DESIGN IN A SIMULATION ENVIRONMENT

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DESIGN IN A SIMULATION ENVIRONMENT

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To my son, with the hope that his opportunities are without limits.

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I wish to thank my advisory committee for the time and input they have given in the development of this thesis.

Deepest appreciation goes to my wife, Sarah, whose love and support have been invaluable during my pursuit of this degree. Here's to some quality time together.

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1. ABSTRACT

The Intergovernmental Panel on Climate Change, as an objective reporter of global climate data for the United Nations [1], stated In its report; *Climate Change 2007: The Physical Science Basis*; that “warming of the climate system is unequivocal”[2] and attributes the warming to “an observed increase in anthropogenic greenhouse gasses”[3].

Citing figures published by the US Energy Information Association, Architecture 2030, an organization committed to a carbon-neutral built environment, shows that the operation of the buildings uses nearly half of the total energy and three quarters of the electricity consumed in United States,[4] making them the largest contributor to the emission of greenhouse gasses[5]. I believe it is the responsibility of the architectural profession to address the impact of the built environment on climate, with a goal of creating buildings that reduce energy consumption, eliminate carbon emissions and eventually have a positive net effect on the environment.

When designing a building, the architect has typically relied on the input of outside experts to determine the performance of building systems. When done properly this collaboration can yield highly effective designs, but typically this reliance has left the architect outside of the loop on performance based decisions and impeded the development of innovative solutions. With the availability of powerful building simulation tools, designers can have direct access to building performance attributes and use them to qualify the

environmental impact of design-decisions. With knowledge of fundamental principles in building performance and computer modeling, a designer can effectively harness the power of these tools from the beginning of the design process. While this does not eliminate the need for expert opinion, it allows the designer to further develop and have more control over the solution through collaboration. By working effectively in this digital design environment, the practice of architecture can meet its responsibility to reduce the impact of buildings on the physical environment.

To test this statement, a brief overview of the integration of analysis tools in two projects that represent the current state of the art for digital performance simulation describes the need for multiple tools to achieve effective results. Based on this experience, a study was done to explore the capabilities of four representative simulation tools to support a design process that is entirely digital. The software evaluated was Energy-10, eQUEST, Sketch-Up with Demeter (a recently released plug-in for energy analysis) and ECOTECT. These tools were chosen because they have been targeted toward architects and claim to be easy to use. The results of this investigation were used to determine an appropriate tool set to develop a design for submission to the Leading Edge Competition, chosen because one of the requirements is that entrants perform energy analyses on their schemes to show how design decisions led to improved performance, making it a good vehicle to explore the process of designing in a simulation environment.

2. INTRODUCTION

The award of the 2007 Nobel Peace Prize to Albert Gore and the International Panel on Climate Change for their separate efforts to document and publicize the causes and effects of global climate change significantly reframed the public debate on the validity of claims made for the existence and causes of global warming.

The timing of the award coincided with reports of the highest recorded seasonal ice melt in the arctic[6] and local droughts in the U.S. that have left reservoirs at their lowest recorded levels. While both recipients acknowledged the work of the scientific community for providing the information they presented, the award was not in one of the scientific categories. Local trends in weather are hard for the average person to quantify. The constant variation of climate (along with the detachment our contemporary society has with the environment) makes it hard to firmly grasp the ebb and flow of weather over several seasons. Because the award for bringing to light the causes and potential effects of climate change was the peace prize, the argument for action to curb global warming is not framed as a scientific based endeavor, but as one of ideology.

The science behind tracking changes in the global environment is now backed by years of observation, from real time measurements and historical data gleaned from coring glaciers and examining tree rings[7]. This data, has led to an increase in the sophistication of predictions from computer simulations that now form the core of information by which policy is being formed. But still, the complexity of weather systems makes their modeling a difficult task. With so many factors at play, the models must simplify many of intricate interactions that occur between air, land, water, sunlight and countless other physical influences in the atmosphere. These generalizations limit the ability of models to definitively pinpoint future performance, and no amount of sophistication would really be able to do this. Instead information is given as a range of possible scenarios. This uncertainty, along with a misunderstanding of the complexity of the issues being investigated (both deliberate and unintentional) has enabled some to question the occurrence of global warming, its causes if it does exist, and what actions should be taken to slow it, if any. Many of those who question the legitimacy of global warming have a particular agenda, from maintaining economic status quo to fearing loss of personal freedom due to regulations that would be implemented based on the research of climate scientists. From this perspective, proposing that the practice of architecture radically change its methods, and its clients fundamentally rethink the way in which they develop and use the built environment is tantamount to demanding a great leap of faith.

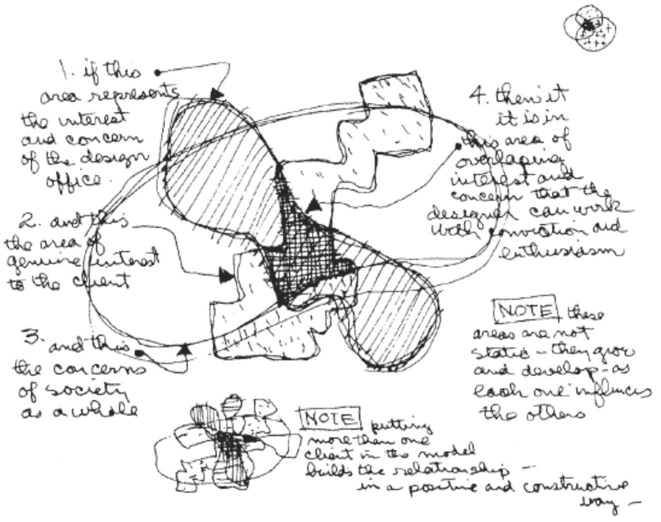


Figure 1 Eames Diagram

This diagram from Charles and Ray Eames[8] (Figure 1) expresses the area within which an architect can design as the intersection of the interests and concerns of the designer, the client and society as a whole. In 1969, when this elegantly simple diagram was drawn, the needs of the client and the concerns of society were not only mostly congruous to the concerns of the designer, but it was also within the methods and abilities of the architect to meet these needs. But now, as society worries about greenhouse gasses that are causing perceptible changes in the climate and clients fear uncertain energy costs, the area where designers can work with “conviction and enthusiasm” becomes constricted by an inability to effectively address these concerns. This constriction originates in a design ideology that has not had to address these issues in anything other than an experimental manner, or viewed the work required to address them as “additional services”. Thus, the design field has not developed a clear method to utilize tools that exist or develop a practice that integrates performance aspects from the very beginning of the design process. How could the integration of design and analysis tools change the design process, and expand the area within which designers can work with conviction?

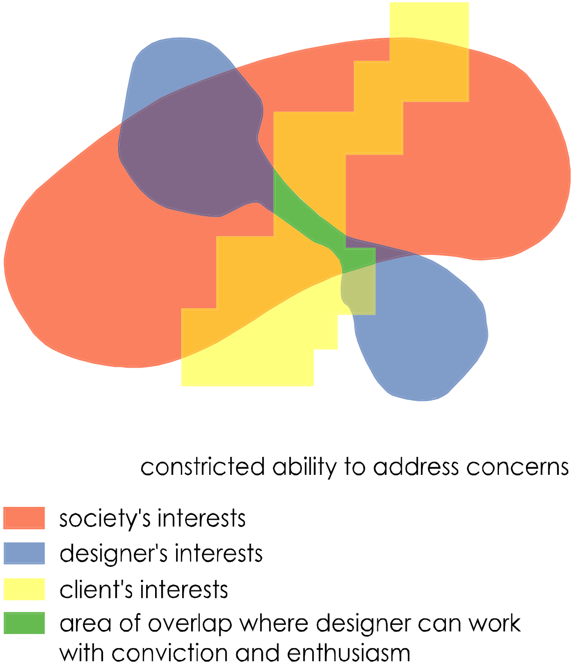


Figure 2 Eames Diagram, Modified

3. CASE STUDY

Computer analysis tools for the simulation of building performance have been available for decades. But it is only with recent advances in computer processing abilities that these tools, which require a significant amount of processing power, have become accessible to anyone with a computer. With the advent of the Building Information Model, the profession of architecture is currently faced with having to adapt the way in which it documents a building for construction. Instead of graphically representing each aspect of the project two dimensionally, it is built virtually, with the digital representation containing data related to cost, weight, and other variables to communicate the design intent for construction and operation. But as these two case studies show, the use of these models for performance analysis is still not viable because to the complexity of date needed and the methods in which it is process for accurate simulation.

Digital Design Ecosystem

During the spring and summer of 2007, I was involved as a student assistant with a research project sponsored by the architecture firm Skidmore, Owings and Merrill (SOM). The goal of the project was to develop a direct link between design and analysis tools that will give designers instantaneous feed-back on the performance of a scheme as it is being developed, allowing them to achieve functional targets as well as desired form.

The first test case was a tower in the schematic design phase, for a major corporation on the Arabian Peninsula. The design beautifully addressed issues of culture, structure and form. But when it came time to determine HVAC systems, it was unclear if the expansive glazing placed too great of a burden for cooling systems to handle. The first task was to identify what should be measured. Given the region's extreme heat gain from exposure to the sun, it was determined that an insolation analysis on the flat glass facades would provide the most valuable information to guide the development of tourqued support shafts, the concept being that the shafts, or leaves, would function as shading devices for the glazing. Because of the strength of its solar analysis tools and its ability to handle complex geometry, ECOTECT was the chosen platform for this exercise. To this point, the design had been developed entirely in Rhino, which can quickly develop and edit complex geometry, but to get the answers needed for the HVAC systems, the model must be translated for analysis in another tool. To ease the transfer of geometry and increase the speed with which ECOTECT can calculate solar gain, the original form was stripped to the essential components required to observe the gains on the glass due to solar radiation. The next step was to determine the best file format for export. The .obj format was chosen because some members of the design team had used it successfully to move Rhino geometry into rendering software for visualization. The major task of the export process was balancing the resolution of the mesh so that it preserved the subtlety of the geometry but did not weigh down the model for analysis. The number of polygons is critical because in ECOTECT, solar analysis is guided by the shading mask. Shading masks are determined by the projecting of rays from a grid of points on each polygon to determine the distance and direction of any obstructions relative to a subdivided hemisphere around the point. The location of these obstructions is compared to the position of the sun to determine if and when they block the suns ray from striking that point. The user has control over both the number of points in the grid, and the number of subdivisions in the hemisphere to control the speed and accuracy of the solution. The goal is to find the right balance of polygons to accurately represent the form and the appropriate resolution at which to perform the analysis. With a 5x5 point grid and a 10° x 10° division of the hemisphere typically used for preliminary analysis run, it would require millions of calculations to generate the shading mask in a highly detailed building model. .

Even with a relatively loose mesh, the import successfully interpreted the form. But, in what turned out to be a peculiarity of the .obj format, it did not recognize the planarity of the floor plates and left a number of stray line segments that would have to be deleted to reduce the calculation time and avoid any influence on the calculation of the shading mask. At the heart of this exercise was the need to reduce the amount of time required to adapt and analyze a design model to provide the designers with information from which they could make informed decisions regarding performance and aesthetics. Little quirks like these stray nodes have a huge impact on the process. At the suggestion of the developer of ECOTECT the import was tried with greater success using the .3ds format.

One of the more powerful features of ECOTECT is its ability to map analysis results directly to the form being measured. The results of calculations for multiple types of analysis including daylight factors, illuminance and luminance levels, and solar radiation levels can be represented numerically and through a color coded key on any surface the uses wishes to measure. The analysis may be further refined by physically sub-dividing the surface or utilizing an orthogonal mesh called and analysis grid.

