TEACHING THE ENGINEERING OF A HOUSE AS A WHOLE SYSTEM

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[H]igher education…is divided into static, antique disciplines that actively work against badly needed interdisciplinary approaches to the most serious human problems."

Paul R. Ehrlich, *Human Natures: Genes, Cultures, and the Human Prospect*, 2000, p. 325 [1]

ABSTRACT

Teaching a "whole systems design" approach to energy conservation is complicated by the inherently multidisciplinary nature of the activity. Because universities are organized around disciplines and sharp areas of expertise, interdisciplinary instructional programs are notoriously difficult to create and manage. Furthermore, the academic reward system provides few incentives for faculty to invest the substantial effort required by team design projects. The U.S. Department of Energy's (DOE) Solar Decathlon contest has offered a strong motivation to overcome the obstacles. The University of Virginia (UVA) Solar Decathlon Team, jointly sponsored by the School of Architecture and the School of Engineering and Applied Science, consists of a group of students from several engineering disciplines and architecture working together to design and build a solar-powered house. The 800-square foot, fully functional house will publicly demonstrate the effectiveness and benefits of solar energy, energy efficiency, and technological innovation. The design process has focused on sustainable building through the use of passive solar design, "green" building materials, photovoltaic generation and energy efficiency technologies. The team has been accepted as one of fourteen university teams competing in the 2002 Solar Decathlon.

The faculty advisors from engineering and architecture have used a combination of existing and special topics courses to provide the student members with needed disciplinary background for the project. The UVA engineering school's undergraduate thesis requirement and the capstone design requirements of the engineering programs provide additional vehicles for integrating student efforts on a team design project. Through the project, students obtain a far more integrated experience of "real-world" energy systems design than could be obtained from traditional disciplinary classroom instruction. In addition students gain practical experience in communication, fundraising, budgeting, and project management activities that are essential to successful engineering and architectural practice but often get neglected in analysis-heavy curricula.

INTRODUCTION

Industrial production has progressed by the application of specialization and division of labor. Similarly, intellectual inquiry has been advanced by its subdivision into specialized academic disciplines. Yet, as always, this progress has come with a price. The isolation of different functions such as research, design, manufacturing, and marketing has been widely recognized as an impediment to successful product development and has been addressed by initiatives such as "concurrent engineering" and "design for manufacturability". Similarly, the isolation of disciplines has limited the ability of academia to address significant "real-world" problems, that have complex causes and demand multidisciplinary solutions.

One such area that has been hampered by the "divide and conquer" approach is energy conservation. It is widely recognized that industrial civilization has been built on a foundation of fossil fuels that is unsustainable. It is therefore imperative that we conserve our finite reserves of these precious resources as we develop more effective and affordable ways of tapping more sustainable resources, such as the sun. Amory Lovins and others have drawn attention to the importance of approaching these efforts with an integrated "whole systems" approach--that optimizing individually the subsystems of a system, such as a building, almost inevitably leads to a suboptimal design for the whole system. [2]

Engineers have been profoundly successful at both innovating and refining the designs of many energy-consuming devices yet, with the notable exception of the EPA's Energy Star Buildings program, little effort is being currently expended in applying the engineer’s talents to the design of a house as a whole. Engineering effort is most easily justified when its costs can be spread out over many units of production, as with a mass produced item. Unfortunately, of all the items in our daily lives, housing remains one of the most resistant to standardization. As such, the engineering investigation of our shelters has been largely restricted to mass produced appliances, components, and building materials, such as engineered lumber, insulation and infiltration barriers. Few pursue the interaction of these components in the whole device.

When mass production has been applied to houses as complete units (mobile homes, apartment complexes, condominiums, modular homes), energy efficiency has seldom been regarded as a primary measure of a successful design. In general, the residential building industry is driven by sales as an avenue for maximizing profit. The relevant measure in this environment is maximizing “perceived sales value” relative to “production cost”, and in this case the customer’s perception is limited to a walk through. Only after the first energy bills arrive does this perception shift. By then the manufacturer has been paid. (Commercial real estate is dominated by lease-holders where customers are more cognizant of operating costs. New commercial construction strikes a balance between amortized purchase and energy costs.) Only during periods of high and/or rapidly increasing energy costs does the pursuit of energy efficiency become a dominant factor in the engineering efforts applied to houses as complete units.

