AC 2007-1776: MODELING, SIMULATION, MONITORING AND VERIFICATION IN A DESIGN-BUILD RESIDENTIAL HOUSING PROJECT

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P. Paxton Marshall, Professor of Electrical and Computer Engineering and Associate Dean for Undergraduate Programs, has been active in developing multidisciplinary design courses to help students experience the joy of engineering and develop their creative capacities. He was engineering advisor for the UVA solar house project, an energy independent house designed and built by students. The house placed second overall, and first in the Design and Livability and Energy Balance categories, in the 2002 DOE Solar Decathlon. Marshall is currently working with the UVA School of Architecture on ecoMOD, a research and design / build / evaluate project that aims to create a series of ecological, modular and affordable house prototypes. One house was designed for Habitat for Humanity, and shipped to a low income family in Mississippi that lost its home to hurricane Katrina. The house incorporates a photovoltaic power system designed and installed by UVA engineering students. A focus of the current house, being designed for low-income elderly residents, is the development of a commercializable energy and medical monitoring system, to assist resident to live affordably and independently. The house also incorporates a green roof and a state of the art evacuated tube solar water heating system. Marshall has is the former Chair of the Energy Conversion and Conservation Division and the Engineering and Public Policy Division of the American Society for Engineering Education. Marshall's classes have worked with UVA Facilities Management on energy assessment projects which resulted in UVA being designated as EPA Green lights and Energy Star Partners of the Year in 1999 and 2001 respectively. Marshall also teaches a University Seminar "Designing a Sustainable Future" that engages students in community service projects while exploring the global challenges of sustainability, and partners with drama faculty to engage first-year engineering students in designing, building and operating special effects for student written and directed plays.

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Modeling, simulation, monitoring, and verification in a design-build residential housing project

Abstract:

Energy conservation is one of the major challenges of the 21st century. Residential energy usage currently represents over 20% of all consumption in the US. While many energy efficiency technologies such as fluorescent lighting, energy efficient appliances, and improved windows have made headway in the residential housing market, home owners, buyers, and even builders still have little solid information on the question of “Where does all the energy go in my home?”

ecoMOD, a sustainable, affordable design-build project engages architecture and engineering students in modular residential design and construction. Over the past two years the team has designed and built two houses, and is currently in the design-phase of a third. This paper will describe our use of modeling, simulation, and post-construction monitoring of energy usage to improve the energy-efficient design and operation of these houses. We modeled the ecoMOD 1 house using CFD software, Simulink, Energy plus, eQUEST, and Excel, and tested simulation results against data obtained with our data monitoring system.

The ecoMOD team designed and installed a residential energy monitoring system in each house to measure energy usage and ambient conditions (indoor and outdoor temperature, humidity, CO and CO2 levels). This ecoMOD 1 system is capable of monitoring, analyzing, and displaying energy data using National Instrument’s Compact Fieldpoint, and remotely reports it through the internet for analysis. For ecoMOD3 the team is focused on creating a low cost, portable system that could be used in any home. By helping students and residents better understand energy consumption in a house, we hope to advance the art of energy-efficient residential design and operation.

Introduction

As demand for energy has continued to increase, efficiency has become a byword among engineers, architects, and politicians alike. Fortunately, energy efficiency is a win-win situation for everyone. Reduced energy consumption eases the burden on finite energy supplies, reduces pollutants, and reduces costs for the end users as well. In fact, savings in energy costs are generally proportional to the reduction in pollutants [1]. The ecoMOD project seeks to reduce energy consumption in affordable residential housing through exploration of existing and new energy saving technologies, savvy architectural design, and public awareness [2].

ecoMOD is a research and design / build / evaluate project at the University of Virginia that aims to create a series of ecological, modular and affordable house prototypes. Our goal is to demonstrate the environmental and economic potential of prefabrication, and to challenge the modular and manufactured housing industry in the U.S. to explore this potential. In the context of this multi-year project, an interdisciplinary group of architecture, engineering, landscape architecture, historic preservation, business, environmental science, planning and economics students are participating in the design, construction and evaluation phases of the project. Three prototypes are being developed for Piedmont Housing Alliance, and one for Habitat for

Humanity.

The first ecoMOD house was designed for energy efficiency through several key features. These included high R-value wall construction using structurally insulated panel system (SIPS), a solar water heating system, a selection of Energy Star approved appliances, and particular window placement designed for solar gain in the winter and natural ventilation in the summer. The second house, developed with habitat for Humanity for a family in Mississippi that lost its house to hurricane Katrina, includes Thermasteel panels, a Photovoltaic system and a desuperheater to heat water with waste heat from the heat pump when operating in cooling mode. The third house is currently being designed for construction during spring and summer 2007.

As with any project, it is important that we assess the achievement of our objectives. How effectively were the architectural and engineering designs implemented? How well did the implementation improve or promote energy efficiency? The attempt to answer that question was made by an evaluation team which included both engineering and architecture students. This paper addresses our efforts to assess the energy performance of our designs through modeling, simulation, and energy monitoring.

