#1

DOE Award Number: 10EE0003921
Project Recipient: Cornell University
Project Title: Advanced Interaction, Computation and Visualization Tools for Sustainable Building Design
Project Director: Donald Greenberg
Principal Investigator: Donald Greenberg

#2

There is no patentable material or protected data

#3

Executive Summary

Current building energy simulation technology requires excessive labor, time and expertise to create building energy models, excessive computational time for accurate simulations and difficulties with the interpretation of the results. These deficiencies can be ameliorated using modern graphical user interfaces and algorithms which take advantage of modern computer architectures and display capabilities. To prove this hypothesis, we developed an experimental test bed for building energy simulation. This novel test bed environment offers an easy-to-use interactive graphical interface, provides access to innovative simulation modules that run at accelerated computational speeds, and presents new graphics visualization methods to interpret simulation results.

Our system offers the promise of dramatic ease of use in comparison with currently available building energy simulation tools. Its modular structure makes it suitable for early stage building design, as a research platform for the investigation of new simulation methods, and as a tool for teaching concepts of sustainable design. Improvements in the accuracy and execution speed of many of the simulation modules are based on the modification of advanced computer graphics rendering algorithms. Significant performance improvements are demonstrated in several computationally expensive energy simulation modules. The incorporation of these modern graphical techniques should advance the state of the art in the domain of whole building energy analysis and building performance simulation, particularly at the conceptual design stage when decisions have the greatest impact. More importantly, these better simulation tools will enable the transition from prescriptive to performative energy codes, resulting in better, more efficient designs for our future built environment.

#4

Comparison of the Actual Accomplishments with the Goals and Objectives of the Project

Most of the original goals of the project have been accomplished and are described in detail with the tasks that were performed according to the original project objectives (SOPO). Although earlier versions of EnergyPlus were used at the beginning of the grant, the final thermal simulation engine and the documented version was EnergyPlus, V. 8.00.

During the entire three-year grant period, we concentrated on the creation of easy-to-use, interactive graphical interfaces to define complex model geometries and the development of new graphical visualization methods to interpret simulation results. Innovative simulation modules that run at accelerated computational speeds were added to the software base to improve the accuracy and execution speed of the simulation code. Most of these improvements were based on the modification of advanced computer graphics rendering algorithms. The resulting system proved to be significantly easier to use compared to currently available building energy simulation tools.

A key goal was to make thermodynamic analysis available early in the design process as it enables architects to analyze the impacts of form, siting, the definition of the external envelope and material choices on a building's energy consumption at a very early stage of the design process. This enables clients to make informed choices between alternative schemes at a time when the choices have the greatest impact. To accomplish this, it was necessary to translate from common, surface-based CAD modeling software such as SketchUp, Rhinoceros, and 3ds Max to a building energy model (BEM) suitable for energy simulations. This was accomplished by developing software for accurate, semiautomated translation of these models into a thermal form compatible with the simulation engine. It was necessary for the computer code to translate the imported geometric building data augmented with material data to generate the required hierarchical relationships between building components. Once the building energy model was completed, it was then possible to run simulations in parallel on our compute cluster and utilize the graphical visualization tools to interpret the output.

Although the speed-ups were exceptional, particularly with respect to eliminating the constraints of building complexity, the reduction in computation time was significantly hindered by the structure of Fortran 90 code of the current EnergyPlus simulation engine. Although conversion of this code into a more modern computer language is now being considered by the Department of Energy, a new version was not available during the time period of our grant. With respect to the user interfaces, we were also limited by the delayed deployment of the next generation, large area, interactive, touch-panel display devices which we expect will be available next year.

Lastly, we suffered from the tragic losses of two of our principal investigators. Professor Ken Torrance, who was an original co-investigation of the proposal, died of a heart attack before the funding was received. To complicate the matter, a second principal co-investigator from the architecture department, Assistant Professor Kevin Pratt, died of a heart attack early this year. The tragic loss of both of these individuals with their unique scientific and leadership qualities cannot be measured.

In spite of these difficulties, as described in the next summary section, we demonstrated almost all of our intended objectives. Our outstanding publication record describes many of the important algorithms which were incorporated into our test bed software, and the documented source code has been delivered to the Department of Energy.

#5

Graphical User Interface

Figure 1. SUSTAIN interface: a three-panel graphical user interface for data input (left), simulation output (right), and simulation control (center).

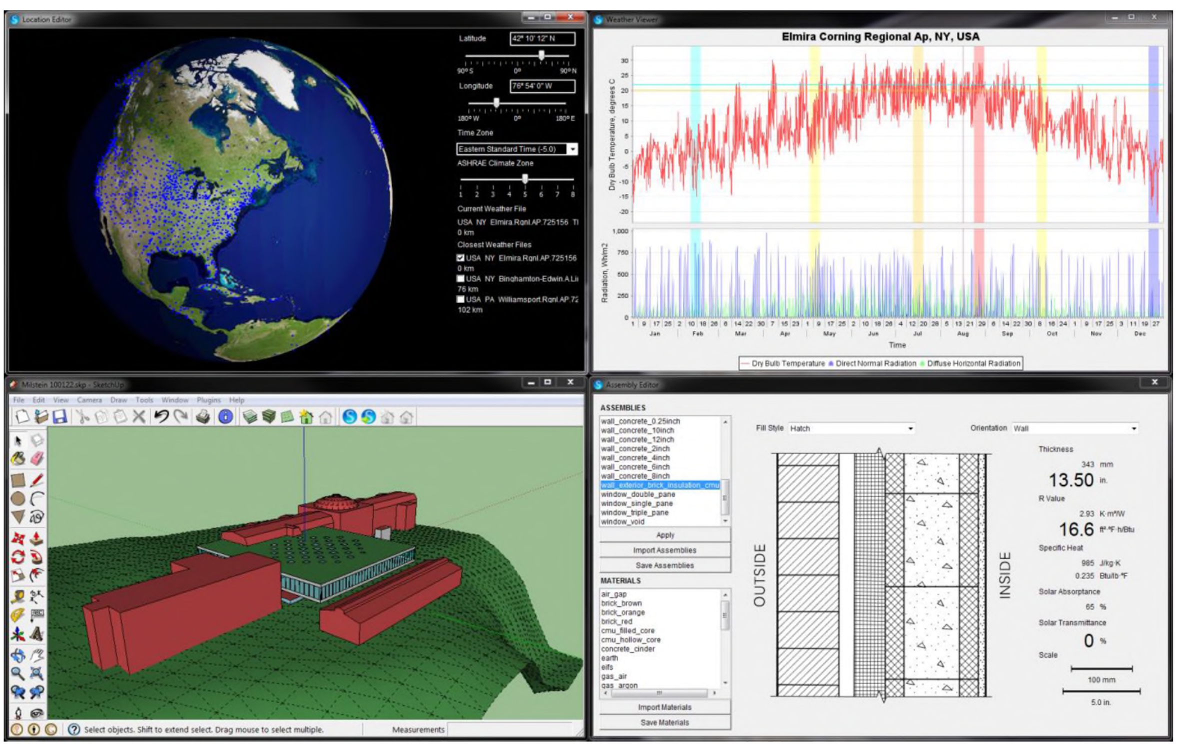

Figure 2. Model input panel.

