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# Rapid Prototyping: A Sustainable Design Aid

Jacob Bolda
Architectural Engineering
Milwaukee School of Engineering
1025 North Broadway
Milwaukee, Wisconsin 53202

Rapid Prototyping Center
Milwaukee School of Engineering
1025 North Broadway
Milwaukee, Wisconsin 53202

Faculty Advisor: Professor Michael McGeen

## Abstract

The purpose of this research is to explore the feasibility of performing energy analyses early in the design stage of building. Currently, energy analyses are not performed on a building until 80%-90% of the design decisions have been finalized. Once this point has been reached, passive solutions are hard to incorporate and designers depend on active measures to correct deficiencies in design. If energy modeling becomes a higher priority in designing a building, passive design solutions might easily be incorporated. Utilizing computer programs simplifies and expedites the energy modeling process. Energy modeling was examined to determine the ease of use and feasibility of using such a device to help designers understand the priorities behind passive design. This research focuses primarily on illumination with respect to solar energy uses. Values obtained from an energy model making use of daylighting and solar energy to help illuminate the room can then be compared to the same room using primarily electric illumination. A visual, as well as a textual, analysis can be performed and used to help educate not only designers but the client. Using rapid prototyping, a striking visual model can be created to help convey the energy efficiencies as well as the architectural highlights of the building.
**Keywords: Ecotect™, Energy Analysis, Rapid Prototyping**

## 1. Introduction

The amount of new topics regarding energy has been increasing. There are legislators trying to make the general population aware of the environmental concerns attributed to our energy use. Increases in the price of gasoline and other fossil fuels not only spurred great political debate, but also military action as some politicians claim. The United States uses about 109 quadrillion

BTUs per year of energy amounting to about 22.5% of the total energy use in the world. Incredibly, America is only about 4.6% of the world's population. The industrial and commercial sectors account for about half of this energy use[1].

Two benchmarks are being used today to evaluate a building's impact on the environment: the

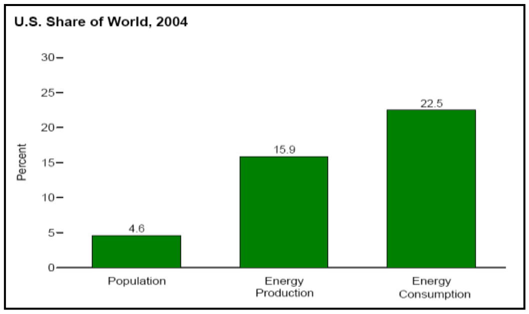


Figure 1. U.S. Share of the World Energy[1]

Leadership in Energy and Environmental Design (LEED) and the carbon-neutral system. "The LEED® (Leadership in Energy and Environmental Design) Green Building Rating System is the nationally accepted benchmark for the design, construction, and operation of high performance green buildings[2]." Carbon-neutral promotes the ideas of eliminating greenhouse gas emissions or taking measures to offset emissions. Both benchmarks encourage energy efficiency in buildings. Prior to computer programs, all energy calculations were done by hand. With the onslaught of computers into the construction industry, energy calculations can be done much quicker. The output data from these programs is all tabulated requiring a trained professional to understand. Incorporating visual energy analysis early in the design phase has been very difficult up until the past two to three years. Computer energy analysis programs using visually represented data have simplified and made the process much easier. As the energy analysis programs become more efficient and compatible with current design software, such as computer aided design (CAD) and building information modeling (BIM), architects will be more likely to use them to improve designs.

## 2. Programs Examined

This research focuses on the use of software to help architects make energy analysis a priority in design. With the influx of computers into our society, design work is continually moving towards using programs to remove time barriers and improve performance. Typically, programs such as Autodesk AutoCAD, a two-dimensional CAD modeling program, have been used to design and create building documents. The construction industry is trending towards three-dimensional design with Autodesk Revit™, a BIM program. Since this research seeks to mirror the construction industry methodology, the process started out with a Revit™ model. All building and design work would start in Revit™ and continue into the energy analysis software.

When examining the possible energy analysis programs, a few parameters were used to simplify the process. The research decidedly focused on illumination and daylighting in a space. Illuminance is the density of luminous flux incident on a surface. More simply, it is the amount of light per square meter hitting the surface in metric units of lux. Another common measurement of illumination is the footcandle. Daylighting is essentially using solar light to help or completely light a space[3]. Incorporating heating and cooling loads, as well as daylighting, increases the complexity of the project beyond the time-frame of this research project. The research focuses on a location specific two-story school building. Since each building project configuration will be location dependent, a customized energy study will need to be performed for each building.