The Design-Build Experience: The ecoMOD Project

The ecoMOD initiative ("eco" stands for economic and ecological and "MOD" refers to the modular building technique employed) is an interdisciplinary research and design/build project focused on creating well-designed and well-built, modular homes that cost less to live in, minimize damage to the environment, and appreciate in value. ecoMOD strives to create ecological, modular houses for low-income families in central Virginia. Over several years, UVa architecture and engineering students and faculty are designing and constructing four modular houses. Through a partnership with Piedmont Housing Alliance (PHA) of Charlottesville, the 1000- to 1250-square-foot homes will sit in low-income neighborhoods. Families eligible to own the homes will make down payments with financing assistance from PHA. The first house, named OUTin, was designed in 2004 and 2005, constructed during the summer of 2005, and assembled on a lot in the Fifeville neighborhood of Charlottesville.

The engineering design-build process engages students with customers' needs and with the material and technological enablers and constraints required to achieve project goals. The National Academy of Engineering's The Engineer of 2020: Visions of Engineering in the New Century stressed the need to balance economic, social, and environmental factors. Students have the opportunity to work with engineers, architects, landscape architects, affordable housing experts, modular housing manufacturers, builders, planners, government officials, building scientists, electricians, plumbers, and HVAC consultants to understand and quantify the energy fluxes in the house. Students will also perform a post occupancy evaluation and a modular housing market analysis. The houses will eventually be prototypes of a modular house system, with many variations and options.

In the construction domain, the line that separates different disciplines has been blurred. Undergraduate students usually do not realize architecture and engineering are so closely related until their first job. The ecoMOD project provides a unique opportunity to prepare student for professional practice with a real-world project that engages architecture students with students from a variety of engineering disciplines. Engineering teams were formed at the beginning of the project to tackle different aspects of the project. These teams included:

- Structural Design
- Mechanical, Electrical, and Plumbing Design
- Modeling and Simulation
- Energy Monitoring System Design
- Data Analysis and presentation

Students were allowed and encouraged to select which teams they would join based on interest. This freedom resulted in multi-disciplinary teams as students worked together across engineering and architecture disciplines.

Undergraduate students typically have little experience in the building industry. Fortunately, because ecoMOD is a continuously developing project, it offers different tasks in different semesters and students are allowed and encouraged to enroll in the course for multiple semesters. Undergraduate students of previous semesters usually stay in the project until they graduate, allowing the necessary knowledge to accumulate. This ensures the continuity of the project, and helps students acquire real-world knowledge and experience.

Modeling and Simulation

All three ecoMOD houses have been designed with the aid of modeling and simulation. The objective of the Modeling and Simulation team has been to provide quantitative predictions of energy consumption, CO2 emissions, HVAC system control methods, and indoor air quality.

The modeling and simulation team includes students from electrical engineering, mechanical engineering and architecture. Members of this team attended two in-class meetings and one team meeting outside of class every week. During the presentation and discussion time of these meetings, the modeling and simulation team gathered information about the current design status and gave advice to architects based on numerical simulation results. In the design-phase of the 3rd ecoMOD house, the simulation team will work with architects in HVAC selection and passive solar design.

In the green building simulation domain, there are several types of simulation packages for different purpose, for example, FLUENT, PHOENIX and STACH3 for computational fluid dynamic (CFD) modeling; EnergyPLUS, eQUEST, DeST, EcoTect and MicrosoftExcel for energy simulation; Simulink for controlling simulation. The ecoMOD team aims to expose students to the fundamental principles and through using some of these software packages. STACH3, Simulink, Energy plus, eQUEST, EcoTect and Excel have been adopted in the past semesters. Among these approaches, the spreadsheet built by Excel requires students to build their own models and thus better understand conduction, convection and radiation losses. Figure 1 and Figure 2 are examples of simulation result using Excel in ecoMOD1. For the 1st house, the team used SIPs, a high performance heat pump, a solar hot water system and fluorescence lamps to lower energy consumption. Figure 1 shows that the energy break down simulated in ecoMOD 1 is very similar to the Residential Energy Consumption Survey [4]. Figure 2 provides a more detailed monthly breakdown of energy consumption. In contrast with excel, the energy simulation package eQUEST could finish a professional report automatically. But the result requires batter understanding of the underlying physical mechanisms to check. Figure 3 is an example using eQUEST done by the simulation team.

