SIMULATION ENHANCED PROTOTYING OF AN EXPERIMENTAL SOLAR HOUSE

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ABSTRACT

This paper reports the design analysis process undertaken by the Georgia Tech Solar Decathlon 2007 team for an 800 sq.ft. solar-powered house. It presents the simulation process engaged over the entire design development cycle of the house (from conceptual to built), and demonstrates why, when, and how particular tools were deployed or developed on the basis of queries coming from diverse design team over several design iterations. Through this project, the paper purports a need-based and tool independent analysis process that not only supports design from its conceptual development to incremental evaluations, but is also usable for final testing and fine-tuning of building components as they are brought on site, as well for optimal control of energy management when the house is fully operational.

KEYWORDS

simulation and monitoring; energy analysis; design analysis process; solar decathlon; simulation-based control

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; an appealing suggestion is to use an arsenal of different tools to perform increasingly more refined analyses of incremental design decisions. 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. Although the advent of formal building information models (BIM) has led to speculations about how ordered processes could be developed that reflect design evolution, there is little hope that these speculations will become reality any time soon, unless we drastically change the nature of architectural design. One of the dominant views on architectural design, at least from a generative perspective, is the translation of function to form. In its very essence, this translation constitutes a vastly under-constrained problem that invites and induces many "unplanned" and unforeseeable design explorations and creative interventions. It is therefore not realistic to assume that any form of pre-defined process logic could lead to a predictable and controllable design evolution process. Only if we drastically change the nature of the under-constrained architectural design problem, e.g. by adopting parametric design approaches, we may be successful in enforcing rigorous (and partly automated) process logic. In parametric design, such rigorous control of design evolution steps, information flows and decision making is indeed feasible, as for instance exemplary studies in mechanical engineering have shown (Hazelrigg 1996). A benefit of any pre-defined process is the identification of analysis methods that support the solution of the parametric problem.

The subject of this paper is the design of an experimental solar house, driven by the overarching goal to obtain net-zero energy performance while being functionally optimal and aesthetically pleasing. Reaching these objectives requires the exploration of different layouts, enclosure types, materialization and system (solar and other) options. The design team consists of a multi-disciplinary team of students from architecture and engineering schools.

This paper looks at the project as 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 from the building performance analysis perspective with emphasis on the use of simulation.

THE SOLAR DECATHLON

Brief Overview of the Competition

Georgia Tech is participating in the Solar Decathlon 2007 competition sponsored by the Department of Energy (www.eere.energy.gov/solar_decathlon). The competition invites 20 international universities to design, build, and operate an 800 sq.ft. all electric solar powered house within a tight set of performance criteria in Washington DC. The nature of the competition predisposes the project to parallel objectives of pushing boundaries in design and construction, and at the same time, operating the house under a given precise set of environmental conditions within very limited reserves of energy produced by solar panels installed on the house.

The participating teams will be evaluated in October 2007 within 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. While the objective scores test the house as it operates during the competition week, the subjective scores are given by panels of "expert" juries. In the 2002 competition, the subjective scores focused on innovation and market appeal of technologies and systems used in the house. In the 2005 contest, the Department of Energy increased the percentage of subjective judging towards design and livability of the house – which essentially demonstrated their push to market solar technology at the residential scale. In effect, it required the teams to focus on "selling their ideas" to the market. This year, a bulk of the subjective scores will evaluate how the teams assess their own house during the design process; use the assessments to inform design-decisions, and how they project its operation annually and over the life-cycle of the house (Wassmer and Warner, 2005). This change demonstrates the thrust by the Department of Energy towards a strong design analysis process that is supported by means of simulation and monitoring. What this trend also shows is that building simulation has become more and more mainstream and accessible to the design process.

