Sustainable Energy Systems Design Using Rapid Prototyping

Kali Wildey
Rapid Prototyping Center
Milwaukee School of Engineering
1025 North Broadway Street
Milwaukee, WI 53202. USA.
Faculty Advisor: Professor Michael McGeen

Abstract

This research explores the use of rapid prototyping as a tool for selecting the building composition with the greatest potential for energy efficiency. The research examined methods to translate the data gathered from energy modeling software, synthesize that data with a three-dimensional (3-D) CAD file of the proposed structure, and then translate this combined information into 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 highly technical examination of the many variables that together create the energy requirements of a structure. The research evaluated two energy modeling software programs that are compatible with rapid prototyping, EnergyPlus with Design Builder and ECOTECT. The research also examined two other energy modeling programs, DOE-2 and Energy-10. DOE-2 and Energy-10 are popular energy modeling programs and were investigated to determine what level of customization is required for the programs to gain compatibility with rapid prototyping systems. 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 the project.
Keywords: Energy Performance Simulation, Energy Modeling, Sustainability, Rapid Prototyping.

1. Introduction

Approximately 70% of electric power consumed in the United States is used to power buildings.[2] 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. Currently, energy modeling involves use of specialized software applications that analyze a series of variables that affect the energy needs of a structure. This is a potentially laborious task; often numerous iterations of the analysis are required to compare the projected energy needs of any one variable with its possible alternatives. The task of interpreting and translating this data into a medium suitable for communicating the results to others involved in the project brings another level of complication. Ultimately, the time requirements of this process may outweigh the desire for energy efficiency. This research explores the usefulness of rapid prototyping as a tool for selecting the building composition with the greatest potential for energy efficiency. The project examined methods to translate the data gathered from energy modeling software, seamlessly integrate that data with a three-dimensional (3-D) CAD file of the proposed structure, and then translate this combined information into a format compatible with 3-D printing technology.

2. Background

2.1. sustainability

Defined by the World Congress of Architects in June 1993, “Sustainability means meeting our needs today without compromising the ability of future generations to meet their own needs.”[1] Buildings in the United States consume 37% of the nation’s primary energy supply.[2] This puts strain directly on U.S. coal, oil and other natural resources. Additionally, buildings consume 68% of all electricity produced in the United States.[2] As the designer, the architect holds the power to influence the amount of energy a building will require.

2.1.1. the LEED program

The LEED (Leadership in Energy and Environmental Design) program is an initiative created by the United States Green Building Council (USGBC) to promote and encourage sustainable design within the construction industry. The LEED program involves the accumulation of credits obtained during all phases of construction including preplanning, design, commissioning and erection. The LEED initiative is viewed as a leading-edge system for designing, constructing, operating and certifying the world's greenest buildings.[7] Since the release of LEED version 2.0 in March 2000, over 1900 project teams have registered buildings, thus expressing the intent to apply to the USGBC for official LEED certification. This number continues to rise. Additionally, the LEED program standards have been adopted for use in over 17 state and local governments throughout the United States.[8]

A project is certified LEED compliant when it obtains at least 26 of the 69 available credits. Distributed across six categories, the energy and atmosphere division contains 17 possible credits, more than any other category. Among the 17 credits is a requirement for building performance simulation modeling.

2.2. energy modeling

Energy modeling is a highly technical examination of the many variables that together govern the energy requirements of a structure. The model is an attempt to simulate the energy operation of a yet-unbuilt project.[9]

Many different energy modeling analysis tools are available. Accuracy of these software programs widely varies, as does the level of effort and cost associated with each. Most importantly, the architecture of these programs determines when in the design process they are of benefit to the architect or engineer. Energy analysis tools are primarily classified as being one of four generic types.[6]

1. Screening tools for use primarily during budgeting and programming of retrofits.
2. Architectural design tools for use primarily during programming, schematics, and design development of new construction and major retrofit.
3. Load calculation and HVAC sizing tools for use primarily during design development and construction documentation of new construction and major retrofit.
4. Economic assessment tools for use throughout the design process.[6]

The type of energy modeling most often used is category three, load calculation and HVAC sizing tools. Engineers typically utilize load calculation and HVAC sizing tools after the building design is finalized. Although building designs may be enhanced by the early use of energy simulation modeling, architects do not often utilize this tool.