## 2.1. DOE-2 and Green Building Studio (GBS)

DOE-2 is a free energy analysis utility created by the Department of Energy. Unfortunately, this program is not very user-friendly. Green Building Studio is a web-based applet recently bought out by Autodesk on June 26, 2008 [4]. GBS uses a .gbXML file type export from Revit™. GBS is a graphic user interface that wraps around DOE-2 and creates a more user-friendly environment. Certain parameters are entered (global position, season, energy cost) and GBS creates a tabulated energy analysis. This is done based off the parameters entered and calculated information from DOE-2.

Unfortunately, as aforementioned, a tabulated energy analysis is created, but besides a graph or two all of the information is not visual. As this project aims at creating visual, easy to understand information, these two programs were not used. These programs might be of more use later in the design stage.

## 2.2. Ecotect™

Ecotect™ appears to have the best utility for this project. It is a program designed to be used for early energy analyses. This program provides better utility and visual data than GBS and DOE-2. As such, Ecotect™ is the primary focus of this research project. This program also recently became part of the Autodesk family along with GBS[4]. Consequently, the program will likely undergo many changes within the next year hopefully removing many of the difficulties seen in this research.

The program has a "wide range of performance analysis functions [… but] its main advantage is a focus on feedback at the conceptual building design stages[5]." The aim of Ecotect™ is to provide useful feedback in a visual and interactive environment. Calculations may not be precisely accurate at a pinpoint level, and some assumptions or averages are used to simplify calculations. The program is not designed around highly accurate models (but can use and export formats where more detailed analyses can be performed). It appears that Ecotect™ will be a good choice for architects and designers early in the process to help prioritize energy efficiency.

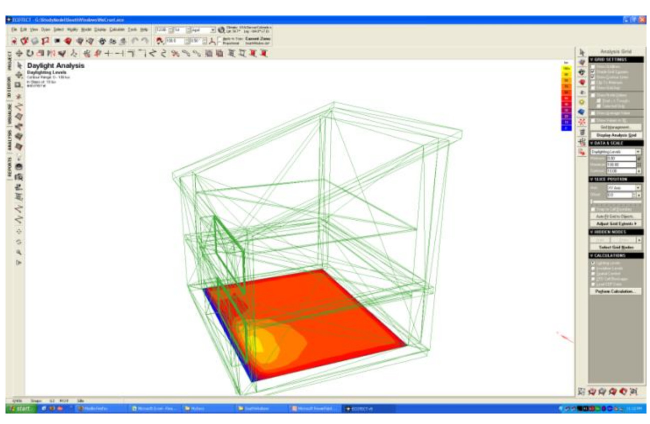

Figure 2. Ecotect™ Interface

## 3. Rapid Prototyping Machine

The machine creating the models for this project is the Z-Corporation Spectrum Z510 3D printer. This 3D printer is the only logical choice for the situation. It is the only 3D printer available that can print 3D objects in multiple colors. Creating models using a 3D printer shaves off the time and labor necessary to create physical models. The printer makes use of relatively low cost materials and requires minimal post processing when compared to current model creation techniques in the construction industry.

Printing on the Z-Corp involves an additive process. Powder is rolled across a platform in 0.0035"-0.008" (.089-.203 mm) increments[6]. A print head moves across the powdered surface and lays down a binder in the same manner as an inkjet printer lays ink on paper. This binder can contain a colored pigment giving the Z-Corp products their color. The platform shifts down and another layer of powder is applied and the process continues. Post-processing requires coating the product with strong glues to help harden the product.

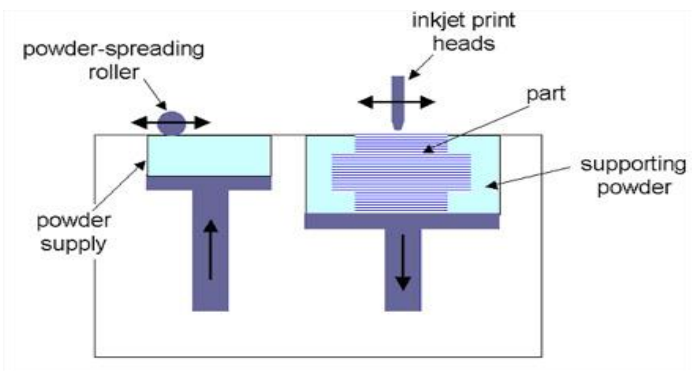


Figure 3. Z-Corp 3D Printer Process and Unit

## 4. Methodology

To simplify the process, a few parameters were kept. Energy modeling is location specific as the sun does not shine uniformly over the earth. Denver, Colorado was picked since Ecotect contained all the weather and climate data needed to perform the analysis. Denver also receives enough sunlight on average to see differences in the models. Ecotect™ is intended to help with conceptual design therefore a simple section of a school building was chosen to perform analysis on. The study model can be seen in Figure 4. The windows are west facing and the north, south, and east sides of the model are assumed to be interior walls contained in the the full building. With the project focusing primarily on illumination, the only item left to vary is the windows and window orientation.

