/Btu) and be well shaded during the summer months to prevent direct solar gains. In order to increase the R-value of the ETFE pillows, the design team configured a section with four ETFE films, where the three films on the top would be filled with two layers of aerogel insulation (Fig. 9). This way, the R-value could be increased without compromising the translucency of the roof. By doing so, the average R-value of 20h·ft^2·°F/Btu could be attained.

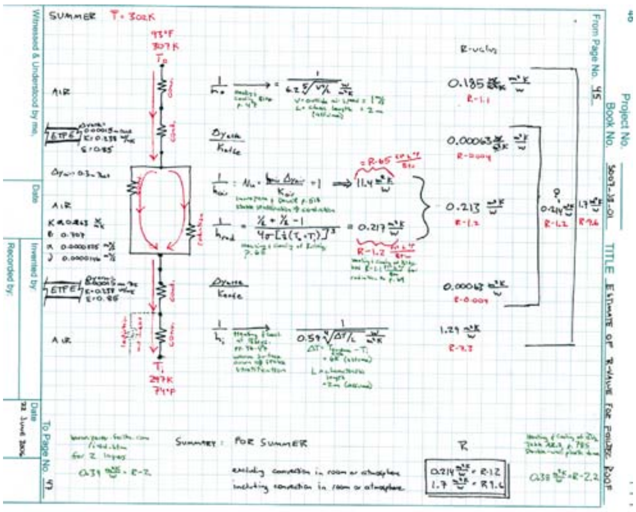

Fig. 8 R-value calculations from the first iteration of ETFE analysis in 06/2006

Zone no.	Total area	Proportional area	R-value	Area-weighted R-value
	m^2	%	m^2·K/W	m^2·K/W
Zone 1	19.04	29.4	4.19	1.23
Zone 2	38.07	58.9	3.28	1.93
Zone 3	5.51	8.5	0.71	0.06
Zone 4	2.04	3.2	5.07	0.16
			R_{avg}	3.38 (19.13h·ft^2·°F/Btu)

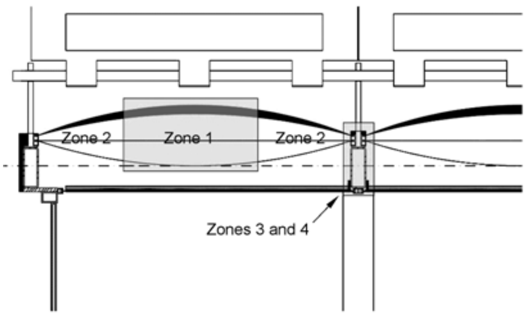

Fig. 9 R-value calculations from the second iteration of ETFE analysis in 11/2006

While 2.3 inches of aerogel insulation increased the overall area-weighted R-value to a reasonable range (R-20), it was not satisfactory because of the large variation between the edges of the pillow to the center. In addition, the electric pump required to maintain the air pressure and acoustic transparency still remained.

At this point, the following requirement list was established for the ETFE roof assembly:

- The R-value of the roof section must be at least 20h·ft^2·°F/Btu at every point in the roof section (except at structural frame).
- The ETFE section must have a weather barrier for water proofing and reducing noise.
- No pump shall be required for the roof.

The final configuration of the roof developed by Hightex / Cabot meets these specifications. Figure 10 shows the layers of the assembly. Detailed properties of each layer are shown in Table 2. Although the values shown in Table 2 result from a series of discussions with the manufacturer later in the construction process, they are consistent with the ranges derived from the analysis and given to the design team as specifications.

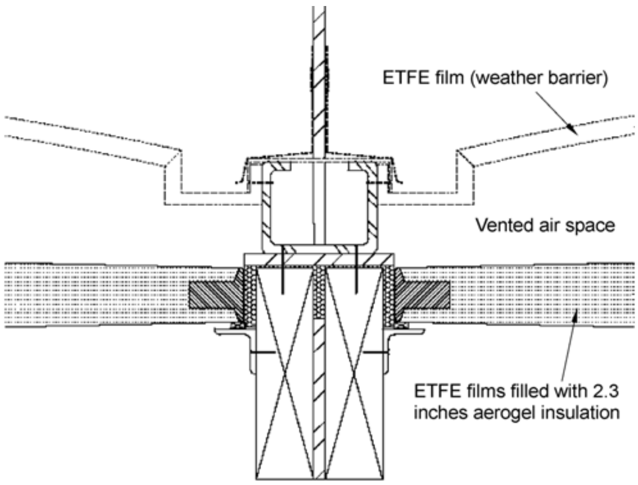

Fig. 10 Section showing the final design of the ETFE roof assembly

Having established a range of properties that would make the ETFE roof feasible, several design alternatives (listed in Table 3) were assessed and compared with respect to the total monthly energy demand of the house over the year. The shading of the roof by the PV panels and shading devices was modelled in *HandCalculator* by lowering the shading coefficient of the roof assembly. The systems included in this analysis are: space heating, space cooling, lights, and plug-ins (DHW, electric car charging, and ventilation systems) are not represented at this stage.

As shown in Table 4, changing the roof to a standard opaque flat roof does not affect energy savings (options 2,

Table 2 Solar/thermal properties of the final iteration of the ETFE roof assembly

Layer	Density (kg/m^3)	Specific heat capacity (J/(kg·K))	Thermal conductivity (W/(m·K))	Thickness (m)	Source
ETFE weather barrier	1750	250	0.24	0.0002	Hightex/Cabot
ETFE membrane	1750	250	0.24	0.0002	
Nanogel	90	800	0.0168	0.06	
ETFE membrane	1750	250	0.24	0.0002	
ETFE solar transmittance = 0.9 per film, solar absorptance = 0.027 per film, solar reflectance = 0.07 per film					
Nanogel solar transmittance = 0.24, solar absorptance ~ 0					

Table 3 List of alternatives compared at early design stages

Options List	
Option 1:	remove north clerestory and extend the structural insulated panel (SIP) walls all the way to the roof
Option 2:	replace roof by standard R-38
Option 3:	remove east and west clerestory and replace them by SIP walls
Option 4:	replace south clerestory by SIP walls
Option 5:	option 2 + no frame effects (overall heat loss coefficient (UA factor) = 48)
Option 6:	replace 50% by R-38 and the other half by glass
Option 7:	option 6 + change 10m^2 south SIP wall into windows
Option 8:	reduce height of clerestory windows

