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Collaborative Research and Education in the Design and Building of a Net-Zero Energy Solar Powered House – Testimony of a Solar Decathlon 2013 Entry

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Abstract

This paper provides a testimony of the experience and the lessons learned during the design, construction and presentation of a net-zero energy house as part of the 2013 U.S. Department of Energy (DoE) Solar Decathlon competition. The Solar Decathlon is a biennial competition which challenges international collegiate teams to design, build, and operate net-zero energy solar-powered houses that are cost-effective, energy-efficient, and attractive. Like the Olympic Decathlon, the Solar Decathlon consists of 10 contests: juried contests (engineering, architecture, market appeal, communications and affordability) and measured contests (comfort zone, hot water, appliances, home entertainment and energy balance). The purpose of the competition is both educative – educational experience for the participating students, for the general public, for the building industry and the policy makers – and research oriented – encouraging multi-disciplinary collaboration towards development of new technologies and methods.

The paper discusses the educational experience of the students participating in this international competition, focusing on the engineering undergraduate students. It describes the plan implemented for integrating the Solar Decathlon into the required curricula within the engineering, architecture, and business departments. A project as large and diverse as this one required accommodating curricular development at various levels and within various modes of teaching and learning. Students were encouraged to participate in the process in five ways: design studios, research labs and seminars, special topics, construction, and monitoring. Although the greatest learning experience for the students occurred in the integrated design process – across engineering disciplines, and school of architecture – the student team members also learned how to raise funds, procure materials and construction equipment, and how to interact with one another towards a mutual goal.

The project provided an opportunity for the development and implementation of new educational materials focused on energy efficiency, sustainable building design, solar energy, and power conversion and conditioning technologies. Being part of a large and varied team seeing a project from the preliminary design phase to construction and commissioning, the students were provided with a true multi-disciplinary hands-on opportunity. The opportunity proved to strengthen their technical skills, acquired in the regular curriculum, via integration of theoretical knowledge and practical experience. Moreover, the students were exposed to the perspective and educational styles of professors and students in each represented academic department (electrical and computer engineering, mechanical engineering, civil and environmental engineering, architecture, marketing and communications). Organized in a multi-disciplinary format, students were then able to share their strengths across disciplines and contribute to a synthesis of process and product.

I. Introduction

The broader frameworks of globalization, economics, as well as environmental and societal perspectives are becoming increasingly more essential to the education of engineering students. The National Academy of Engineering (NAE) report "*The Engineer of 2020*" calls for fundamental change in the structure and practices of engineering education, urging "the engineering profession to recognize what engineers can build for the future through a wide range of leadership roles in industry, government, and academia not just through technical jobs"1. ABET accreditation criteria also call for a consideration to "economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" aspects. Today's engineer must possess more than just what has been traditionally considered technical skills and must do more than just problem solving. He/she must be able to use creative thinking and innovative design principles, while grasping importance of changing technologies. Moreover, working within multidisciplinary teams of other industry professionals and communicating effectively across all disciplines is of paramount importance [2].

Involvement and, for some, leadership roles in "real world" projects that "balance technical solutions with social, cultural, environmental, economic, and sustainability concerns, in an environment that features multidisciplinary peer interaction and mentoring"[3] can expose engineering students to the complexities that come with being an engineer. The Department of Energy Solar Decathlon project has those characteristics and proved to create an ideal "hands-on" learning environment [4].

I.A Solar Decathlon Competition

The Solar Decathlon is a biennial competition established in 2002 by the U.S. Department of Energy (DoE) [4-]9. The competition challenges national and international collegiate teams to design, build, and operate net-zero energy solar-powered houses that are cost-effective, energy-efficient, and attractive. Like the Olympic Decathlon, the Solar Decathlon consists of 10 contests. Each contest is worth a maximum of 100 points, for a competition total of 1,000 points. These contests include juried contests (engineering, architecture, market appeal, communications and affordability), and measured contests (comfort zone, hot water, appliances, home entertainment and energy balance). The winning team produces a house that is affordable, attractive, and easy to live in; maintains comfortable and healthy indoor environmental conditions; supplies energy to household appliances for cooking, cleaning, and entertainment; provides adequate hot water; and produces as much or more energy than it consumes. In 2013, the Solar Decathlon competition was held in October 3-13 at the Orange County Great Park in Irvine, California (Fig. 1).