Utilizing an analysis grid, the solar radiation levels can be measured at specific points mapped across the geometry more efficiently than through the use of multiple surfaces. In benchmarking tests, subdivided surface calculation required upwards of six hours to derive results, while the analysis grid was delivering comparable results in only a few minutes. The cause of this discrepancy was not determined, but the benchmarking showed that with the proper balance of grid density, the designer can develop a quick understanding the physical limits of shading strategies and its overall effect on controlling solar gains. While the numerical figures are critical for an engineer to help size the mechanical systems, the visual map of the measurements ECOTECT provides, allows the designer to intuitively understand their design and how to adapt it to improve performance. By this point in the process is has become quite clear that the direct feedback between the design tool and the analysis tool that was the basis of the SOM project is not merely a matter of linked models continuously updating each other and spewing out analysis results.

At the heart of the issue is that analysis requires more than geometry to provide effective feedback on the performance of a design. While file formats can handle geometric input and typology with little loss between them, the addition of element information such as wall construction or occupancy schedules becomes difficult to translate from a design program to an analysis platform. It's important to note that this preliminary example did not require anything other than basic geometry and weather data for the study performed. Once the question turned to how the insolation values affect cooling loads, the process became exponentially harder.

It became clear at this point that the transfer of data, beyond geometric representation, for continuously updating models was a complex programming issue, well out side the realm of the typical designer, and that any relief of the bottleneck in the working with conviction diagram through this process is most likely several years off. Sparked by these initial investigations though, my personal focus turned to developing an understanding of tools that had well documented use in the design of high performance buildings and some that had recently emerged that show promise in providing effective analysis to designers from the initial stages of the design process.

SOLAR DECATHLON

As a member of the design team for the Georgia Tech entry in the 2007 Solar Decathlon (a competition organized by the Department of Energy which invites schools from around the world to design and build a small house that is powered entirely by the sun), I was in a unique position to utilize my knowledge of analysis modeling while being directly involved with the design development of the house.   At the end of the initial conceptual phase, it was determined that the house should be modeled in Energy-10, based on its suitability for small project with only one thermal zone. The purpose was to see where the house stood from an energy standpoint in its current iteration. The model would also provide a control case for a custom tool being developed by PhD students for the project.

The design focused on a theme of transparency and expressed this through the use of pillows made from a clear Teflon film, known as ETFE, for the roof structure. While ETFE has been used widely in Europe for applications such as green houses and swimming pool canopies and long span atria, it use for a project of this scope had never been attempted. The uniqueness of the product and it’s unusual thermal characteristics required special calculations of its thermal performance for input into the Energy-10 model. The initial energy runs that the house was calling for cooling during the coldest days of the year. When analyzed in “free-run “ mode, which assumes that HVAC systems have been shut-off and that windows will be utilized to control the indoor environment, the interior temperature readings would climb to 120 degrees Fahrenheit during the day, regardless of outside temperatures.

Iterations were done with a conventional roof replacing the ETEF skylights and the results showed heating and cooling loads typical to that of a more traditional house. While this did point to the roofing material as the prime contributor to the abnormal heating of the interior, is also revealed that the Enegy-10 model was not accounting for the shading provided by the roof mounted photovoltaic array. Energy-10 does not allow the input of shades on skylights so a method to “cheat” the model was developed using the insolation analysis capabilities of ECOTECT.

A separate model of the house was built in Ecotect which included a simplified representation of the PV array on the roof. Over an analysis grid, the solar radiation was measure with and without the PV array in position. The ratio of the two insolation values was used as the Solar Heat Gain Coefficient (SHGC input for the skylight glazing. While this did have some effect on the performance of the model, it was still not performing to acceptable levels. These initial studies had a profound effect on the future course of the design, demonstrating the need to improve the performance of the roof.

These results could not have been obtained in either tool alone, but instead required an inventive interplay of the specific functions of each tool to derive a useful result. Additionally, had I not been involved closely with the design process, the decision to search for a thorough understanding of the modeling results may not have occurred until much later in the process when significant changes in the design may have been impossible.

4. ANALYSIS

The initial explorations with the SOM project showed that modeling for simulation requires a highly specific approach, in which geometry must be carefully simplified, while the model is made more complex by the need for physical parameters and environmental information to derive useful results on the performance of a design. While comparisons of analysis tool have been done looking at the complexity of buildings that can be modeled and when and why designers chose to use analysis tools[9], or have simply cataloged tools according to their features[10] ,the purpose of this study is evaluate the input and output of analysis tools from a designer's perspective. To keep the modeling process simple and focus on the input methods, a 20' cube has been modeled in four programs that have varying levels of simulation capability, Energy-10, eQUEST, Sketch-Up with the Demeter plug-in, and ECOTECT. Each of these tools makes the claim that is has been developed for use early in the design process and can be used with proficiency by architects. From the input side, the interface and types of information that need to be entered for analysis are being evaluated. The output is evaluated for its ability to communicate the analysis results in a manner that will allow designer to not only make good decisions early in the design process but communicate these decisions to the client and consultants. The appendices contain sample of the primary simulation output of each tool.

Energy-10

Energy-10 is a simulation tool that was developed specifically for smaller buildings, less than 10,000 square feet and no more than two thermal zones, which are early in their design stages, to give architects a sense for how their initial decisions affect energy performance[11]. The software was developed in collaboration between the Sustainable Buildings Industry Council (SBIC), the National Renewable Energy Laboratory (NREL), the Lawrence Berkeley National Lab (LBNL), and the Berkeley Solar Group[12].

Input

There is no graphical interface in which the design is actually drawn. Instead, the geometry is assumed to be rectangular and the shape of the building is controlled by entering the square footage and a ratio of length to width. Weather data, utility rates, building use and HAVC systems are also entered on the initial screen for each new project. Information on the construction types and thermal properties of walls, floor and ceiling can be entered though a series of data cells and pull down menus. Custom assemblies and material can be created easily with data input cells.

Output

Despite its rudimentary interface, the simulation capabilities of Energy-10 are fairy robust. Utilizing the California Non Residential Engine (CNE) it performs a full year hourly, energy balanced simulation. In addition to running the calculations on the building attributes input by the user, it will run a second simulation that finds a value within the initial model that, if improved, will reduce energy usage, and analyzes a second iteration with an optimum parameter set for that attribute. This immediately gives the designer an understanding of where their design can be improved and the impact of these improvements. Energy-10 can also assess the impact of daylighting on lighting power loads and heat gain and incorporate solar technology as a contributor to reduced energy consumption. After the analysis is complete, the first screen displayed is the data sheet. The building construction is summarized and system types and set points are listed. The systems are sized based on the analysis. The results of the energy analysis are given in the amount of energy consumed, both for gas and electric, and as cost, based on the utility information provided on the first screen.

Additional output is available in the form of graphs that can display highly specific performance characteristics, including a breakdown of energy use by function, comparing the two simulated models and the daily energy use for heating and cooling along with the outside and inside temperature. While this information can provide critical insight into the performance of the design, these graphs are also helpful in vetting the integrity of the model. In addition to the side by side comparison of iterations Energy-10 allows for the optimization of design through a process known as elimination parametrics. The effects of one factor in the buildings performance, e.g. insulation, glazing, internal gains, are “eliminated” from the model by setting its contributing value ridiculously high or low to see how it effects energy use. For instance, to see if conduction losses are a primary contributor to heating and cooling loads, a parametric run is done with the R-value of all walls and ceiling set to 1000. The difference in energy consumption between this model and the base model are compared to see the effect. This is done for several attributes, lighting loads, occupancy, U-values of glazing, and the results are mapped against each other. The actions that produce the most significant changes indicate that tweaking those attributes with realistic values in the base model will have the greatest effect, giving the designer great insight on where to focus their design efforts for energy reduction.

Summary

The limitations of building size, number of zones and few HVAC system options narrow the application of Energy-10 to the simplest of building types, or only allow the tool to be utilized at the earliest stages of design to develop envelope strategies without the complexities of modeling more advanced HVAC options. The ability to incorporate daylight strategies and model the effects of renewable technologies on energy use provide significant help in the design of high performance buildings. Its lack of a visual representation of the modeled design may discourage some designers, but at the same time it simplifies the entry of geometry and physical construction, reducing the learning curve and time spent building the model. Energy-10's data out put is extremely thorough and can be parsed for specific performance characteristics, and its presentation is clear, though a bit lackluster in appearance. Overall, Energy-10 is an effective tool for early phase performance analysis of small, simple buildings.

eQUEST

eQUEST is a graphical interface to the DOE-2 analysis engine, which is one of the most robust simulation tools available. It can be used to demonstrate compliance with California Title 24 and ASHRAE 90.1 standards for building performance. As such, it has become a standard of performance analysis for projects pursuing LEED certification. It is similar to Energy-10 in its interface and methodology, but does not have the limitations on size and complexity. The geometry of the building can be modeled as designed, although it is best simplify as much as possible for analysis. System zoning and controls sequences can be highly refined and there are dozens of system types available to simulate. Other features include the ability to perform daylighting calculations and link these to lighting controls to determine energy savings. eQUEST also offers the ability to perform batch simulations incorporating multiple parameters for aspects of the building envelope and system design, called Energy Efficiency Measures, to analyze "what-if" scenarios. Batch processing allows for the iterations to run automatically, a significant improvement over Energy-10, which requires the parameters to be manually changed, re-simulated and reported.

Input

eQUEST offers three stages of model development. Beginning with the Schematic Design wizard, information about building use, location and utility rates are input though a series of drop down menus and data fields, similar to Energy-10. The building footprint and zoning can also be developed by tracing an imported .dxf file. Each window in the wizard asks for a different function of the building to be input. While it is called the Schematic Design Wizard, the level of detail requested in each field seems to suggest that eQUEST is best started after some consultation with the project's engineers. The next phase is the Design Development Wizard, which again uses a series of pull downs and data fields. The DD wizard expands the number of system types available and allows for the modification of schedules and more detailed input of envelope information and controls set points. The third phase of building a model in eQUEST is through the Detailed Interface. This give the modeler access to every aspect of each component in the model and allows for fine tuning the inputs to make the simulation as accurate as possible. For the nature of the cube exercise, only the schematic design wizard was utilized, accepting several default values through the process.

Output

The initial output eQUEST delivers provides a breakdown of energy consumption by end use for the design. While this provides a quick overview of the performance of the model, the most valuable information lies in the one-thousand plus pages of charts and tabulated data with information on everything from total annual electric an gas consumption to daylight levels in sky lit spaces and static pressures for every air handler. While the cube exercise does not exploit this, in a building with dozens of systems, and multiple zones within each system, this becomes a tool that allows a knowledgeable designer, working in conjunction with a good engineer to create a highly refined design in terms of energy efficiency.

Summary

eQUEST is the benchmark for whole building simulation, with decades of development and thousands of users providing each other support through online list-serv. While it claims to be an easy to use design tool, the complexity of the tool requires knowledge of building systems and performance characteristics that the typical designer does not have. That said, anyone with this knowledge can systematically construct a thorough representation of a design as well as several iterations for analysis and expect reliable results to form good design decisions.

Sketch-Up w/ Demeter

Sketch-Up is a 3-d modeling tool that is easy to use and, with some of it's advanced functions disabled, freely available from Google. It is effective for initial visualization and conceptual studies as well as communicating design intentions to clients and consultants. It also has a broad network of users, connected through 3dWarehouse, a web site in which models and techniques are freely exchanged. Its use as an analysis tool has been limited to shadow studies with the professional version, but this has changed with the recent beta release of Demeter, a plug-in that links Sketch-Up with the Green Building Studio (GBS) online analysis tool. GBS is a web based application that uses DOE2.2 (the same engine utilized by eQUEST) to perform full year energy analysis. Utilizing its proprietary gbXML file format[13], Green Building Studio also interfaces with Revit and Archicad for design file input. Results can be exported to Doe-2, eQUEST, Energy+ and Trane700 energy modeling tools for more intensive analysis.