Table 4 Comparative studies for reducing total energy consumption

Month	Energy consumption (kW·h)								
	Base case design	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
1	869	866	790	874	914	702	666	655	506
2	663	663	606	668	698	545	550	571	514
3	596	595	558	599	612	520	632	686	397
4	513	503	494	506	504	479	701	759	425
5	514	482	517	488	476	523	855	911	482
6	546	499	554	510	499	563	931	982	543
7	641	593	641	604	589	641	1009	1064	579
8	576	537	583	543	518	590	917	980	564
9	501	477	505	478	452	512	762	831	496
10	519	510	503	512	509	489	638	707	729
11	603	601	560	606	630	514	539	569	532
12	769	766	704	773	808	631	610	605	484
Sum	7310	7093	7015	7160	7209	6707	8809	9319	6251
% reduction in annual energy		3.0%	4.0%	2.1%	1.4%	8.2%	−20.5%	−27.5%	14.5%

5, and 6). In fact, the results suggest that the energy balance of the house is best maintained by increasing solar gains in the winter time (or by increase in internal loads). Cooling could potentially be decreased during the summer months by introducing natural ventilation strategies, such as opening the doors and the clerestory windows to allow cross ventilation during the summer months. In fact it was not the roof, but a reduction in the height of the clerestory windows that yielded maximum energy savings when compared to the base-case house.

4.1.3 Sizing the solar array

Following design development and as more details became available, it was necessary to re-examine the energy consumption of the house against energy produced by the PV system. Figure 11 shows the annual difference in supply and demand curves for this house for the weather of Atlanta. The values shown (also listed in Table 5) represent monthly totals.

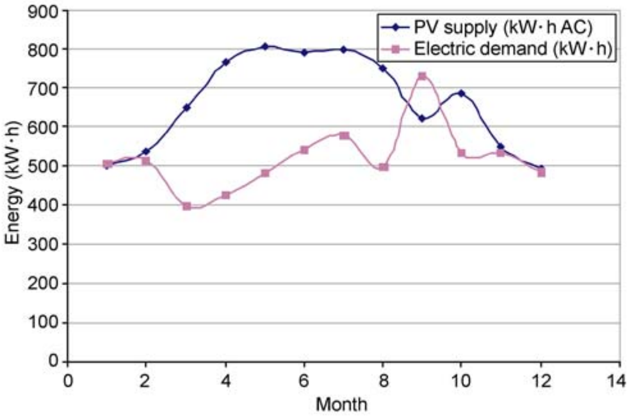

Fig. 11 Comparison between supply and demand curves at the first iteration of PV sizing (27 roof panels adjusted for optimum tilt and corrected for cell temperature for Atlanta)

Table 5 Monthly total electric demand and supply for Atlanta with the preliminary photo-voltaic system design

Month	PV supply (kW·h AC)	Electric demand (kW·h)
1	501	506
2	535	514
3	648	397
4	765	425
5	804	482
6	790	543
7	796	579
8	750	496
9	623	729
10	687	533
11	548	532
12	491	484
Sum	7937	6220

For an off-grid application, this analysis would be critical for balancing the supply and demand curves. Figure 12 shows the curves for an ideally balanced house with some allowance for transmission and system design losses. Indeed, this balance is impossible to achieve in the context of the solar decathlon competition: the narrow range of thermal comfort conditions required to be maintained inside the house (for the competition) makes it difficult to keep the house as free-running. Furthermore, transporting the house to Washington imposes weight constraints, which eliminated the potential of using thermal mass to either offset heat gains or use them beneficially. Still, the supply and demand differences were critical for two reasons—to ensure net zero balance over the entire year when the house is grid-tied and to ensure adequate energy supply during the competition month.

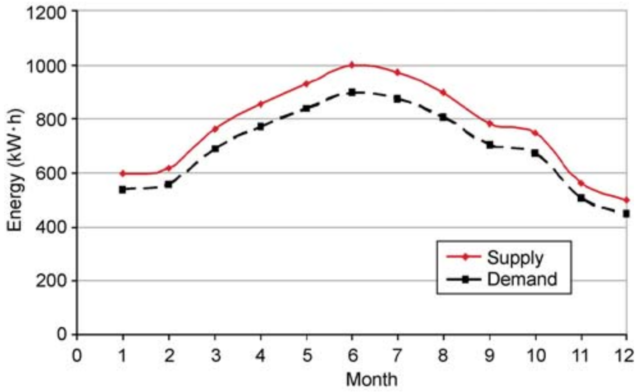

Fig. 12 Monthly energy supply and demand of an ideally balanced off-grid solar house

Figure 13 showed us that while the roof array of 27 SPR-220 panels (at 6kW capacity) produced 27% more total energy than what the house consumed, the supply may not be sufficient for the house to operate during the competition week. Figure 13 shows how the other design options (described in the previous section) would compare against this, and it can be noted that the options with higher transparency (options 6, 7, and 8) have a better balance of supply and demand curves since they have more solar gains in winter to offset heating demand. Of course, the same designs have a much higher cooling demand in summer, but it follows the fact that PV production is also much higher in the summer. Options 6, 7, and 8 are most unbalanced during the intermediate months when the house requires both heating and cooling. The main conclusions derived from Fig. 14 were:

- decrease the height of the clerestory windows,

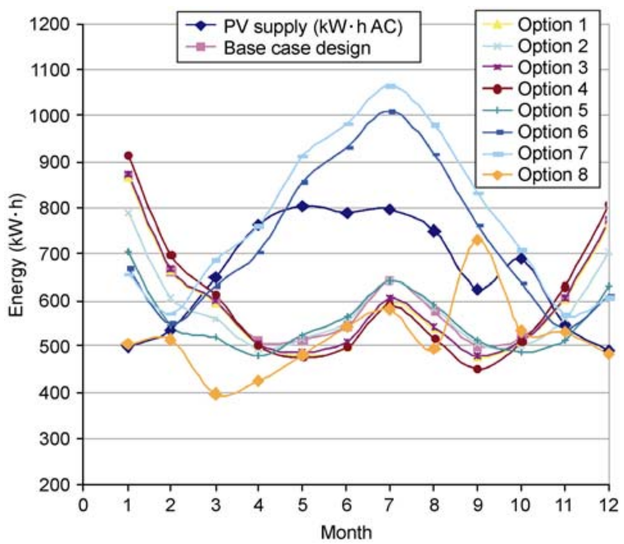

Fig. 13 Simulated monthly energy supply and demand assessment of different design options with the first iteration of PV sizing (27 roof panels, SPR-220 adjustable to optimum tilt)

- the team may need to increase the size of the solar array for the house to operate during the competition,
- in order to balance the system the team shall have to lower the energy demand during the intermediate seasons (March and October in particular).