The DOE's Solar Decathlon solar house contest aims to inspire universities to address the problem of whole house energy conscious design on an academic level. The participating students must design and construct an 800-square foot, fully functional solar-powered house in which all aspects of daily life including transportation and a home business are powered solely by the sunlight falling on the house. This decathlon is intended to publicly demonstrate the effectiveness and benefits of solar energy, energy efficiency, and technological innovation as applied to housing—in a way that reaches a very broad audience.

THE SOLAR DECATHLON AS AN INVITATION TO ENGINEERS

The DOE initiated the solar decathlon to parallel its successful Sunrayce solar car contest. From the outset, the DOE [3] realized that while the winner of a car race can be largely determined by who crosses the finish line first, the judgment of the "best" house design was much less obvious. The DOE settled on a "Solar Decathlon" that measures ten aspects of our current concept of a house: space conditioning, lighting, hot water, refrigeration, overall energy balance, design and livability, design presentation and simulation, graphics and communication, home business, and transportation. The contest is heavily oriented towards engineering with nine out of the ten events being measured quantitatively and electricity produced/consumed as a primary measure of energy efficiency. The tenth contest, architectural design and livability, was included to ensure that the results would have an aesthetic appeal to the general public. By including transportation and a home office, the DOE has attempted to bring a very broad concept of shelter into this investigation. They are asking us to provide a model of an entire "lifestyle" that is sustained by the energy that falls on the house site alone.

Fourteen institutions of higher education have qualified for the Solar Decathlon competition. In Fall 2002, the houses will be transported to Washington, DC, with all of the permits and logistical complexities that that will entail, and erected on the National Mall between the Capital Building and the Washington Monument. Following the contest the UVA house will be transported back to the University of Virginia where it will serve as both visiting faculty housing", and a testbed for evaluating continued energy performance.

THE EDUCATIONAL CHALLENGE

Teaching a "whole-system" approach to the design of an energy independent house, in a university setting, is complicated by the inherently interdisciplinary nature of the subject. The detrimental effects of academic specialization, noted above, are compounded by the organization of student education on the same model developed for the organization of intellectual inquiry. Most engineering students will not spend their careers in specialized research like their professors, but will enter jobs that require integrative skills and approaches as well as specialized training in a "discipline". Engineering education has emphasized teaching specific components of knowledge-- “Statics”, “Strength of Materials”, “Heat Transfer”, “Electric Power” --without providing sufficient opportunities to relate all of these components into a unified understanding of system behavior. At the engineering undergraduate level, the curriculum is organized around a discipline such as “Civil”, “Mechanical”, or “Electrical” engineering with a selection of courses from various subdisciplines, such as communication, controls, and structures. At the engineering graduate level this specialization becomes even sharper. Universities are organized around disciplines and interdisciplinary instructional programs are notoriously difficult to create and manage. The current tenure environment at most universities, requires a clear demonstration that the faculty member is at the forefront of his or her area of expertise. The usual measures of this in engineering are research funding and number of publications. Interdisciplinary design projects are very demanding of faculty time that is difficult to justify in terms of professional advancement. Nor does success in such projects easily translate into success in national rankings of programs conducted by such organizations as US News and World Report.

On the other hand, the new ABET EC 2000 criteria, especially criterion 3 with its a-k competencies, provide a strong push in the direction of curricular breadth and integration. Outcome (d) of Criterion 3, for example, specifically requires that all graduates of accredited programs be able to function on multi-disciplinary teams. [4] The DOE’s Solar Decathlon contest offers an excellent opportunity to overcome the obstacles to integrating interdisciplinary design and management activities into the engineering education mainstream. Under the joint sponsorship of the School of Architecture and the School of Engineering and Applied Science, the University of Virginia’s Solar Decathlon Team has attracted students and faculty from a variety of educational disciplines including electrical, mechanical, chemical, and computer engineering, architecture, landscape architecture, and commerce.