The Georgia Tech Solar Decathlon House

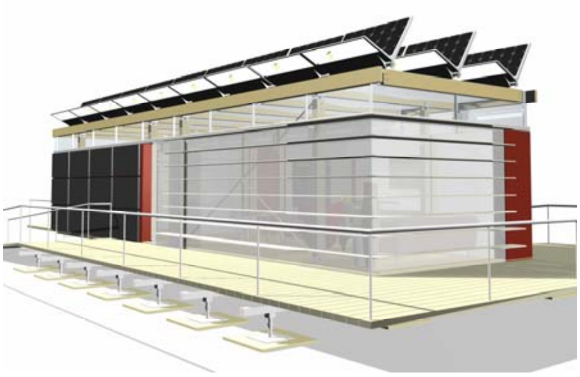


Figure 1 South-East View of the House

In addition to the design and operational constraints prescribed by the Department of Energy, 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 argument:

"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?"

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 is translated into design primarily through a translucent roof and wall assembly and a clerestory window that runs across the entire perimeter of the house (Figure 1). The roof is used for collecting the two main forms of desirable solar energy – electric power and natural light. The PV panels are visible and integral to the design of the house both from inside and out. They would also serve to shade the semi-transparent roof.

The Environmental Context

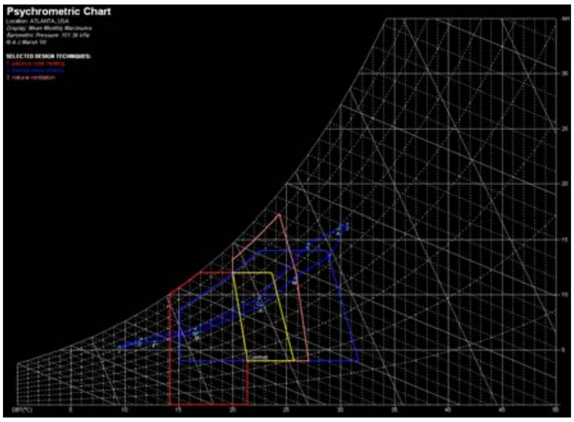


Figure 2 Pyschrometric plots showing average monthly conditions and applicable passive strategies for Atlanta and Washington DC.

The Georgia Tech solar decathlon house is optimized for both Atlanta, Georgia where it will be finally located, and for the competition period (october) in Washington DC. The location of the house falls under Zone 3 of the 2006 IECC code and Zone Cfa by Köppen scheme of climate classification, which characterizes mild mid-latitude conditions (average temperatures > 22°C, coldest month averages between -3°C and 18°C, and constantly moist). As shown in Figure 2, passive heating (particularly by the use of thermal mass) can be used to heat the house in the months of March and November. The high mass with night time ventilation can be also used to mitigate most of the cooling needs for the months of April, May, and October.

These passive strategies are however infeasible in the given context where weight constraints associated with transporting the house to Washington and operating it within a tight temperature and humidity range render both the use of thermal mass and natural ventilation as infeasible options.

The Design Analysis Framework

In addition to the constraints and objectives set by the competition brief given by the Department of Energy, the design analysis framework for this project was based upon the aforementioned architectural intents and environmental parameters. The key objectives thus formulated were:

a. To provide quick estimates of energy loads in response to meta-level design options given by the architecture team.
b. To support the incremental development of the translucent roof and wall assembly by evaluating the impact of each alternative on energy use and thermal performance.
c. To help the design team choose appropriate glazing configurations and assemblies for the clerestory window.
d. To guide appropriate selection of system components for controlling the indoor conditions of the house.
e. To develop a simulation strategy that would be extendable to final testing and fine-tuning of building systems and components
f. To develop a simulation-based optimal control strategy that would be used for achieving required operational conditions during the competition period.

The following sections describe the development and implementation of these analytical components. The first section summarizes the broad queries supported at the schematic design stage using a series of analytical tools ranging from commercially available simulations to steady state approximations and dynamic heat transfer models developed specifically for the Georgia Tech decathlon house. The second section explains the rationale for developing the dynamic simulation and how it is projected to support the actual deployment of building systems and their control logic. The final section outlines the steps ahead from simulation, to monitoring, and optimal control when the house is fully operational.

