AC 2011-1207: ENERGY EFFICIENT DESIGN USING BUILDING INFOR-MATION MODELING AND ENERGY SIMULATION

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Instructional Modules Demonstrating Building Energy Analysis Using a Building Information Model

Abstract

The design and analysis of buildings require a high level of collaboration and coordination among the disciplines of architecture, engineering, and construction. Efficiencies can be gained through the sharing of data across disciplines; however, this prospect has not been fully realized. Traditionally, building energy models have been created separately from architectural building information models (BIMs), and energy analyses have relied on a single analysis tool. By leveraging existing data from the BIM, energy models can be generated more quickly and the use of multiple analysis tools is more practical. A lack of information sources and an absence of BIM software in engineering curricula have been identified as key factors standing in the way of BIM's success. While some tutorials and education resources on BIM-based energy simulation are available, they are scattered and mainly non-comprehensive.

A set of three instructional modules is developed to demonstrate BIM-based methods of building energy analysis and simulation. The workflow leverages existing data in the architectural model for energy analysis, as opposed to creating separate models within each analysis program. Autodesk Revit Architecture is used to create a building information model based on a residential dwelling designed by Frank Lloyd Wright. Relevant data from the building information model is exported to two separate analysis tools - Autodesk Ecotect and DesignBuilder. Ecotect is used to provide early feedback on weather, heating and cooling loads, and heat loss information, and DesignBuilder is used to evaluate the effect of adding various energy conservation measures (ECMs). The two programs are used in conjunction to analyze the effects of solar orientation and passive solar design elements.

This paper summarizes the content of the three modules. The BIM data is able to successfully generate the two external energy analysis models. Issues are encountered in the process of importing BIM data into the analysis tools; however, all issues are able to be resolved. The features of the BIM workflow found to add the most value are the ability to export building geometry and thermal zone information and the ability to use material take-offs for comparing the cost of design alternatives. Simulation results from Ecotect and DesignBuilder show a 15% difference in annual heating and cooling energy between the best case and worst case passive solar design strategies. Results from the DesignBuilder ECM study indicate that a total energy savings of 21% can be achieved cost-effectively compared to a baseline design, for a 10-year time horizon.

Introduction

In the past decades, building energy simulation programs have been used increasingly as a tool to design energy efficient buildings. During this time, simulation programs have grown in both their number and scope. Currently, more than 300 software tools are available for evaluating energy efficiency, renewable energy, and sustainability in buildings[1].

Another recent development in this area has been the integration of building information modeling (BIM) software with building energy simulation tools. The green building eXtensible Markup Language (gbXML)[2] file format has been used to provide a link between BIM software and external simulation tools. Despite the progress, the prospect of integrating these multi-disciplinary tools has not yet been fully realized. Recent studies have shown that a major factor slowing the uptake of such multi-disciplinary work flows is a lack of education and information sources on BIM software. From a survey of experts' views on building information modeling, Howard and Björk found that "students getting more information on BIM" was seen as essential for its eventual success[3]. Another survey of BIM use performed by Young, et. al. found "lack of adequate training" as the most significant impediment to BIM adoption[4]. Sacks and Barak found that the use of Computer Aided Design (CAD) tools in civil engineering curricula lags the use of those tools in other curricula, such as mechanical engineering and industrial design, even though these tools are the main medium for design expression and communication in the industry[5].

Instructional Modules

Some tutorials and education resources on BIM-based building energy simulation are available; however they are scattered and mainly non-comprehensive. Building models are "pre-baked" and the tutorials tend to cover a small portion of the overall process. Learning a complex process can be difficult in such a piece-wise fashion. To address this issue, a set of instructional modules has been developed to consider the entire process: from creating the BIM, to exporting BIM data to external analysis programs, and finally, simulating the building's energy use and evaluating design alternatives.

There are three modules in total, each consisting of about 50 presentation slides. The content of the modules is summarized in this paper. The first module considers the creation of the building model, the second module addresses the export and import of BIM data, and the third covers energy simulation studies. The highs and lows of the workflow are highlighted along the way. Once the modules have been tested "in-house" by University of Illinois students, they will be made freely available.

Methodology

Software Selection

Autodesk Revit Architecture 2011 is chosen as the software package for creating the building information model. Revit provides various build strategies for model creation and accommodates the export of building data for the purpose of external energy analysis. It is also the required program for all 2011 Solar Decathlon entries[6]. For energy analysis, Autodesk Ecotect 2011 and DesignBuilder v2.2 are selected. Both programs support the ability to import BIM data for energy analysis. Ecotect is chosen for its ability to generate quick, early design studies as well as for purposes of visualization. DesignBuilder is chosen for its ability to execute detailed, sub-hourly energy simulations using EnergyPlus v5.

The two energy analysis tools are used both separately and in conjunction. According to Crawley, et. al. although many users rely on a single tool for design decisions, it may be more productive to use multiple tools. Additional tools can be used to provide information that a single tool could not provide, or they can be used as "second opinions" to build confidence in a design decision[7].

Building Selection

The design and floor plan of the building used in the modules are based on the First Jacobs House[8] (Figure 1), a 1550 square foot residential building designed by Frank Lloyd Wright in 1936. The First Jacobs House was part of Wright's Usonia movement. The building, located in Madison, Wisconsin, was chosen for two main reasons. One, its smaller size as a residential building made it more tractable for the purpose of a comprehensive study. Two, the

Figure 1: Frank Lloyd Wright's First Jacobs House in Madison, Wisconsin[8].

analysis of a well-known design was thought to be of more interest than one created from scratch.