Both engineering and architecture are known as rigorous, demanding programs that leave students with limited time for extracurricular activities. The first task of the project organizers was to spread the word to potentially interested students and to provide a mechanism that would allow them to make the substantial commitment that successful completion of the project would require. In Spring 2001, the School of Architecture sponsored a Solar Design Studio in which fourth year undergraduate architecture students explored the conceptual design phases of a “solar house. The engineering school established a special topics design class dedicated to designing the photovoltaic, electrical and mechanical systems of the house. The two groups interacted via weekly meetings. In Fall 200l, a joint engineering and architecture course was organized with half undergraduate engineers and half architects to complete the detailed design drawings of the house. Currently, in Spring 2002, the construction phase of the project has begun with the cooperation of architects, engineers, and construction professionals

The Undergraduate Thesis

In engineering, the senior thesis provides a mechanism for the required interdisciplinary collaboration. Engineering students at the University of Virginia are required to write an undergraduate thesis; this thesis is directed by the Division of Technology, Culture and Communication through two core courses: TCC 401: Western Technology and Culture and TCC 402: The Engineer, Ethics and Society. These two courses also help place the thesis project in a larger context by exploring the cultural assumptions underpinning technological innovation as well as the ethical dimensions of professional engineering practice. Specifically, the undergraduate thesis challenges the students to use engineering expertise to solve a real need. In the context of the solar decathlon, the undergraduate thesis project treats the building of a solar home as a case study [5], requiring the students to:

- communicate technical information to a broad audience of experts and non-experts
- investigate the conventions that have shaped home building technology
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- think critically about technologies that may solve the puzzle of building an energy-efficient yet comfortable solar home
- anticipate public reaction to the solar home
- examine the ethical dimensions of resource use
- manage a major project involving a variety of resources

For the thesis project, the engineering students working on the Solar Decathlon Project have had several advantages over other students. In the first year of the project (2000-2001), three students, one civil and two electrical engineers, used the solar decathlon project as the basis of their undergraduate theses and formed the leadership core of the engineering team. All three students were named finalists in our competitive Undergraduate Research and Design Symposium, which recognizes the best theses each year. In the second year (2001-2002), we have 12 students currently working on theses related to the decathlon. Because our approach to the decathlon uses a collaborative and holistic approach, these engineering students can more readily address nearly every aspect of the thesis project.

In the first year of the decathlon project, the three engineering students who used it as the basis for their theses clearly established the real need for the project's work by envisioning the user/consumer. In addition to producing the individual proposals and technical reports required for the undergraduate thesis project, they collaborated with the architecture students to create a formal business proposal. That business proposal thoroughly discusses need with respect to dwindling natural resources and rising consumer interest, as well as the challenges posed by competing environmental and economic concerns.

Each document produced by the engineering students working on the decathlon--whether the document is a course requirement intended to fulfill the undergraduate thesis project or a decathlon initiated document—clearly establishes multiple contexts for the project. Depending on the student's area of focus within the decathlon, he or she may delineate social, environmental, economic, health and safety, aesthetic, and even political frameworks, as required by ABET criterion 4. For many undergraduate students, establishing such contexts for their work is quite difficult; they often see their thesis projects as meeting a real need of providing more information or answering a question that will help other researchers perform further experiments. While those are certainly respectable needs for a thesis project to meet, they can make articulating a larger context for the work difficult. The students on the decathlon can more clearly see the ramifications of their work because it is tangible, because it immediately affects the user, and because they collaborate with architecture students who force them to attend to issues beyond the merely technical.

Attending so closely to real-life needs, also enables the students to articulate both quantitative and qualitative measures for the value of the project. Because we intend for the home to have a second life as a cottage for guest faculty, the students consider not only the technical challenge of building a house within the constraints posed by the decathlon, but they also consider the actual experience of inhabiting such a house. The aesthetic and practical consequences of their work thus become tangible.

CHALLENGING TRADITIONAL ROLES AND CONTRIBUTIONS

Because this is a new contest, the DOE invited early participants to submit input to the process of drafting the contest rules. This allowed students, faculty, and advisors from the local business community to meet in a common forum to present their different perspectives of what this new contest should be. The students were invited as peers to participate in animated discussions. This somewhat chaotic setting has persisted throughout this first Decathlon and has shaken the students' perception of their role as passive receptacles for knowledge and the professors/professionals as being authorities on every question. A new role of the professors being facilitators has evolved. Indeed, many students were simultaneously attracted to and frustrated by the fact that there was not "one right answer" and that they "were expected to listen to and know about things outside their area of interest/expertise" [7]. The consensus conclusion though, was that they had learned more from this experience than in any of their other classes.