SCHEMATIC DESIGN ANALYSIS

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 (shown in Figure 3) was thus generated and translated into the total PV supply for the house based on information found in (Messenger and Ventre 2004; Richter and Schwan 2005; Strong 2004; www.evsolar.com). This step resulted in establishing the upper limit on the total daily energy demand of the house at 18.66 kWh as a constraint. This meant a total number of 27 PV panels (220 W each) had to be accommodated on the roof.

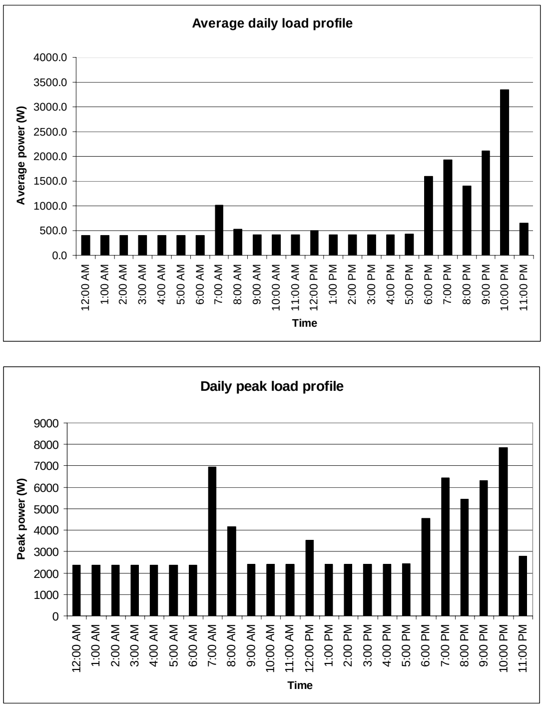


Figure 3 Average and Peak Load Profile for a typical house in Atlanta

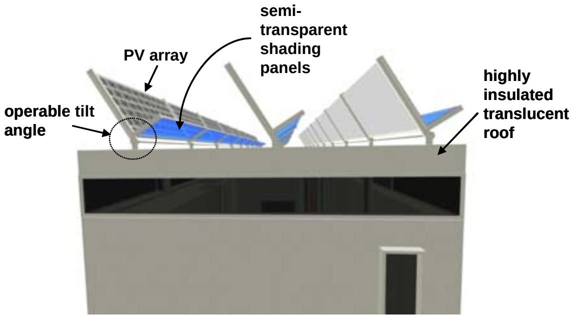


Figure 4 Main elements of the roof design

The PV panels had to be now placed within the constraints set by the design proposal where the PV panels were arranged in rows over the 14' x 48' roof and could be rotated to their optimal tilt angle with respect to the solar incidence (Figure 4). The PV rows had to be spaced within the 14' width so that the panels would not self-shade one another at any tilt angle. A series of geometric shadow analysis (using ecotect –www.squ1.com) were used to calculate 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.

Once the supply from the PV panels was fixed, the first series of analysis constituted the evaluation of the building skin as proposed by the design team against maximum allowed heating and cooling demand. The proposed design was also benchmarked against a base case that had standard values of thermal envelope as prescribed by the 2006 IECC code and preliminary load estimates were derived using energyPlus (www.energyplus.com). The cooling demand of the house at this stage far exceeded the upper limit set by the PV supply. Transparency through a horizontal roof was particularly challenging because it is also the element that receives maximum heat gain from solar radiation relative to any other surface of the building envelope. In lieu of glass, potential use of ETFE texlon pillows combined with aerogel insulation was explored for the roof assembly. Early estimates showed that aerogel insulation was much more effective thermally than any high performance glazing (yielding a summer R-value of 9.6 Btu/hr.sq.ft.degF – Figure 5).