2.3. massing

Massing refers to the size of buildings and how they meet the street. These qualities influence the type of experience that the pedestrian or resident has with an example or grouping of built form.[10] Examples of massing studies are illustrated in Figure 1 and Figure 2.

Figure 1 Basic massing study

Figure 2 Elaborate massing study example with detailed surroundings

The architect's use of massing studies during design development is well established. Traditionally completed by hand, massing studies are also used as an aid for displaying the finalized design. Building a massing study by hand is time and labor intensive. This has limited the practicality of their frequent use.

2.4. rapid prototyping

2.4.1. the need for models

The researcher arrived at the idea of rapid prototyping architectural models while working with sustainability issues as a student intern at Glaserworks Architecture and Urban Design in Cincinnati, Ohio. This idea stems from a coworker's wisdom: Nothing sells a concept like a model. While easy for building professionals to interpret, 3-D drawings do not have the same impact for someone who is not in the construction field, a position the project's key decision maker is usually found. However, presenting the decision maker with the design in 3-D model form elicits a more powerful response and can reshape their internal, ideal design. Presenting at a poster session of the Society of Manufacturing Engineers in July 2005, a woman approached and asked this researcher to describe more about the research. A conversation ensued regarding the impact of using models to communicate designs. The woman was able to instantly appreciate the idea. As a Project Manager with the National Science Foundation, the woman had the opportunity to examine a model of the reconstruction plans for the Pentagon. The project manager related to this researcher the power of that visualization. It appeared that the influence of examining this model was far greater than it would have been if the design were described using illustrations only. This conversation underscored for this researcher the real potential of using models as a tool for communication. The Project Manger has already seen this technology make an impact.

2.4.2. three-dimensional printing technology

Three-dimensional printing is the technology that makes it possible to produce many models for quick comparison. This is a type of rapid prototyping technology developed at the Massachusetts Institute of Technology (MIT) in the 1990's.[4] Illustrated in Figure 3, the basic method of 3-D printing involves the use of a vertically moving bed of powder onto which layer upon layer of binder material is printed. As each layer is complete, a roller moves across the surface of the already built layer and deposits another layer of virgin powder. In this way, the model's form is built up layer-by-layer within the powder bed. Once complete, the build platform can be moved up and the model extracted from within the powder.[4] Using a 3-D printer, an architectural model is created in only a few hours and for as little as $20.00 a piece.[5]

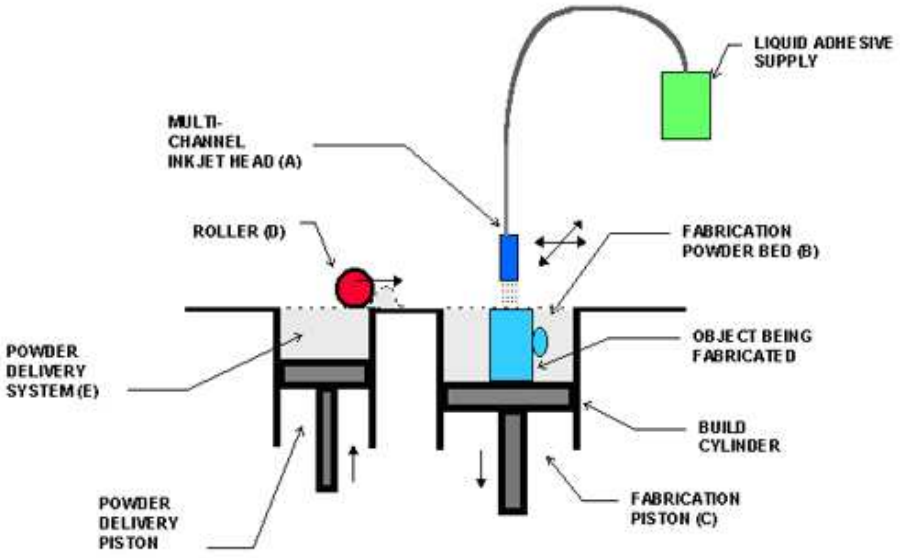

Figure 3 Three-dimensional printing process[14]

