Rapid Prototyping as an Aid to Sustainable Design

Xavier Lange
Department of Physics
Eastern Illinois University
600 Lincoln Avenue
Charleston, IL 61920. USA

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

Faculty Advisor: Professor Michael McGeen

Abstract

This research explored the use of rapid prototyping as a tool for selecting the building composition with the greatest potential for energy efficiency. This research examined methods of translating the data gathered from energy modeling software to a format compatible with 3-D printing technology. The growing public awareness of the finite quantity of natural resources available for power generation has stimulated interest in energy modeling during the design phase of new construction projects. Energy modeling is a technical examination of the variables that together create the energy requirements of a structure. Past research evaluated two energy modeling software programs that are compatible with rapid prototyping, Energy Plus with DesignBuilder and ECOTECT. This research focused on the use of ECOTECT to transfer visual data containing energy characteristics to the Z Corp Spectrum 510 3D Printer. The ECOTECT energy modeling program offered visual data which could be prepared for prototyping. The emerging software interoperability format green building extensible markup language (gbXML) was also examined for its utility in performing energy analysis on buildings. Rapid prototyping holds the potential to present the results of energy modeling studies in a medium that improves and enhances communication among all persons involved with energy conscious project.
Keywords: Rapid Prototyping, 3D Printing, Energy Modeling, Green Building Extensible Markup Language (gbXML), ECOTECT

1. Introduction

Architects research building designs without an energy modeling professional due to the time and costs associated with integrating another professional into the team and due to the specialized software required. The orientation of the building is chosen by using a massing study, which is a study which examines the relative roles of buildings in their environment; the orientation of the building is an important consideration because it cannot be altered after construction. The orientation and shape of the building is one of the first creative steps of the architect and according to Dr. Larry Sass of MIT, this creative process is best suited to a feedback comparing candidates and refining until the most suitable design is achieved [1]. Rapid prototyping of building geometry offers an intuitive interface for the creative process at the beginning of a project, 'design candidates' can be manufactured more easily thereby improving the architect's design process. These physical models can then be used to refine the project design.

The 3D models which architects create are currently being used to replace hand-built models. Due to the flexible process of creating physical objects from computer data, architects could extend the utility of rapid prototyping technology to encompass other visual data. This research focused on prototyping energy modeling data on the geometry of a building.

2. Rapid Prototyping Through the Z Corp 3D Printer

The machine used for this research was the Z Corp Spectrum Z510 3D Printer. The Z Corp 3D Printer technology was first developed by MIT in the 1980s. The printer process is shown in Figure 1. A corn starch or plaster powder is transported from the powder supply to the build area by the powder-spreading roller. The inkjet head then applies a low viscosity binder to create the layer of a model. The printer head can also be used to apply color ink directly to the model, important in creating display models. This additive process continues until the entire model is created.

The Z Corp printer offers a relatively low cost machine as well as low cost materials, although the system is not as simple as sending the proper data straight to the machine. The Z Corp 3D Printer does necessitate post-build processing using strong glues to fortify the object, a labor intensive process. These drawbacks may limit the usage of the printer to larger firms which can support the labor necessary to keep the machine running.

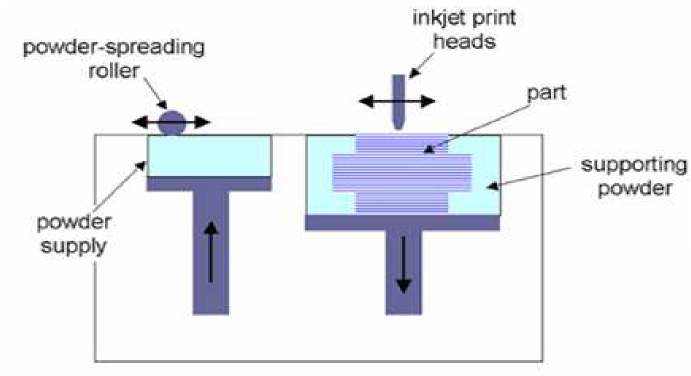

Figure 1 The Z Corp 3D Printer Process

3. Energy Modeling

Energy modeling is an examination of the physical characteristics of a building and how they relate to the energy characteristics of the building. According to the Economist, buildings in the United States "… account for 65% of electricity consumption, 36% of total energy use and 30% of greenhouse-gas emission" [2]. Energy modeling is a highly technical field and common practice is to add an energy expert to the team late in the design cycle when most details are finalized. Figure 2 illustrates this workflow, where energy modeling is positioned between Design Development and Construction Documents. Richard Paradis, Director of the Natural Areas Sector at the University of Vermont, states that "not only do energy analysis software programs have varying levels of accuracy, they are also intended to be used at different phases of the design process; and require very different levels of effort and cost" [3].