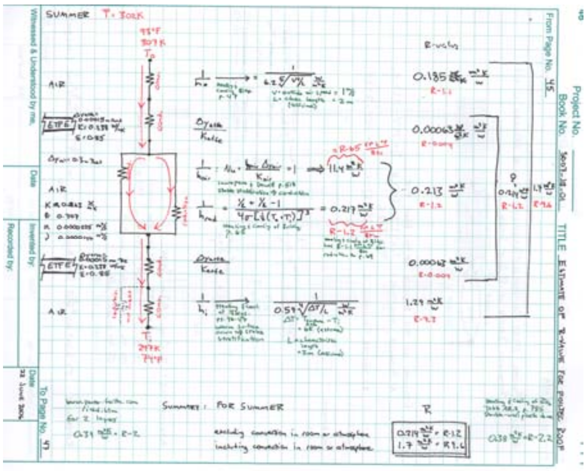


Figure 5 Summer U-value of the ETFE texlon pillows combined with aerogel insulation

Since R-10 is significantly lower than the standard thermal resistance of a roof, the team explored the use of shading panels over the roof with the intention of lowering the cooling loads by decreasing the overall shading coefficient of the roof. While a quick calculation using energy10 showed that the shading coefficient had a significant impact on the cooling loads, it was insufficient to derive further estimates on how the shading should be configured and controlled so as to maximize its benefits during both heating and cooling seasons.

Table 1 summarizes these and some other queries that were supported by the analysis team during the first phase of the project. Following these preliminary estimates, it was determined that the analysis needed to develop simultaneously around two models: One a steady state heat balance approximation that would allow quick evaluation of various options for the transparent/translucent assemblies as the design developed, and a dynamic simulation that would allow detailed sensitivity analysis for refining those assemblies.

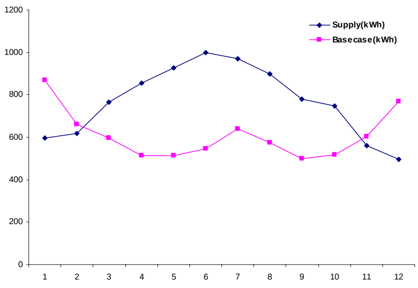


Figure 6 Monthly Electric Supply and Demand Curves of the House

Steady State Analysis

Although the decathlon house is required to operate as an off-grid solar house during the competition week in Washington, it is evaluated and benchmarked over the whole year as a grid-tied application. Since the demand for operating the appliances (including an electric car) is pre-determined based on the competition, the steady state heat balance approximation was used to compare the net electric supply by the PV system versus the heating and cooling demand of the house. As shown in Figure 6, the PV supply exceeds demand in the cooling season and is below the required amount for the heating season.

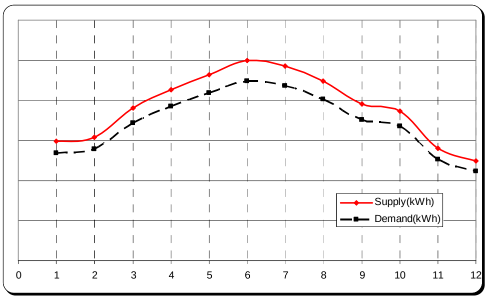


Figure 5 Ideally Balanced Solar House

For an off-grid application, this analysis would be critical for balancing the supply and demand curves (Figure 7). This balance is impossible to achieve in the context of the solar decathlon competition because the narrow range of thermal comfort conditions that are required to be maintained inside the house combined with the lack of thermal mass typically expected in passive solar applications. However, the supply and demand differences were critical for examining the impact of various thermal envelope assemblies on the demand curve – both to assess adequate balance during the competition month and to ensure net zero balance over the entire year when the house is grid-tied.