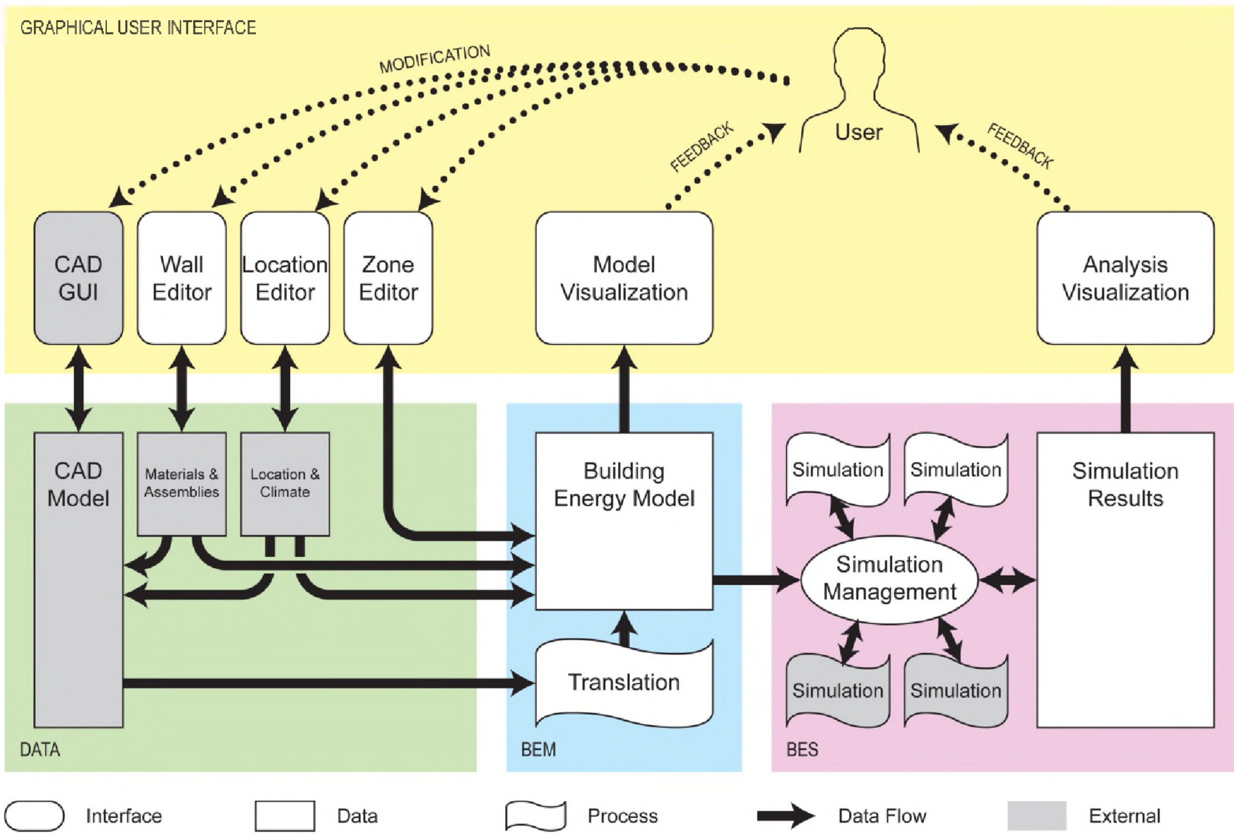

Figure 3. SUSTAIN software framework: input geometric (CAD) data and metadata from external sources are converted to a thermal model (BEM) and made available for simulation execution (BES).

Building performance simulations in architectural design are hindered by three key bottlenecks: the significant time and skill required to create building models for energy simulations, the time required to compute accurate simulations for geometrically complex models and the difficulty of understanding and visualizing the results. The difficulty in making models amenable to analysis is an input problem, and the difficulty in understanding the simulation results is a visualization problem. Both of these problems can be alleviated by creating graphically oriented user interfaces which take advantage of the next generation computing environments. We have incorporated these procedures in a novel test bed environment, SUSTAIN, which provides access to simulation modules that run at accelerated computational speeds. The modular structure of this software makes it suitable for use in early stage building design, for use as a research platform for the investigation of new simulation methods, for use as a tool for teaching concepts of sustainable design. The following figures depict the graphical user interface both for input and output, and an abstract software framework indicating the relationship between modules. Details of our test bed, SUSTAIN, are described in the paper published in Energy & Buildings entitled, "SUSTAIN: An Experimental Test Bed for Building Energy Simulation."

Translation

Perhaps the most important module within SUSTAIN is the automated translation module which converts the complex geometric data from an un-zoned CAD model into a multi-zone building energy model. This process usually requires a tedious manual alteration of the data, an expensive and inefficient process, and one that limits the number of design alternatives to be evaluated.

A series of steps are necessary for this conversion including the removal of degenerate geometry, the identification of boundary and parent surfaces, and the definition of space boundaries, and the grouping of spaces into zones. Although BEM models can be attained with solid modelers, the manipulation and modifications of these models are too cumbersome for the investigation of alternative design strategies. Thus, we chose to utilize easy-to-use commercially available CAD modeling software combined with our translation routines.

Early versions of our translation schemes are described in "SUSTAIN: An Experimental Test Bed for Building Energy Simulation," but our latest version will be presented at SimBuild 2013 and is described in "Automated Translation and Thermal Zoning of Digital Building Models for Energy Analysis."

In the future, we expect that new modeling systems will be developed which will be easy to use and automatically convert from CAD to BEM or solid models as the definition of the design matures.