Baseline Energy Model Specifications

The U.S. Department of Energy's *Building America Research Benchmark Definition*[9] is used as a guiding standard for most baseline energy model parameters of the study. The goal of the Building America program is to reduce energy consumption of new homes by 40% or more with

little to no impact on the cost of ownership. The Building America Research Benchmark (subsequently referred to as *Research Benchmark* or *Benchmark*) establishes baseline energy usage for residential buildings. It is generally consistent with construction practices from the mid-1990s. Using factors such as the building's type (e.g. single family attached, single family detached, multifamily), size, and location, the benchmark provides values for the energy model input parameters. These parameters include material constructions of building elements, HVAC and hot water system types and efficiencies, lighting density and efficiency, building occupancy, plug loads and associated heat gains, natural infiltration (air leakage) rate, natural ventilation, and operating schedules.

In certain cases, a standard other than the *Benchmark* is used for parameter definition. For example, energy usage figures for the refrigerator, clothes washer, and dishwasher are taken from Energy Star. This is done so that cost estimates for Energy Star appliances are consistent with their energy use. In other cases, a parameter specified by the *Benchmark* may be inconsistent with a parameter required by either Ecotect or DesignBuilder. Acceptable parameter values can typically be established using references such as *ASHRAE Fundamentals*.

While the original Jacobs House was not built to the standard set by the *Benchmark*, it is assumed for energy simulation purposes that the building is upgraded to meet modern standard practice.

Module 1: Building Model Creation

Digital Sketching
A floor plan of the Jacobs House was found online. Photographs of the building reveal three distinct roofline elevations. As a result, the building's external walls are not a constant height. In order to visualize the location of the different wall heights, a tablet PC is used to bring the floor plan into a digital sketching program. Setting the floor plan to a background sketching layer, a second sketching layer can be added on top of the original sketch to visualize the grouping of similar walls. In Figure 2, the red outline indicates walls connecting to the building's lowest roof. These walls, at a height of 7½', are used in the private space of the building composed of the bedroom and study. The blue outline indicates the next level of walls, at 9½', which are found in the building's main public space, or living area. Finally, the kitchen and bathroom space, outlined in green, has the highest walls (11½') in the building.

A third sketching layer is added to the floor plan, consisting of the building's major dimensions. These dimensions, listed in feet, will be used to create the building information model. To complete the digital concept sketch the floor plan background layer is hidden from view, leaving only the color-coded building blocks and block dimensions shown in Figure 2.
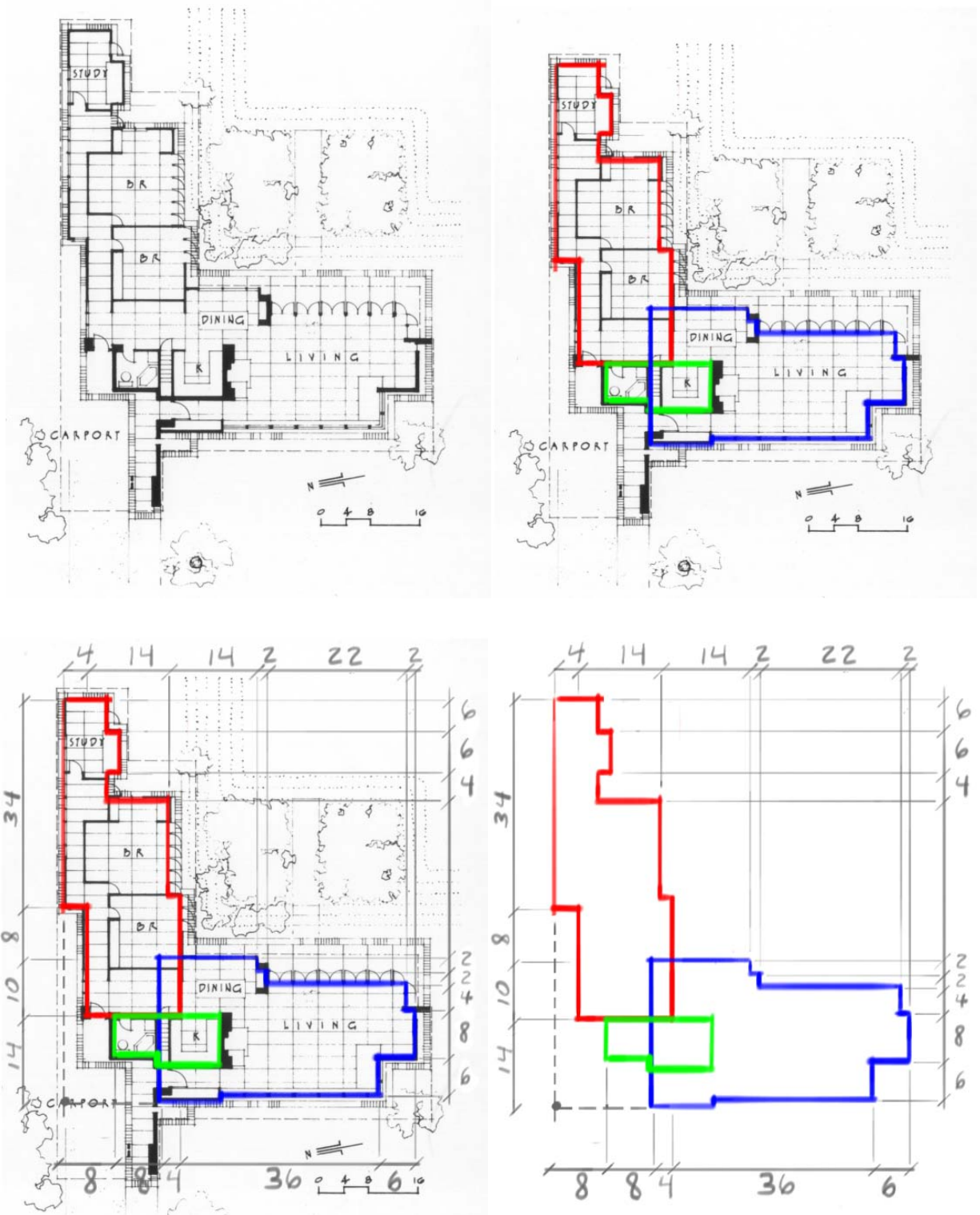
Figure 2: Top left – a floor plan of the First Jacobs House. Top right – colored sketching layers are added on top of the floor plan using a tablet PC. Bottom left – major dimensions are added as a third sketching layer. Bottom right – the floor plan layer is turned off, leaving only the major building blocks and dimensions of the building.