Figure 8 Impact of Design Options on the Monthly Demand Curve of the Solar Decathlon House

Design Query	Option Space	Performance Indicator	Analysis Tool / Simulation	Source
Climate Assessment	passive skin strategies	avg. monthly outdoor conditions	psychrometric chart	www.squ1.com
Size of the PV Array	Roof Area (14'x48')	total electric demand per day	typical wattage profiles + PV-DesignPro	www.mauisolarsoftware.com
spacing of PV panels	14' width	shadow length at lowest and highest tilt angle	Solar Analysis	www.squ1.com
Transparency of the South and East walls of the living room	Triple Glazing versus Kalwall	Absorbed vs. Transmitted Solar Rays Incident on the East and South Surfaces of the Living Room	Solar Analysis	www.squ1.com
Thermal Envelope Assessment	UA of the Envelope against a standard benchmark	Heating and Cooling Loads	EnergyPlus	www.energyplus.com
Preliminary System Selection	HVAC -- radiant / air (ducted) / direct (mini-split); Solar Water Heating -- Flat Plate / Evacuated Tubes	Efficiency + Thermal Comfort + Hot Water Temperature	RETScreen + EnergyPlus	http://www.retscreen.net + www.energyplus.com
Feasibility of translucent roof	ETFE w/ nanogel insulation / Glazing	U-value	1D conduction calculation	hand calculation
Height of Clerestory windows	1.5'-2.5'	Heating and Cooling Loads	EnergyPlus	www.energyplus.com
Code Compliance		UA method	energy10	http://www.sbicouncil.org/store/e10.php
Review of Electric Demand		PV supply vs. Electric Demand	Steady State Heat Balance Approximation	georgia tech
Peak and total Electricity Demand during the competition period	schedule of competition tasks	Total electric demand during the competition week	spreadsheet	
Explore Options for Reducing Heating and Cooling Loads	Thermal Properties of Roof and Windows	Heating and Cooling Loads	Steady State Heat Balance Approximation	georgia tech
Sizing the Shading Panels on the Roof	space between the PV panels	Direct Solar Radiation on the Roof	Solar Analysis	www.squ1.com
Impact of Adding Retractable Shading Panels over the Roof	shade on/ shade off -- hourly control	Heating and Cooling Loads	Dynamic Simulation	georgia tech
Update Wattage Profile based on actual appliances and loads		PV supply vs. Electric Demand	Steady State Heat Balance Approximation	georgia tech
Sensitivity Analysis of Glazing options for the windows	Glazing types	Heating and Cooling Loads	Dynamic Simulation	georgia tech
Sensitivity Analysis of the Translucent Roof Assembly	Height of Air Cavity, Insulation thinckness, Shading Coefficient	Heating and Cooling Loads	Dynamic Simulation	georgia tech
Sensitivity Analysis of Internal and External Shading of Windows	Retratable Blinds versus external shades	Heating and Cooling Loads	Dynamic Simulation	georgia tech
Optimal Control Strategy during the competition period	All subsystem controls	Performance + Energy Use	Dynamic Simulation	georgia tech

Figure 8 shows the impact of different design options explored for the thermal envelope. In order to balance the supply and demand curves, the winter energy demand needs to be decreased, which is most effectively achieved by choosing a glazing assembly that has higher solar transmittance and not shading the translucent roof during winter. In fact, if the shading devices over the roof are well- controlled (open during the heating mode and closed during the cooling mode), the performance of the translucent roof could be comparable to an equivalent R-38 roof. While the general direction is to have low UA envelope but higher solar gains (within limits so that it does not exceed the summer energy demands beyond the supply limit), at this point the team needed a dynamic model to further develop the thermal envelope and the two critical components – the windows and the roof, to test against various operation scenarios and a range of typical weather conditions. Among the operation scenario was the use of the retractable shading on the roof, vented cavity between the weather screen and roof layers, and the solar heat gain coefficient of the glazing systems at each orientation.