Input

The modeling process in Sketch-Up for performance analysis is not very different than the beginning step of building a typical design/visualization model. As with eQUEST, the key is to keep the model very simple, using single planes to represent walls and windows, and clearly delineating spaces for zoning.

The actual preparation of the model for analysis occurs entirely in Demeter, which is run on top of Sketch-Up. The user defines zones and occupancies through the selection of surfaces. Then each surface is identified as either interior or exterior and if is a wall, floor or ceiling, window or door. No material specifications can be made beyond this and it is not clear what the default materials are. After assigning all materials the model is exported to

Green Building Studio's online simulation engine for analysis where location data is chosen before the simulation is processed by a GBS server.

Output

Because the simulation is run on a remote machine, the results are delivered via e-mail. The output from the analysis includes the total annual energy consumption and cost, based on user supplied. The lifetime use is also provided, which is valuable for life cycle cost analysis of efficiency strategies. An additional piece of information shows the source of the electric power.

With the base subscription though, much of the information GBS can provide is not available. While the first few simulation runs are free, GBS charges for additional analysis iterations by the space being modeled.

Summary

Though it seems promising to link a freely available modeling tool with a well proven and powerful simulation engine, the results of the Sketch-Up/ Demeter analysis do not provide designers with enough information to evaluate the performance of their designs and make clear decisions on the best strategies to improve performance. The inability to edit materials, occupancies and systems coupled with the fees for additional iterations make the process of evaluating multiple strategies difficult, if not impossible. Also, given the fairly quick simulation times of Energy-10 and eQUEST, the need to wait for results to be e-mailed could also be a hindrance to design process. In Energy-10 and eQUEST, the simulation run is an opportunity to check the model for errors. Because the simulation is done remotely with GBS, this is not possible. The future development of the Demeter plug-in may be jeopardized by the recent announcement that Green Building Studio has been purchased by Autodesk[14].

A solution to these short comings may be on the horizon with a plug-in that will allow a Sketch-Up model to be exported, with material definitions, for analysis in Energy Plus. Physical attributes, according to a recent simulation user's group bulletin board post, will be able to be "painted" on just as graphical representations of glass, brick and other materials are. Although the results of the Demeter plug-in create some reservations toward these claims, the notion of a free design tool linked to one of the most powerful simulation tools available is promising, assuming the results can be interpreted intelligently and used effectively.

ECOTECT

ECOTECT is unique in that it combines a highly graphical interface with a broad range of analysis tools. The types of analysis directly available within the software are shading, shadows and reflections, solar, lighting, thermal, and acoustic. The target audience is architects in the schematic and design development phases and it appealing interface and output are one the reasons it was chosen buy SOM for the DD Ecosystem project outlined in Chapter 1.

A climate analysis module packaged with ECOTECT, Weather Manger, provides clear diagrams of climate information which can be derived from several weather file formats. While it performs a multitude of analyses, the thermal, acoustic, daylighting, the calculation methods it utilizes lack sufficient detail for reliable investigation. They may be adequate for the earliest stages of design, but intensive analysis required for useful design development must be done in other software. ECOTECT addresses this by offering the ability to export to several popular analysis formats, but specific modeling conventions must be followed for each format type, limiting the ability to move one model freely among different tools. Modeling conventions also required for each analysis also make it difficult for one model to be used for all calculations within the tool as well.

Input

The interface of ECOTECT is controlled though a series of tabbed views each with a specific function for setting up, creating, viewing and analyzing the model. The drawing interface, or 3D EDITOR tab, is the most CAD-like of the analysis tools evaluated in this study, with buttons activating commands such as line, plane, and zone, to generate the geometry of the model. This is also where windows, doors and other opening are assigned to surfaces. There is a parent-child relationship between surfaces and the openings that is common in other analysis tools. In ECOTECT this relationship must be explicitly modeled, whereas in Energy-10 and eQUEST, it is automatically generated. When any object is created a default set of material properties are assigned to it. These properties are required for every analysis, and the default types can be changed from a menu of existing material definitions. Custom materials can also be defined by the user, but because ECOTECT uses a thermal calculation method peculiar to England, the Admittance Method, some of the properties required are difficult to obtain for uncommon materials.

The 3D EDITOR tab provides a wireframe view of the model, and this is the only view in which the geometry and object properties can be edited. The VISUALIZE tab displays an OpenGL rendering of the model and is used for most of the analysis of shading, sun-path and sun-penetration.

Output

While the ease of modeling and access to multiple types of analyses make ECOTECT an attractive tool for designers, the manner in which it displays results is the most valuable feature of the software. Tabulated data can be exported to excel for post processing. Graphs of data for the various analyses map the information in clear, almost expressive formats. With the analysis grid, discussed in the summary of the SOM project, the results of several types of analysis can be displayed in conjunction with the geometry being measured, or represented directly on the surfaces themselves. This also applies to the use of data from some of the third party tools that ECOTECT can generate export files for, most notably Radiance lighting software, which can provide accurate simulation of daylight and artificial lighting. An additional feature is the ability to quickly save the results of all analysis in both of raster (.jpg, .bmp) and vector (.wmf) formats for editing in graphics software. One bug in the current version is the mislabeling and, in some cases, the incorrect conversion of SI units to IP, which requires some diligence on the users part to interpret the results correctly.

Summary

ECOTECT is the closest to a one tool solution for providing early phase performance analysis to designers. Its ease of input, ability to import several types of geometry, clear graphics, ability to export results for presentation and evaluation, and model information for use in more advanced tools show it to be a suitable starting point for the integration of simulation into the design process. Some aspects of a building design, such as those dealing with shading and solar control can actually be refined to a high level within ECOTECT alone, but many of the analysis methods lack the rigor or rely on overly simple calculations that make it them insufficient for use in final performance design decisions. ECOTECT attempts to address this with the ability to generate several file formats for more complex simulation tools. Aside from the Radiance interface for lighting studies though, most formats require such strict modeling protocols that their use is limited. As a starting point for designers looking to improve building performance from an energy and comfort standpoint, these shortcomings do not outweigh the benefits of the analysis feedback ECOTECT can provide, as long as the designer knows when the limits of the tool have been reached and can turn to the appropriate method for future development.

Conclusion

The experiment of the cubes shows that there is not one single tool that can effectively provide all of the data designers require for making effective performance based decisions. The software evaluated in this exercise represents a broad array of the options available to designers today, but all reveal that the use of simulation as an integral part of the design process requires an understanding of the physical possesses at work in a building in conjunction with proficiency in the nuances of modeling for analysis. In addition to these aspects of the process, multiple factors must be considered from the very beginning, including macroclimate, microclimate, building codes, and performance requirements of the program. At the current level of technology available, designers must have the ability to move between a variety of design and analysis tools to effectively explore strategies and effectively address these issues. Figure 3 highlights how these paths can operate within some of the more popular programs available now. It is also important to consider the level at which each can contribute through the phases of design, construction and even occupancy, to ensure the appropriate information is being analyzed and communicated. (Figure 4)

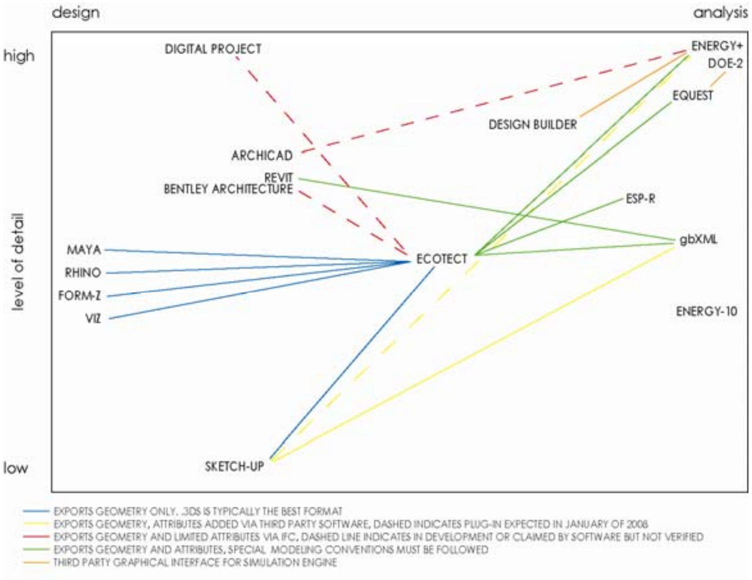


Figure 3 - Interoperability of Design and Analysis Tools

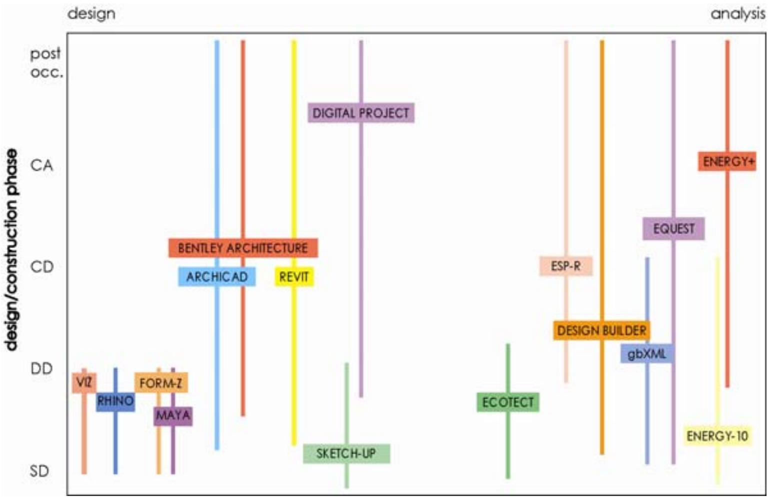


Figure 4 - Phase Appropriateness of Design and Analysis Tools

The development of Building Information Modeling (BIM) software holds the promise of fully integrating analysis abilities with design tools, allowing designers to utilize one model for design and simulation, but, as the SOM project shows, this level of integration is far from reaching the mainstream. The largest hurdles are the ability to transfer the information on materiality and occupation, which drive energy simulation, and the creation of modeling conventions that allow a detailed design model to be simplified for analysis. Overcoming these obstacles will likely require a major retooling of the way most software operates, and solving this issue will be a significant achievement in programming. But, just as the transition from the drawing board to digital media in the design realm has not eliminated the need to still have good design sensibility, the integration of analysis into design tools will still require thoughtful interpretation based on sound knowledge of performance of the built environment. Given the immediacy of our global climate situation, and the ability of the design profession to make significant contributions toward reducing our impact on climate change, making this knowledge accessible to all involved with design, and having a clear process for using it should be one of the pressing concerns of the architecture profession.