As previously mentioned, this research project started out with a Revit™ model. Using Revit™, multiple study models are created with varying amounts of glazing, or window space, in the model as well as adding lighting shelves. Lighting shelves act as reflectors to help reflect light deeper into spaces. Lighting shelves also act to direct light into the walls and ceilings. When the light reflects and hits the walls and ceilings, the light diffuses creating a soft, ambient light. Using this principle, spaces can be lit using the sun while avoiding high contrasts in the

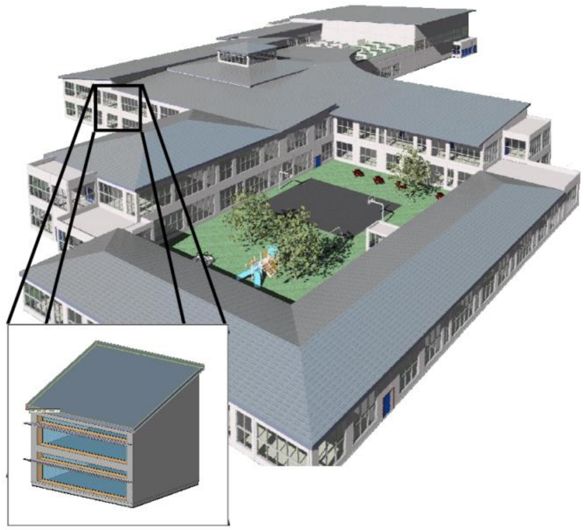

Figure 4. Study Model

light. High contrasts will light a space, but tend to be counterproductive. High contrasts in light create bright and dark spots inducing eye strain and fatigue. For example, a light bulb with a shade (or a white coat over the bulb itself) will create less contrast then having a clear bulb without a shade. After each model is created, it can be exported to a format that can be read by Ecotect™.

Importing the file into Ecotect™, the materials and geometry are checked to ensure proper results. The energy analysis grid is placed on the floor surface (and other surfaces if needed) and the energy analysis is run using the weather and climate data from Denver. In this study, the energy analysis dialog asks for parameters such as window clarity, cloud cover, and accuracy of results. Parameters representing sub-par conditions are recommended such as clouds restricting direct sun and adjustment values for degradation of light transfer through dirty windows. This helps ensure that the building design will perform not only during perfect conditions, but during imperfect conditions also. After the analysis is complete, the performance scale is recorded and the model is exported.

The part is imported into Materialize Magics™ to ensure proper recognition of the part. If this step is skipped, internal geometry or surface oddities can crash the Z-Corp software during printing. The product is processed and moved into the Z-Corp software and printed. The part ready to be built can be seen in Figure 5. The scale previously recorded in Ecotect™ is applied to the side of the part. This specific build took about six hours to create at 1.5% of the original full size. After post-processing, the part is ready to be displayed.

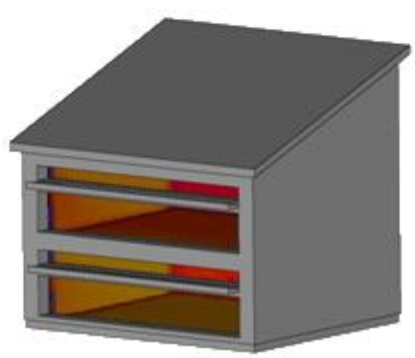

Figure 5. Finished Product

## 5. Detailed Process - File Types and Program Compatibility

The Z-Corp printer imports two prominent rapid prototyping file types in which to create a product. The Stereolithography file (.stl) and a Virtual Reality Modeling Language file also known as VRML (.wrl). These file formats utilize triangles to form geometry. The number of triangles increases as the geometry becomes more irregular. Unfortunately, Autodesk Revit™ does not natively export in either of these file types. Using a plug-in which is still in the testing phase from the Autodesk Labs, a Stereolithography file (.stl) can be exported. Because this technology is new to Revit™, missing triangles and irregularly joined triangles appeared in the study models.