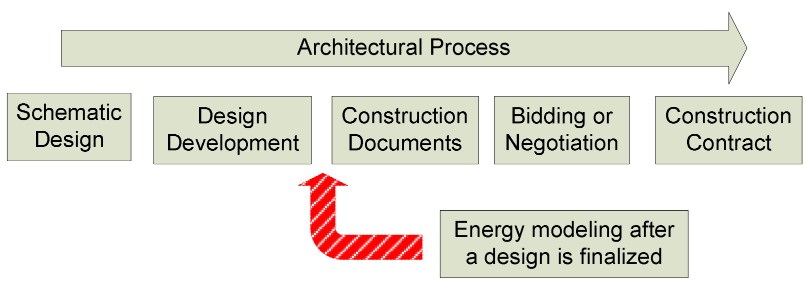

Figure 2 Current energy modeling workflow [4]

Therefore the programs with more complicated input requirements are used later in the design process because only then are the proper variables defined. The tool needed for an architect at the beginning stages of design must run without all the variables of a final project. This new workflow recommendation for integrating more energy analysis may introduce new costs to a project, but according the United States Green Building Commission, a body which advocates energy conscious designs, "the 2% increase in construction costs required to achieve a LEED gold rating typically pays for itself in lowering running costs within two years."[5]. LEED is an energy usage certification process which requires energy modeling as one of the first steps. There are multiple ratings for the LEED program, gold is the second to best with platinum being the highest achievable rating. The improvements due to energy modeling are logical because without energy analysis feedback the architect does not have the necessary information to research energy conscious plans.

A revised workflow would involve an architect having direct access to energy modeling tools. Figure 3 illustrates the positive feedback loop which would allow an architect to refine and improve the energy characteristics of a building. One example: the architect might examine the building orientation during the winter and summer to determine how the building performs in the extremes of weather. For this desired feedback loop, the position of energy modeling from Figure 2 should instead be positioned under the Schematic Design phase where the energy modeling feedback can affect the building's design. All tools are not applicable to this revised workflow, however. Richard Paradis has also said that "... other [programs] such as DOE-2 and BLAST require more input time and detail. Consequently, they are generally reserved for later in the design process when many architectural decisions have already been finalized."[6] Determining the proper energy analysis tool to use is one focus of this research.

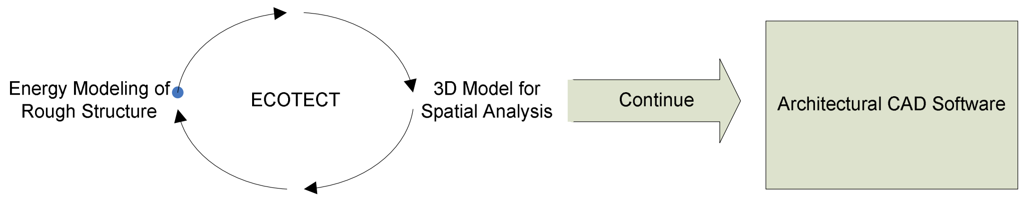

Figure 3 Proposed generative feedback loop

4. Combining Rapid Prototyping and Energy Modeling

The goal of this research is to combine rapid prototyping and energy modeling into a spatially relevant model which emphasizes the energy characteristics of a structure. Rapid prototyping was used to build the model because it offers architects a time and quality effective method for manufacturing building models. The models are built without human intervention and are built to the specifications of the data file. Dr. Larry Sass of MIT has said that through the use of rapid prototyping technology architects "will be empowered to create artificial worlds (Simon 1996) of many physics scales, evaluating manufactured ideas and engineered solutions with models built of paper, plaster, acrylic and resin" [7]. The architect will not be encumbered with the manual creation of the model but instead create the model from CAD data. Sass has defined the physical representations of design as integral to the creative process because of the ability to examine spatial relations. By lowering the barrier for creating this spatial relationship the architect will be able to create a scale model, empowering them to research possible iterations through an intuitive interface.

A physical model with color encoded data applied to the surface of the structure would allow an architect to apply more creative energy conscious design patterns such as brisolées and building orientation and allow for positive feedback. Armed with the proper information while researching a building configuration, the architect could modify the building as needed to achieve decreased energy usage. Using this approach to researching a building configuration, the exterior of the structure is of the most immediate interest. This research will focus primarily on examining the exterior of a building, specifically studying the building to determine the levels of sunlight exposure.