5. TEST CASE

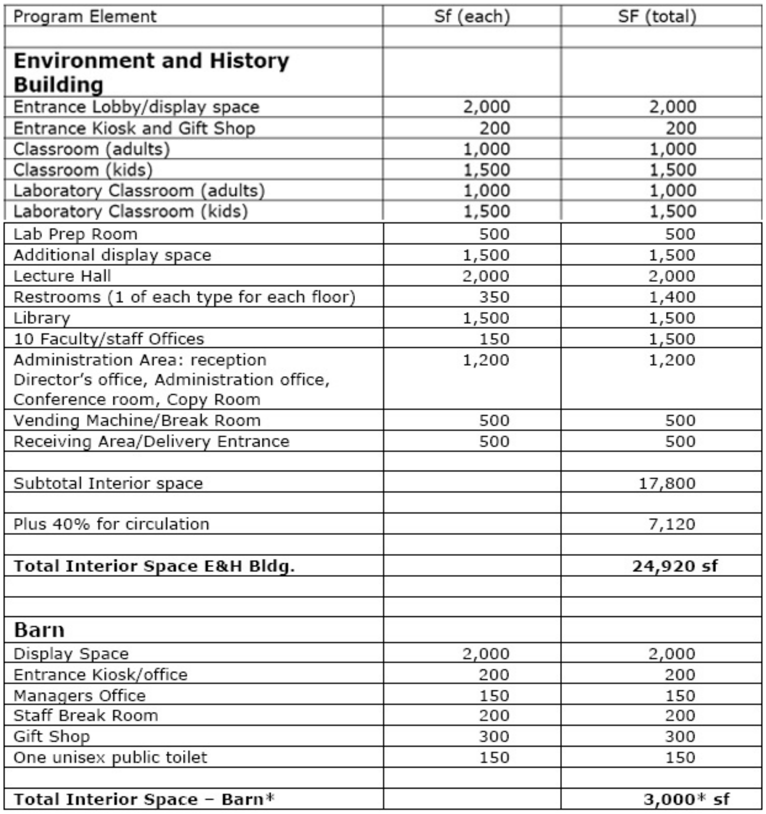
To explore the process of integration of performance analysis into the early phases of design, it was felt that the use of a competition with a well structured program and defined site would allow for the focus on performance issues, the peculiarities of site analysis, and development of performance parameters. The Leading Edge Competition provides just such a vehicle. Sponsored by the California Energy Commission, it is a student competition, held annually every spring, which requires that the entrants perform a series of manual calculations or a full energy simulation on their design and then improve their design from an energy stand point based on the analysis.

The program for this year’s edition of the challenge focuses on the design of an Environment and History Center on the West Campus of the University of California, Santa Barbara. While the program requires the integration of a wide variety of spaces, including exhibition areas, offices and a lecture hall, the focus of the energy analysis is to be on one of the four classrooms scheduled in the brief. Entrants must still develop a comprehensive strategy for energy efficiency for the entire building but calculations are only required for the classroom. Because of the competition’s focus on the classroom, it will be the module in which all of the supporting analyses are done as well. Focusing on one discreet element simplifies the task of modeling and analyzing, and its results can be extrapolated for use throughout the design. The competition is judged by a panel that includes architects, engineers and representatives of the energy industry, which should ensure that projects are evaluated for both aesthetic and technical merit.

Program, Context, and Climate

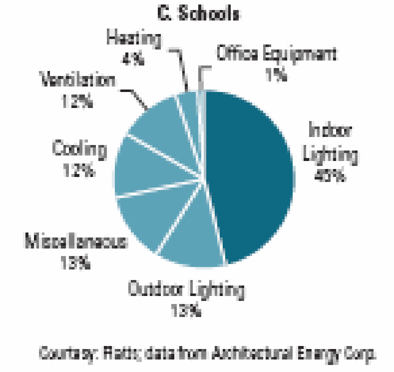
Because the program has been spelled out by the competition brief, the design process begins, as it does with most projects, with an evaluation of the program, a thorough study of the context of the site, and code requirements for the area of the project. The integration of passive an active energy efficiency strategies require an additional layer of information, that of the local climate conditions. An understanding of when and how weather patterns affect a site is critical to choosing the appropriate strategies for both the programmatic and thermal comfort requirements of a building's users. The most common source for this information is known as a Typical Meteorological Year (TMY) file. TMY files are an average of 30 years of weather data, incorporating a broad range of measurements such as temperature, humidity, rainfall, cloud cover, and wind speed and direction, which are collected at specific locations throughout the world. Because California contains wide variety of climatic conditions, an additional level of information is required for compliance with the California Energy Code. The state is divided into 16 climate zones, each with its own TMY file. While the design of a building should be done with the appropriate regional weather file, code compliance is determined with the climate zone data. [15]

Figure 5 - California Climate Zone Map with Site and Regional TMY File Locations; California Energy Comission



Program Element	Sf (each)	SF (total)
Environment and History Building		
Entrance Lobby/display space	2,000	2,000
Entrance Kiosk and Gift Shop	200	200
Classroom (adults)	1,000	1,000
Classroom (kids)	1,500	1,500
Laboratory Classroom (adults)	1,000	1,000
Laboratory Classroom (kids)	1,500	1,500
Lab Prep Room	500	500
Additional display space	1,500	1,500
Lecture Hall	2,000	2,000
Restrooms (1 of each type for each floor)	350	1,400
Library	1,500	1,500
10 Faculty/staff Offices	150	1,500
Administration Area: reception Director's office, Administration office, Conference room, Copy Room	1,200	1,200
Vending Machine/Break Room	500	500
Receiving Area/Delivery Entrance	500	500
Subtotal Interior space		17,800
Plus 40% for circulation		7,120
Total Interior Space E&H Bldg.		**24,920 sf**
Barn		
Display Space	2,000	2,000
Entrance Kiosk/office	200	200
Managers Office	150	150
Staff Break Room	200	200
Gift Shop	300	300
One unisex public toilet	150	150
Total Interior Space – Barn*		**3,000* sf**

Figure 6 - Competition Program



Courtesy: Ratti; data from Architectural Energy Corp.

Figure 7 - End-use Distribution of Energy Consumption for School Buildings in California; EDR Design Brief, Integrated Building Construction

The determination of appropriate strategies for energy efficiency must also consider the programmatic requirements and what factors contribute most to consumption. From the program provided by the competition brief (Figure 6) the use of the environmental center, while diverse, is in many ways similar to a school. Looking at end-use consumption for school buildings in the state of California, indoor lighting is the dominant load, using nearly four times the power of any other system.[16] (Figure 7) Because schools are usually occupied during the day, this indicates that the most effective strategy to pursue for energy conservation is daylighting. Effective daylighting can significantly reduce the need for electric lighting in a space, not only saving energy from the fact that the lights are not directly using electricity, but also in that light fixtures produce heat which contribute to the cooling loads of building.

Review of the context, code and climate should be cognizant of issues that would affect the performance of daylighting systems as well investigate the potential for additional strategies that can improve comfort and energy efficiency that may have synergies with daylighting techniques.

Context

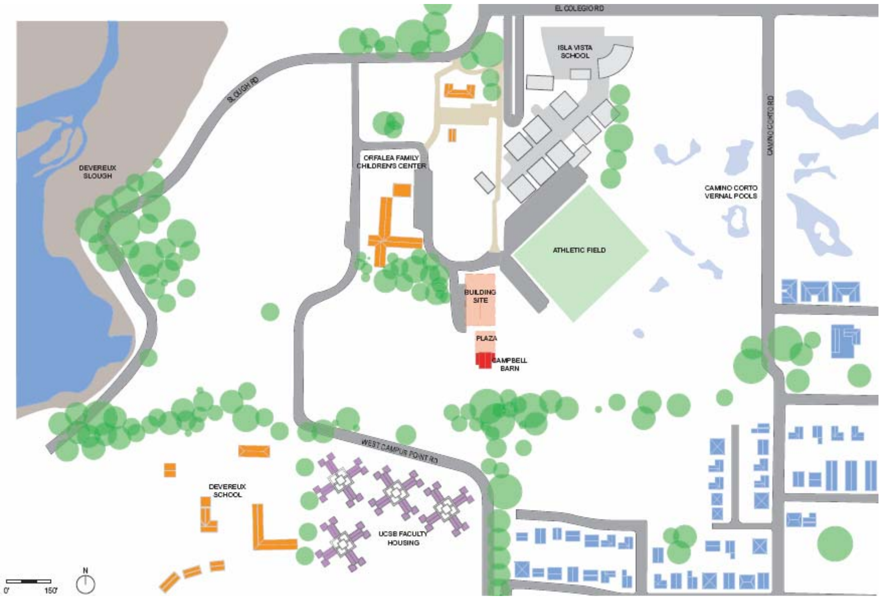


Figure 8 -Map of Site Context

Looking at context first, the competition site occupies an area that contains the remnants of farm that existed when the region was predominantly agricultural land.(Figure 8) A growing population and the expansion of the University of California have shifted the land to residential and institutional uses, destroying much of the natural environment. The site is adjacent to an elementary school, a series of vernal pools, near a lagoon, and located at the confluence of conservation areas managed by state and local governments.

The conservation areas (Figure 10) have come about in response to the regional development and the Environmental Center will serve to educate its visitors on the natural and cultural history of the area. Its vehicular access is limited to a service drive.(Figure 11) Noise levels and air quality are not likely to be affected by cars, since the nearest major road is over 300 yards from the site. A series of informal footpaths connect the site to the residential development and the school. The program encourages the building design to address connections to these areas (Figure 12) with emphasis given to the Campbell Barn, Isla Vista School and Devereux Slough. Additional research also showed a need to understand the influence of the Santa Ynez Mountains, located a few miles north of the site.

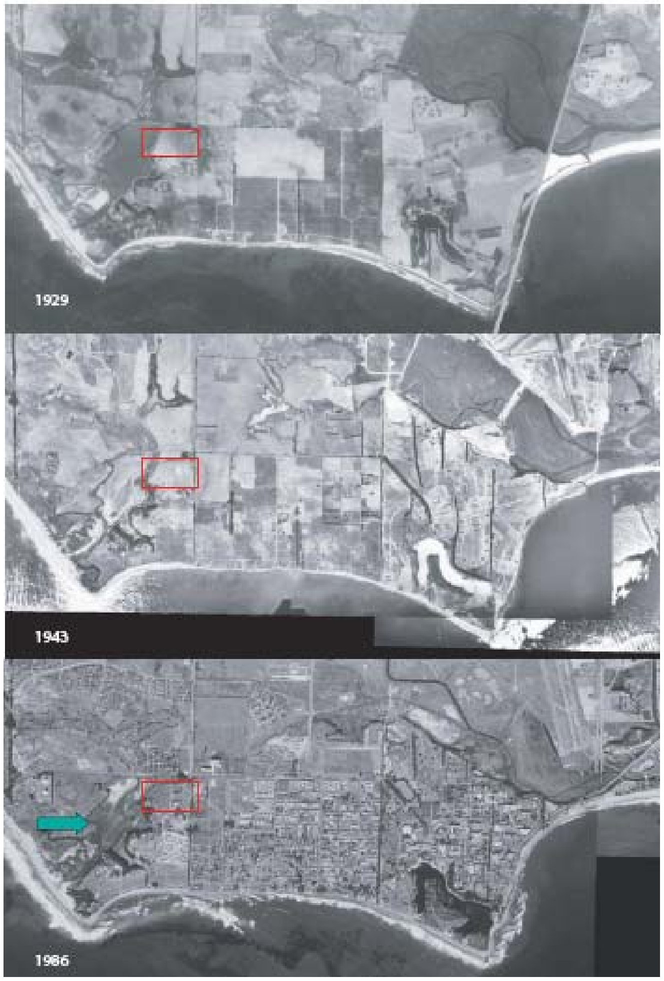


Figure 9 - Aerial Images Showing Development of Region Over Time, area shown in Figure 8 indicated by red rectangle.