The next solution depends on Ecotect's™ ability to export a viable file type which can be read by the Z-Corp. The Stereolithography file (.stl) only contains geometrical data, but a VRML (.wrl) represents not only geometrical but color data also. Color data is important since the energy analysis data needs to be represented visually and color is the best choice for this. Ecotect™ has the ability to export a VRML file (.wrl). The project can be exported from Revit™ into Ecotect™, and then Ecotect™ can export a VRML to be read by the rapid prototyping software.

The next step to create a rapid prototyping model of this data is exporting a file type from Revit™ which can be recognized by Ecotect™. When importing a Stereolithography file (.stl) into Ecotect™ from Revit™, the file is imported as a solid block and loses its material properties so objects such as windows and lighting shelves have to manually be identified within Ecotect™. The only other viable file type left is called Data Exchange Format (.dxf). Ecotect™ imports the Data Exchange Format (only a dxf exported as a polymesh is compatible) also recognizing different parts of the object such as windows and masses. This allows easy editing of material properties such as allowing the windows to transmit light. The energy analyses are conducted within Ecotect™. Using a feature within Ecotect™ called Daylight Autonomy, the color scales can be normalized. Each grid is normalized using 400 lux as the benchmark. This is a common illumination unit, and 400 lux is the amount of lighting needed for a well-lit office space[7]. Since the project focused on passive solar energy studies, different window configurations can be explored to allow the best intake of light into the room. After running an energy analysis, a color-coded analysis grid is created on the user-defined surface. The model can then be exported as a VRML (.wrl) which will retain the model data as well as color data.

At this stage, the model contains excessive internal geometry. The internal geometry could possibly be ignored, but then during and after creation, the internal geometry can create weak points in the model. Materialize Magics™ is employed to touch up and help solidify the model. Magics™ is primarily a design and pre-rapid prototyping software which can export in the file type recognized by the Z-Corp (.ply). Even though the Z-Corp software can read a VRML (.wrl), this extra step is necessary to insure proper recognition and printing of the object. Also when importing a VRML into the native Z-Corp software, some color detail can be lost. So using Magics™, the internal geometry can be removed, and the necessary color data can be examined and ensured that the data will be represented clearly in the model.

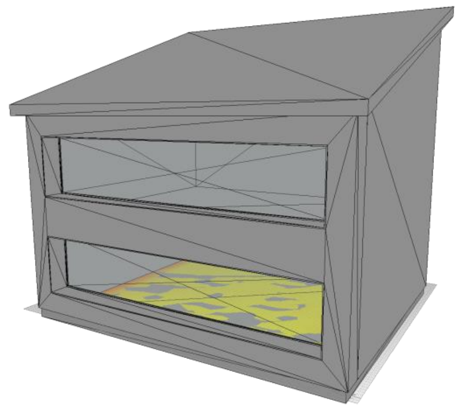

Figure 6. Conflicting Floor Geometry

The analysis grid from Ecotect™ also has to be examined in Magics™. Ecotect™ exports the analysis grid without thickness (nor does it attach it to any objects). When using Magics™, the analysis grid appears as just another surface. This creates the same problem as the internal geometry. For example, when the analysis grid is applied to the floor in Ecotect™, the floor and the grid appears to be "on top" or "within" each other. The floor as well as the color grid will both show creating the spotty affect that can be seen in Figure 6. The floor then has to be removed and the analysis grid essentially becomes the floor to the model. Ecotect™ will only apply a grid on one surface also. If an analysis grid is needed on more than one surface in a model, a few "different" models will need to be combined. The only difference between the models is the location of the analysis grid (the geometry does not change). The internal geometry is removed from one model, and each model is imported into the clean model (clean meaning without internal geometry). The analysis grid is removed from every imported model and applied to the clean model. The analysis from each imported model replaces surfaces in the clean model. This process is repeated until each analysis grid is applied to the clean model.