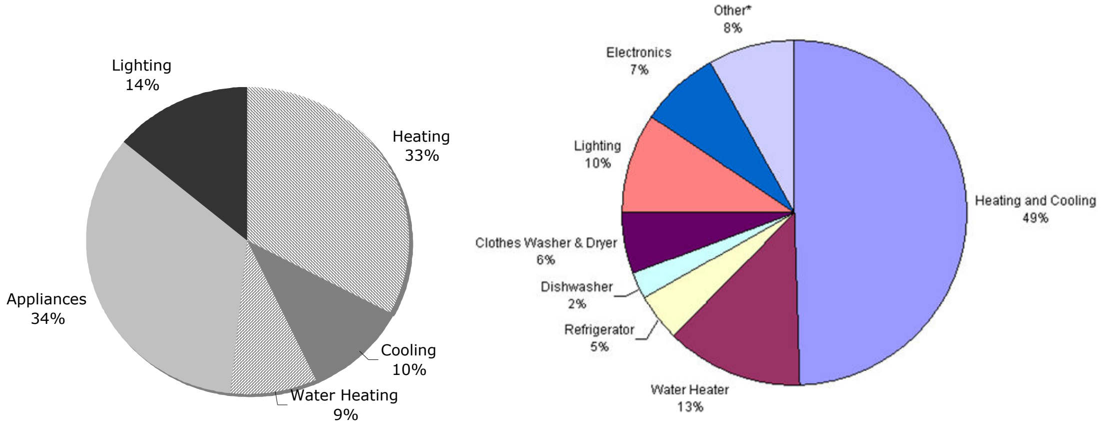

Figure 1 – (a) Excel simulation result for ecoMOD1 (b) Residential Energy Consumption Survey [4]

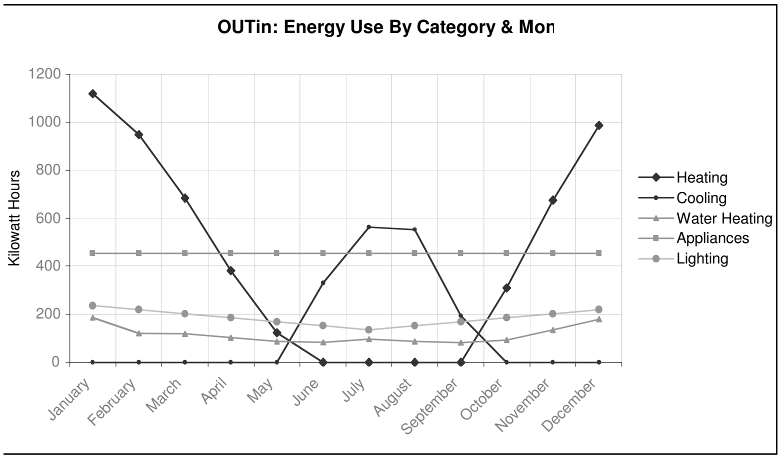

Figure 2 – Excel Simulation Result for ecoMOD 1

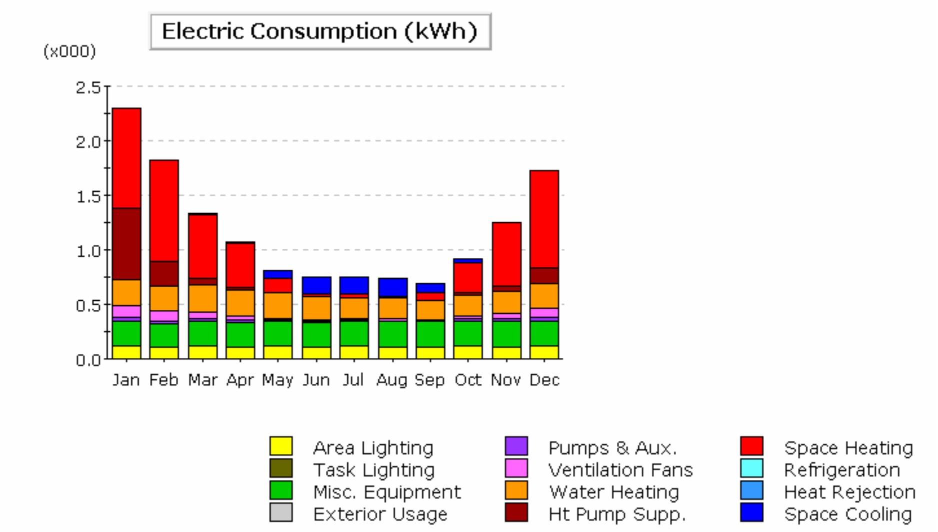

Figure 3 - eQUEST simulation result for ecoMOD 3

Through the design and simulation process, students are able to learn how design issues affect energy consumption differently in different climates. ecoMOD 1 is located in Charlottesville, Virginia, while ecoMOD 2 is located in Mississippi. During the HVAC system sizing process, the simulation team noticed that the system size of ecoMOD 1 is determined by heating load in winter. EcoMOD 2, has a higher cooling load, which determines the system size. In the past studies, students focused in different design details like HVAC system control methods, how west windows effect energy consumption, and the effects of window overhangs. Table 1 has shown an example done by the simulation team to improve the window design. The team simulated annual energy consumption for 5 cases: pre-determined window area/location, added south window area, added overhang on windows, and use of blinds in summer. ecoMOD 3 is an addition to an historical old house in Charlottesville, VA. Added south window area and added overhang on windows could only be adopted in the new house. Use of blinds in summer, however, could be used in the whole house. Again Charlottesville has more heating days than cooling days. Larger window area results in higher cooling load in summer and lower load in winter. Overhangs work in an opposite way. The three methods mentioned above would cause little change in annual consumption because they only work in the addition. The analysis above inspired the team to find a way that could work in the whole house and could block the solar radiation only in summer. The simulation result confirmed using blinds in summer in the whole house works best.