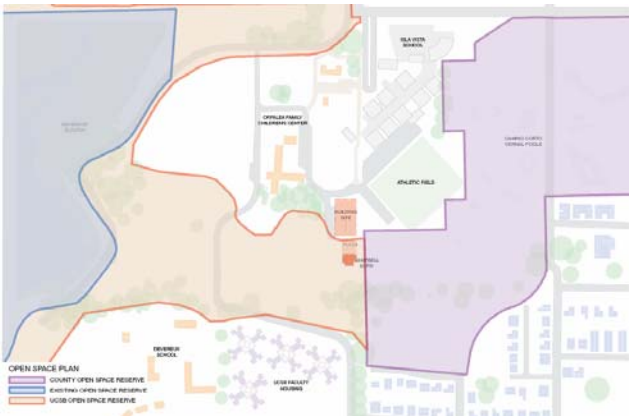


Figure 10 - Natural Reserve Areas Adjacent to the Site.

Figure 11 - Vehicular and Pedestrian Access

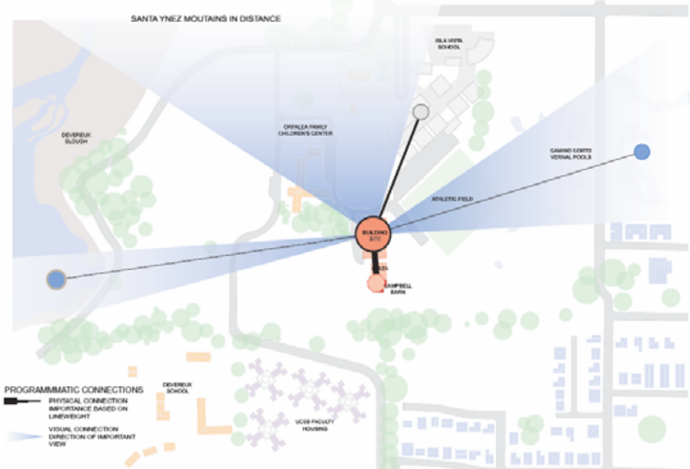


Figure 12 - Physical and Visual Connections

Figure 13 – Campbell Barn from Slough Rd.

Campbell Barn

According to the competition guide, the Campbell Barn was constructed in the 1920's as a horse barn for the farm that once existed on the site. Because of its proximity to the building site and historic

Figure 14 - Interior View of Barn

status, the competition Guide strongly recommends that the project respect the scale and style of the barn. As part of the design challenge, the barn's interior must be designed to fit additional display and administrative space, but competition rules assume that the barn's exterior has been restored to original condition. A plaza space between the barn and interpretive center must be integrated into the design.

Isla Vista School

Figure 15 - Isla Vista Elementary School; photo: RNT Architects

Adjacent to the competition site is the Isla Vista Elementary School. Constructed in 2000, the school's orientation and space layout are designed to take advantage of daylight and the prevailing winds for natural ventilation. With modeled energy consumption 30% better than Title 24 requirements, the school's designer, Roesling, Nakmura, Terada, received an award from the American institute of Architects for integrated design. [17]

Vernal Pools

Figure 16 - Aerial View of Pools with site in the foreground; source unknown

Directly East of the project Site are a collection of vernal pools, small, seasonal ponds that occur after heavy rains in December and January fill depressions in the costal mesa. They disappear during the spring and do not return until the rains fall again. The pools are protected as part of the Camino Corto open space by the city of Goleta, and are home to several unique plant species that have adapted to the constantly changing conditions.[18]

Devereux Slough

Figure 17 - Devereux Slough, Santa Ynez Mountains in the distance; photo: http://pinker.wjh.harvard.edu/photos/california_2007/pages/Devereux%20Slough.htm

Sloughs (pronounced "slew") such as this once dotted the coastal mesa that is now the location of the cities of Santa Barbara, Goleta, and Isla Vista. Most have been filled in, including a large portion of this particular slough. Soughs are lagoons in which the water level fluctuates with seasons. Each winter, the basin overflows into the ocean from winter rains, but a combination of sediment build-up and lowering water level eventually plug the drainage channel. The water level continues to recede through the remainder of the year, when very little rain falls, until the cycle is repeated again in December. The slough is protected as part of Coal Oil Point Nature Reserve, one of a series of research sites controlled by the University of California. As a habitat for several native and migratory bird species as well as home to several species of plants unique to the slough environment, the preservation of Devereux Slough is critical because of the development that has destroyed most of the other habitat in the region. Exhibits on the natural history of the slough and the vernal pools are to be the focus of interpretive center display areas.

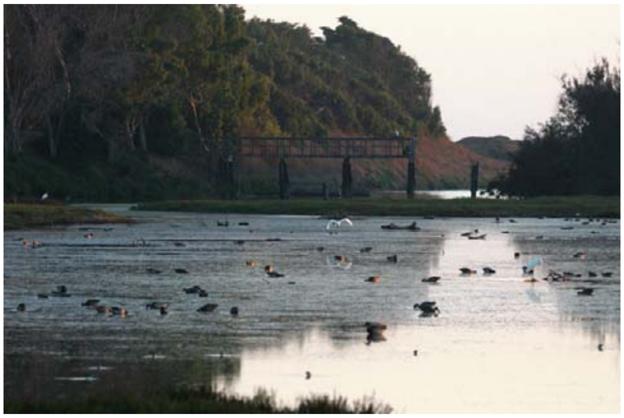


Figure 18 – Birds at the Slough; photo: http://www.calliebowdish.com/DevereuxStory.htm

Santa Ynez Mountains

Dominating the northern vista, the Santa Ynez Mountains are part of Traverse Ranges, a series of mountain ranges that cross California from east to west. In addition to being a prominent visual feature, the range contributes to the local climate through a wind condition known as *foehn*, which is a warm, dry, down slope wind that occurs on the leeward sides on mountain ranges[19]. Locally they are referred to as sundowner winds as they

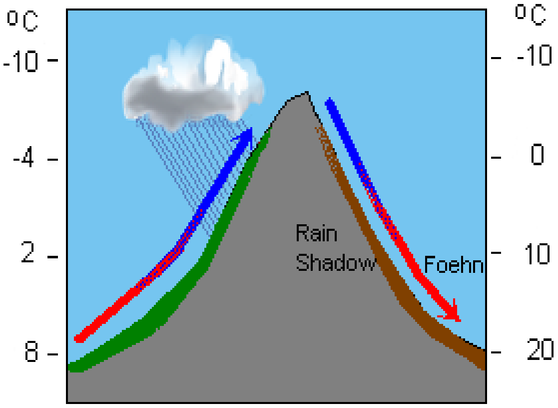


Figure 19 - Diagram of a Foehn's Effect on Wind Temperature; http://upload.wikimedia.org/wikipedia/en/a/aa/Foehn1.png

typically occur in early evening[20]. The warming effect can be significant, as can the wind velocity. One event recorded in 1859 measured a temperature fluctuation from the mid 70s at midday to 130 degrees by 6pm and back to the mid seventies by the evening. Wind gusts can exceed 100 miles per hour.[21] While regional weather files provide a good general understanding of local climate, such micro-climatic conditions need to be understood. Though sporadic, these extreme winds occur with enough regularity to be a concern, but like most meteorological extremes, should not be the driver of design.

Figure 20 - Snow on the upper slopes of the Santa Ynez; photo: http://www.calliebowdish.com/BirdsCOPR.htm

Temperature, Enevelope and Energy Analysis

Research on the contextual elements of the site has given a glimpse of some the climatic factors at play in the region, including the annual pattern of rain fall, a brief spell of rain in the winter followed by extremely dry conditions for the rest of the year, and the occurrence of the sundowner winds. To get a true understanding of characteristics of the local climate several tools are available to graphically display the data from TMY files. Climate data was analyzed using Weather Tool, developed by Square One Research. Weather Tool is a more robust version of the Weather Maker module that is bundled with ECOTECT which adds the ability to plot data on a psychrometric chart and evaluate climatic potential for passive design strategies. Weather Tool offers the ability to ability to sift the data into fairly specific time-frames such as morning, mid day, and afternoon for monthly or annual periods, to develop a deeper understanding of the climatic trends at hand for a site. Like ECOTECT, Weather Tool can export its graphics to vector and raster formats. Not only is this valuable for presenting the data, but it allows the layering of programmatic information for an even greater level of interrogation.

The initial investigation was of annual temperature ranges to evaluate the climate against a seasonally adapted comfort zone. This will highlight the periods when heating or cooling is required to maintain thermal comfort, and to what extent the temperature deviates from the comfort zone. The weather file from Santa Maria California was chose because of its proximity to the competition site for all of the design analysis. For the temperature analysis the local weather file was compared to the Climate Zone 6 weather file that will be used for the energy analysis to be run on the classroom. Evaluating the differences between the two will help with the analysis of the energy model, especially when the simulation results seem contrary to expected behavior.

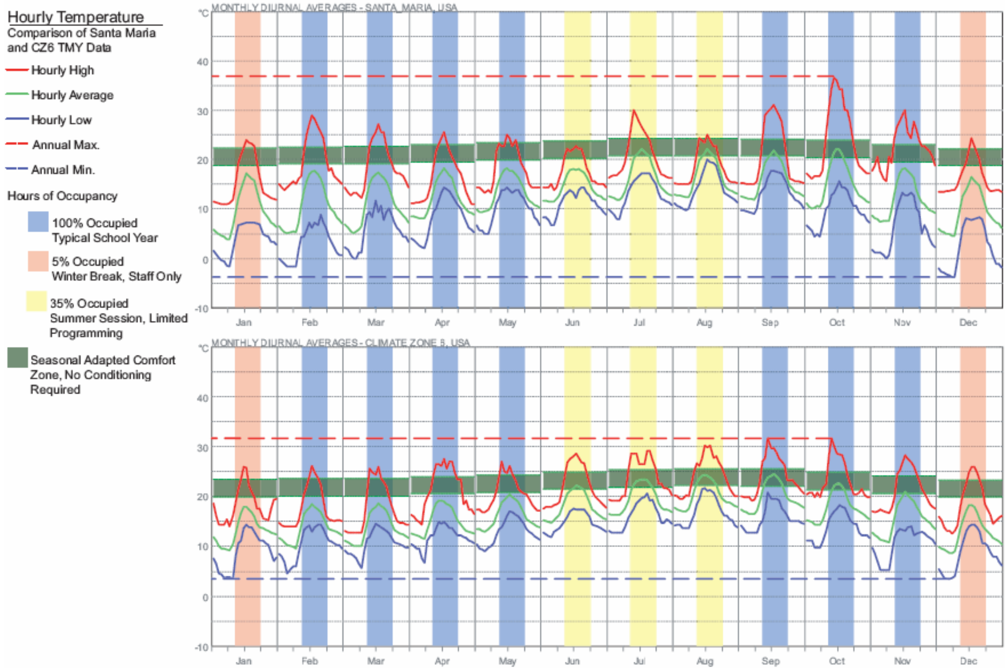


Figure 21 -Hourly Temperature Comparison, with Occupancy Timeframe and Adapted Thermal Comfort Zone

The data presented is the monthly average readings of the temperature at each hour of the day. The vertical bars have been added to highlight the typical hours of occupancy for the class room, 9am-3pm. The color indicates the level of occupancy, with red indicating a low occupancy during the holiday beak, blue being a fully occupied period during the school year and the yellow a partial occupancy for summer programs.

Working form the point of view which says systems should be designed for peak conditions, but optimized for averages,[22] the main focus at this stage in the process is the average temperatures represented by the green line. Both weather files show that nearly all year, even in the occupied hours, the temperatures are below the comfort zone. The difference is more extreme in the local TMY file. During the design phase, additional analyses that factor internal gains from occupants and equipment, and external gains from solar radiation will help determine if the deficiencies can be compensated for. ECOTECT is effective at measuring insolation at the building component level, and makes for an effective tool to develop solar gain strategies. The incorporation of internal loads will be done within an energy simulation tool. Because the competition only requires the modeling of one classroom, Energy-10 is an adequate choice to handle these calculations. Care will have to be exercised in the modeling of adiabatic surfaces to ensure that losses or gains are not factored as if these surfaces were exposed to the exterior. To account for this, a method similar to that of the Elimination Parametrics described in the first chapter will be explored.