## 6. Using the Model Analysis

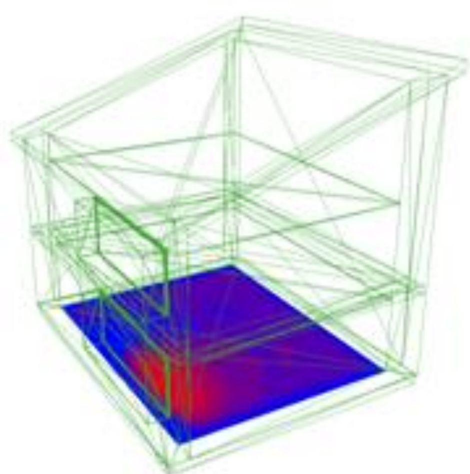

Figure 7. Small Southwest Windows

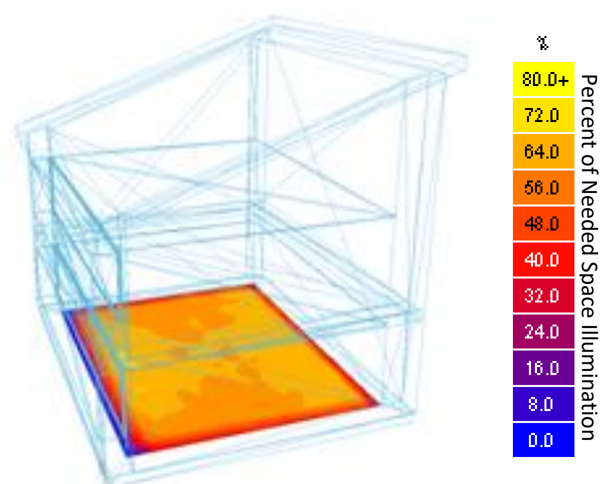


Figure 8. Large Westward Windows

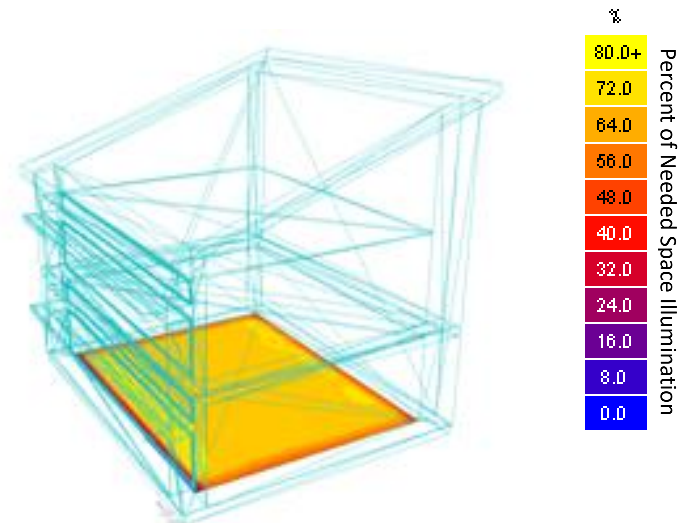


Figure 9. Large Windows Including Lighting Shelves

The model is not just created solely on looks. Comparing study models holds the most benefit. The architect can take the conceptual models and compare them to each other to choose the best orientation. This might be most easily seen with the preceding examples. All of the scales have been normalized for best comparison. Knowing that the brightest colors represent the most light, the third orientation (Figure 9) is the best choice. The third configuration has, on average, 80.72% of the needed illumination for this space (400 lux). Whereas Figure 7 and Figure 8 only have, on average, 14.98% and 62.70% respectively.

While this information might be enough for an architect to act on, the client might request the annual dollars s/he will save by choosing one configuration over another. The client will want to see justifiable cause to spend extra money. At this time, Ecotect™ appears to contain the capibility to provide data showing a photoelectric sensing lighting system. A photoelectric sensing lighting system will sense the amount of light in the room, and turn on and off the lights to supplement the daylight effects as well as turn off the lights when no one is in the room. This data would be very useful in providing feedback not only for the architect, but for the client to work on. Unfortunately, this author was unable to operate the module that would extract this data. This feature, when it is operational, will add important new data to future researchers who are looking at ways of making buildings more energy efficient.

## 7. Conclusion

Making buildings more energy efficient creates a win-win-win situation. Using energy modeling software, the client will have a more energy efficient building providing cost savings for years to come. The architect and client receive monetary incentives as well as greater recognition. Lastly, the environment will undergo less human related stress. Models can be used to educate designer and client alike as well as provide comparisons to better energy efficiency in design.

At the current time, compatibility and ease of use are still of concern. Since Autodesk very recently bought out Ecotect™, changes to improve compatibility between Ecotect™ and Revit™ should be seen within the next year. Removing internal geometry and applying the analysis grid to multiple surfaces was also quite time-consuming and it requires training and expensive software not usually found in architectural offices. This can simply be remedied by a few minor software additions or tweaks. If the energy analyses can be made more efficient as well as the shift from Ecotect™ to 3D printing of the model, this process can become very simple. With the onslaught of building information modeling, this author foresees low cost 3D-Printers such as the Z-Corp being employed in architectural and construction firms to quickly represent data or make a model for client viewing.

## 8. Acknowledgements

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## 9. Disclaimer

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