3. Objective

3.1. the possibilities

The potential impact of utilizing energy modeling is great. Performing energy simulation early allows the architect to examine design methods that will potentially enhance the efficiency of their design. In the example below, the original design (Figure 4a) was run through the simulation program Energy-10. The program found that the efficiency of the design could be improved with the addition of sun shading and skylights. The original design is updated (Figure 4b) to reflect these suggestions.

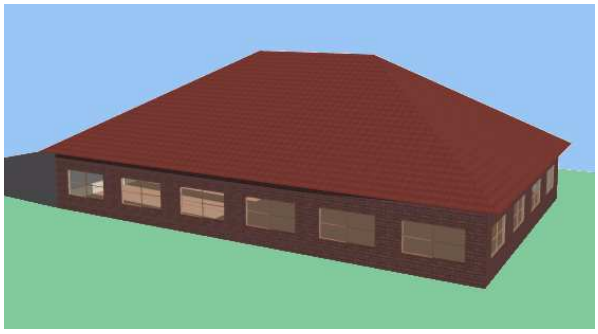

Figure 4a Original design concept

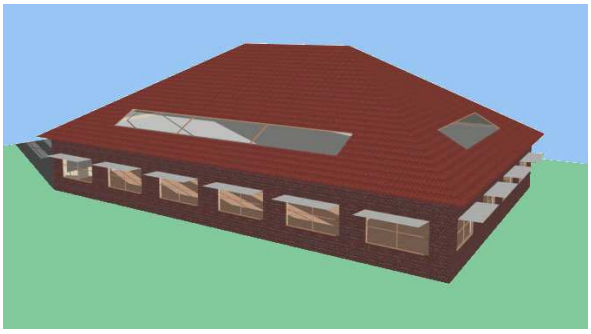

Figure 4b Revised design using suggestions for greater efficiency

3.2. objective

The motivation that fuels this research is furthering the goal of sustainable design through enhanced energy efficiency of buildings. With this in mind, the objective of this research is the integration of energy modeling analysis and 3-D drawing plans to create a singe file format compatible with rapid prototyping. The successful integration of energy modeling results with 3-D CAD geometry will create a tool that, when coupled with rapid prototyping capability, allows for input that is more meaningful at the conceptual phase of the project. This supports the goal of sustainable design by providing a means for all those involved to make more intelligent design choices.

This objective will be reached with the successful realization of a tool that meets the following criteria:

- Tool will have a slight learning curve
- Tool will analyze initial design and offer suggestions for improving efficiency
- Tool will utilize software currently used in the architectural field (e.g. AutoCAD)
- Tool will support creation of file types compatible with rapid prototyping technology (e.g. STL, VRML)

3.2.1. tool will have a slight learning curve

Architecture is a fast-paced and demanding field. The necessity to meet the scheduling demands of a construction project mandates that for a new technology to be adopted into the design process the technology must be accessible, user-friendly and require a minimal amount of user instruction in order to obtain proficiency.

3.2.2. tool will analyze initial design and offer suggestions for improving efficiency

At the onset of a new building design project, little information is established. However, the known pieces of data are the use of the proposed building, its location and the anticipated level of occupancy. With this basic information, an estimate of the building's footprint and location upon the site is determined. Successfully incorporating energy minimizing elements into the evolving design requires a quick analysis of what effect the initial choice of footprint and location has upon the energy load of the structure. Additionally, the tool must also make suggestions to the architect for improving the energy performance of the evolving design.