Creation of the Building Information Model

The building's natural separation into three major blocks suggested that a top-down modeling approach would be ideal. Revit Architecture allows such an approach with the use of its *conceptual massing* environment. First, the three blocks can be sketched separately in a two-dimensional view. After each two-dimensional shape is created, the shape can be extruded to a given height, resulting in a three-dimensional volume. In this way, the bedroom, living area, and kitchen/bath sketches can be extruded to heights of 7½', 9½', and 11½', respectively. Once the three individual masses are defined, they can be joined to create a single mass. The mass surfaces can be edited to create additional cut-outs and details associated with the building's geometry. The finished massing model is shown in Figure 3. Red, blue, and green lines have been superimposed on the figure to show how the three-dimensional masses correspond to the original 2D concept sketch.
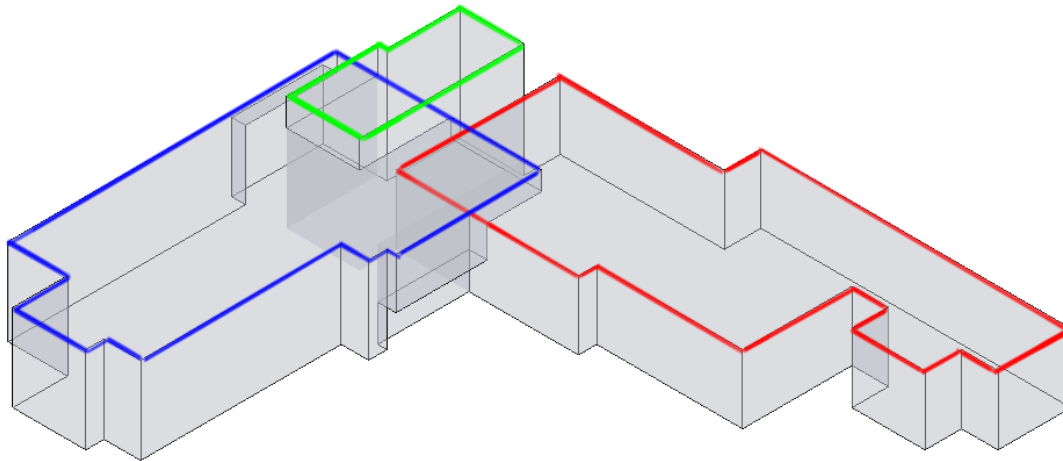

Figure 3: The massing model shown in Revit Architecture.

Revit allows the addition of building elements such as floors, walls, and roofs directly to mass faces. In this example, the walls and floors are added to the building information model in this way. Figure 4 illustrates a progression of the build process. The first building model at the top of Figure 4 shows the massing model with the addition of brick and wooden walls to some of the mass faces. Notice that this first model also includes the outlines of the conceptual mass. For the rest of the models shown in Figure 4, the outline of the conceptual mass is turned off.