The modeling of the classroom must also demonstrate an improvement in performance based on design decisions. To show this, the compliance method of the California Energy Code (CEC) will be used. Based on climate zone, the CEC mandates minimum thermal performance values for envelope components. A model of the design is built with all of the values for glazing, walls, roof, etc, set to the code minimums. An energy analysis is run and the annual costs of energy to maintain thermal comfort in the building is calculated based on the amount consumption and the price of utilities. This is referred to as the baseline model energy budget. The model is then modified to incorporate actual; designed thermal properties and analyzed. The design model must have an energy budget lower than the baseline to be code compliant. The level of performance is determined by the extent to which a design is improved over the baseline model.

Sunpath, Cloud Cover, and Daylighting Design

Because daylighting has been identified as a major strategy from the programmatic analysis, the next study looks at a mapping of the annual sunpath, derived from ECOTECT, superimposed over the site. Again, hours of main occupancy have been indicated though the use of a yellow screen. Superimposing the path over the site allows for a quick under standing of the relationship to the sun's position relative to the orientation of the site. It also shows if there are any potential issues from overshadowing caused by adjacent buildings or trees.

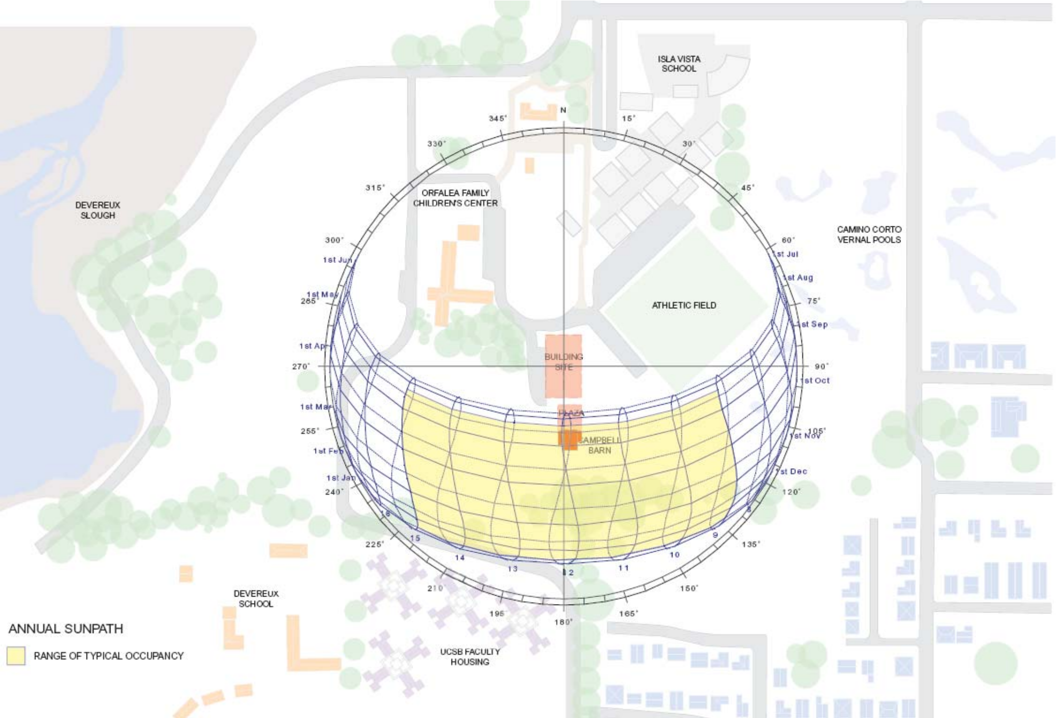


Figure 22 - Sunpath with Hours of Occupancy Shaded

An initial survey indicates that because the site is flat and open, there are no significant overshadowing issues. The trees to the west may cast some shadows over the site, late in the day during summer months. The exposure to morning sun may be useful for providing some direct gains to help warm the spaces. To further understand the potential daylight cloud cover was also analyzed through Weather Tool to see if there were any significant trends that would hinder the natural light levels. In this study, the level of cloud cover is mapped like topography, with areas of heavy cloud cover indicated by yellow line and light cover in red. The hours of the day make up the vertical axis and the weeks of the year the horizontal. Hours and levels of occupancy are also indicated.

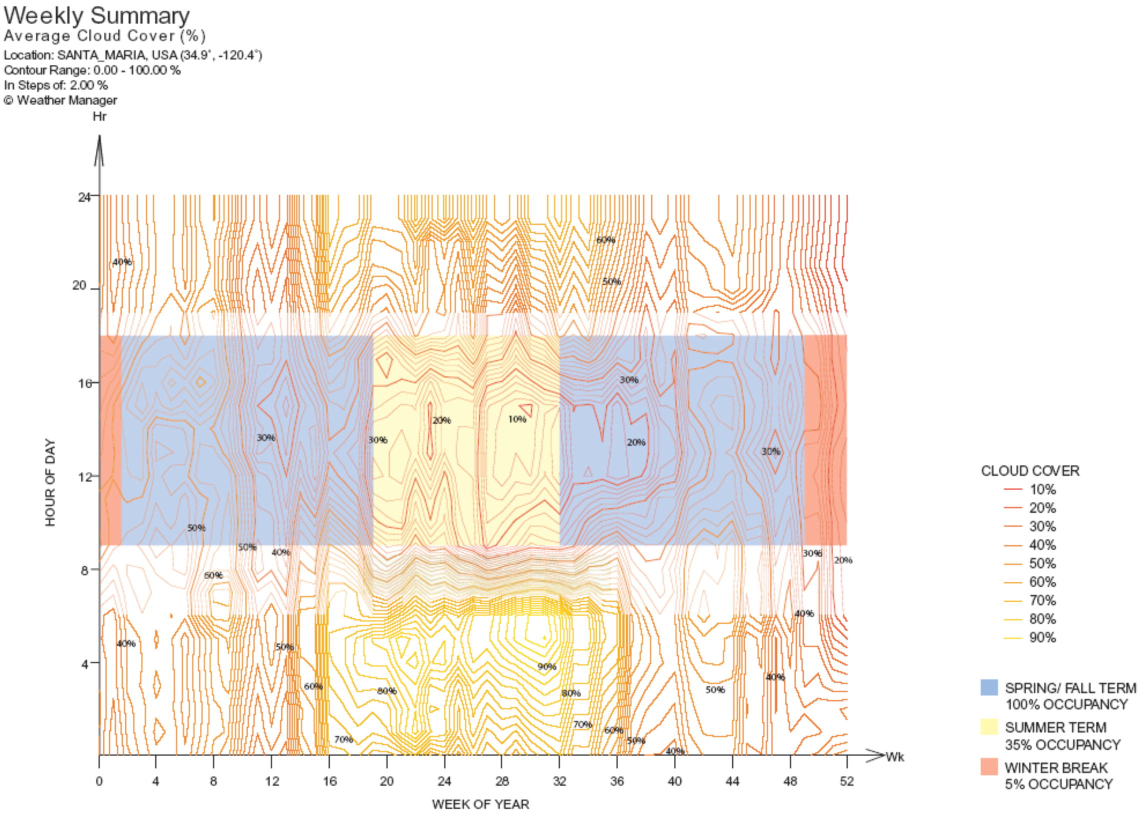


Figure 23 - Annual Cloud Cover with Hours and Level of Occupancy.

These readings indicate that most of the year there is a consistently moderate level of cloud cover, but that summer evenings are characterized by a dense cloud cover which rapidly burns off as the sun rises. Locally, this phenomenon is known as the "June Gloom".[23] None of this should adversely affect typical daylighting strategies.

To begin the design of the daylighting system for the model classroom the ASHRAE *Advanced Energy Design Guide for K-12 Buildings* was consulted. This publication outlines strategies to improve the performance of school building by 30% over the ASHRAE 90.1 standard that forms the basis of most energy codes. For adequate daylighting the guide states that for 50% of occupied hours the following criteria must be met, 45-50 fc of illumination on horizontal work surfaces, 30 fc on vertical teaching planes (chalkboards) an illuminance uniformity ratio of less than 8:1 and a glare index ratio of less than 20:1. Overlaying these parameters with research done by William Lam will help choose an appropriate strategy from which the design will be derived. A series of "generic model" tests were performed and documented in *Sunlighting as Formgiver for Architecture*[24]. Using physical models of a variety of sidelighting and toplighting strategies and a controlled light source, light levels were measured across the center of a scaled representation of 40'x40'x16' room. Because the variations explore derivations of the major influences on daylighting, opening location, room shape, and surface reflectance, this study is a valuable tool for developing daylighting strategies.

The design iterations will be tested through computer analysis, exploiting ECOTECT's simple modeling interface that allow for the physical characteristics of materials to be modified quickly. The ECOTECT model will be exported into Radiance for lighting analysis. Radiance is a ray trace rendering tool that allows for accurate calculation of light levels at specific locations and times of the day. It can handle complex geometry and produce realistic renderings of the modeled scene[25]. Its interface with ECOTECT not only allows for the model information to be exported from ECOTECT to Radiance for calculation, but the results can be brought back into ECOTECT and mapped to geometry for further analysis and presentation.

Natural Ventilation and the Limits of Early Phase Analysis

Several other factors could be incorporated into this study of the integration of simulation and the design process. Natural ventilation, for example, could prove to be a highly effective strategy for meeting both air quality and thermal comfort requirements. Yet, wind patterns are not as predictable as the path of the sun, and they are also heavily influenced by factors of microclimate and site context that require highly detailed analysis to incorporate natural ventilation beyond a “rule of thumb” level. Computation Fluid Dynamics modeling tools can provide the designer with highly detailed simulations of how air moves though a space and influences temperatures and perceived comfort levels. But the accuracy of input is critical to obtain accurate results. The design of the test case will incorporate the macro-scale wind analysis provide by the weather file, a study of the influence of site conditions from Olgyay’s, *Design With Clime, A Bioclimatic Approach to Architectural Regionalism*[26], and the incorporation of basic concepts for passive ventilation from Awbi’s *Ventilation of Buildings*[27]. Addressing these concepts and determining any synergies with the daylighting design strategies will allow for the more advanced development of passive ventilation at a later design stage, beyond the scope of this study.

CONCLUSION

The profession of architecture has an enormous responsibility in the drive to curb global warming. It must incorporate the consumption of natural resources into an already complex list of requirements to bring a design to reality. The knowledge to design buildings that can use less energy to maintain the health, safety, and welfare of its occupants exists and is readily available, but implementing it is often left to engineers and specialty consultants or not done at all. While no one tool can provide all of the information and resources to make effective decisions in the early design process, there are several pieces of software that can help guide a designer when used together. The evaluation of site, climate, and initial design choices presented here are by no means the only solution for producing a high performance building, but it does suggest a broader approach to the schematic design phase in which the link between performance and environment are intertwined. While the development of an entire building requires a concerted effort of multiple disciplines, beginning the design in this simulation environment is a means by which the architecture profession can address its responsibility, for the betterment of all involved.