The remainder of this section presents the next iterations of PV sizing—i.e., steps taken to increase the PV production for the competition period. It shows the dynamic analysis of the competition house and assesses how the house will perform during October 15 – 19, 2007 in Washington DC.

Figure 14 shows an estimate of the monthly DC energy production (without cell temperature correction) of the set of 27 roof-mounted PV panels, and in addition, two sets of vertical wall-mounted panels (shown in Fig. 15). The 9 panels considered for the west wall did not provide a significant increase in energy production, but the 12 panels on the south wall were sufficient for the twofold purpose of demonstrating how solar panels could be integrated within the vertical skin and for adding power to perform during the competition week. Thus, the total electric power for the Georgia Tech Solar Decathlon house was provided by 27 SPR-220 panels (6kW capacity) and 12 SPR-215 panels (2.5kW capacity), yielding an overall system of 8.5kW. Table 6 shows the energy production by both the vertical array (12 SPR-215 panels) and the set of roof panels (27 SPR-220 panels). The kW·h (AC) values assume a DC to AC derate factor of 0.77.

The values shown in Table 6 are necessary to show that:

- A quarterly (three monthly) adjustment of the roof array tilt angle to its optimum position will be sufficient to increase the PV adjustment by 4%. There is no additional significant benefit in adjusting the PV tilt angle daily to the optimum N-S angle.
- The energy losses due to increase of cell temperature can be overcome by adopting strategies to cool the PV

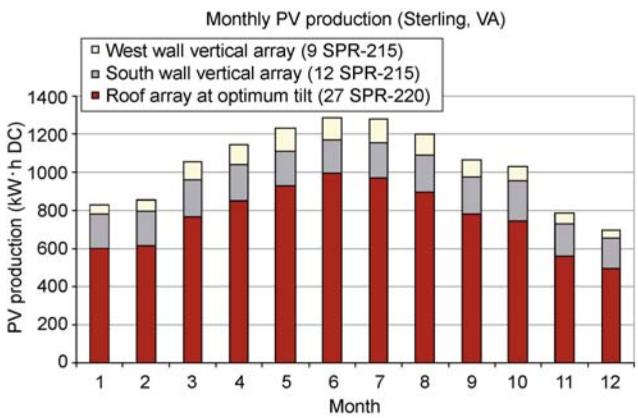

Fig. 14 Simulated monthly PV production by three different sets of PV arrays in Washington DC

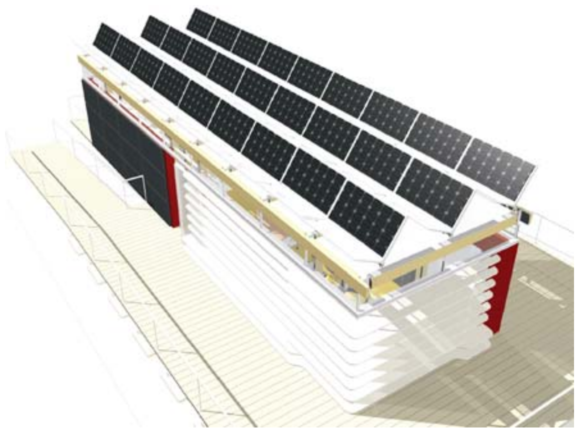

Fig. 15 South view of the competition house showing 27 SPR-220 panels on the roof and 12 SPR-215 panels on the south wall

Table 6 Values of energy production for the final design of the PV array

PV array	Atlanta		Sterling		Phoenix	
	kW·h (DC)	kW·h (AC)	kW·h (DC)	kW·h (AC)	kW·h (DC)	kW·h (AC)
South SIP wall array, 90°	3,601	2,773	3,438	2,647	4,080	3,141
South SIP wall array, 90°; corrected for cell temperature	3,447	2,654	3,296	2,538	3,865	2,976
Roof array, tilt adjusted daily	10,934	8,419	9,761	7,516	14,161	10,904
Roof array, tilt adjusted daily; corrected for cell temperature	10,308	7,937	9,249	7,122	13,151	10,126
Roof array, tilt at annual optimum	10,476	8,067	9,393	7,232	13,420	10,334
Roof array, tilt at annual optimum; corrected for cell temperature	9,896	7,620	8,914	6,864	12,495	9,621
Roof array, tilt adjusted quarterly	10,853	8,357	9,691	7,462	14,023	10,798
Roof array, tilt adjusted quarterly; corrected for cell temperature	10,235	7,881	9,185	7,073	13,030	10,033

panels—such as space for convective cooling behind the panels coupled with evaporative spray cooling.

- The addition of South Panels will increase the PV power available during the competition period by as much as 33% and will be required to perform during the competition.

4.2 Sensitivity studies for fine-tuning design components

Purpose: respond to specific design development queries to facilitate optimum decisions for energy management.

Method: conduct sensitivity analysis of specific components and demonstrate their impact on overall energy savings.

Tools: *GTSim*.

This section summarizes the sensitivity studies that were undertaken as part of design development. The main interest was in observing the effect of different material choices and their configurations on the hourly energy use of the house during the competition. Therefore the house was simulated for the competition week in Washington DC and the activities upon which the house would be judged were used to build the daily energy demand of the house.

4.2.1 Impact of roof membrane on space heating/cooling loads

As shown in Fig. 9, the topmost membrane of the roof served as a rain screen for the aerogel insulated ETFE panels below. The effective height of the air cavity between the insulated roof panels and the weather barrier was flexible and the design team needed to know if it would have any impact on the thermal performance of the insulated panels. Also, the material of the roof membrane was to be selected and the question was whether it needed to be printed or coated to reduce solar heat gains. These queries were translated into the following analysis tasks:

- Estimate classic U-value for the whole structure and run the simulations with a variety of air cavity heights and air exchange rate (ACH).
- Estimate the effective SHGC. Run the simulations with a variety of air cavity heights and air exchange rates (ACH).

The impact of air cavity thickness is almost ignorable in terms of energy. Probably its impact on light quality would be more essential. As shown in Table 7, the thickness of air cavity (H) does not play an important role to space heating / cooling load. The two alternatives for the weather barrier—(1) applying selective coatings to the transparent ETFE films (the properties of which are listed in Table 8) and (2) implementing retractable shading control over the roof—can almost bring the same benefits to the house in terms of load reductions. However, there is a larger benefit in cooling load reduction brought by retractable shading (see Table 9).