Although roof elements also can be added to mass faces as well, due to its large overhangs and atypical geometry the roof is easier to implement using a separate sketch feature. After the main envelope elements of the building are defined, additional elements such as windows, doors, and internal walls can be added to the model.
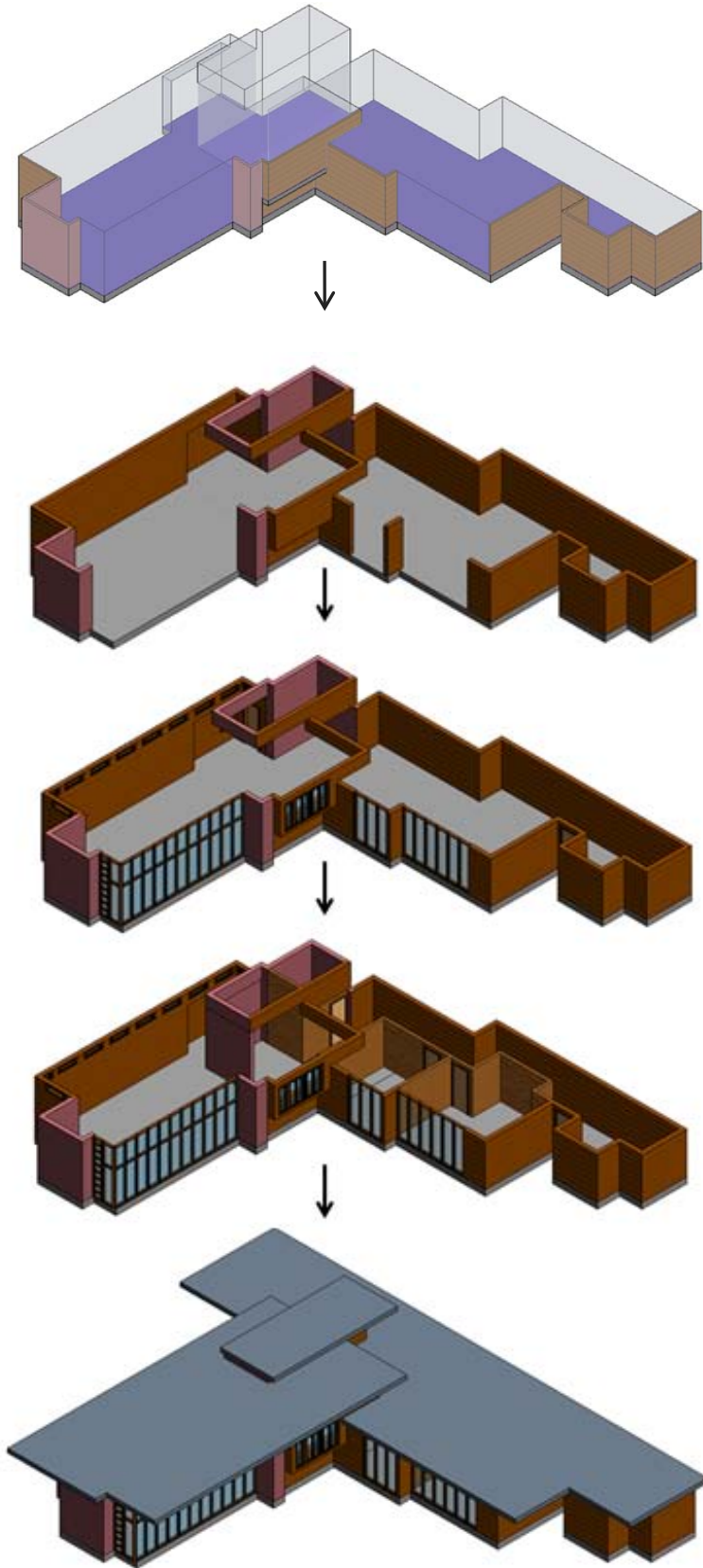
Figure 4: A progression of the build process in Revit Architecture.

In order to visualize how the building model would look in reality, a photo-realistic image can be rendered within Revit. Building surfaces can be edited to look like wood, brick, or any other material that can be created. A topography can be added to the building model, as well as site elements such as trees and shrubs. The rendering is created by placing a camera in one of the building model views. The camera takes a snapshot of the view, capturing a realistic, perspective view of the building. Figure 5 shows a rendered image of the building's completed geometry.

Figure 5: A rendered image of the final building model generated in Revit Architecture.

Module 2: BIM Data Export and Import

The building information model can be exported as a thermal analysis model using the Green Building Xtensible Markup Language (gbXML) file format. A gbXML file provides a number of options for export complexity. For example, one can choose whether or not to include features such as shading surfaces and window mullions. Since the roof of the example building has substantial overhangs, the decision is made to export the model as *complex, with shading surfaces*.

The imported gbXML model is shown within Ecotect in Figure 6. Although the imported building data looks generally complete and correct, the integrity of all model surfaces should still be confirmed. Errors in the building information model or the export/import process can result in analysis model inaccuracies. Such inaccuracies could include unintended voids or additional surfaces. Voids could cause thermal zones to be unenclosed, which is not permitted for thermal analysis. Additional surfaces could create a number of issues, including unwanted shading or overlapping building elements. A close inspection of the Ecotect model reveals several gaps and

additional surfaces in the building's geometry. One such inaccuracy is indicated in Figure 7, showing several unconnected surfaces located at the building's cantilevered wall.
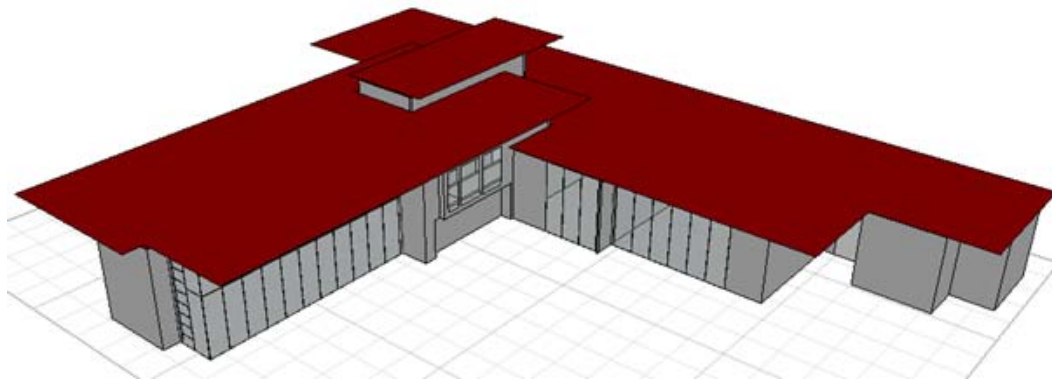