5. Energy Modeling Packages

Determining which of the many modeling package which would provide the necessary tools for creating a visual representation was not a trivial task. One of the findings of a joint report between the US Department of Energy, Energy Systems Research Unit, University of Wisconsin-Madison and National Renewable Energy Laboratory study of energy analysis tools was that "the simulation community is a long way from having a clear language to describe the facilities offered by tools and the entities that are used to define simulation models" [8]. Energy modeling software packages do not announce their ease of use, an important consideration for an architect who has no formal training for using energy analysis software.

5.1. Green Building Studio

The first software package investigated was the Green Building Studio gbXML software extension. This software extension is novel in that it provides an easy to use interface from Autodesk Architectural Desktop (ADT) to a web-server based service. The gbXML software extension translates the CAD information into a gbXML data structure which is sent directly to Green Building Studio's analysis server. From the server, the gbXML is processed into data DOE-2 can process. DOE-2 is an energy modeling suite developed by the United States Department of Energy. This tool does not interrupt the standard workflow of an ADT user because it is a software extension built to interface with the native data objects in the CAD environment. This research only examined the plug-in as used with ADT release for 2006.

The Green Building Studio service does exhibit limitations. The building geometry can on occasion prove to lose surfaces such as a roof. Lacking a roof, the simulation will produce meaningless results. These occurrences were difficult to reproduce, despite defining roofs per ADT documentation. This inconsistent and non-standard error makes the Green Building Studio a poor choice for performing quick analysis while researching a building design. The geometry problem would force the architect to either discontinue energy analysis and forgo the benefits of feedback or alter the design to produce an energy analysis compatible file. The utility of this DOE-2 output was also not directly pertinent to the final goal of visualizing the energy characteristics because the output was primarily given by tabulated data.

5.2. ECOTECT

The ECOTECT energy analysis suite is actively under development by Square 1 Research of Perth, Australia. ECOTECT offers both visual output from energy modeling as well as limited CAD development functionality.

5.2.1. importing geometry for analysis

Methods of importing data from ADT 2006 were attempted. The DXF file format was successful in that all geometry was transferred, although there was an unnecessary increase in geometry to describe the surfaces. This increase in geometry is demonstrated by the door shown Figure 4. A simple building with only five walls, one window, and one door resulted in excess geometry around the windows and doors. This unoptimized transfer could potentially increase the analysis time of the model because, in the case of the solar radiation study, each face of the object is individually analyzed. With increased faces comes increased analysis time, thereby raising the barrier for an architect to run many consecutive analyses. The second method attempted was by using the recommend 3D Studio file format. This format also had the increased geometry problem found with the DXF file format.

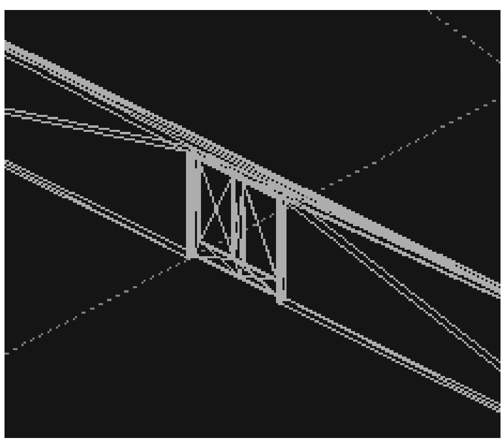

Figure 4 Imported Geometry of Door

The increased difficulty with transferring data from outside software into the ECOTECT environment leads this research to propose that ECOTECT be used at the beginning of a project to run quick analyses. The geometry should be defined used the native ECOTECT tools to avoid potential problems associated with extraneous geometry.

5.2.2. using the native ECOTECT CAD tools

The benefits of using ECOTECT are that calculation times are reduced and the desired visual feedback is produced. For this research, a massing model was created in ECOTECT, as seen in Figure 5.

Initial design sketches were run through an energy modeling program at the earliest stages in design. Energy Star, the joint program of the US Department of Energy and US Environmental Protection Agency, recommends that a project begin with energy modeling in mind [9]. ECOTECT offers a visual feedback which Sass found important for the creative design process [10]. Combining conscientious energy usage with creative design at the beginning stages of researching a building's characteristics will remove the necessity to make important design changes as the design is being detailed.