Shading and Shadows

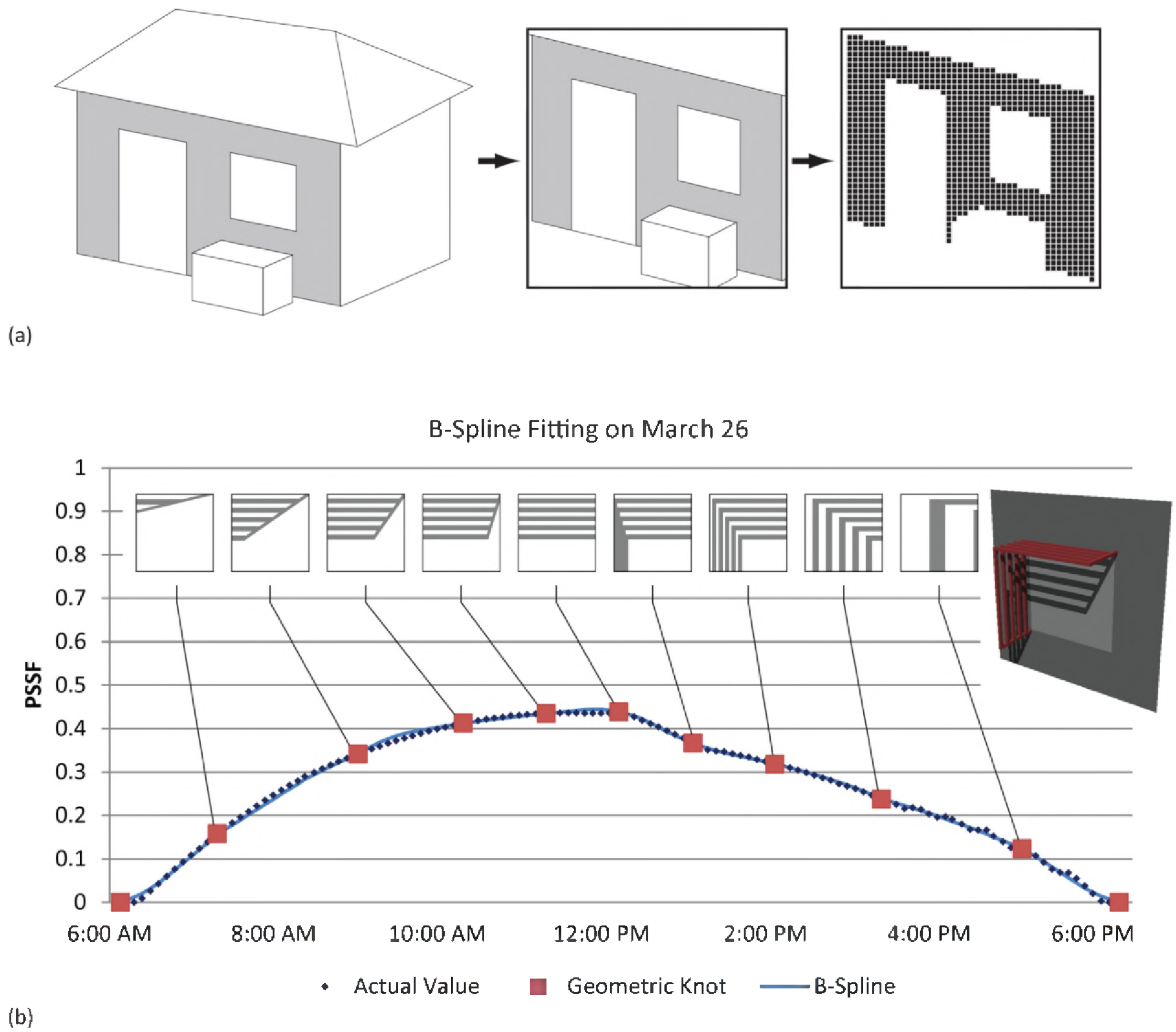

Figure 4. Orthogonal view frustum clipping planes are fit to a receiving surface, shown highlighted, to create a pixelated image for counting to find the projected sunlit surface fraction (PSSF) (a). A B-spline curve (line) is created for interpolating the PSSF over the course of a day by sampling at only the geometric knots (squares), but closely follows the actual PSSF values

calculated at 6-min intervals (diamonds). The data interpolated from the B-spline curve remain accurate even when knots are more than an hour apart with intricately detailed shading devices (b, inset).

Direct solar radiation has a major influence on a building's thermal behavior, yet current simulation engines cannot accurately model solar gains for buildings with complex or curved geometries, or buildings sited in dense urban areas. Accurate thermal performance prediction is hindered by excessive computation time and incompatibility between architectural models and building energy simulation software. Using a combination of modern computer graphics rendering techniques and parametric B-spline interpolation methods, we can now quickly and accurately calculate solar gains over a full year based on sparse data using a continuous interpolation method. We utilized a new hardware-assisted pixel counting algorithm to generate an off-screen digital image buffer and then B-spline surfaces to accurately interpolate the sparse data and thus calculate the solar gains over a full year very rapidly. These new procedures accommodate complex building geometries intricate shadow patterns and thus we were able to accelerate the shading calculations by several orders of magnitude. Details of the algorithm are described in the paper, Fast Computer Graphics Techniques for Calculating Direct Solar Radiation on Complex Building Surfaces. The technique was illustrated using CAD models of two existing buildings that were gradually made more complex through the addition of intricate louvered shading devices in adjacent urban structures. With only a minimal increase in pre-processing time and no effect on energy simulation time, details of this demonstration were reported in Fast Computation of Incident Solar Radiation From Preliminary to Final Building Design.

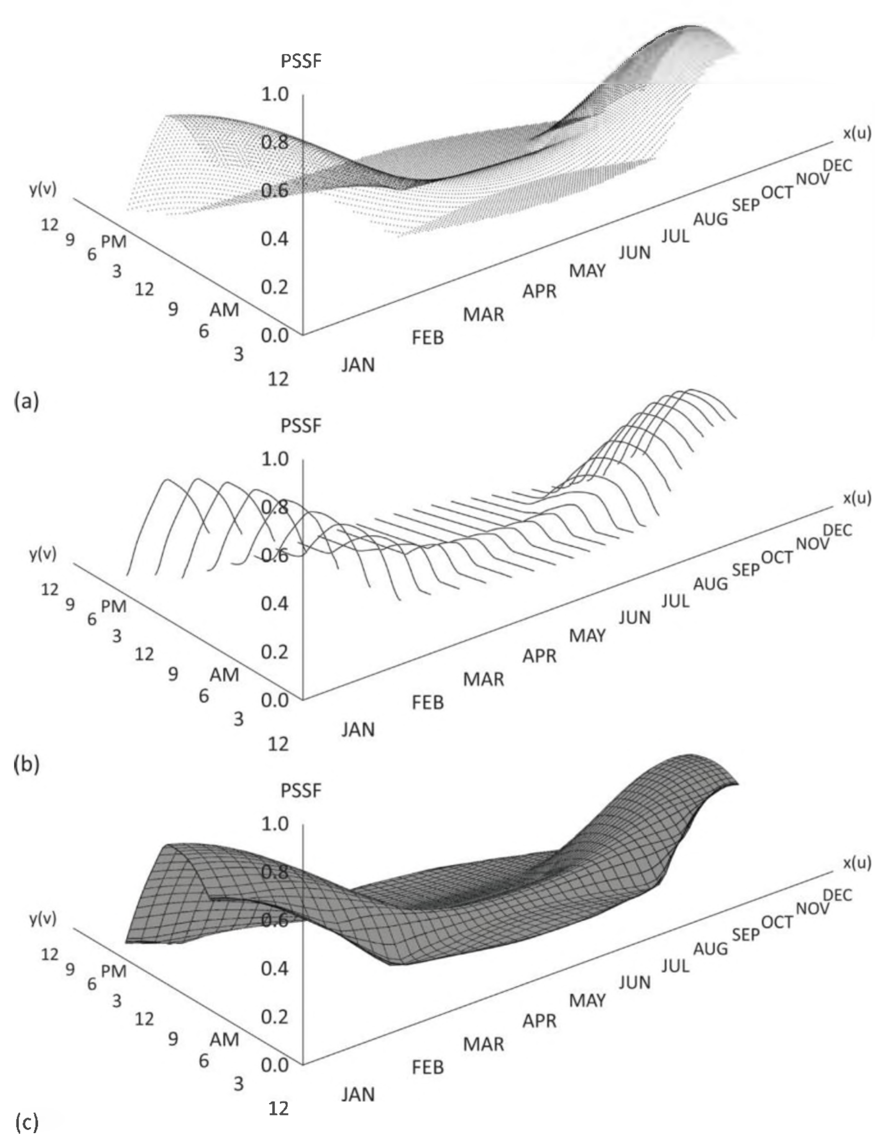

Figure 5. Plotting calculated values of the projected sunlit surface fraction (PSSF) frequently enough creates a point cloud in which all points lie on a continuous surface (a). A set of B-spline curves fit to the PSSF data for individual days forms the sectional contours of the B-spline surface (b). B-spline interpolation between the control points of these contours allows additional sections to be calculated, creating a surface that closely approximates the values of PSSF for all date–time pairs (c).

Figure 6. The Blaas General Partnership building, as built, in Bolzano, Italy was modeled with SUSTAIN.