Figure 6: Ecotect model created using imported gbXML data from Revit.
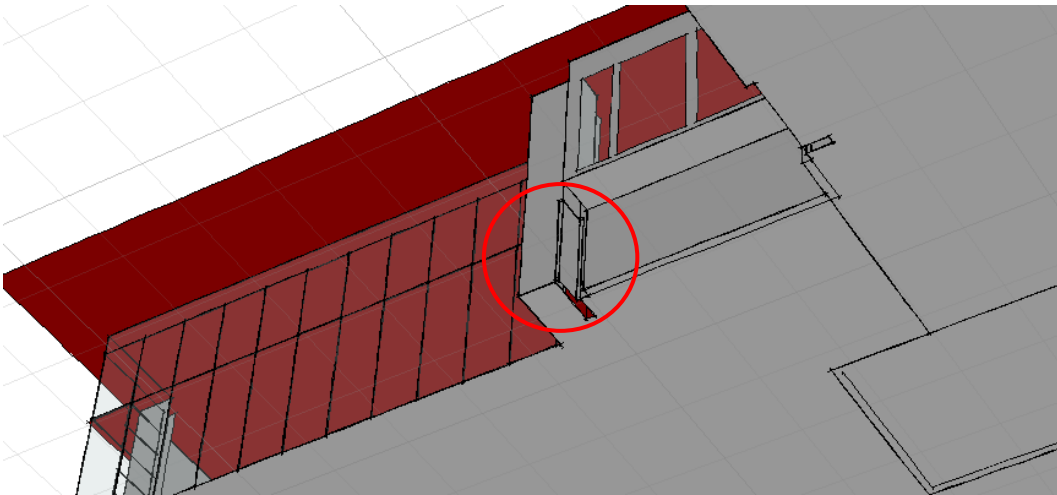

Figure 7: A geometric inaccuracy is shown near a cantilevered section of a building wall.

Similarly, gbXML data is imported into DesignBuilder. The first attempt at importing BIM data into DesignBuilder is unsuccessful. Figure 8 shows a rendered view of the imported building model. From the figure, it is clear that the main living area of the building is not correctly imported into the analysis program. All other building data, however, appears to be generally correct. It is hypothesized that a simplified thermal zone configuration in the building information model may improve import results.

A simplified two zone Revit model is imported instead of the original five zone model. The two zone model breaks the building into private and public space, rather than the five zone model which considers each room as a zone. The resulting DesignBuilder model, shown in Figure 9, is significantly improved compared to the first attempt. The large living area space is now included as part of the building. The import model data is not completely error free, however. Close inspection of the analysis model reveals a few extraneous shading surfaces (Figure 10).

Figure 8: First attempt at importing gbXML data into DesignBuilder

Figure 9: Successful gbXML import in DesignBuilder.
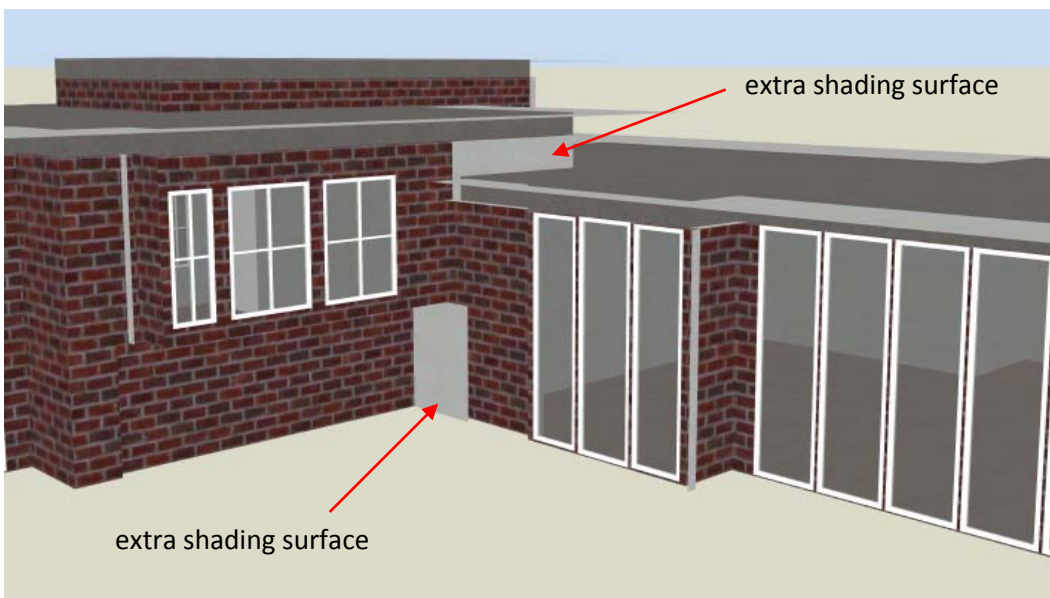

extra shading surface

extra shading surface

Figure 10: A close-up of the DesignBuilder model shows extra shading surfaces imported in error.

Final Analysis Models

The geometric inaccuracies of the Ecotect and DesignBuilder models can be fixed within each program's respective 3D editing environment. Module 2 describes this process in detail. Once this is done, the energy model parameters can be set to meet the *Research Benchmark*, and the models will look like the ones shown in Figure 11 and Figure 12.
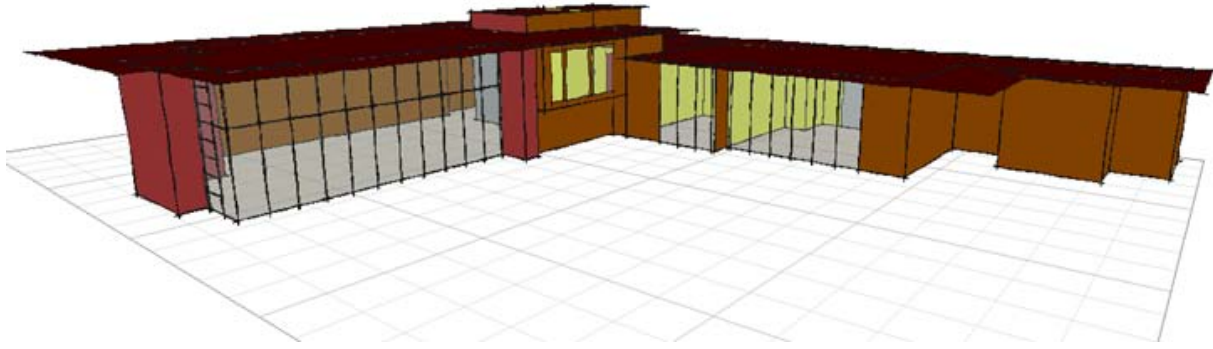

Figure 11: Final Ecotect model, ready for analysis.