3.2.3. tool will utilize software currently in use in the architectural field

Modern architecture practice requires the use of computer aided design (CAD) software. Autodesk AutoCAD software is the program most often used. Purchase of AutoCAD is a serious investment for a firm; the manufacture's suggested retail price is $3,750 per license.[13] Therefore, any tool intended to enhance the design process must include interoperability with AutoCAD. Successful interoperability with AutoCAD is realized when the energy modeling tool is able to run the simulation based upon building geometry imported from AutoCAD. Additionally, the tool must be able export building geometry to AutoCAD after analysis.

3.2.4. tool will support creation of file types compatible with rapid prototyping technology

The new file created upon integration of the energy modeling results with the 3-D CAD geometry will then need to be translated into a file format compatible with 3-D rapid prototyping technology. Three common file types used in rapid prototyping are sterolithography (STL), virtual reality modeling language (VRML), and the polygon file format (PLY). Autodesk AutoCAD 2004 software is capable of creating and exporting an STL file.

4. Approach

4.1 energy modeling software evaluation

To accomplish the research objective, two areas were identified for initial examination. First, the functionality of established energy modeling programs must be evaluated. Second, any program claming to offer a function useful to this research must be tested to determine to what degree that program successfully completes the operation.

Mindful of the ten-week time frame for this research, the researcher investigated only the most often used energy modeling programs or energy modeling programs that appeared likely to assist the research objective. The titles selected for evaluation are DOE-2, Energy-10, EnergyPlus with DesignBuilder interface, and ECOTECT.

Table 1 summary results of energy modeling software evaluation

	Easy Learning Curve	Analyze Initial Design	Offer Suggestions for Improving Efficiency	Compatible with CAD Software	RP Compatible
DOE-2		√			
Energy-10	√	√	√		
EnergyPlus with DesignBuilder	√	√		√	√
ECOTECT		√		√	√

It is important to note that none of these programs was designed with the rapid prototyping process in mind. Therefore, faults the researcher found with any single program are not meant to imply that the program is incapable of completing the intended analysis. Rather, the program simply is unable to complete the analysis in a manner that lends easily to rapid prototyping.

4.1.1. DOE-2

DOE-2 is a detailed, hourly, whole-building energy analysis of multiple zones in buildings of complex design. It is a widely used program.[6] Simulation results produced by DOE-2 fulfill the building performance simulation credit available under the LEED certification program. While these are attractive benefits, DOE-2 is a poor selection for early energy modeling simulation. DOE-2 is a highly complex program that requires many hours of user training before mastery. Additionally, the program operates without a user-interface and must be run in DOS mode. Finally, DOE-2 lacks the ability to display building geometry, making file exchange with CAD software impossible.

4.1.2. Energy-10

Energy-10 is a design tool for small residential or commercial buildings that can be treated as either one- or two-zones.[6] The program analyzes areas of 10,000 square feet or less (hence the number 10 in the program name). Energy-10 performs whole-building energy analysis for 8,760 hours/year, including dynamic thermal and daylighting calculations.[6]

It is somewhat easier to learn how to use Energy-10 than the other programs evaluated. That is not to say it is simple for the novice user to pick up and use. Energy-10's user interface is non-intuitive and the program's Help section is incomplete. Energy-10 is the only program evaluated that provides clear strategies for improving a design's energy efficiency. Unfortunately, the program is unable to display building geometry, making file exchange with CAD software impossible.

4.1.3. EnergyPlus with DesignBuilder interface

EnergyPlus includes innovative simulation capabilities including time steps of less than an hour, modular systems simulation modules that are integrated with a heat balance-based zone simulation, and input and output data structures tailored to facilitate third party interface development.[6] DesignBuilder is a third party interface developed for the EnergyPlus simulation engine.[11] The evaluation examined these two programs as a single piece of software. At the time of this research, DesignBuilder is not yet commercially available. The researcher utilized beta version 0.7 of the program for this evaluation.