Table 7 Total heating/cooling loads for the competition week (Oct 15 – Oct 19)

H(mm)	$Q_{cooling}$(kW·h)	$Q_{heating}$(kW·h)
25	137.5	28.5
50	137.1	28.3
100	136.9	28.0
150	136.8	27.6
200	136.7	27.7
300	136.5	27.5
400	136.5	27.3

Table 8 Optical properties of different ETFE films

	Transparent film	Film with selective coatings
Solar transmittance	0.9	0.57
Solar absorptance	0.027	0.027

Table 9 Weekly total heating/cooling loads during competition week (Oct 13 – Oct 19)

Options	$Q_{cooling}$(kW·h)	$Q_{heating}$(kW·h)	%$Q_{cooling}$	%$Q_{heating}$
Transparent film	136.809	27.699		
Film with selective coatings	122.154	28.115	−10.71%	1.50%
Transparent film with retractable shading ON	116.192	25.738	−15.07%	−7.08%

4.2.2 Window material

This section describes the process of selecting the glazing system for the doors and windows of the house. All the transparent envelopes (doors, windows, and clerestory) are assumed to be made of the same glazing system. The angle dependent solar transmittance and absorptance values of windows are assumed to be proportional to its solar heat gain coefficient (SHGC) values. This assumption was made due to the lack of angle dependent optical properties of various window alternatives considered for the house.

Table 10 shows the optical properties for the window alternatives considered for the house. Each alternative is assessed with respect to the total energy load on the house during the competition week in Washington DC (also shown in Table 10). The SHGC value has dominant impact on the cooling load while U-value dominates heating loads. Since the COP (coefficient of performance) of a heat pump in

Table 10 Different glazing systems with resulting total energy loads for the competition week (Oct 13 – Oct 19)

	U-value (SI unit)	SHGC	$Q_{cooling}$ (kW·h)	$Q_{heating}$ (kW·h)	Electricity* (kW·h)
Option 1: triple pane fiberglass frame, argon gas, 2 low-e	0.79	0.31	152.9	44.9	47.9
Option 2: triple, clear, low-e2, low-e2, argon, WE	1.14	0.23	123.5	56.4	45.6
Option 3: triple, 2 low-e (RLE 7138), 2 KRP, 2S/S	0.74	0.29	147.4	43.2	46.2
Option 4: triple, 2 low-e2 (cardinal), 2 KRP, 2S/S	0.74	0.30	150.4	43.1	46.8

* This electricity is estimated with the assumption of COP (heating) = 2.93 and COP (cooling) = 4.69.

Table 11 Parametric changes of optical properties with weekly loads and energy consumption

	U-value (SI unit)	SHGC	$Q_{cooling}$ (kW·h)	$Q_{heating}$ (kW·h)	Electricity (kW·h)	%$Q_{cooling}$	%$Q_{heating}$	%Electricity
Window 1	1.13	0.2	113.97	57.01	43.76			
Window 2	1.13	0.23	123.52	56.39	45.58	8.38%	–1.09%	4.17%
Window 3	1.13	0.4	178.40	54.17	56.53	56.54%	–5.00%	29.17%
Window 4	2.26	0.2	102.19	94.15	55.76	–10.33%	65.14%	27.41%

cooling mode is much higher than that in heating mode the total electricity demand for space heating and cooling is dominated by space cooling. According to these results, a glazing system with the lowest SHGC, together with a middle level U-value would work best for reducing the total energy consumption.

The next analysis checks the acceptable numerical range of SHGC and U-value for selecting windows for the house. As shown in Table 11, doubling the value of SHGC from 0.2 to 0.4 results in an increase of electricity consumption about 29% and doubling U-value brings almost the same impact to the total weekly electricity consumption, increasing it by 27%. However, Fig. 16 shows that although the total electricity demand of window 3 and window 4 are close their hourly energy demand profiles are different. The hourly energy demand due to window 3 matches the PV electricity production curve more than that of window 4, which is eventually better because this is a solar house; using electricity directly from PV system is much more efficient than drawing from the battery because of inverter

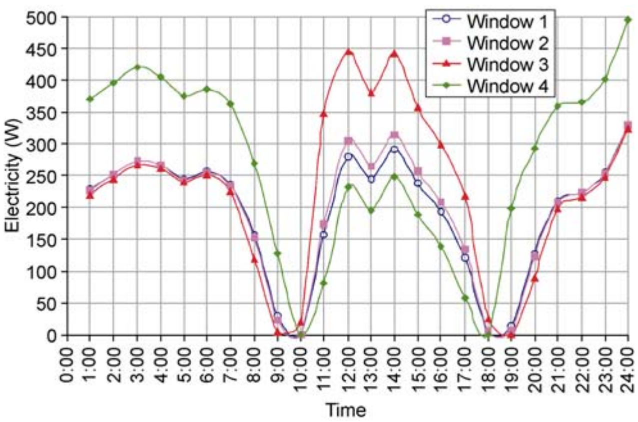

Fig. 16 Dynamic simulation of hourly electricity consumption profiles of four different glazing systems

losses. Hence, the following recommendations were made for selecting an appropriate window for the house: (1) the lower the values of SHGC and U, the better; (2) when there is a conflict between SHGC and U-value the SHGC can be sacrificed a little. In sum, window 3 would be a better choice for the solar house.

4.2.3 *Configuration of the translucent wall panels*

The translucent wall panels were custom built using two sets of polycarbonate panels filled with aerogel insulation. This analysis was to check if the air cavity between the two panels would affect the heat transfer through the walls. The analysis was based on an estimate of the classic U-value for the wall section with the following parameters: $Q_{solar} = 0$, $T_{amb} = 0$ and $T_{sky} = 0$ and Control $T_{room} = 1$. According to $Q_{heat} = UA(T_{room} - T_{amb})$, $U = Q_{heat}/A$. The simulations were run with different possible air cavity thickness to check if the U-value estimated above will be significantly affected by different heat transfer coefficients ($h_c = 3,5$, and 10 W/(m^2·K)) over interior air cavity surfaces. In fact, the air cavity thickness did not influence the overall U-value of the wall panel. Consequently its impact to house load was also almost ignorable.