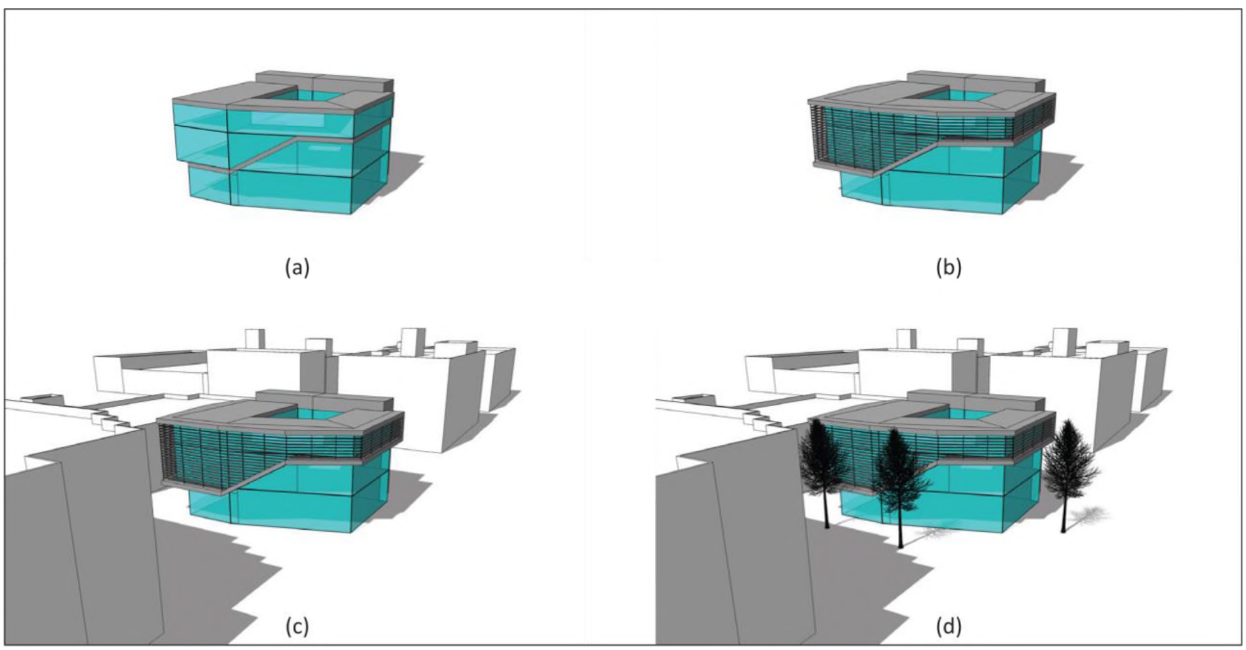

Figure 7. The Blaas design sequence showing the thermal zone geometry alone (a) and the addition of louvers (b), neighboring buildings (c), and street trees (d). In all cases, where the number of shading surfaces range from zero to 233,000 with modeled trees, the shading calculation takes only seconds and the time for a full EnergyPlus run varied only between 3.6 and 3.7 minutes.

Environment Mapping

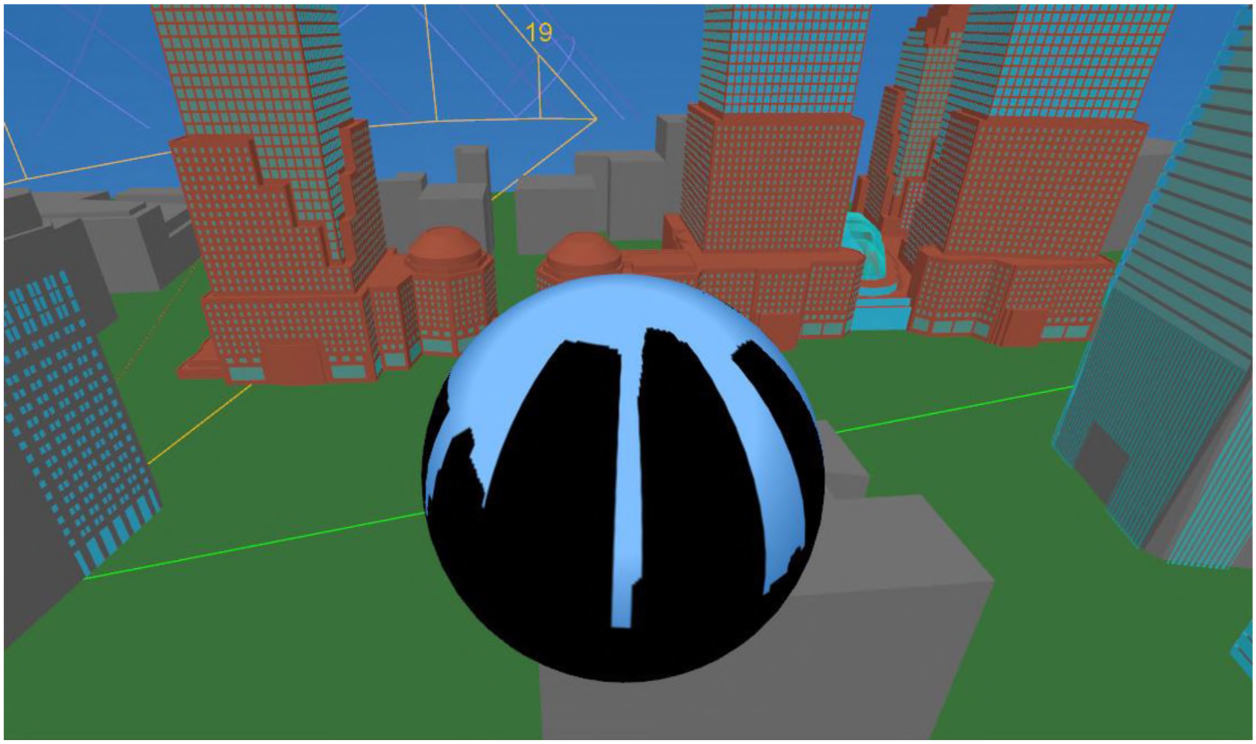

Figure 8. Hypothetical World Trade Center, New York City environment mapped onto a hemisphere centered at a point on a building's surface.

To improve the accuracy of the thermal gain from the radiant energy from both the sun and the sky dome, it is necessary to incorporate the indirect radiation exchange between a building and its environment. While the impact of this indirect radiant energy is potentially large when considering the effects of the indirect reflected energy from the terrain or neighboring buildings in an urban environment, most energy simulations either simplify the environment models or omit the indirect radiation calculation altogether.

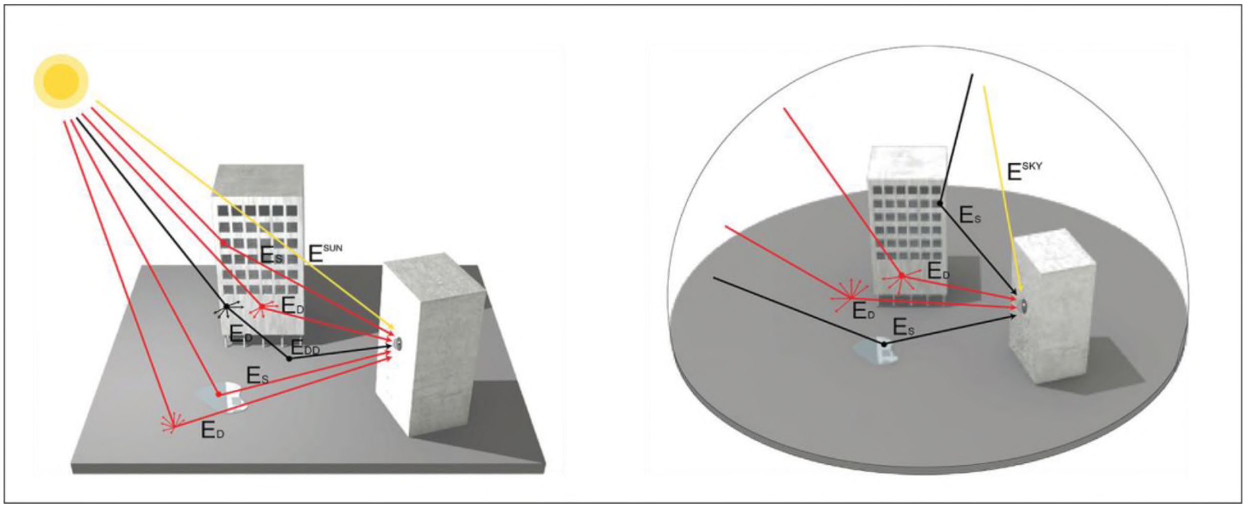

Figure 9. Direct and indirect energy transport paths from the solar disk (left) and the sky dome (right) to a building's surface include direct radiation (yellow), calculated by other means, and specular and diffuse reflections. We evaluate all indirect paths shown in red, but do not evaluate the multiple bounce paths.