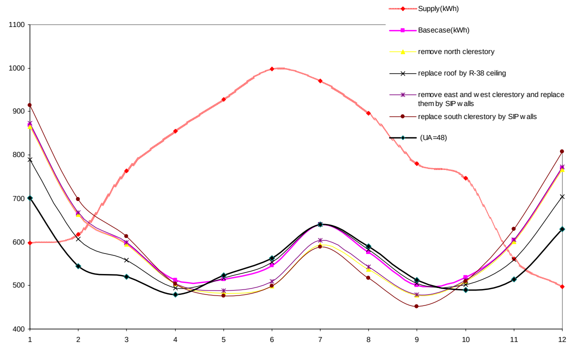


Figure 8 Impact of Design Options on the Monthly Demand Curve of the Solar Decathlon House

Dynamic Simulation Model

The models from the previous sections are not suited to study the detailed dynamic behavior of the house and its interacting systems. The reasons for dynamic simulations are twofold: (1) the study of behavior under peak loads, in relation to equipment sizing, comfort and consumption patterns, (2) fine tuning and verification of dynamic control strategies.

As a first step, a finite element based simulation model was developed and programmed in Matlab. For this reason 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 modeled with only one-dimensional elements.

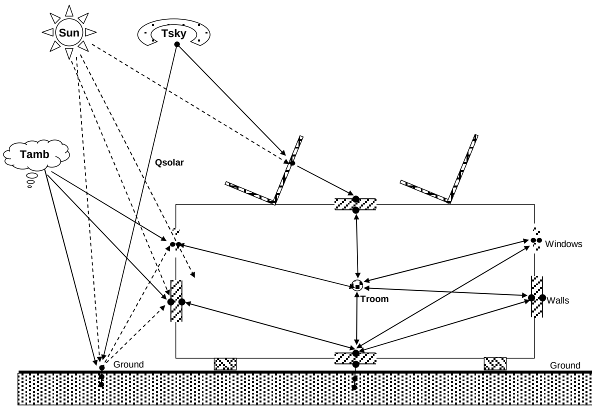


Figure 9 Finite element mesh (simplified)

Figure 9 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:

$$M(\theta,t)\, d\theta/dt + S(\theta,t)\, \theta = f(\theta, t) \qquad (1)$$

Where M is the mass matrix, S is the stiffness (or conductivity) matrix and f is the load vector (solar loads) The state vector θ represents, depending on type of node, the unknown state variables temperature, stored energy level, humidity. As some of the equations have a zero mass matrix, it should be noted that the system in equation (1) is a differential algebraic system. The system is time variant and non linear as a result of the terms that reflect time and/or temperature dependency, such as occurs as a result of time varying ventilation flows, movable insulation panels, and temperature dependent heat transfer coefficients.

The analysis of the roof (including the operation of the shades) was developed in close interaction with the manufacturers to refine the estimates of all material properties included in the assembly. One of the first tests was to assess the impact of the height of a vented cavity between the roof and its weather screen on the total space heating and cooling loads of the house. Having determined that the thickness of the air cavity did not have any significant impact, the team also analyzed the effect of venting the cavity on the U-value of the roof by varying the air changes per hour through the cavity (figure 10).

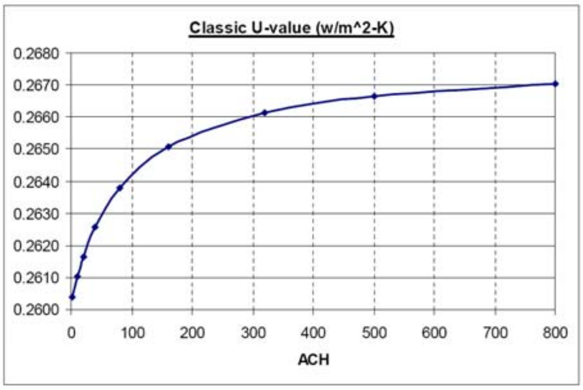
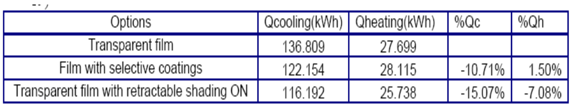