Figure 12: Final DesignBuilder model, ready for analysis.

Module 3: Simulation and Data Analysis

The third instructional module includes a number of example energy studies within Ecotect and DesignBuilder. These include a weather study, heating and cooling load analysis, solar orientation study, passive solar design study, and a parametric analysis of various Energy Conservation Measures (ECMs). A brief summary of the solar orientation, passive solar design, and ECM studies is given here.

Solar Orientation Study

A solar orientation study is performed using a combination of Ecotect and DesignBuilder. Ecotect is used to visualize amounts of solar radiation falling on building surfaces. Surfaces

receiving greater amounts of solar radiation are represented by brighter colors (yellow and red), while surfaces receiving lower amounts are shown as darker colors (blue and purple). For Madison's heating-dominated climate, it is hypothesized that the best orientation will maximize solar radiation falling on the building's glazed areas so long as adequate shading is provided in the cooling months. DesignBuilder is then used to test the hypothesis by generating annual energy use figures for each building orientation at 30 degree intervals.

The result is shown in Figure 13. The chart displays annual heating and cooling energy generated by EnergyPlus, and solar radiation images from Ecotect have been superimposed on the chart. The qualitative and quantitative attributes of each analysis tool are leveraged to generate a big picture understanding that neither program alone could provide. The programs are in agreement that the optimal solar orientation is located at 150 degrees, in which the large glazing faces mainly south.
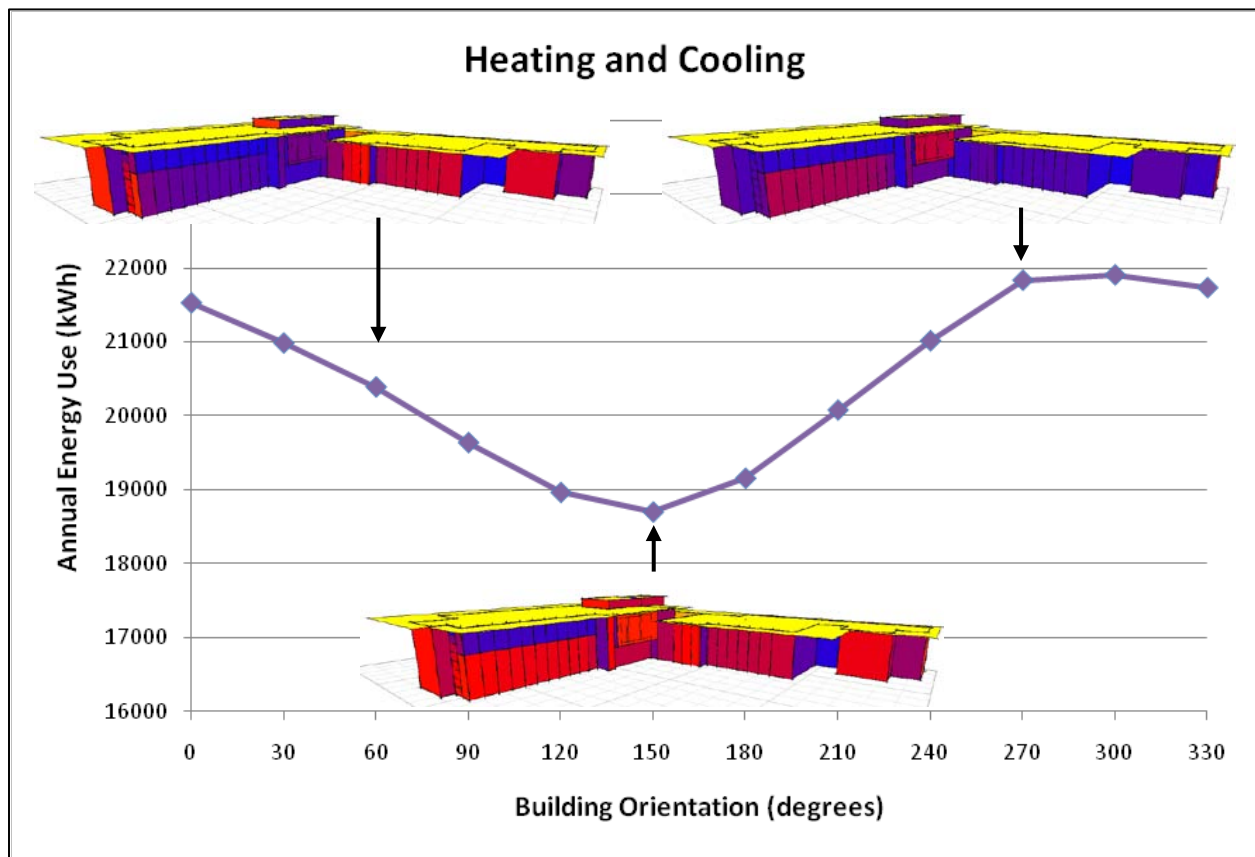

Figure 13: Annual heating and cooling energy shown for various solar orientations.