We utilized a computer graphics algorithm environment mapping to accurate calculate the indirect reflected radiant energy from the environment. We encoded the complete panoramic environment to rounding a surface as an image texture that serves as a look-up table parameterized by direction. By storing different pieces of information such as the sky, clouds, buildings, or obstructions as separate textures which could be quickly overlaid, the method proved to be fast, accurate, robust, and scalable. The advantage of using texture maps is that modern CPUs and graphics boards include texture-mapping hardware providing both fast access and the ability to composite textures.

Our algorithm assumed that the reflection could be subdivided into components based on the two major sources, the sun and the sky dome, and also subdivided into two components, the specular and diffuse reflections, and all were stored as independent textures. When combined with an occlusion map, these could be composited to provide the total indirect energy. The complete algorithm is described in our publication, Environment Mapping for Fast and Robust Calculation of Indirect Radiant Energy, which was presented at SimBuild 2012. The computer code for this algorithm is not included in our source code since we did not have an accurate sky model nor could we obtain the accurate reflection characteristics of neighboring environments. Although not within the scope of this grant, we intend to research this area in the future.

Radiosity Exchange Between Surfaces

Radiant heat transfer accounts for the thermal radiation emitted and absorbed between surfaces, and it is a major component of the flow of thermal energy within an environment. In the thermal regime, every surface emits radiation and is thus a source. This radiation can travel long distances and may reflect off other surfaces before being absorbed at a receiving surface. Thus the radiant interchange couples all the surfaces within a region or zone, making it potentially expensive to solve. Finite element methods, commonly referred to as radiosity methods in computer graphics literature, are a good choice for simulating radiant energy transfer.

For architectural environments, a full matrix radiosity method described above is a very efficient solution. A zone can typically be adequately modeled by a relatively small number of surfaces (typically several hundreds of elements) while the radiant transfer needs to be solved for a very large number of time instances over the year. Thus for intrazonal radiant interchange, we can execute a pre-process that constructs and inverts the transport matrix and then rapidly solve the radiant heat flow at each time step. We use ray-casting to compute the form-factors between all pairs of surfaces and cache the inverted matrix before solving for each time step. For a prototypical zone consisting of 1,000 polygons, we build and invert the transport matrix in seconds and solve for the heat flow in milliseconds per time step. Since typical methods used to simulate of the radiant energy exchange is computationally expensive, our approach offers orders of magnitude improvement in speed. Furthermore, when EnergyPlus code is rewritten, individual zone computations can be executed in parallel. Further details of this approach can be found in "SUSTAIN: An Experimental Test Bed for Building Energy Simulation."

Model Decomposition

The notion of a space carries along with it aspects of architectural, thermal, and heating ventilation and air conditioning. Zones are a fundamental unit of building energy simulation comprised of aggregated spaces. Simulation time increases with the number of zones within the building energy simulation, thus motivating, in standard practice, the aggregation of spaces into relatively few zones. Yet, the aggregation of spaces into zones relies on modeling expertise, which does not scale well for unconventional buildings and early design analysis. Algorithms that decompose or aggregate the building energy model, based on thermal connectivity, represent an automated rationale for zoning building energy simulations.

Comprehending and identifying the relative degree of thermal connectivity among spaces and the ambient environment for other than conventional designs is a challenging and time consuming task. Given an appropriate model abstraction, one can systematically analyze the relative degree of coupling among the building energy model elements (see Figure 10.a). A resistor-capacitor (RC) network approximation produces a model abstraction amenable for graph decomposition algorithms (see Figure 10.b). We have investigated several candidate graph decomposition algorithms out of the many in the literature, see "A Comparison of Thermal Zone Aggregation Methods". Subsequently, the graph decomposition algorithms identify the weakest edges, representing the weakest thermal connectivity, to cut in order to decompose the model into an increasing number of zones (see Figure 10.c). The resulting decomposed graph is mapped back through the resistor-capacitor network to define zones within the building energy model (see Figure 10.d).

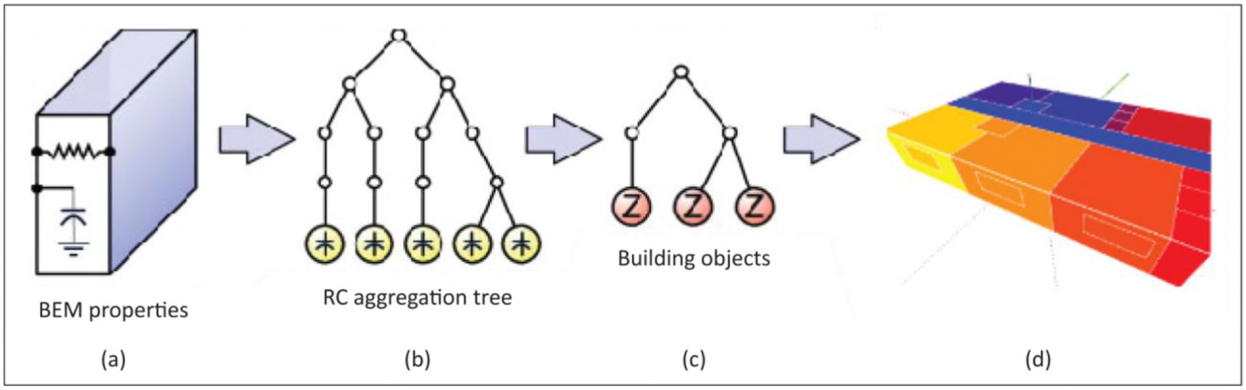

Figure 10. SUSTAIN readily enables abstraction of the building energy model for the purpose of zone decomposition/aggregation.

The simplified case studies performed have demonstrated that the investigated method creates intuitive zones, i.e., small spaces are automatically lumped with adjacent spaces. See “Automatic Model Reduction in Architecture: A Window into Building Thermal Structure”. Furthermore, the ability to decompose models according to relative thermal connectivity also maps well to the prospect of parallel execution within building energy simulations, such as EnergyPlus. See “Structured Model Reduction Towards Parallel Simulation”.

Parametric Studies

As the time to simulate the design loads on a building falls to the scale of minutes or less, a designer becomes increasingly free to test multiple variations and to compare metrics of performance in the pursuit of better designs. Existing energy modeling work flows may allow for one-to-one comparison between models, but the need to evaluate multiple lines of investigation demands digital tools capable of visualizing the implications of multi-parametric variations.