4.3 Projected annual performance of the house

This section presents the annual energy performance of the house in Atlanta and also for climates in Washington DC and Phoenix. Projecting the annual energy performance of the house for these cities was part of the competition requirement. The comparison between the three different cities demonstrates the feasibility of the house for different levels of energy production. As Fig. 17 shows, it is even more critical for solar powered buildings to be assessed against climate. Indeed, variation in climate makes a big

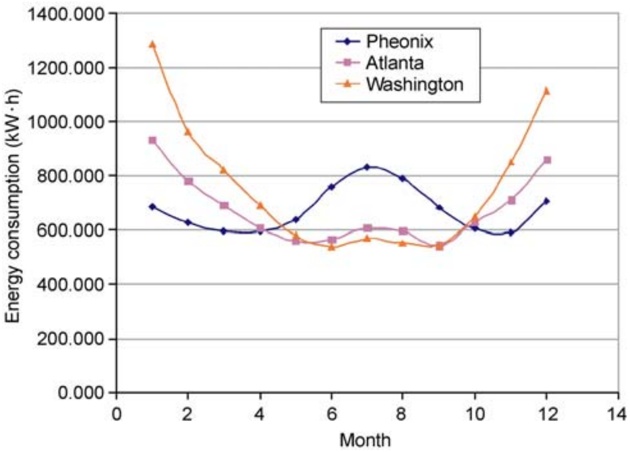

Fig. 17 Simulated annual energy consumption of the house for three different cities in the US

difference to both the energy supply and demand of the house. Figure 17 shows that the same house will be much more balanced for the climate of Phoenix in terms of matching supply and demand curves. Quite predictably Atlanta and Washington DC are heating dominated and hence also show a higher percentage of DHW loads.

Month by month values of energy consumed by the house in Atlanta point out how the house responds to seasonal variations. It is clear that passive heating strategies would be beneficial to bring down the heating demand during the winter months. Finally, this analysis was also used to assess the impact of occupancy. As shown in Tables 12(a) and 12(b), operational savings from occupant interventions such as pulling interior shades, allowing a larger range of thermostatic set-points, and use of daylight can yield

Table 12(a) Monthly energy demand and production for Sterling, VA in kW·h (energy production represents kW·h AC)

Month	HVAC	Appliances	Lighting	DHW	Total consumption	Total consumption with controls	Total production
1	960.33	132.39	182.22	6.78	1281.73	1150.05	779.29
2	667.75	126.13	164.58	3.94	962.41	855.51	796.12
3	504.69	132.39	182.22	4.24	823.54	720.87	963.63
4	377.45	130.31	176.34	4.52	688.62	598.07	1041.19
5	258.11	132.39	182.22	4.90	577.62	499.00	1110.05
6	224.75	130.31	176.34	5.38	536.78	464.26	1170.85
7	248.75	132.39	182.22	5.00	568.36	504.83	1154.12
8	230.90	132.39	182.22	5.19	550.70	483.20	1089.80
9	232.23	130.31	176.34	4.82	543.70	466.85	974.47
10	327.40	132.39	182.22	5.09	647.10	558.09	956.51
11	537.94	130.31	176.34	3.84	848.42	745.55	731.52
12	794.03	132.39	182.22	3.35	1112.00	989.58	651.58

Table 12(b) Monthly energy demand and production for Atlanta, GA in kW·h (energy production represents kW·h AC)

Month	HVAC	Appliances	Lighting	DHW	Total consumption	Total consumption with controls	Total production
1	610.41	132.39	182.22	6.89	931.91	810.26	836.72
2	484.94	126.13	164.58	3.70	779.35	677.06	882.88
3	371.86	132.39	182.22	4.39	690.87	587.81	1046.66
4	295.50	130.31	176.34	5.33	607.47	519.40	1179.76
5	237.41	132.39	182.22	5.27	557.28	485.22	1216.07
6	252.81	130.31	176.34	4.88	564.33	504.14	1181.26
7	287.99	132.39	182.22	5.20	607.80	545.60	1196.69
8	273.85	132.39	182.22	5.47	593.93	535.20	1158.70
9	230.39	130.31	176.34	4.72	541.77	482.46	997.15
10	307.55	132.39	182.22	5.30	627.46	534.39	1118.36
11	398.96	130.31	176.34	4.16	709.77	605.39	911.86
12	539.98	132.39	182.22	3.66	858.25	741.34	822.71

Table 13 Daily energy production and demand during the competition week (energy production values represent the AC Power available during the week)

Energy log	Competition week				
	Mon.	Tue.	Wed.	Thu.	Fri.
Energy production (kW·h)	34.24	34.97	13.03	26.07	40.08
Energy consumption (kW·h)	27.16	25.39	21.62	24.46	12.50
Energy left for car (kW·h)	7.08	9.58	0	1.61	27.58
Energy left in storage (kW·h)	20.11	23.26	–7.37	10.90	3.30
Daily car mileage achievable using energy left for car	42.48	57.46	0	9.67	165.45
Daily car mileage achievable using energy left in storage	120.64	139.56	0	65.39	19.82
Appliances (kW·h)	7.11	7.11	7.11	7.11	0.74
Washer/dryer (kW·h)	0.00	1.15	0.00	1.15	0.00
Heat pump (kW·h)	10.75	14.42	11.39	13.49	10.84
Hot water (kW·h)	8.41	1.82	2.22	1.82	0.52
Hot water-basic (kW·h)	1.82	1.82	1.82	1.82	0.52
Hot water-electric backup (kW·h)	6.59	0.00	0.40	0.00	0.00
Energy recovery ventilator (ERV) (kW·h)	0.89	0.89	0.89	0.89	0.41

significant reductions in the total consumption of single-family residences and should perhaps be one of the foremost strategies for reducing total energy demand.

4.4 Projected performance of house during competition

This section analyzes the house as required to perform during the competition week in order to derive optimum strategies for maximizing points. Table 13 summarises a simulation of daily energy consumption versus production during this week. In order to win the objective scores, the house had to operate as per competition requirements, but then also have enough energy left over to drive an electric car. All the tasks (including driving the electric car) had to be performed using the PV power collected during the competition week. Any power used from the battery bank would result in losing the points of the energy balance contest.

As per Table 13 the energy produced from the PV panels would be sufficient to perform all of the above activities and still run the car within an average range (with an exception for Wednesday when the house was monitored all day without breaking for public tours). Reasonable values of expected mileage on the car were derived from the amount entrants drove their car in 2005 (shown in Table 14).