Passive Solar Design Elements
In another study, Ecotect and DesignBuilder are used to study the individual and collective effect of passive solar design features. First, a solar ray analysis is performed in Ecotect to visualize the effect of passive solar elements in the winter and summer months. Roof overhangs are

turned on and off to compare the amount of solar rays allowed into the building. DesignBuilder is then used to perform annual simulations for four different configurations: the building with overhangs and thermal mass (in other words, the building as it was designed), no overhangs with no thermal mass, no overhangs with thermal mass, and overhangs with no thermal mass. Here, the thermal mass refers to a large, brick fireplace that sits in the building's public space.
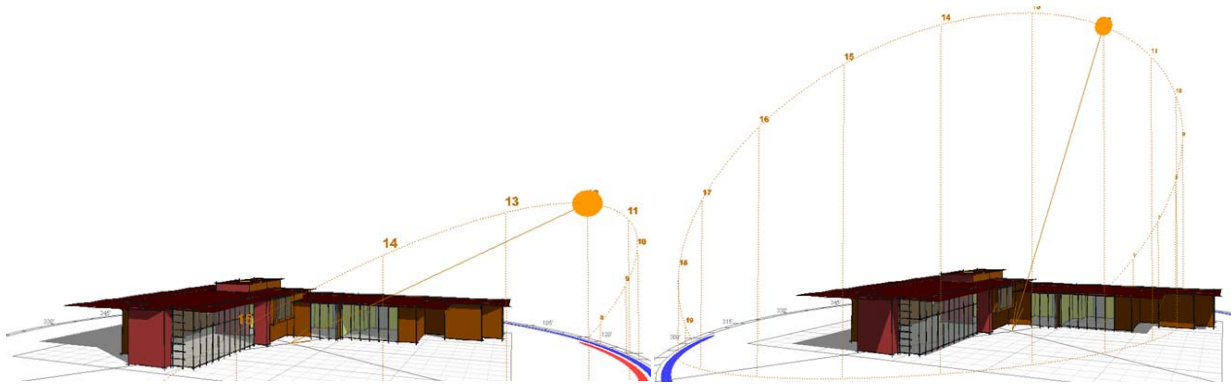

Figure 14: On the left - the sun's relative position in Madison, WI on December 28th. On the right - the sun on July 28th.

Because the sun's position in the sky is changing constantly, the amount of solar rays entering a building's spaces changes throughout the year. Figure 14 shows the sun's position on December 28th at 12:00pm on the left and on July 28th at 12:00pm on the right. In the winter months, the sun's relatively low angle in the sky allows solar rays to penetrate the building, either with or without roof overhangs (shown on the left of Figure 15 and Figure 16). In the summer months, the scenarios are far more different. On the right side of Figures 15 and 16, solar rays are shown for scenarios with and without roof overhangs for July 28th at 12:00pm. With overhangs, the building is able to block the majority of solar heat from entering the living area space. Without overhangs, solar rays are allowed directly into the living space, heating the space during the cooling months of the year.
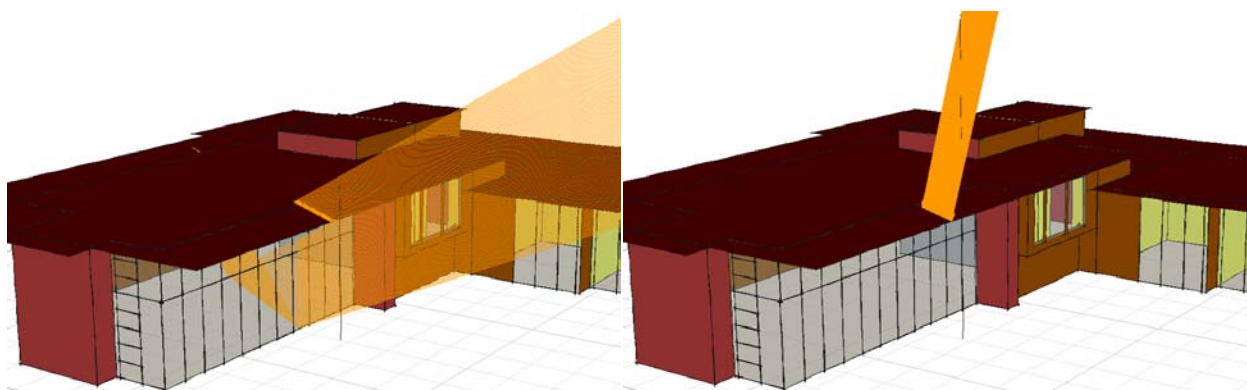

Figure 15: The building shown with roof overhangs in the winter (left) and summer (right).
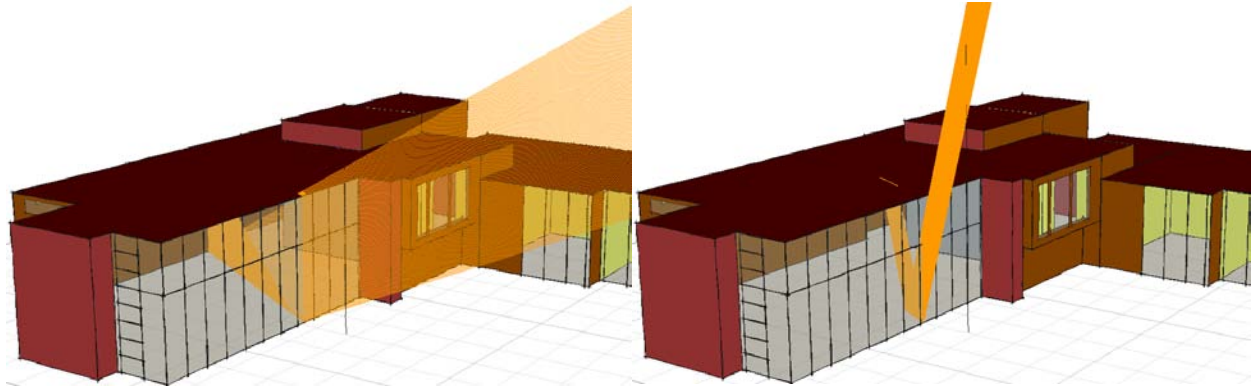
Figure 16: The building shown without roof overhangs in winter (left) and summer (right).