Table 1 - eQUEST Simulation Result for ecoMOD 3

	Summer (1000 kwh)	Winter, spring, fall (1000 kwh)	Annual (1000 kwh)
Pre-determine window area/location	3.07	11.23	14.3
Double south window area of new house	3.11	11.22	14.33
2ft overhang of new house	3.01	11.3	14.31
5ft overhang of new house	2.96	11.38	14.34
Use blind in summer in whole house	2.93	11.23	14.16

It is a consensus in the literature that validation constitutes one of the central epistemological problems of computer simulation methods [5]. Few studies, however, have emphasized the importance of validation. The simulation team of the ecoMOD project worked together with the monitoring team to develop a monitoring system for the 1st ecoMOD house. This system monitors the energy consumption, indoor/outdoor temperature, indoor/outdoor humidity and CO2 concentration. In 2006, when the first ecoMOD house was finished, the simulation team compared simulated data with the monitoring results to detect any problematic sensors. In February of 2007, a family will be moving into this house, providing the simulation team with the opportunity to validate their simulation models with actual data during the 2007 spring semester. The monitoring results of an actual house vividly impress on simulation students where the energy really goes, and the limits on the accuracy of their simulations. Students have also had several fieldtrips and workdays at the ecoMOD houses, which has helped the simulation team build the virtual house by computational software, see Figure 4.

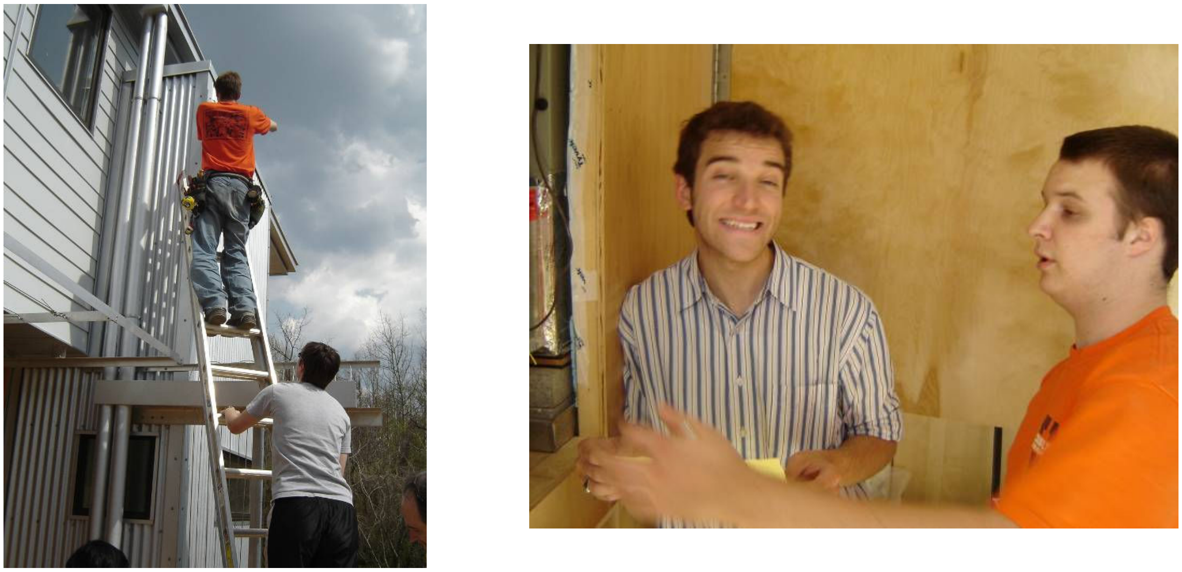

Figure 4 - Field Trip to ecoMOD 1 House

Overall, the ecoMOD project has been a successful effort in modeling and simulation education, by presenting students with an opportunity to simulate, design and build actual houses that people will live in. More experience will be gained from the upcoming houses in this project.

Monitoring System

Residential consumers make up more than 20% of all electrical energy use in the United States. As demand and subsequently energy costs continue to rise, the residential energy consumer can expect significant increases in their electricity bills. Increased generation also increases the amount of pollutants released into the atmosphere, impacting both the environment and human health. For these reasons (and many others), it is becoming more and more essential that residential consumers reduce their electricity usage. While there are many energy saving suggestions and strategies provided through various organizations, one very important question remains: Where does all that electricity go?

The monitoring system team for the ecoMOD project is attempting to answer that question. The team is made up of engineering students interested in the design and development of a fully functional residential energy monitoring system. This includes the design of both hardware and software to process, record, and report data obtained from the ecoMOD houses.

The engineering team has designed and installed an energy-monitoring system throughout the house. Data from temperature, humidity, current, voltage, and flow sensors are being monitored remotely by a National Instruments LabVIEW system.