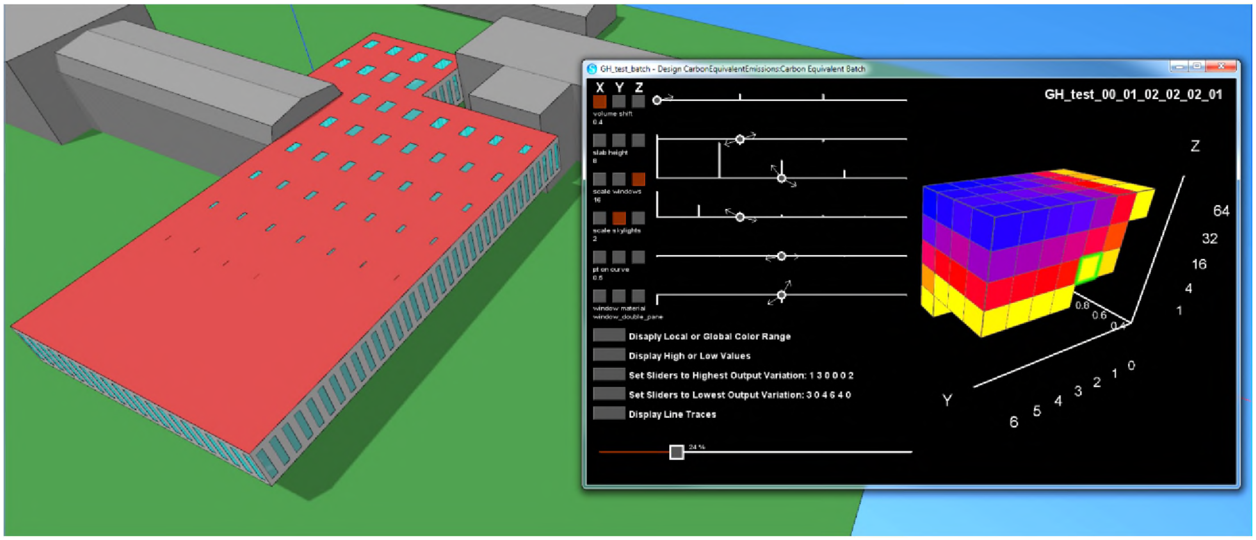

Figure 11. The design for Milstein Hall at Cornell University is remodeled with variable parameters for massing, materials, percent glazing, and skylight position. In SUSTAIN, the model space is visualized with colored cubes that represent the relative performance of design variations.

Architects are routinely faced with decisions to balance competing interests of design or aesthetic principles with a client's desires, occupant comfort, and lowering operational costs. In early-stage design, parameters under the control of the designer include building massing and orientation, programmatic layout, fenestration, and shading strategies, among others. But changes to one aspect of a building will either support or work against enhancements to another. For an energy-conscious designer, the danger is that optimizing one building parameter may diminish the building's overall performance. For a designer with access to multi-dimensional comparison tools, the opportunity is that disadvantages, caused, for example, by site, client, or code restrictions, may be strategically offset to achieve both the architect's design intention and a better-performing building.

Our research included the development of tools to produce, simulate, and visualize large numbers of model variations, including the ability to compare the relative effects of more than three parameters at once.

Projects Involving Computer Modeling

During the final few months of the grant period, we recruited and trained seven recent architecture graduates to use the SUSTAIN software. These designers had no special technical training in addition to their professional bachelors or masters degrees. Our user test group began by using SUSTAIN to investigate two buildings on the Cornell University campus that feature complex shading devices and non-prismatic geometry.

Figure 12. The Cornell Plantations Welcome Center (left) and its energy model in SUSTAIN (right).

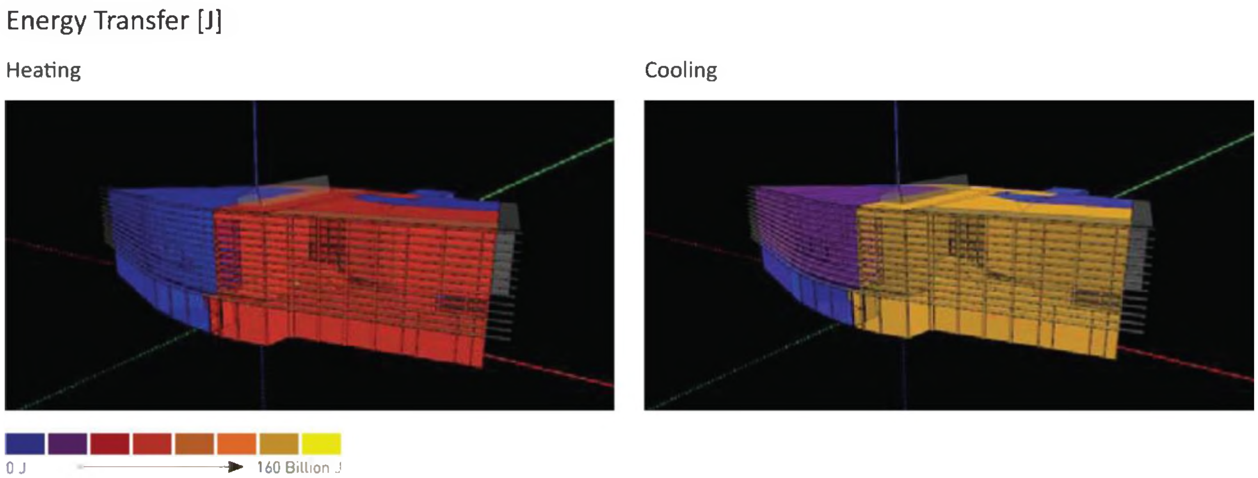

Figure 13. SUSTAIN graphically displays **e**nergy needed to heat the Welcome Center in the winter (left) and cool the building in the summer (right).

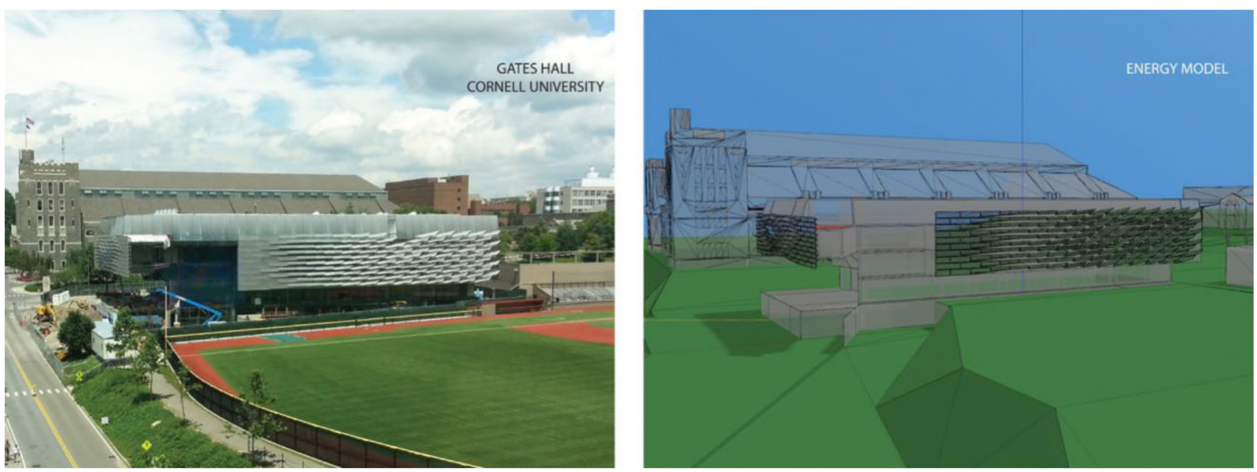

Figure 14. Gates Hall, under construction at Cornell University, (left) features perforated metal screens and fritted glass as shading devices, which was accurately modeled in SUSTAIN (right).