Figure 10 Classic U-value of the Roof Assembly as a function of different ACH through the Roof Cavity



Options	Qcooling(kWh)	Qheating(kWh)	%Qc	%Qh
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%

Figure 11 Space Heating and Cooling Loads during the Competition Week for Variations in Shading over the Roof Assembly

The next step in the analysis of the roof was to evaluate the advantage of applying selective coatings on the ETFE membrane on the roof and/or have controllable shading panels over the roof. Figure 11 shows their impact on heating and cooling demand during the competition week. Applying selective coatings to the transparent ETFE films and implementing retractable shading control over the roof can almost bring the same benefits to the house in terms of load reductions. However, controlled operation of the retractable shading works better by allowing the shading coefficient to be optimized for variations in weather and internal demands.

The same simulation was also used to determine which property of the glazing assembly is critical for overall load reduction. It was found that raising SHGC from 0.23 to 0.4 results in an increase of electricity consumption about 27% while doubling U-value only brings an electricity consumption increase of 3.69%. In other words, electricity consumption on space heating/cooling is more sensitive to SHGC changes. The suggestion was thus to choose a glazing with lower SHGC and instead sacrifice U-value relatively if trade-offs between performance and costs are critical.

The above two experiments reflect an ongoing series of design queries to which the dynamic simulation responds. Additionally, the simulation has been further developed to support the real-time installation and testing of the system components of the house. The following section outlines these efforts.