EnergyPlus with DesignBuilder is the most satisfying of the four programs evaluated. Designed for use by architects and building service engineers, the program makes the most of the EnergyPlus engine with the many evaluation options given to the user. For example, using EnergyPlus with DesignBuilder it is possible to evaluate a range of façade options for the effect on overheating, energy use and visual appearance. Also possible is the visualization of site layouts and solar shading. Another attractive option is the ability to check for optimal use of natural light, useful in modeling lighting control systems and calculating savings in electric lighting.[11] Unfortunately, at this stage of development, DesignBuilder is unable to offer the user suggestions for improving the energy efficiency of a design.

DesignBuilder is primarily a visual program. The geometry of the proposed design is visible at all times. This allows the program to export the building geometry to CAD software, specifically AutoCAD. Currently, it is only possible to export geometry. Importing is not functional at this time.

4.1.4. ECOTECT

ECOTECT is a highly visual and interactive building design and analysis tool that links a comprehensive 3-D modeler with a wide range of performance analysis functions covering thermal, energy, lighting, and shading.[12] ECOTECT has an easy to use interface with commands similar to those found in most CAD programs. The researcher did not call the program user friendly (see Table 1, above) only because of the large breadth of the program. Nevertheless, even casual users will find this program helpful. Of the four programs evaluated, ECOTECT is the only title able to fully support file exchanges with CAD software. Both the importing and exporting of building geometry is possible. However, as in the case of EnergyPlus with DesignBuilder, ECOTECT does not currently offer suggestions for improving the design's efficiency.

ECOTECT is the only energy modeling software examined that is capable of directly importing a STL file. The program is also able to export a file in the VRML format. This functionality allows ECOTECT to be the only utility of the four listed here that is directly compatible with rapid prototyping technology.

4.2 issues with exporting to CAD

While both DesignBuilder and ECOTECT are able to export building geometry to AutoCAD, the result achieved by either program is unsuited for rapid prototyping. The geometry imports to AutoCAD as a wireframe object. The wireframe assumes the default lineweight value of zero. This nullifies creation of an STL file because a lineweight of zero is the same as if the line did not exist at all. As rapid prototyping is intended to create an actual product, the STL file format only reads geometry in solid form, that is, geometry with a lineweight greater than zero.

Currently, the only solution to this problem is for the user to manually assign a lineweight to each individual section of the imported wireframe object.

5. Recommendations

It is the belief of this researcher that the melding of energy modeling analysis with rapid prototyping technology is worthy of further investigation. The evaluation of existing energy modeling software programs provides a wealth of inspiration for future investigation. For example, a software plug-in that enabled the results of an energy analysis to link with an existing CAD file might enable the CAD geometry to update in real time as the analysis progresses. This would enable architects to easily compare the energy modeling results based upon a specific change, such as the effect of utilizing sunshades versus reorienting the building away from the East and West. This is exactly the type of scenario in which rapid prototyping will be helpful. Modeling each of these will help the architects and the owner evaluate the two options.

For the research to continue, this researcher recommends the services of a software engineer. The next phase of this research will examine methods to extrapolate the information from energy modeling programs and synthesize that data with a 3-D CAD file. Additionally, methods of assigning a lineweight, or thickness, to the building geometry exported from the energy modeling programs must be devised in order to support the creation of file types associated with rapid prototyping technology.

6. Conclusions

Buildings designed using input from energy modeling software programs enable designers to minimize the energy needs of a structure. Though traditionally utilized by engineers after the design is finalized, use of energy modeling software during the conceptual phase of a project provides early feedback to the architect as the design continues to evolve. Currently, several available tools encourage the early use of energy modeling. Unfortunately, architects have not embraced these products en masse. By fusing energy modeling analysis with rapid prototyped massing studies, a new kind of tool is created. The visually oriented result of this process will encourage architects to use energy modeling early, especially architects specializing in the fast moving area of sustainable design.

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