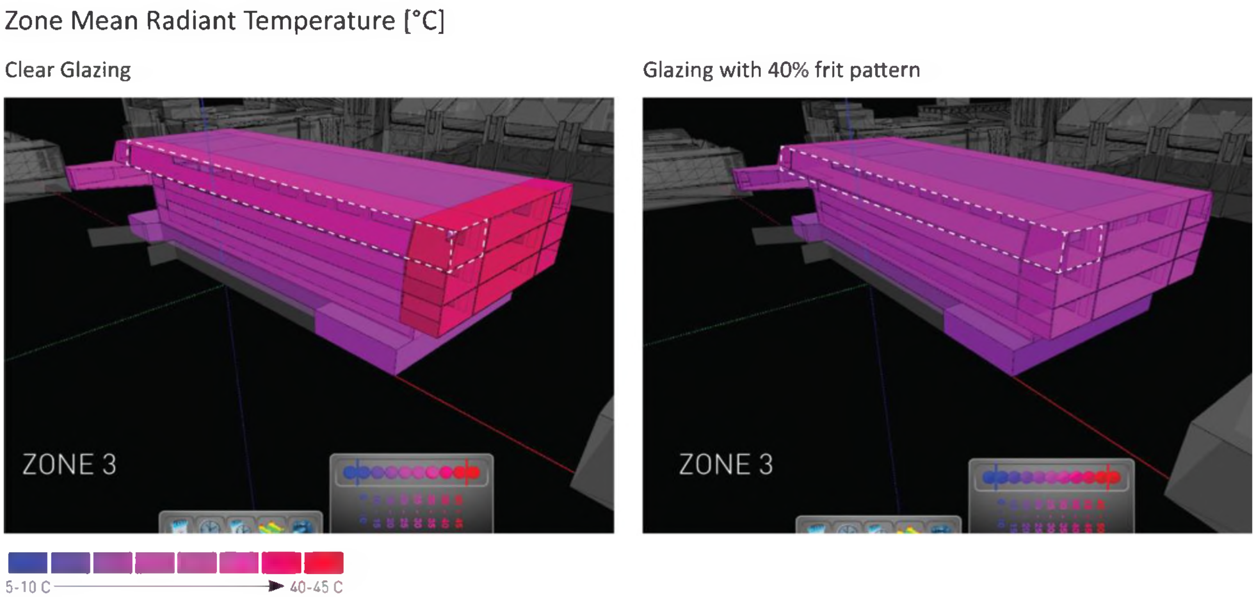

Figure 15. Comparison of zone mean radiant temperatures on June 21 if the glazing is clear (left) or printed with a 40% frit pattern (right).

We then collaborated with a set of architecture firms in New York and San Francisco to use SUSTAIN to investigate designs for building projects that were currently in the early stages of development. Questions posed by the architecture firms included the relative effects of various shading schemes, implications of building massing and orientation decisions, and the effects of a building's context on its energy loads. All analyses were carried out by our trained group of designers and reported, by them, to the architecture firms.

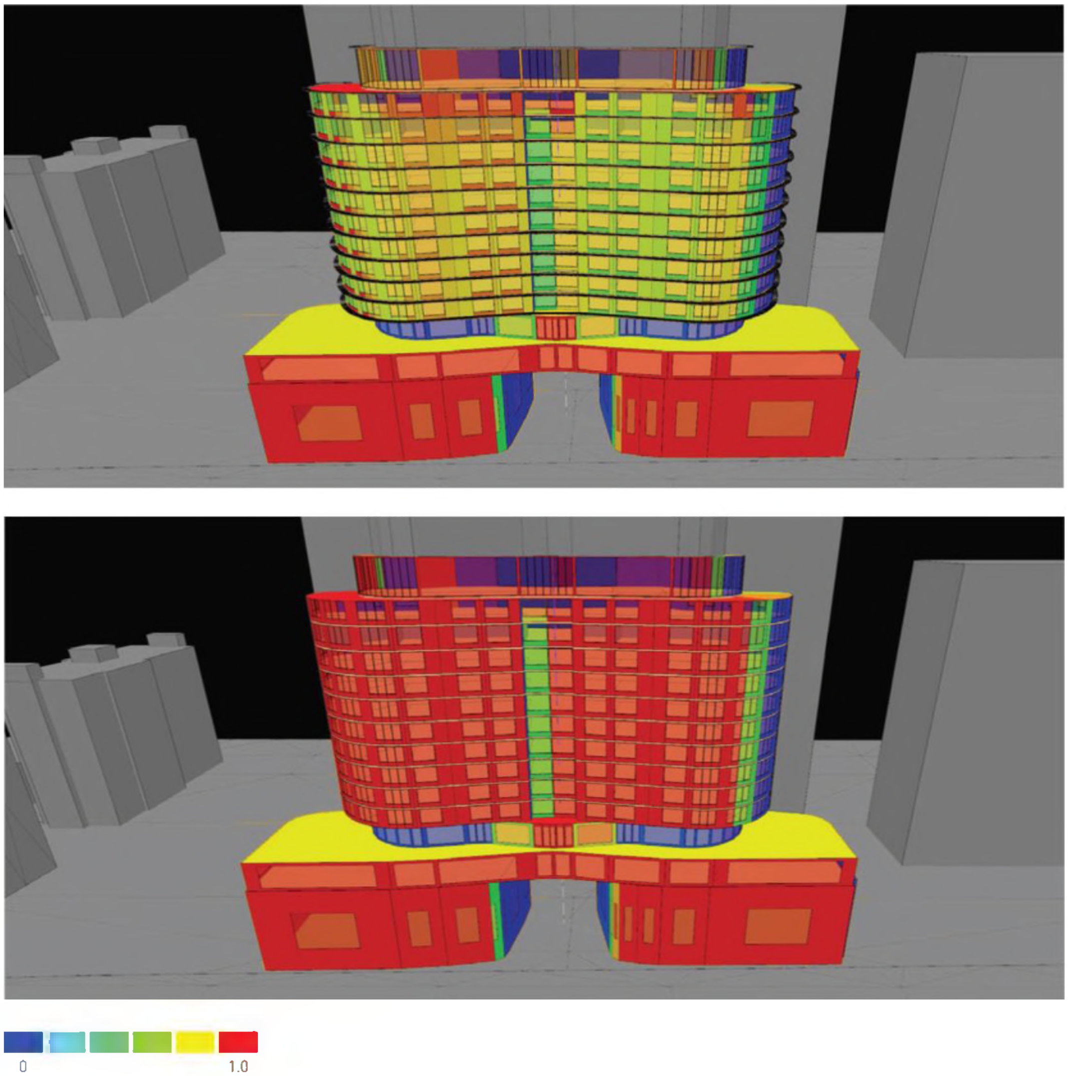

Figure 16. A health care facility simulated with (top) and without (bottom) proposed shading devices. Above, the surfaces are colored according to the percentage of direct sunlight they receive at a given time. An annual analysis shows that the horizontal shading devices are most effective in the summer months when the sun angle is high.