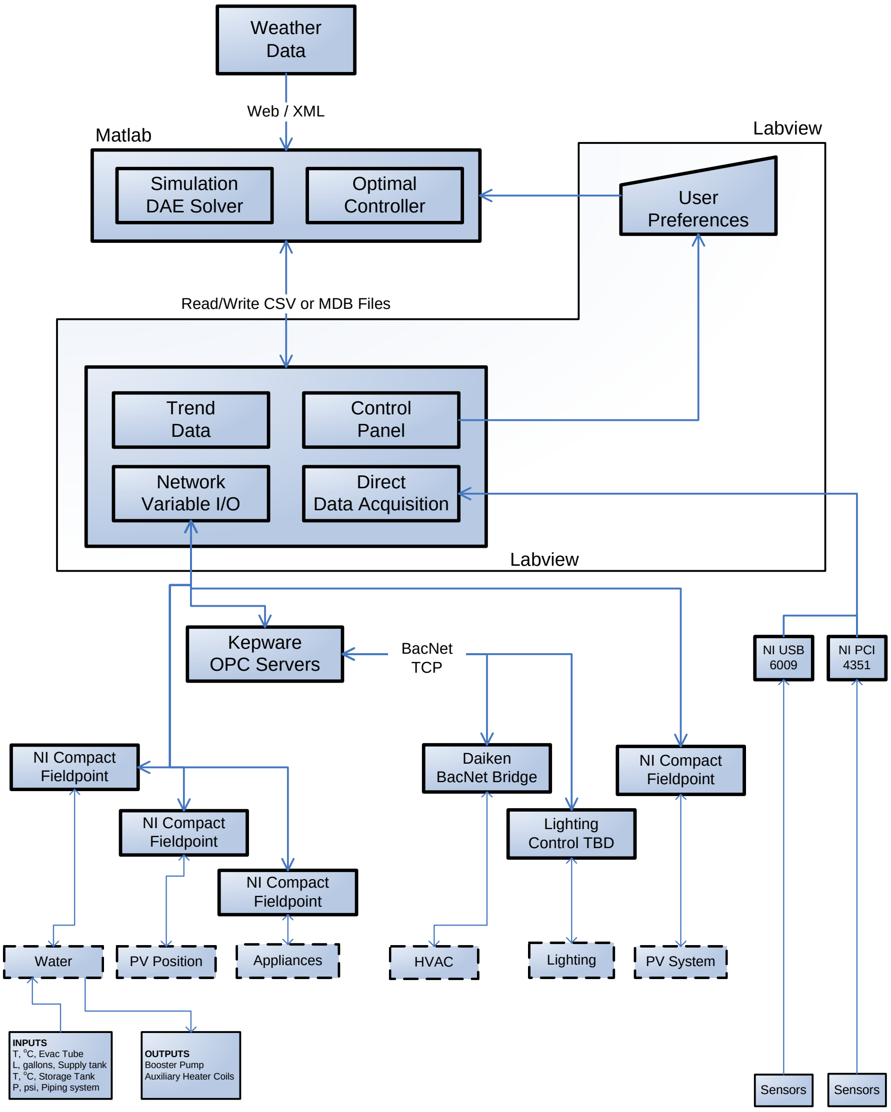


Figure 12 Control system topology and devices

EMBEDDED SYSTEM WITH DYNAMIC CONTROL

The model from the previous section can be used to study the role of different control options. For that purpose, the role of control must be made explicit in the model equations, by adding the control vector u explicitly to the system equations:

$$M(\theta,t))\ d\theta/dt + S(\theta,t\ ;\ u)\ \theta = f\,(\theta,\ t\ ;\ u) \qquad (2)$$

Each control variable u_i in the vector u represents a particular device action (e.g. by an actuator) or occupant intervention in the system behavior. The interesting thing to note here is that there are two levels of control system intervention. On the macro level, the major operation modes (such as decisions whether to run certain appliances or to charge the car with excess battery power) are controlled, whereas on micro-level the operational modes of specific devices are controlled. The system design is done concurrently on the two levels accordingly. The micro-level controllers (mostly PID) are programmed by experienced system designers and represented in the simulation by the identical or simplified set of control rules that are supplied by the system engineers. The strategy and operational rules for the macro-level control are much harder to define and may not be left completely to human judgment during occupation of the house. Therefore, an optimal control component is added to the simulation. This component computes the optimal u(t) by optimizing an objective function and a set of other criteria, within certain constraints. The optimal control optimizes the control objective within a certain chosen time horizon. Figure 12 shows the system control architecture that reflects this set-up.

A complicating factor is that macro and micro controllers need to be in tune with each other. In the simplest case this could require that the value of a macro control variable is embedded in the rules of a micro controller. A thermostat setpoint (as a macro variable value that is exported to a PID) is a typical example of this. In some cases a bi-directional relationship between the two control levels may exist. This obviously makes the optimal control problem harder to solve because the macro control cannot be derived independently from the micro controllers. A good control design will however avoid these situations. The choice of macro control variables and objectives is in fact a major control design decision that greatly affects the ultimate performance of the project as a whole.

The optimal control system is currently being developed and tested in different weather and usage scenarios. Results will be presented in future publications.

ONGOING WORK AND CONCLUSIONS

We have discussed the use of simple models to inform design decisions, followed by a lumped lightweight simulation model for more refined system development. The simulation supports the verification of design options in different weather and usage scenarios. It also supports decisions about control system architecture and the development of control strategies.

In the currently ongoing prototyping phase, the “lumps” in the simulation model are being replaced with more detailed representations where needed, i.e. for novel and critical components. Some of these detailed component simulation models are added to the simulation architecture in such a way that they can easily be replaced by their real world counterparts, when these are brought to the test site and mounted in stand-alone set-ups. The substitution of a simulated component by a real component is used for incremental calibration and testing of the total system. It is enabled by flexible model architecture and suitable digital/analog interfaces. The model components are validated one by one as they are brought to the test site. The combined virtual-real simulation will be used to propose design changes to individual components before they are integrated in the full scale prototype.

Meanwhile the embedded simulation with optimal control component is being used to develop a set of macro control rules that help an occupant to continually optimize the system under the predicted weather conditions. The rules will be implemented through two parallel modes, i.e. fully automatic, and suggested user interventions.

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