Table 14 Driving mileages of three schools from 2005

Past driving mileages	Mon.	Tue.	Wed.	Thu.	Fri.
SD05-Colorado	73.1	46.8	80.2	77.5	40.2
SD05-Cornell	49.1	17.7	37.9	68	21.5
SD05-NYIT	28.1	11.9	34.8	47.7	26.4

Figure 18 shows the hourly production and consumption profile based on a typical meteorological year (TMY). In 2005 many entrants could not perform all the scheduled activities because of weather conditions throughout the week. In order to factor in the risk due to weather uncertainty and thereby derive appropriate strategies for competition scoring, Tables 15 and 16 show the daily energy log based on two worst case scenarios during the competition week—one when temperature is highest, and the other when the temperature is lowest. As shown by these values, the house will use less energy on days with low solar radiation, but high temperatures. This is because of the heating required in the latter case. In both scenarios there would not be sufficient energy to perform all the competition tasks as well as drive the electric car and not use any energy from the batteries.

5 From simulation to competition

The analysis shown in the previous section also confirms that it was necessary to weigh trade-offs between energy consumed versus points gained for each activity tested during the competition. For instance, within limited reserves of energy, if the choice was between conditioning the house at required levels and driving the electric car, then it is the latter that yielded more points per kW·h consumed during the competition. These choices were subtle and often counter-intuitive to generally understood standards of energy performance of the house. Table 17 lists all the activities on which the house was scored along with daily points per activity, the amount of energy each activity consumed, and points gained per kW·h for each activity. It is quite interesting to observe that the points per kW·h are

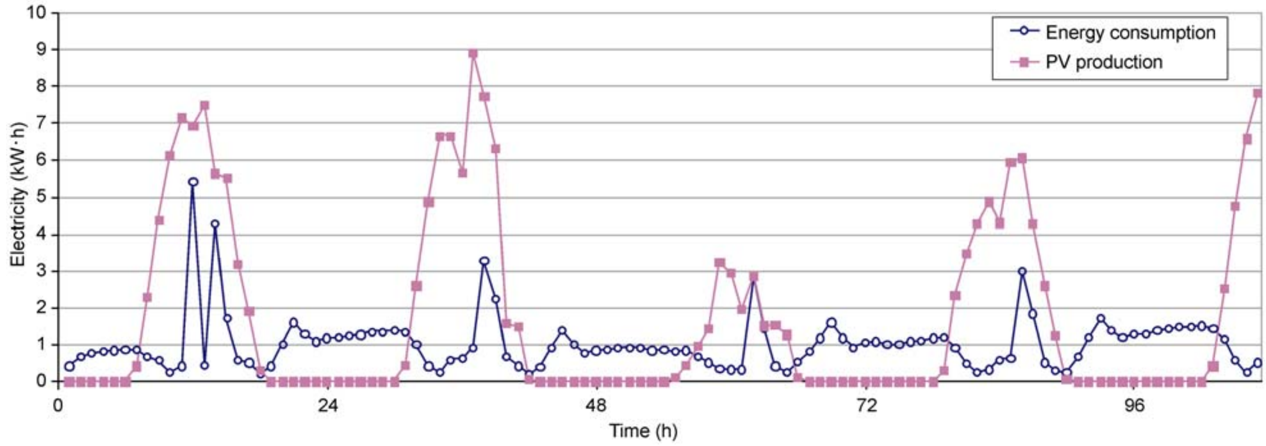

Fig. 18 Comparison of simulated hourly energy production and consumption during the competition week

Table 15 Daily energy log of worst case scenario with maximum temperatures

Energy log	Competition week				
	Mon.	Tue.	Wed.	Thu.	Fri.
Energy production (kW·h)	7.09	3.42	2.80	12.13	1.71
Energy consumption (kW·h)	20.98	15.77	13.87	14.37	2.64
Energy left for car (kW·h)	0	0	0	0	0
Energy left in storage (kW·h)	–18.69	–16.05	–14.39	–4.46	–1.41
Daily car mileage achievable using energy left for car	0	0	0	0	0
Daily car mileage achievable using energy left in storage	0	0	0	0	0
Appliances (kW·h)	4.65	4.65	4.65	4.65	1.28
Washer/dryer (kW·h)	0.00	1.15	0.00	1.15	0.00
Heat pump (kW·h)	1.38	1.78	1.61	1.30	0.43
Hot water (kW·h)	14.07	7.30	6.72	6.38	0.52
Hot water-basic (kW·h)	1.82	1.82	1.82	1.82	0.52
Hot water-electric backup (kW·h)	12.25	5.48	4.90	4.56	0.00
ERV (kW·h)	0.89	0.89	0.89	0.89	0.41

Table 16 Daily energy log of worst case scenario with minimum temperatures

Energy log	Competition week				
	Mon.	Tue.	Wed.	Thu.	Fri.
Energy production (kW·h)	7.09	3.42	2.80	12.13	1.71
Energy consumption (kW·h)	26.86	22.11	21.55	23.27	8.87
Energy left for car (kW·h)	0	0	0	0	0
Energy left in storages (kW·h)	–26.11	–24.23	–24.33	–15.77	–9.77
Daily car mileage achievable using energy left for car	0	0	0	0	0
Daily car mileage achievable using energy left in storage	0	0	0	0	0
Appliances (kW·h)	4.65	4.65	4.65	4.65	1.28
Washer/dryer (kW·h)	0.00	1.15	0.00	1.15	0.00
Heat pump (kW·h)	6.96	7.36	8.59	9.47	6.67
Hot water (kW·h)	14.36	8.06	7.41	7.11	0.52
Hot water-basic (kW·h)	1.82	1.82	1.82	1.82	0.52
Hot water-electric backup (kW·h)	12.54	6.24	5.59	5.29	0.00
ERV (kW·h)	0.89	0.89	0.89	0.89	0.41