The ecoMOD 1 house currently employs a system that uses sensors from a variety of vendors combined with a Compact FieldPoint computer system (Made by National Instruments) for processing and storage of the data. This system, programmed in NI's proprietary software called LabVIEW, made for an excellent prototype monitoring system. As such, it provided the Monitoring team with data not only on the functioning and efficiency of the existing house, but also the number of sensors and placement of sensors to obtain relevant data.

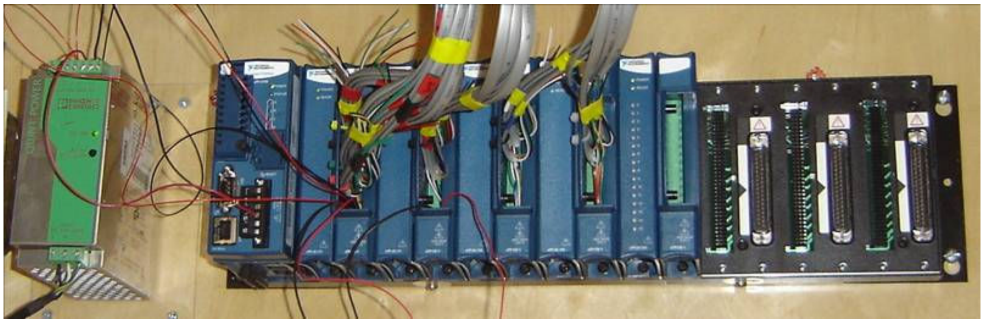

Figure 5 – ecoMOD 1 Compact FieldPoint Monitoring System

The monitoring team is made up of several electrical and computer engineering students, one computer science student, and one biomedical engineering student. The project itself includes many educational opportunities. The system involves much hardware and software design. Hardware and software currently under design includes:

- Sensors (temperature, humidity, electrical voltage and current),
- Data processing and storage
- Internet connectivity
- Web-enabled data storage in centralized database
- Custom web-enabled data analysis and graphing

Each of these aspects presents tremendous practical learning opportunities to the students. In addition to the design experience, the students must work closely with other members in the team, communicating design objectives and details carefully. As with any real-world application, the solution must fit the problem. In the case of ecoMOD, the house is primarily designed by architecture students, and the sensor system must be carefully integrated into the physical layout and appearance of the house.

On top of the practical experience of an interdisciplinary project, the students are exposed to the workings of the existing energy infrastructure, and gain a better understanding of the needs of the future. Sustainability is a key focus for the ecoMOD project as a whole, and the monitoring team provides a critical role in determining how well that focus is realized.

Currently, a prototype system is under development for the second ecoMOD house. This system, simpler than the ecoMOD 1 monitor, uses commercial off-the-shelf (COTS) electronics components to track electrical energy usage as well as temperature. This system then sends its data in the body of an email message every ten minutes to a “gmail” account. This data is automatically received and imported by Outlook Express into an Excel spreadsheet using Visual Basic for Applications.

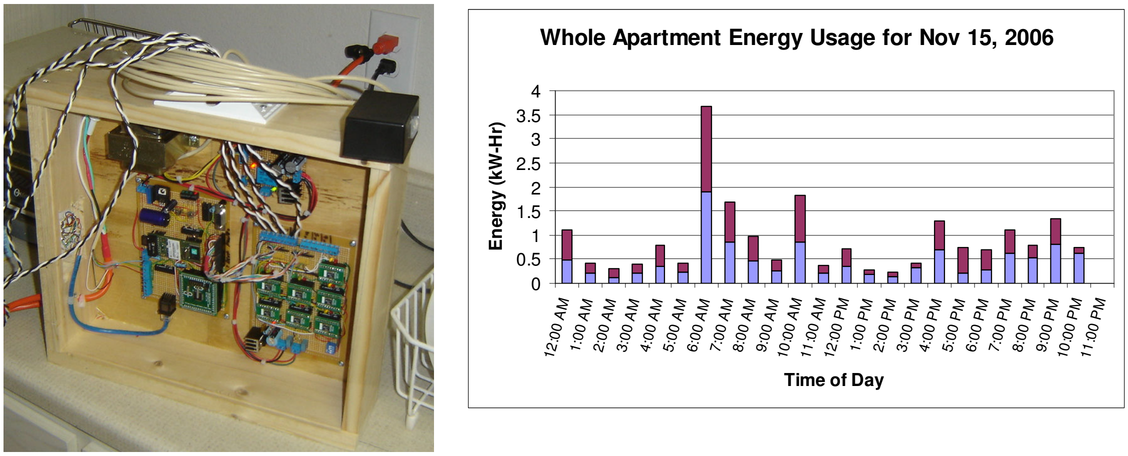

Figure 6 - ecoMOD 2 Prototype system undergoing testing with sample data pictured to the right

The ecoMOD 3 system, currently in its design stage, will be designed with both energy and medical monitoring in mind. This system will incorporate wireless battery powered technology for all remote sensors in order to greatly simplify installation and reduce setup time. Medical monitoring will be part of a collaboration with the UVA Medical Automation Research Center (MARC) and will most likely include a gait monitor and sleep analysis bed sensor, with possible addition of a wireless pulse oximeter unit. The long term goal is to develop a commercially viable system available to residential consumers for evaluating their own houses.