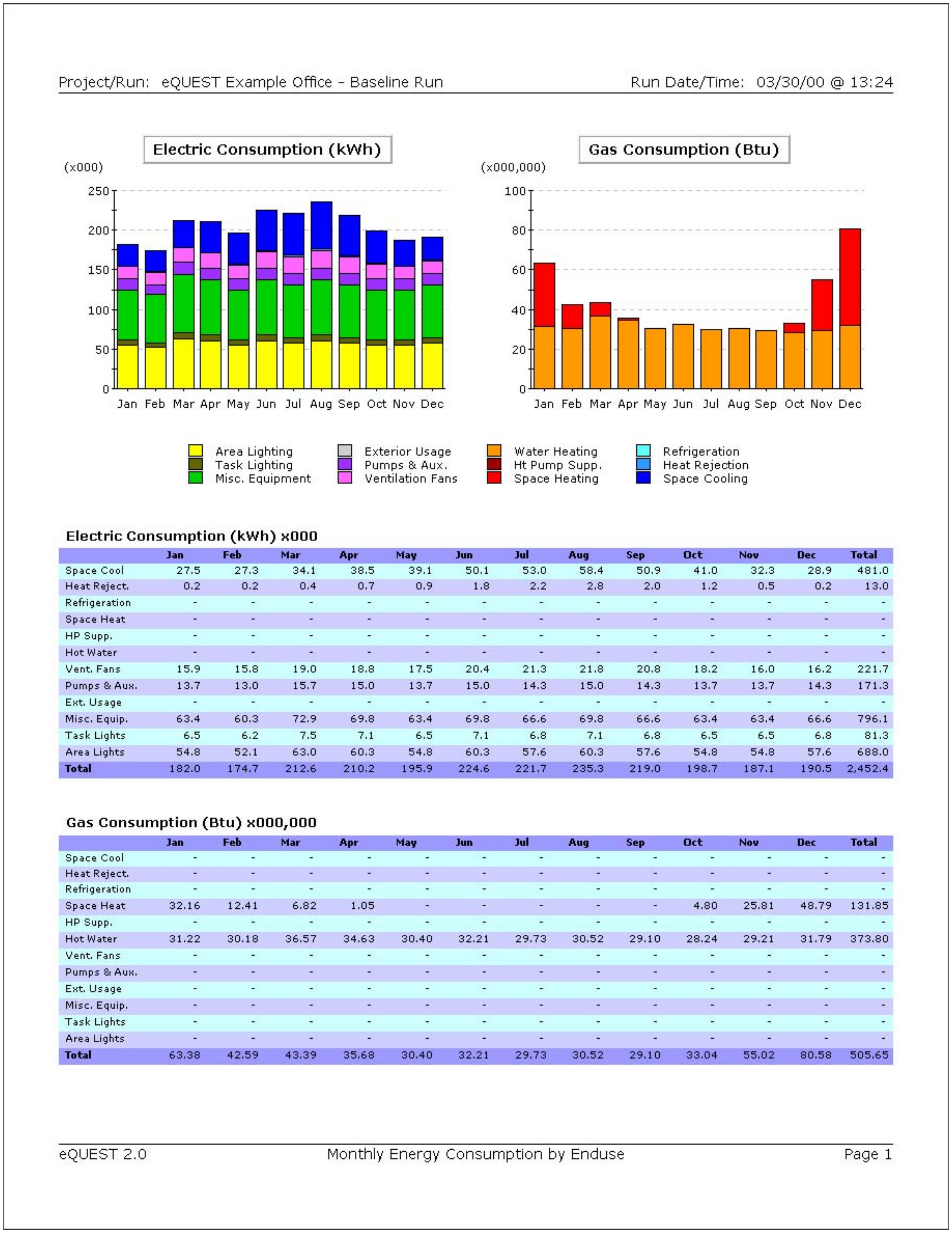
APPENDIX A

PRIMARY SIMULATION OUTPUT: ENERGY-10

```
   Energy-10 Summary Page                                                Nov 16, 2007
   Project: cube                Project Directory:  C:\Program Files\Energy-10\Version 1.8\Projects
\PROJ2

   Description:                            Reference Case             Low-Energy Case
   Scheme Number:                           1 / Not Saved               2 / Not Saved
   Library Name:                               ARCHIVELIB                  ARCHIVELIB
   Simulation status, Thermal/DL                       valid/NA                    valid/NA
   Weather file:                              ATLANTA.ET1                 ATLANTA.ET1
   Floor Area, ft²                                  400.0                       400.0
   Surface Area, ft²                               2400.0                      2400.0
   Volume, ft³                                     8000.0                      8000.0
   Total Conduction UA, Btu/h-F                     247.1                       247.1
   Average U-value, Btu/hr-ft²-F                       0.103                       0.103
   Wall Construction                  2 x 4 frame, R=12.6         2 x 4 frame, R=12.6
   Roof Construction                   flat, r-19, R=19.0          flat, r-19, R=19.0
   Floor type, insulation         Slab on Grade, Reff=5.6     Slab on Grade, Reff=5.6
   Window Construction          4060 double, wood, U=0.47   4060 double, wood, U=0.47
   Window Shading                                    None                        None
   Wall total gross area, ft²                        1600                        1600
   Roof total gross area, ft²                         400                         400
   Ground total gross area, ft²                       400                         400
   Window total gross area, ft²                        48                          48
   Windows (N/E/S/W:Roof)                       0/2/0/0:0                   0/2/0/0:0
   Glazing name                            double, U=0.49              double, U=0.49

   Operating parameters for zone 1
   HVAC system                           Fixed COP Heat Pump         Fixed COP Heat Pump
   Rated Output (Heat/SCool/TCool),kBtu/h       26/12/16                     17/11/15
   Rated Air Flow/MOOA,cfm                             1367/0                       864/0
   Heating thermostat                    70.0 °F, no setback         70.0 °F, no setback
   Cooling thermostat                      78.0 °F, no setup           78.0 °F, no setup
   Heat/cool performance                    COP=3.5,EER=18.0            COP=3.5,EER=18.0
   Economizer?/type                                    no/NA                       no/NA
   Duct leaks/conduction losses, total %             2/0                          2/0
   Peak Gains; IL,EL,HW,OT; W/ft²        0.20/0.04/0.66/0.36         0.20/0.04/0.66/0.36
   Added mass?                                          none                        none
   Daylighting?                                           no                          no
   Infiltration, in²                               ELA=212.8                    ELA=57.6

   Results:
    Energy cost   0.400$/Therm,0.054$/kWh,2.470$/kW 0.400$/Therm,0.054$/kWh,2.470$/kW
   Simulation dates                      01-Jan to 31-Dec            01-Jan to 31-Dec
   Energy use, kBtu                                 27132                       20897
   Energy cost, $                                     500                         375
   Saved by daylighting, kWh                        -                              NA
   Total Electric (**), kWh                          7951                        6124
     (** less Sellback, if any)
    Internal/External lights, kWh                      314/34                      314/34
    Heating/Cooling/Fan+Aux, kWh               3350/570/1583                2255/562/859
    Heat Pump/Elec. Res., kWh                        3148/202                      2254/1
    Hot water/Other, kWh                             1147/953                    1147/953
    Peak Electric, kW                                 4.9                         2.2
   Fuel, hw/heat/total, kBtu                        0/0/0                       0/0/0
   Emissions, CO2/SO2/NOx, lbs                10686/63/33                  8231/48/25
   Construction Costs                               66935                       65395
   Life-Cycle Cost                                  87690                       80652


   Photovoltaics System Summary:
   Description:                            Reference Case             Low-Energy Case
   PV System Definition Status:                 Undefined                   Undefined
   Total PV Array Area, ft² / m²                          --                          --
   Total PV Rated Output, kW                           --                          --
   Total Inverter Rated Capacity, kW                   --                          --
   Total PV System First Cost, $                       --                          --
```

APPENDIX B

PRIMARY SIMULATION OUTPUT: EQUEST



Project/Run: eQUEST Example Office - Baseline Run Run Date/Time: 03/30/00 @ 13:24

Electric Consumption (kWh) x000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	27.5	27.3	34.1	38.5	39.1	50.1	53.0	58.4	50.9	41.0	32.3	28.9	481.0
Heat Reject.	0.2	0.2	0.4	0.7	0.9	1.8	2.2	2.8	2.0	1.2	0.5	0.2	13.0
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	15.9	15.8	19.0	18.8	17.5	20.4	21.3	21.8	20.8	18.2	16.0	16.2	221.7
Pumps & Aux.	13.7	13.0	15.7	15.0	13.7	15.0	14.3	15.0	14.3	13.7	13.7	14.3	171.3
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	63.4	60.3	72.9	69.8	63.4	69.8	66.6	69.8	66.6	63.4	63.4	66.6	796.1
Task Lights	6.5	6.2	7.5	7.1	6.5	7.1	6.8	7.1	6.8	6.5	6.5	6.8	81.3
Area Lights	54.8	52.1	63.0	60.3	54.8	60.3	57.6	60.3	57.6	54.8	54.8	57.6	688.0
Total	182.0	174.7	212.6	210.2	195.9	224.6	221.7	235.3	219.0	198.7	187.1	190.5	2,452.4

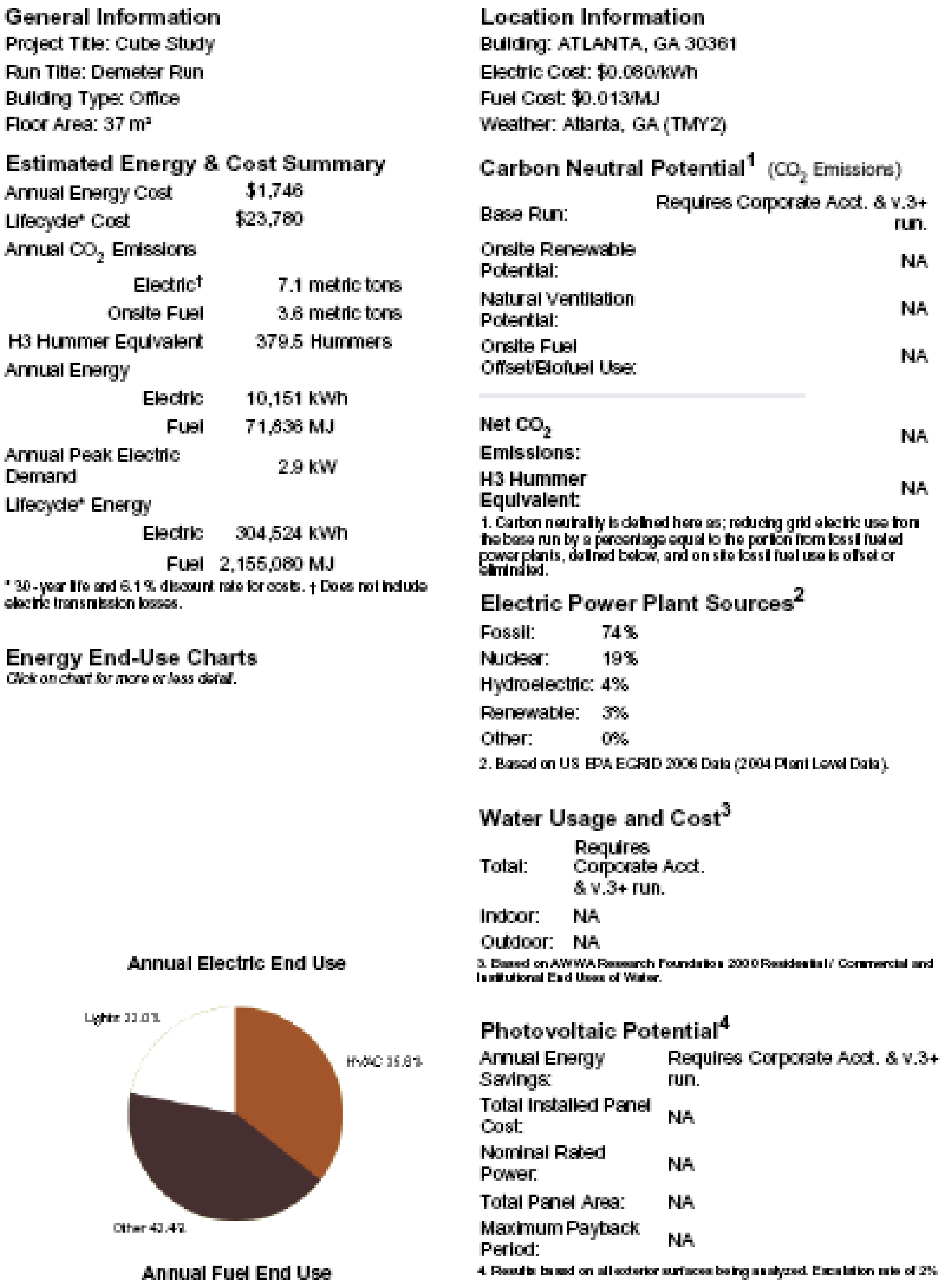
Gas Consumption (Btu) x000,000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	32.16	12.41	6.82	1.05	-	-	-	-	-	4.80	25.81	48.79	131.85
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	31.22	30.18	36.57	34.63	30.40	32.21	29.73	30.52	29.10	28.24	29.21	31.79	373.80
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	63.38	42.59	43.39	35.68	30.40	32.21	29.73	30.52	29.10	33.04	55.02	80.58	505.65