Table 17 Points per kW·h for each scored activity during the competition

Category	Task	Daily points	Daily kW·h consumption	Daily points per kW·h
HVAC	Humidity	6.5		
	Temperature	6.5	10	0.7
Appliances	Fridge & freezer	4.84	2.5	1.9
	Computer	1	0.66	1.5
	TV/video	1	0.36	2.8
	Cooking	5	1.76	2.8
	Dishwashing	2.5	0.64	3.9
	Clothes washing	5	0.48	10.4
	Clothes drying	10	0.67	14.9
Lighting	Electric lighting	5	1.86	2.7
	Daylighting	2.35	—	
DHW	Shower	20	2.16	9.3
Car	Car driving	20	7.5	2.7

higher for tasks such as running an electric washer dryer and dishwasher versus running the refrigerator. Or, car driving and having the electric lights on are equally weighted. It should be mentioned that the daily energy consumption value of the HeatPump is for the scenario when it would be on for 60%–70% of the day, and listed value for car charging is for approximately 50–55 miles of driving. Within certain limits, the points per kW·h can be of course increased by reducing the energy consumption of each activity. For example, a highly efficient HeatPump consuming say 3.0kW·h per day and controlling the temperature and humidity as required would give up to 4.3 points per kW·h. However, the energy consumption values of appliances listed here are representative of lower values of energy consumption available in the market. Furthermore, the choice of each appliance is derived from a typical design process where choices are based on the balance among several factors such as energy use, client's aesthetic choice, reliability, size, cost, availability, etc. The main insight that this exercise brings forth is a systematic view of the trade-offs associated with running an off-grid solar house in times of low energy production. Indeed the HeatPump was not operated from the second day of the competition week because it was just not "worth-it" in the points per kW·h structure of the competition. Instead, the team targeted car-driving and water heating (when needed) as the high priority activities for gaining maximum competition points.

It should be noted that the shower test, clothes washing test, and the dishwashing test required hot water at specified temperature (in addition to the electric energy needed for running the pump and associated appliances). These activities became very energy intensive when the water had to be heated using the back-up electric element rather than the solar water heating system. For instance, the morning shower test was energy intensive because the water temperature in the tank decreased overnight, and two hours of morning sun were not sufficient to heat the water at required temperature. This issue raises the second important aspect of operating the solar house—time of activities. As also mentioned earlier in the design process, it is much more efficient to use solar power in real time than to store for re-use due to losses.

Figure 19 shows the energy going in and out of the batteries during the competition week. The graph reflects all of the above mentioned choices and how the house was operated during the competition. Positive energy flow represents energy going into the batteries and is the surplus accumulated off real-time use. Likewise, negative flow represents energy taken from the batteries. The sum of the two is in fact the energy balance of the house, and each team gained 100 points if the net sum at the end of the week was more than zero. In Fig. 19, the negative flows result from two scenarios both of which highlight the third point we want to make regarding the transition from simulated to actual energy consumption—that of commissioning the systems. Note the negative energy flow from the batteries during the first night of the competition week. This drop occurred during the period the temperature and humidity were controlled as required in the competition rules. So the losses represent the energy used by the HeatPump when it was operating in heating mode and energy required to charge the electric car. The simulation estimated 10–14kW·h of energy required to run the HeatPump per day, whereas actual consumption is higher by 70% (despite the fact that the HeatPump had a high efficiency rating of 10 heating system performance rating (HSPF)). Also, the car was left to charge overnight, and this resulted in 50% higher losses than expected because of the energy draw even after the car

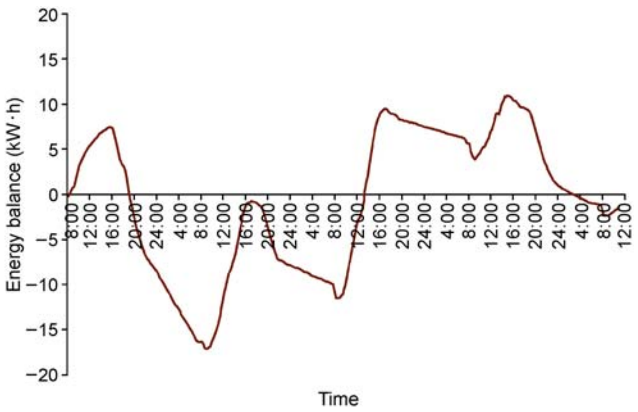

Fig. 19 Energy balance of the house during the competition week (positive energy balance represents electricity stored in the batteries and negative energy balance represents electricity used from the batteries)

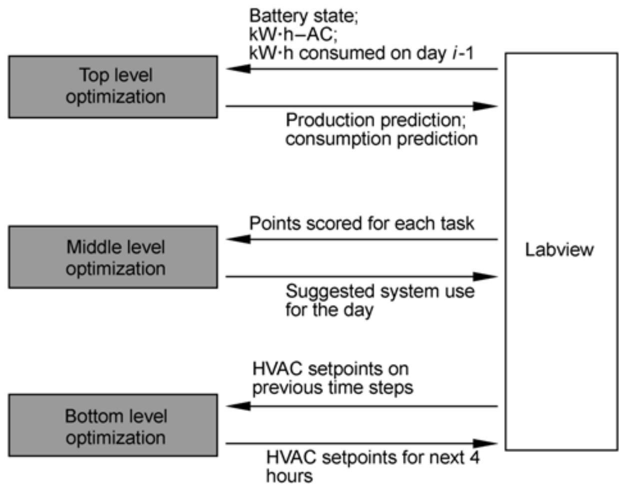

Fig. 20 Structure of the optimal controller

was sufficiently charged. As mentioned earlier in the paper, this project was experimental and also did not conform to traditional construction management and schedules because it was built by students. Hence, there was no time for calibrating the simulation and tweaking the control logic before the house was put to test. The lack of time for commissioning and calibrating the systems resulted in large and unexpected energy losses during the competition week. These issues highlight the point that no matter how efficient the design and system choices may be; using them without calibrating optimum operating conditions can quickly defeat expected energy efficiencies.

The final point to be made for transitioning the house from predicted performance to reality is visibility of information. Discrepancies and deviations between projected and actual use occur in buildings all the time and are one of the common causes of performance failures and excess energy use. For instance, changes in occupancy, use, weather variations, or control design can easily result in sub-optimal operation of buildings and their systems. Availability of predicted energy use by each component allows timely detection and trouble-shooting. Albeit in a very “hands-on” way, the availability of both the projected and actual energy data enabled the Georgia Tech Solar Decathlon team to examine trade-offs in real-time, discover discrepancies early enough, and make informed choices during the competition week. In fact, during the competition week the team was simulating the house’s energy supply and demand based on short-time weather forecast rather than the TMY climate data file so as to continuously refine the predicted information closer to actual values.