This system will be both affordable and simple to install, either by the homeowner or a technician. The system will then process the data obtained and communicate it to the resident through a touch screen display. Data will also be available through a network connection, which will allow the engineering team to do more detailed analysis.

Implications for Engineering Education

Engineering is primarily taught using the 'engineering science' model, consisting of loosely-connected lecture courses dealing with technical subjects germane to the respective disciplines. Knowledge is transmitted in narrow specialized units: the NAE states, “Students are still largely assigned to and educated in a single department, and, as engineering disciplines have proliferated … clearly delineated specialties within those sub disciplines have evolved.” [9] Graduates and employers frequently discover that this academic background has not prepared students well with some skills needed for the interdisciplinary, collaborative, and cost-driven environment of the professional engineer.[10] Engineering design projects can bridge this gap between theory and reality and develop both analytical skills taught in lecture and professional skills such as communication, interdisciplinary teamwork, creative, open-ended problem solving, and ethical evaluation. These latter skills are difficult, if not impossible, to impart by lecture; rather, they require an active learning approach in which the student develops the required habits in the context of engineering practice.

Practical design, product development, and project management skills require a synthesis of knowledge from engineering, business, and humanistic disciplines. Too often, research-based academic settings do not integrate these practices effectively to communicate the societal impact of technology. Undergraduate engineering students study humanities and social science in required classes that do not relate the humanities to relevant engineering applications. As an example, an economics class might discuss the effects of rising oil prices, but generally will not examine the technical ways in which builders can reduce home-energy use and costs. Still, engineering graduates enter professional worlds where success depends upon critical judgment informed by an understanding of the interactions among technology, the economy, and society. Leadership in engineering, business, government, and society at large increasingly depends upon an understanding of the context and consequences of technological development.

Engineering design is an active learning experience which lends itself to interdisciplinary transfer of information, as called for by the National Academies' Commission on Behavioral and Social Sciences and Education. Decision making and evaluation of feedback become easier in a more active learning environment.[11] Participation in engineering projects with a social purpose increases the likelihood that students will remain in the discipline.[12] Perhaps most importantly, the multi-disciplinary, experiential learning approach advocated here can attract students to and retain them in the study of engineering by making it more relevant to their lives and their aspirations to make the world a better place.

Ninety years after the publication of Democracy and Education, in which John Dewey laid out a case for the importance of education in preparing young people to participate in public life and "alter conditions," engineering education is beginning to recognize that experiential learning is the core of true education [13].

Implications for Energy-efficient residential housing Design

The new owners of the ecoMOD 1 house moved in February 1, 2007. Figure 7 shows their energy use, as collected by the monitoring system from Feb. 1 through Feb. 19. Figure 8 shows the Simulated Energy use of ecoMOD 1 for February, based on excel spreadsheet analysis. A comparison shows broad agreement, but also areas in which the model failed to predict actual energy performance. Detailed analysis will allow the team to both improve our models of the houses, and identify areas where we should be able to improve actual performance.

Figure 10 shows the HVAC energy consumed versus outside temperature for the period February 14-19. The time lag between the two graphs is a good indication of the thermal performance of the house. Figure 11 shows the HVAC energy consumed versus the difference between the inside and outside temperatures. As expected the relationship is linear. The slope of the line is an indication of the insulation and air-tightness of the house.

Clearly the combination of modeling, simulation, and monitoring provides a rich source of data for better understanding of building energy performance, and how to reduce energy consumption. Our next step will be to provide feedback to the resident to improve operational decision making to further conserve energy.