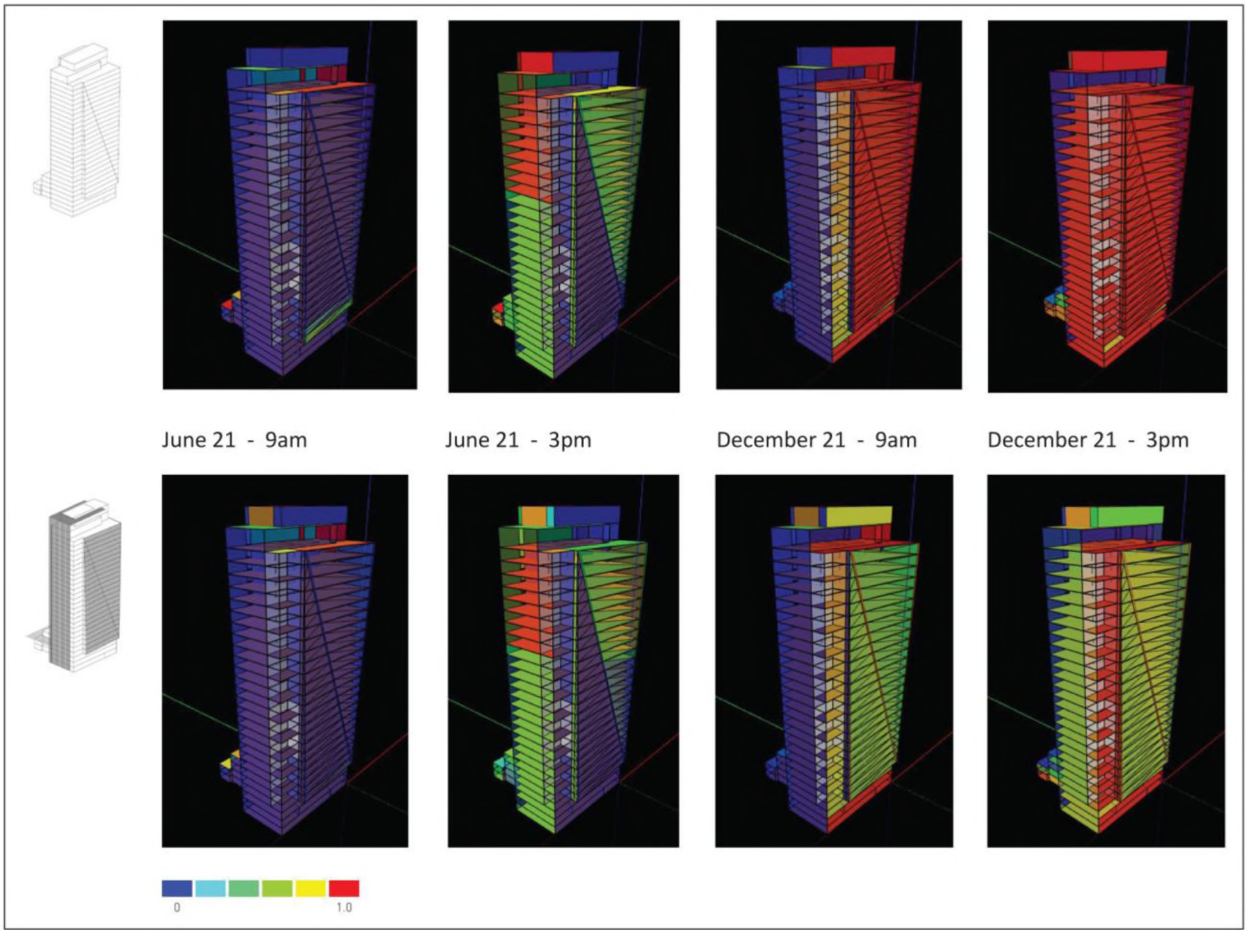

Figure 17. A tower in design development to be built in Fuzhou, China. The effect of the shading system is shown by comparing the fraction of each surface in direct sunlight. The top row shows the building without shading devices and the bottom row shows analysis of the building with the shading devices as proposed.

These collaborations afforded us the opportunity to test SUSTAIN with complex projects and tight time restraints. We were able to confirm that architecture firms can benefit from the ability to answer basic questions about design performance, early in the design process, as a means to guide decision making. SUSTAIN proved capable of handling all of the building models we constructed, ranging in scale from the size of a house to a modern skyscraper. The students were able to construct full, analyzable models in a few hours at the most, and the architecture firms were highly pleased with the results.

#6, #6a

Publications

Nathaniel L. Jones, Donald P. Greenberg, Kevin B. Pratt. "Fast computer graphics techniques for calculating direct solar radiation on complex building surfaces," Journal of Building Performance Simulation, 8/5/2011. http://www.tandfonline.com/doi/abs/10.1080/19401493.2011.582154

Nathaniel L. Jones, Donald P. Greenberg, "Fast computation of incident solar radiaton from preliminary to final design," 12th International Conference of the International Building Performance Simulation Association, 11/9/2011. http://www.bs2011.org/

Kevin B. Pratt, David E. Bosworth, "A method for the design and analysis of parametric building energy models," 12th International Conference of the International Building Performance Simulation Association, 11/9/2011. http://www.bs2011.org/

Kevin B. Pratt, Nathaniel L. Jones, Lars Schumann, David E. Bosworth, Andrew D. Heumann. "Automated Translation of Architectural Models for Energy Simulation," Symposium on Simulation for Architecture and Urban Design, 3/23/2012. http://simaud.com/2012/

Nathaniel L. Jones, Donald P. Greenberg. "Hardware accelerated computation of direct solar radiation through transparent shades and screens," 5th National Conference of the International Building Performance Simulation Association-USA, 7/30/2012. http://www.ibpsa.us/simbuild2012/technical_sessions.shtml

Lars Schumann, Donald P. Greenberg. "Environment mapping for fast and robust calculation of indirect radiant energy," 5th National Conference of the International Building Performance Simulation Association-USA, 7/30/2012. http://www.ibpsa.us/simbuild2012/technical_sessions.shtml

David E. Bosworth, Kevin B. Pratt. "New methods for the construction and interpretation of high dimensional parametric building energy models," 5th National Conference of the International Building Performance Simulation Association-USA, 7/30/2012. http://www.ibpsa.us/simbuild2012/technical_sessions.shtml

Justin R. Dobbs, Brandon M. Hencey. "Automatic model reduction in architecture: a window into building thermal structure," 5th National Conference of the International Building Performance Simulation Association-USA, 7/30/2012. http://www.ibpsa.us/simbuild2012/technical_sessions.shtml

Donald Greenberg, Kevin Pratt, Brandon Hencey, Nathaniel Jones, Lars Schumann, Justin Dobbs, Zhao Dong, David Bosworth, Bruce Walter. "Sustain: An experimental test bed for building energy simulation," Energy and Buildings, 1/8/2013. http://dx.doi.org/10.1016/j.enbuild.2012.11.026

Justin R. Dobbs, Brandon M. Hencey. "A comparison of thermal zone aggregation methods," 2012 IEEE 51st Annual Conference on Decision and Control (CDC), 6/3/2013. http://ieeexplore.ieee.org/Xplore/home.jsp

Nathaniel L. Jones, Colin J. McCrone, Bruce J. Walter, Kevin B. Pratt, Donald P. Greenberg. "Automated Translation and Thermal Zoning of Digital Building Models for Energy Analysis," 13th International Conference of the International Building Performance Simulation Association, 8/26/2013. http://www.bs2013.fr/

Justin R. Dobbs, Brandon M. Hencey. "Structured building model reduction toward parallel simulation," 13th International Conference of the International Building Performance Simulation Association, 8/26/2013. http://www.bs2013.fr/