eQUEST 2.0 Monthly Energy Consumption by Enduse Page 1

APPENDIX C

PRIMARY SIMULATION OUTPUT: SKETCH-UP/ DEMETER



General Information

Project Title: Cube Study
Run Title: Demeter Run
Building Type: Office
Floor Area: 37 m²

Estimated Energy & Cost Summary

Annual Energy Cost	$1,746
Lifecycle* Cost	$23,780
Annual CO_2 Emissions	
Electric†	7.1 metric tons
Onsite Fuel	3.6 metric tons
H3 Hummer Equivalent	379.5 Hummers
Annual Energy	
Electric	10,151 kWh
Fuel	71,636 MJ
Annual Peak Electric Demand	2.9 kW
Lifecycle* Energy	
Electric	304,524 kWh
Fuel	2,155,080 MJ

* 30-year life and 6.1% discount rate for costs. † Does not include electric transmission losses.

Energy End-Use Charts

Click on chart for more or less detail.

Annual Electric End Use

Annual Fuel End Use

Location Information

Building: ATLANTA, GA 30361
Electric Cost: $0.080/kWh
Fuel Cost: $0.013/MJ
Weather: Atlanta, GA (TMY2)

Carbon Neutral Potential[1] (CO_2 Emissions)

Base Run:	Requires Corporate Acct. & v.3+ run.
Onsite Renewable Potential:	NA
Natural Ventilation Potential:	NA
Onsite Fuel Offset/Biofuel Use:	NA
Net CO_2 Emissions:	NA
H3 Hummer Equivalent:	NA

1. Carbon neutrality is defined here as; reducing grid electric use from the base run by a percentage equal to the portion from fossil fueled power plants, defined below, and on site fossil fuel use is offset or eliminated.

Electric Power Plant Sources[2]

Fossil:	74%
Nuclear:	19%
Hydroelectric:	4%
Renewable:	3%
Other:	0%

2. Based on US EPA EGRID 2006 Data (2004 Plant Level Data).

Water Usage and Cost[3]

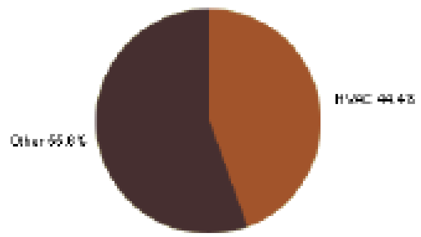
Total:	Requires Corporate Acct. & v.3+ run.
Indoor:	NA
Outdoor:	NA

3. Based on AWWA Research Foundation 2000 Residential / Commercial and Institutional End Uses of Water.

Photovoltaic Potential[4]

Annual Energy Savings:	Requires Corporate Acct. & v.3+ run.
Total Installed Panel Cost:	NA
Nominal Rated Power:	NA
Total Panel Area:	NA
Maximum Payback Period:	NA

4. Results based on all exterior surfaces being analyzed. Escalation rate of 2%



Building Summary

Quick Stats

If values are red or blue they appear to be higher or lower then typical ranges, respectively.

Number of People	1 people
Average Lighting Power Density	13.99 W/m^2
Average Equipment Power Density	16.14 W/m^2
Specific Fan Flow	6.0 LPerSec/m^2
Specific Fan Power	1.381 W/LPerSec
Specific Cooling	10 m^2/kW
Specific Heating	5 m^2/kW
Total Fan Flow	222 LPerSec
Total Cooling Capacity	4 kW
Total Heating Capacity	7 kW

Constructions

U-Value: W/(m^2-K)

Roofs	
R15 over Roof Deck U-value: 0.35	37 m^2
Exterior Walls	
8"Concrete Wall with Poured Cores U-value: 2.81	149 m^2
Slabs On Grade	
Concrete slab R7.5 perim U-value: 0.16	37 m^2
Nonsliding Doors	
R2 Default Door (1 doors) U-value: NaN	2 m^2
Operable Windows	
Single Clear-L Tint (1 windows) U-value: 4.99 SHGC: 0.25 Vlt: 0.13	1 m^2

applied to electric rate. Payback calculation does not include federal or state incentives, loan information, or tax breaks.

LEED Daylight[5]

Area w/ Glazing Factor > 2%:	Requires Corporate Acct. & v.3+ run.NA

[5] Qualifies if glazing factor is > 2% in a minimum of 75% occupied areas.

Wind Energy Potential[6]

Annual Electric Generation:	Requires Corporate Acct. & v.3+ run.

[6] A single 15 ft diameter turbine, with cut-in and cut-out winds of 6 mph and 45 mph respectively, and located at the coordinates of the weather data.

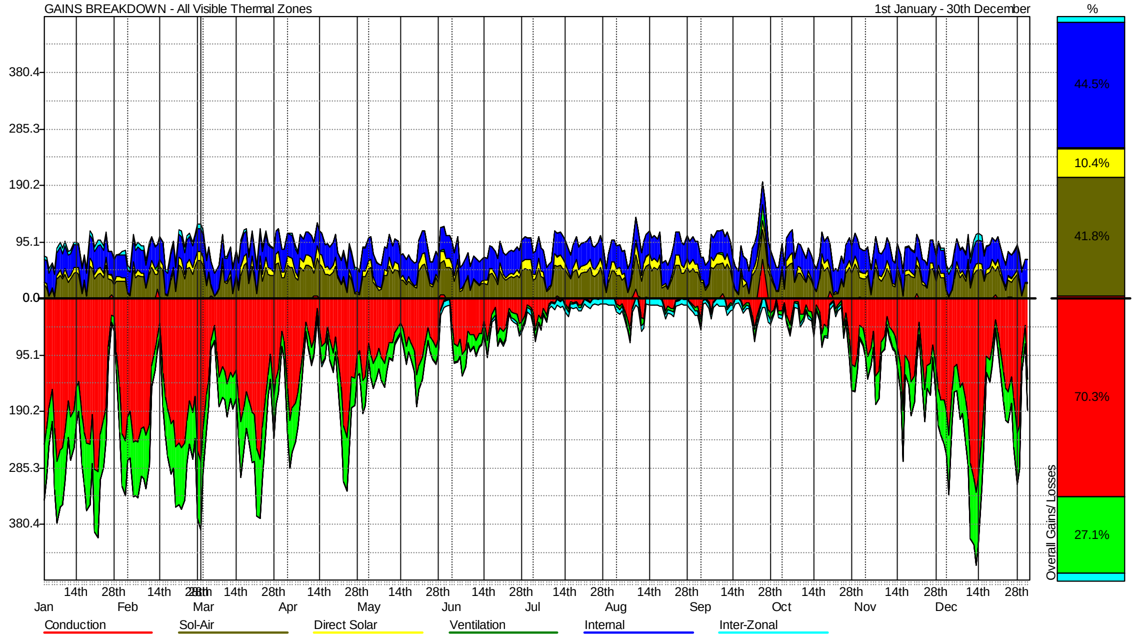
Natural Ventilation Potential[7]

Total Hours Mech. Cooling Required:	Requires Corporate Acct. & v.3+ run.
Possible Natural Ventilation Hours:	NA
Possible Annual Electric Energy Savings:	NA
Possible Annual Electric Cost Savings:	NA
Net Hours Mech. Cooling Required:	NA

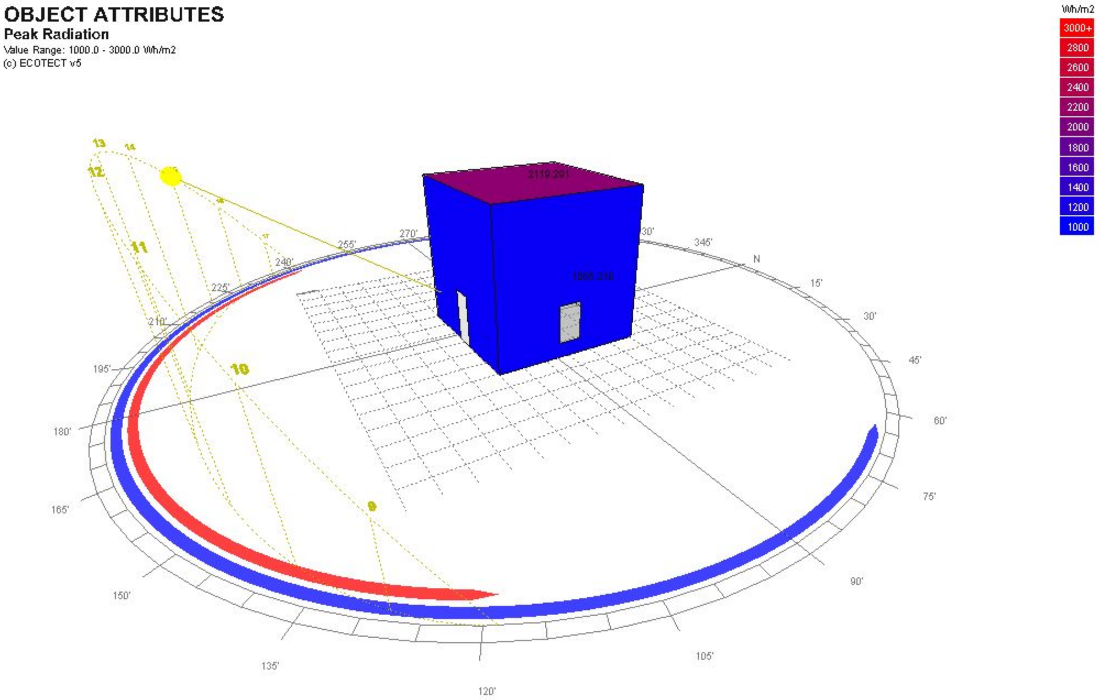
[7] Assumes natural ventilation only during comfort zone periods and air changes per hour are less then 20 ACH. Building form & opening design must be able to allow stack effect or cross ventilation.

APPENDIX D

PRIMARY SIMULATION OUTPUT: ECOTECT



Passive Gains analysis, a study of envelope related loads



Insolation Analysis with daily sun-path, radiation values are mapped to each surface.

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