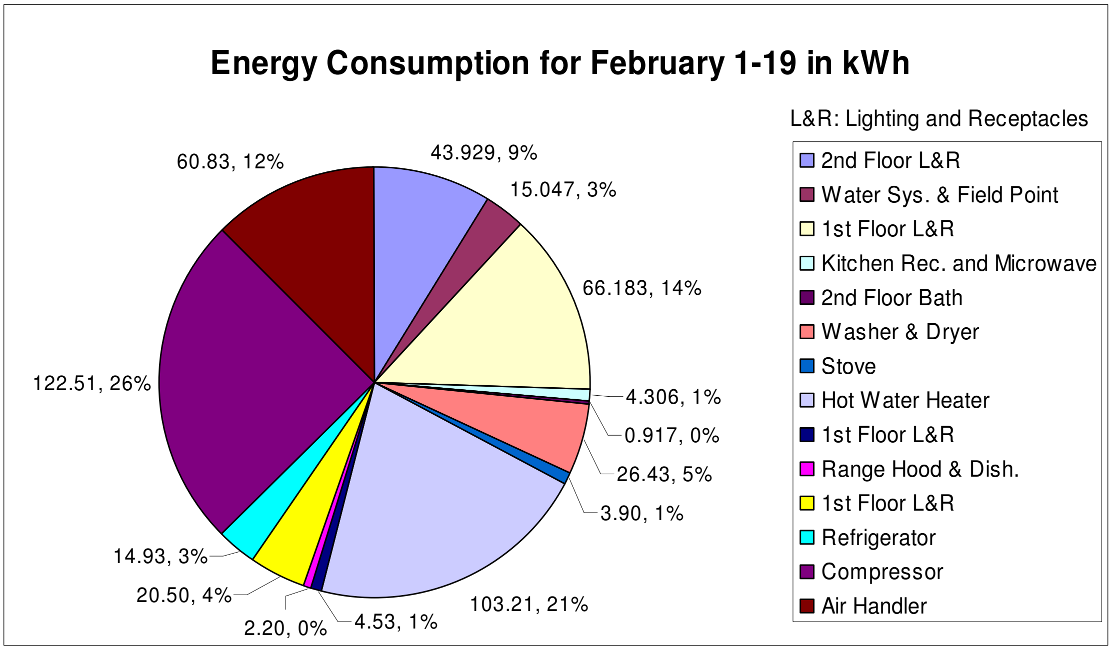

Figure 7. Energy consumption of ecoMOD 1

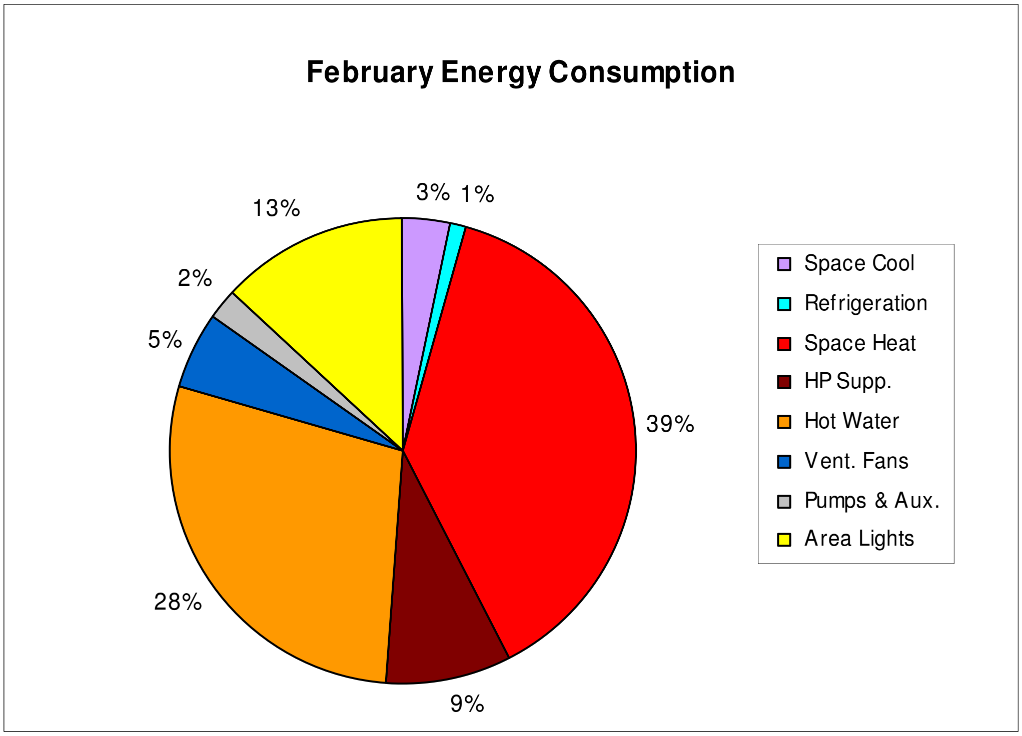

Figure 9. Simulated Energy use of ecoMOD 1 for February, based on excel spreadsheet analysis