Heating and cooling energy consumption data is generated in DesignBuilder and shown in Figure 17. Here, the overall effect of the passive solar design features is realized. The figure shows that there is a 15% difference between the best case (lowest energy use) and worst case (highest energy use) design scenarios. Although the "as designed" scenario is not the best choice at all possible orientations, it is shown to be the best design when all possible designs reach their minimum values. Hence, the inclusion of the overhangs and thermal mass provide the best overall design.
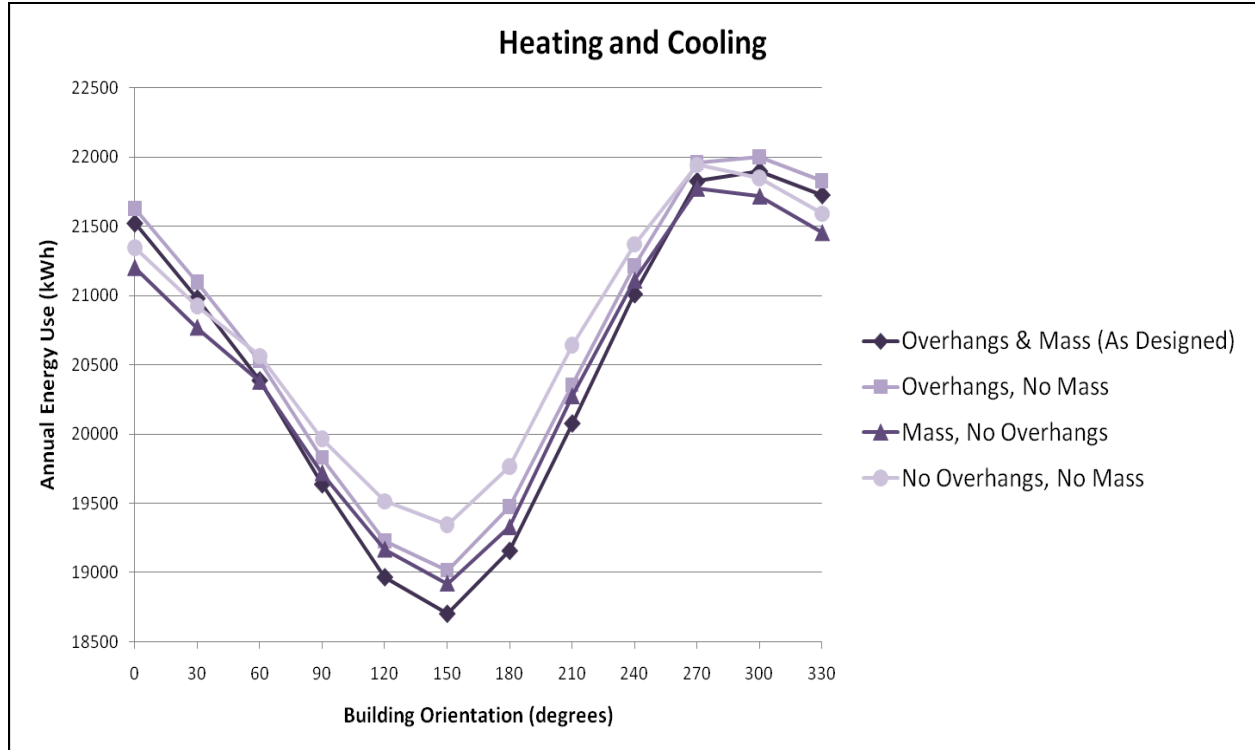

Figure 17: Annual heating and cooling energy data for passive design study, generated in DesignBuilder.

ECM Analysis

The last energy study of Module 3 concerns the addition of multiple energy conservation measures (ECMs) to the baseline energy model. A sample of ECMs are investigated, including additional wall and roof insulation, higher performance glazing, and higher efficiency lighting, appliances, and mechanical systems. A parametric analysis of ECMs can provide insights into energy saving design alternatives. Since energy savings are not the only factor for design decisions, economic factors are addressed as well.

On an individual basis, the greatest energy savings are achieved by the high efficiency furnace and an additional 3" of rigid wall insulation. Both ECMs result in a 13% decrease in annual gas consumption or a 7% decrease in overall energy consumption. Next, ECMs are combined in order to achieve the greatest energy savings and meet a ten-year payback. The combined measures meeting the payback criteria – which include additional wall insulation (2" rigid foam), double-pane argon windows, upgraded HVAC and hot water, and all CFL lighting –result in a 21% energy savings.

Conclusions

The goal of these modules is for students to use them and hopefully spark an interest in building information modeling, building energy simulation, sustainable design, or parametric solid modeling. The modules will be continually improved and expanded based on student feedback. Students at Illinois' Product Dissection Laboratory have already started using the tutorials, and thus far their feedback has been positive and very useful.

Hopefully, this educational content will play a role in fostering future multi-disciplinary courses, research, and academic programs related to energy efficient and sustainable building. While they are a small step, they are a step in the right direction – and a direction where students are leading the charge.

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