6. Rapid Prototyping Energy Modeling Data

The ECOTECT energy modeling program was used to create a massing model study. The massing model without energy analysis is shown by Figure 5. A massing model examines the interactions of building on a large scale. Combining energy modeling and massing models demonstrate the self-shading properties of a building system. This energy analysis can be seen in Figure 6 which illustrates an incident solar radiation study done on a model position in Las Vegas, Nevada. The time chosen for the analysis was an hourly average through the afternoon during the summer months. A brighter color indicates a higher incidence of solar radiation in units of Wh/m^2.

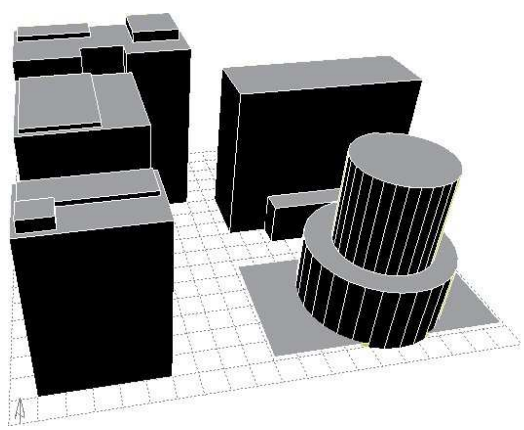

Figure 5 ECOTECT massing model

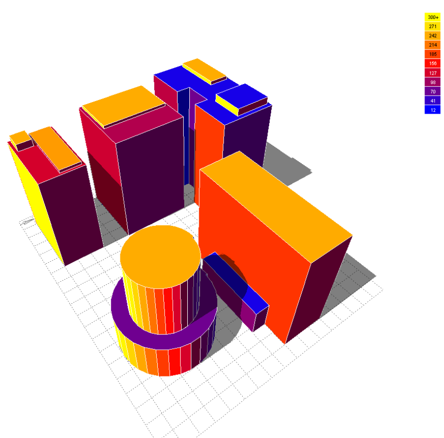

Figure 6 Massing model with shadows and incident solar radiation

Of interest in Figure 5 is the cylindrical building because it shows the more discrete analysis. The rectangular buildings convey a limited amount of information because the value of the incident solar radiation is averaged across the surface, thereby glossing over any changes across the surface. The cylindrical building offers more discrete surfaces because the surface is approximated using multiple rectangles. When the analysis is done, each rectangle receives its own value for the energy analysis. The cylindrical building in Figure 6 demonstrates the gradation which would be expected. The rectangles which are most exposed to the sun would be brightest and as that value decreased their color would follow. The shadows shown in Figure 6 illustrate the self shading characteristics of this building system. The entrance of the right most building shows a low incidence of solar radiation because the cylindrical building is blocking the sun exposure.

6.1. Rapid Prototyping the Massing Model

The color coding of the polygons is important because it is included with the geometry data through the VRML tool in ECOTECT, allowing this information to be exported in a useful format. VRML is the virtual reality modeling language and it is compatible the Materialise Magics rapid prototyping preparation software. The Magics software allows for the correction of problems in the VRML data file and it also helps with manipulation of geometry when the geometric data contains errors. In the case of Figure 6, the buildings were not attached to each other, thus when built in the Z Corp 3D Printer they would have been separated. Adding a base to the model using the Magics software created a single solid which would hold together after the printing was done. The final prepared data file was then prototyped on the Z Corp Spectrum Z510 3D Printer. The prototype created from this work is shown in Figure 7.

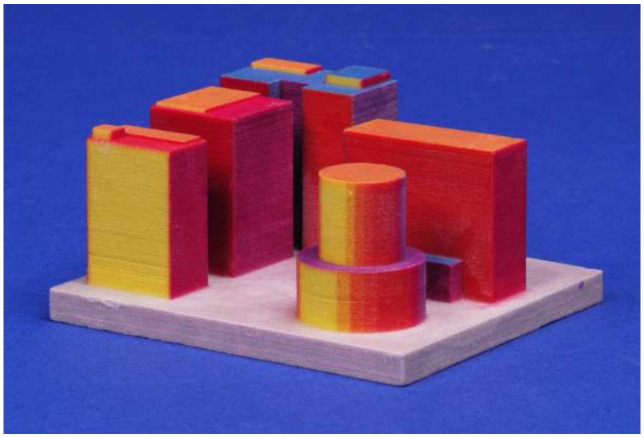

Figure 7 Prototyped Model

6.2. Rapid Prototyping the Analysis Grid Model

To continue the research of this massing model, the ground level of the model was examined to determine the shading effects of the buildings. The buildings not only shade each other, but also create a shading pattern across their common ground. This calculation was performed using the ECOTECT analysis grid utility, creating a mesh of pseudo surfaces. As seen in Figure 8, these pseudo surfaces exist in ECOTECT without volume, they exist only as surfaces against which to run a calculation. The analysis grid shows a higher incidence when there is no building between the face of the surface and sun. The incidence decreases as the buildings create a shading pattern across the surface. The areas of lowest non-trivial incidence occur in areas directly out of the sun's view. The trivial case would be directly underneath the building where the sun will never be cast.