The project has forced both engineers and architects to address many important issues not normally covered in their respective curricula. The integration of design, construction, marketing, and project management in a team environment is typical of the practice of both engineering and architecture, but is rarely achieved in academic instruction.

The team has to raise virtually all of the funds needed to construct the house. Throughout the effort, the students have to cooperate with the university administration to solicit donations from businesses, foundations and alumni, as well as to develop advertising materials to communicate the efforts. Such activities not only provide valuable personal interaction skills for the students, they can also provide benefits for the university. Alumni like to donate to activities that provide tangible educational benefits to students. If they promise to provide publicity for the university and a chance to compete with traditional rivals, so much the better. Involving the students directly in a project like the Solar Decathlon that depends on donations, where they can see the results of giving both on the project and themselves, may also lead them to want to provide the same opportunity for others several years down the road.

The biggest barrier to achieving an integrated design with a team of over thirty students divided into numerous subteams is communication. The architects rely heavily on drawings to communicate and integrate the separate efforts but the architecture and engineering schools are located at a considerable distance from one another and the drawings often appear to the engineers to be in a disturbing state of flux. The engineers, on the other hand, conduct quantitative analyses that are often poorly understood by the other engineers and incomprehensible to the architects. A significant challenge is provided each academic year as one group of highly trained students graduates and a new group joins the effort. This makes it essential that every step of the design be adequately documented and archived. Several mechanisms have been put in place to support the transfer of knowledge in this transient stream of participants. In addition to the public web site required as part of the contest, [8] a private intranet site was created to allow the various individuals and teams to communicate and access information in a centralized facility. Weekly reports submitted electronically, an electronic bulletin board for an open discussion forum, and e-mail have been utilized.

In Fall 2001 all students met in one joint engineering/architecture course., This proved to be a frustrating though ultimately rewarding experience for the students. The balance of presenting topics broad enough for general interest while specific enough to lead each subteam was difficult at best and often seemed a waste of time to many. In spring 2002 several changes were implemented. The Architecture and Engineering courses related to the Solar Decathlon effort were held separately and many tasks were delegated to each group. The engineering course required even further breakdown into seven separate “mini-classes” of one to five students, to focus on the main engineering subtasks. This was vital to leading the undergraduate engineers in what, in many cases, was their first comprehensive design effort. While the intensity of instruction greatly enhanced the ability of the students to contribute to the project there was a risk that the students would loose track of the broader issues. The public forum of the on-line bulletin-board for the project, email, and a once weekly class attended by all engineering students allowed the “critical issues” to be conveyed. The resolution of issues fell in large part to the project management team, consisting of three engineering students and three architecture students which met weekly with the faculty advisors. It is in this top level management group where the issues of whole design must be implemented when each subgroup may have valid reasons for promoting their specific concerns. Every third week the whole team meets.

CONCLUSIONS

Managing a student project of the size and complexity of the Solar Decathlon adds an extra layer of difficulty to the challenge of whole system design. Not only must the energy systems of the house be designed to interact in a way that optimizes the performance of the whole system, but the educational experiences of the students must be designed to optimize the value added by the experience. The demands on instructor knowledge, time, and organizational ingenuity are considerable. But the experience is its own reward. The Solar Decathlon effort at UVa has provided the students and faculty with a valuable challenge that allows all involved to experience how the skills being taught in the separate disciplines can be integrated to achieve the design of a complex system. The students have been eager and thankful for this opportunity.

The DOE has taken a profound and vital step towards improving both our perception of energy use and in how we teach our students at the University level by sponsoring the Solar Decathlon solar house project. Much more will be required if integrated multidisciplinary design is to become established as an essential component of engineering education. Funding agencies such as NSF will need to provide grants and other incentives. Barriers between disciplines, which inhibit interdisciplinary activities, must be lowered. Incentives must be provided to faculty to participate in these activities, especially in the promotion and tenure process. Business and law schools already provide integrated activities that prepare students for professional practice through the case study methods, and these schools typically enjoy much higher levels of alumni giving than do engineering schools. Engineering schools must also recognize the potential of their students as future alumni to support aspects of their education that they perceive as particularly valuable.

Meanwhile, the Solar Decathlon is providing engineering and architecture students at 14 colleges and universities an invaluable experience in whole-system energy design. This will be a small contribution to awakening the public and professional awareness that will be needed if we are to have any hope of achieving a sustainable energy future.

References

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