Earlier in the paper we presented the team’s strategy of using a supervisory optimal control model (Eq. (8) in section 3.3) for the energy management of the house during the competition. Figure 20 shows the structure of this controller, the extension of which can be projected to be useful for buildings powered by renewable energy sources. The model is a multi-level optimal controller with three optimizations involved: macro level, middle level, and bottom level. The macro-level optimization is used in scenarios when energy production is not enough to operate the building as per specifications. For instance, in the case of the Solar Decathlon competition, when PV production is insufficient the team has to examine the trade-off between using the energy from the batteries for car driving and not using it to win the energy balance points. The macro-level optimizer is designed to support such decisions over a relatively longer time frame (a week in the case of the Decathlon house). Middle-level optimization is used if energy production is so limited that the building cannot be fully operated. For example, if choices have to be made among household activities such as cooking, running hot water, and/or lighting the building during evening hours. The middle-level optimizer solves a constrained maximization problem with all tasks represented as integer variables and computes the optimum set of tasks for each day. The bottom level optimization is designed to help determine the best daily task schedule (timing of each task) based on a finer resolution of time-step.

In the case of the Solar Decathlon house, the model is initiated with a five day looking-forward simulation with all DOE-set scored activities. Given that the electric car needs eight to ten hours to be fully recharged from a completely discharged state the maximum charge cycle for the electric car is twice a day. Therefore, if the energy left for the electric car is estimated to be more than 10kW·h, the model is diverted to bottom level optimization. Otherwise, the macro-level optimization is run to derive the optimum value of daily driving mileage. The derived value of the driving mileage is used as a target for the middle level optimization. Given the driving target of each day, the middle level optimization uses one day looking-forward simulation. If simulation result shows that there is sufficient electricity to finish all the tasks including the driving target, it goes to bottom level optimizer for computing the timing of each task. Otherwise, the middle-level optimization generates the list of doable tasks for the day. The bottom level used the list of doable tasks for the day to derive their optimum schedule.

The main challenge in extending models to support decision-making in real time is their calibration with actual system behaviors. One aspect of this is to fine-tune the simulation model and calibrate systems with their real counterparts. The more difficult issue is the differences in climate information and weather forecast. Figure 21 shows the differences in values of energy production during the competition week as predicted using the TMY file, using the weather forecast, and as monitored. Clearly, it is important that tools incorporate uncertainties in weather data to better guide operating decisions in real-time. Furthermore, it is not easy to use optimal solutions returned through optimization process "as-is". The weight factors and penalty coefficients have significantly strong impact on the optima, and finding their appropriate values requires many experiments, understanding client choices, and building use scenarios. On the other hand, equally set weighting factors will not lead to optimal choices when energy production is limited.

6 Concluding remarks

Implicit in the design analysis process presented in this paper are three main aspects—one that it considers actual operation of the building and its context as a key factor at

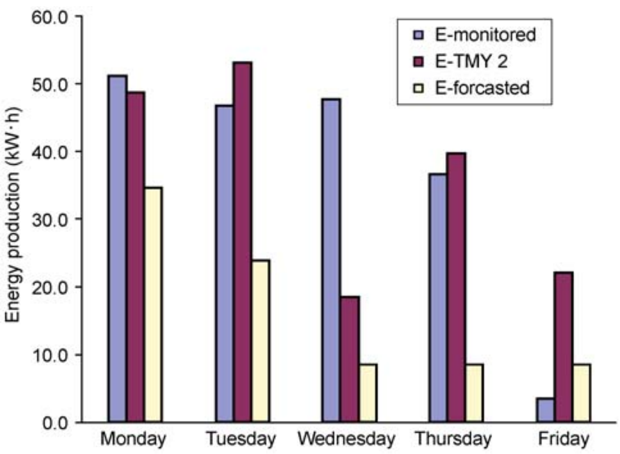

Fig. 21 Differences in values of energy production during the competition week as predicted using the TMY file, using the weather forecast, and as monitored

all stages of the analysis process. The second is the apparent flexibility of the analysis process and the ability to model building use and its context at early stages in the design process, made possible because of in-house development of the simulation models. The third is the ability of extending simulation support to fine-tune the combined operation of building systems once they are installed.

It becomes easily difficult to use our current set of tools for process-support because tools do not offer an easy way to incorporate system descriptions not already embedded—neither explicitly nor in easily configurable manner. Also, our tools are poor instruments for supporting representation of novel concepts of design or implementation (such as the retractable shades on the roof). One of the main issues is that most of our tools are not explicit. Interfaces at the front end are more focused on developing suitable protocols for facilitating geometric inputs rather than providing tools that can be adapted for different system configurations and use-scenarios. On the other hand, the tool requirements of design analysis processes are more or less kept anonymous by simulation users. The anonymity of the simulation processes can be partially attributed to their diverse distribution in design practices, ranging from design firms that have their own set of in-house experts to dedicated engineering consulting firms offering specialized services to architects. The training of the simulation user driving the process is also not standardized or consolidated within a particular academic discipline, and therefore can vary among special concentrations offered within architecture, civil, or mechanical engineering programs. In addition, the simulation user is associated with a set of computational tools in training, whereas in practice "tool-expertise" does not necessarily guarantee a robust analysis process. Therefore and understandably, development of design support tools is not very tightly coupled with real-life requirements of the analysis process because of which their use is often ineffective. Work shown in this paper demonstrates a more bottom-up approach, crafting the tool set as per the requirements of the analysis queries.

References

Crawley DB (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43(4): 661 – 673.

Hendron R (2006). Building America performance analysis procedures for existing homes. National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy06osti/38238.pdf. Accessed August 2008.

ISO 13790 (2008). Energy performance of buildings. International Standardization Institute.

Lam KP, Nyuk HW, Sekhur C (2001). The use of multiple building performance simulation tools during the design process—A case study in Singapore. In: Proceedings of Seventh IBPSA Conference, Rio de Janeiro, Brazil.

Mahdavi A (1999). A comprehensive computational environment for performance based reasoning in building design and evaluation. *Automation in Construction*, 8(4): 427 – 435.

McElroy LB, Clarke JA, Hand JW, Macdonald IA (2001). Delivering simulation to the profession: The next stage? In: Proceedings of Seventh IBPSA conference, Rio de Janeiro, Brazil.

NEN 2916 (1999). Energy performance of non-residential buildings — Determination method. Delft: Dutch Normalization Institute.

Robinson LA (2005). Structural Properties of ETFE. Masters Thesis, Massachusetts Institute of Technology, Boston, USA.

Tomiyama T, Yoshikawa H (1986). Extended general design theory. Amsterdam: Technical report CS-R8604, Centre for Mathematics and Computer Science.

Trubiano F (2007). Icarus Redux, Sustaining Inventions in the Art of Building with Air, Light and Flight. In: Proceedings of the ACSA National Conference, Philadelphia.

Trubiano F (2008). Responding to light + energy, the design + construction of a high performance roof. In: Proceedings of the ACSA Materials Matter Conference, Los Angeles.