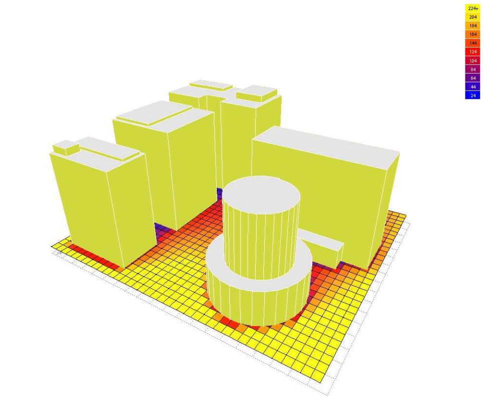

Figure 8 2D Analysis Grid

The mesh seen in Figure 9 can become a more intuitive surface when the color scale is integrated directly into the presentation. This alteration can be performed using the ECOTECT 3D plot tool which uses the relative color scale to determine the vertical position of the analysis grid square. The brightness of the color determines the vertical height of the analysis square. Thus, the ground in this system becomes a 3D mesh. The smooth 3D surface is due to the quality of the gradation. This 3D surface offers a more intuitive model for the architect to evaluate because it helps to show trends much like a topographical map. The color is no longer a simple image, but rather a piece of information integrated into the overall model. The 3D analysis gird show in Figure 9 offers an intuitive idea of the buildings as solar radiation sinks, a consideration when determining loads on building or the ground level due to incident light.

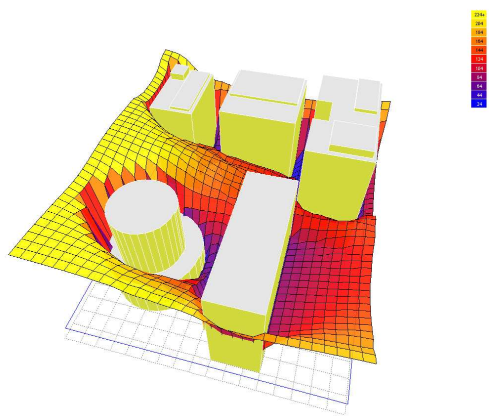

Figure 9 3D Analysis Grid

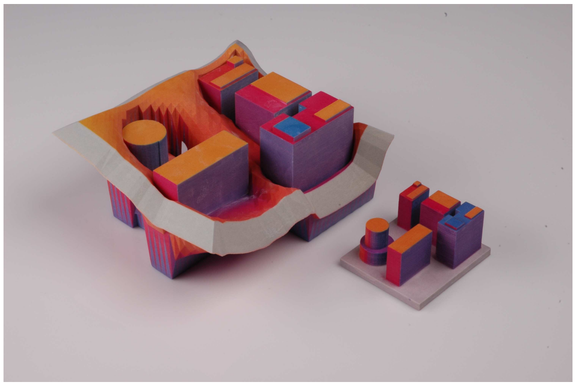

Figure 10 Comparison of analysis grid model and normal model

7. Conclusions

The 3D model can be used creatively in the initial research phases of a building's plan and as an aid in the project proposals. As Dr. Gerard Ryder, senior lecturer of mechanical engineering at IT Tallaght Dublin, stated, "models allow those without an understanding of the information conveyed in 2D technical or building drawings to better understand the design and communicate design intent" [11]. Using physical representations of energy models, the decisions makers will have an intuitive interface into the building characteristics. With more intuitive models displaying energy characteristics, it is hoped that more energy conscious designs will be implemented.

8. Recommendations For Further Research

Future work on this subject should include a review of interoperability formats for CAD packages and energy modeling software. This work would resist removing the architect from their usual workflow. More complicated energy analysis should also be attempted as building materials were not examined in this research. By using building materials, it is hoped that further research will yield more accurate results. Further work could also be done to reduce geometry detail upon import into ECOTECT. This work could allow for the building geometry to be analyzed in a timely fashion.

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10. Disclaimer

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11. Resources

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