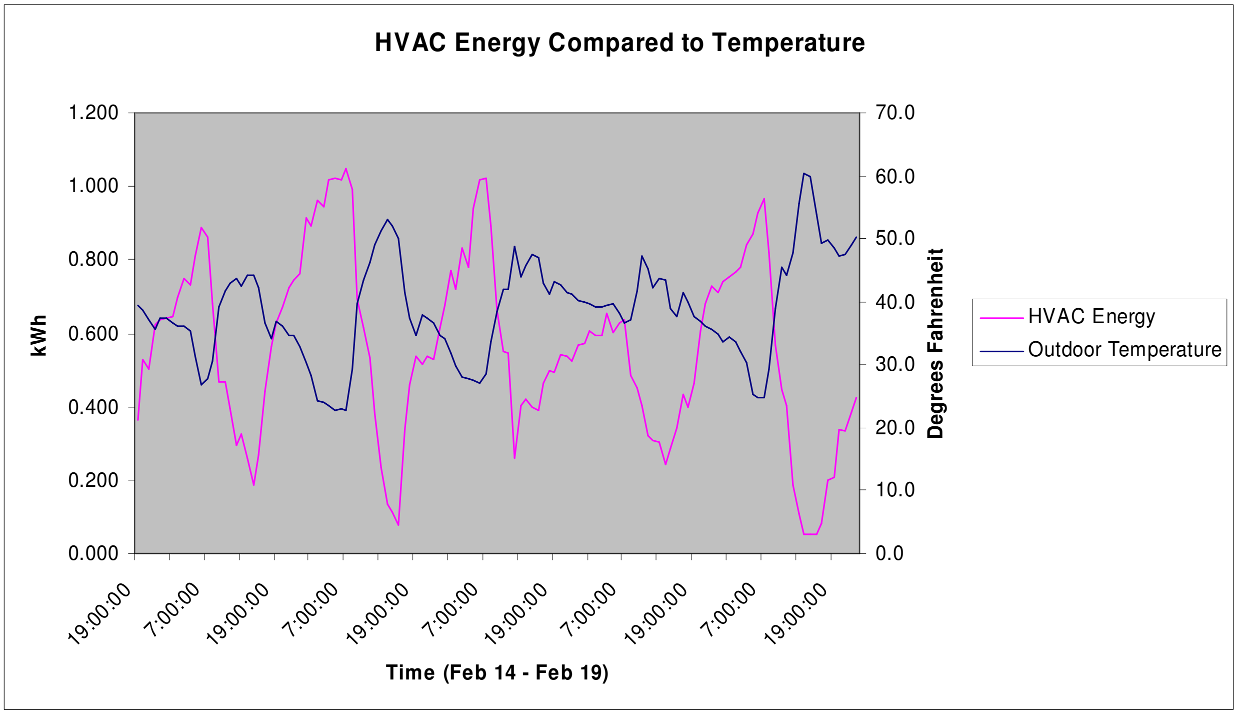

Figure 10. HVAC energy compared with outside temperature

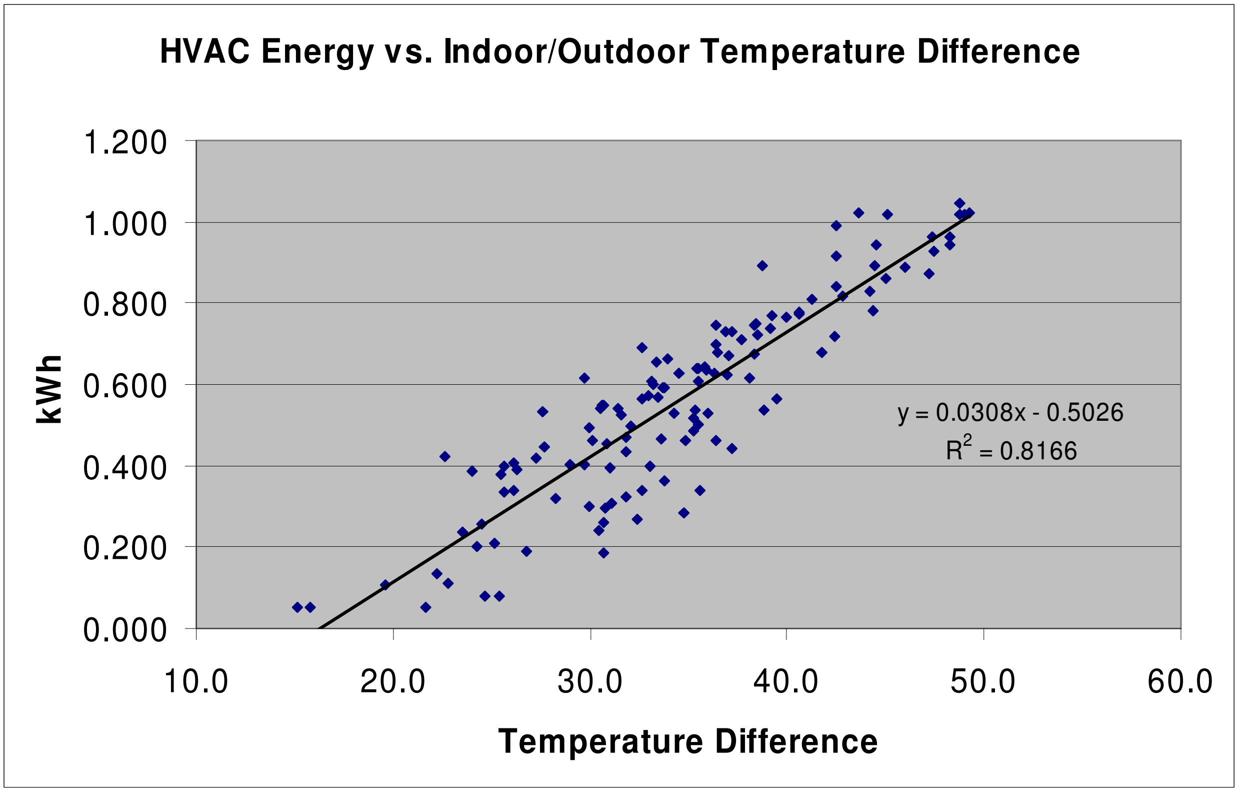

Figure 11. HVAC Energy vs. Indoor/Outdoor Temperature Difference

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