Figure 1. The 2013 U.S. DoE Solar Decathlon Competition in Irvine, CA – October 2013

I.B Overview of our Solar Decathlon Entry

Our entry to the 2013 Solar Decathlon Competition was an 800 sqft house, envisioned as an urban infill project and defined by a strong connection between indoor and outdoor living areas. In order to increase transportability (the house had to be taken apart to be transported to the competition site and then put back together in 10 days) the house has been designed and built in four modules. Each module serves a specific function: one module is the living room, the 2^{nd} the kitchen and dining room, the 3^{rd} is the wet core that houses bathroom and mechanical room, and the 4^{th} is the bedroom with private study area. The house has a main south-north direction with a 100% south glazing that allows solar heat gain and connects the indoor modules to the outdoors. This results in a seamless connection of indoor and exterior spaces and effectively doubles the living area. A south vertical garden provides privacy for the outdoor, allowing one to privately enjoy the outdoors even in an urban context, while defining the space. Figure 2 shows two pictures of our final entry taken during the competition.

The house incorporates revolutionary passive strategies, adjustable dual function photovoltaic (PV) system as well as adaptable furniture for a flexible interior space. The materials used in the house, were chosen based on their environmental impact, durability and aesthetics. Materials' lifecycle and maintenance, as well as their functionality in terms of enhancing the living experience were the three main criteria used to select the house's materials. Sustainable materials such as wood, laminated bamboo, geo-polymer cement concrete, high-recycled content steel framing, and thermally modified ash flooring were the materials used. Several passive and active strategies were integrated to work together to accomplish the net-zero energy goal, while maintaining high level of comfort, such as:

1. Adjustable PV panels
2. Integrated radiant cooling (capillary tubes) with high thermal mass (geo-polymer concrete)
3. Thermally insulated walls with minimum heat and water movement
4. Triple-pane glazing system
5. Cross ventilation
6. Rainwater harvesting

The high-performance envelope reduces heating and cooling loads, thus allowing the PV system to be of smaller ratings.

Figure 2. Our 2013 Solar Decathlon Entry

Our engineering philosophy/strategy was to incorporate long-proven, even ancient, design principles that span the domain of all three major engineering disciplines - Mechanical, Electrical, and Civil - to create an energy efficient dwelling that minimizes its own energy consumption and carbon footprint, while maximizing human comfort and livability. The final design didn’t just use those ancient design principles, but improved on them with the use of three innovative technologies developed by students and faculty at our university.

From the civil engineering perspective, two long-proven design principles for efficient building were implemented: thermal mass and highly insulated building envelope obtained using an ancient building material (i.e. concrete). The improvement on these principles was using an innovative type of concrete mix known as geopolymer cement concrete, never before used in building construction. The geopolymer mix replaces 100% of the Portland cement binding agent used in conventional concrete with recycled fly-ash, which yields a decreased carbon-footprint (up to 90%) when compared to the conventional alternative.

From the mechanical engineering perspective, our design leveraged the principles of radiant temperature control, first pioneered by the Romans, and the concept of the roof-pond cooling system, born out of the University of Nebraska during the environmental movement of the 1970’s. The team coupled these technologies and designed a unique system that passively chills the concrete walls during the cooling season. Thermal energy in the form of radiation is absorbed in the high-mass walls throughout the day, and stored. The system makes use of the capillary tubes – already embedded in the walls for curing the concrete (i.e. multi-use component) – as a vessel to circulate thermal fluid. The capillary tubes provide a vessel through which to circulate water and expel stored heat (a.k.a radiant heating in reverse). After flushing the walls of their stored thermal energy, the heat latent water is pumped onto the roof and circulated through a series of custom built emissive/radiant panels. The clear night sky carries an absolute temperature of 3^{o} K, a nearly ideal heat sink, which enables the transfer of stored thermal energy from the liquid to the atmosphere. The system is designed to manage the “base” cooling load and operates in parallel to an independent HVAC system which manages peak load.

From the electrical engineering perspective, basic principles of passive solar design, specifically shading southern glazing, were incorporated by creating a movable PV array. The designed 7.65 kW PV array, not only generates the home's peak power requirements, but also moves on a plane parallel to the roof of the house. To enable this function, the team designed a custom track, wheel, chain-drive mechanism, and controller. In the cooling season the array is positioned out over the patio to shield the interior of the building from direct solar gains, conversely, in the heating season the array is positioned over the roof enabling solar radiation to enter the house through the southern glazing and soak into our high mass concrete walls. The movable array can also be used to provide a canopy over the exterior patio, as well as to expose or block the radiant panels on the roof from the sky.

In summary, the integration of these three innovations (the geopolymer concrete, the radiant cooling system, and the movable PV rack) results in a building system optimized for energy efficiency through the implementation of long proven design principles further augmented by a quest to innovate on those principles, and a vision for intelligent integration.

II. Curricula Integration of the Solar Decathlon Project

II.A Overview of Engineering Students' Involvement

Our team followed a defined plan for integrating efforts revolving around the Solar Decathlon project into the required curricula across engineering disciplines as well as across architecture and business. A project as large and multi-disciplinary as the Solar Decathlon needed to accommodate curricular development at various levels and within various modes of teaching and learning. Undergraduate and graduate students were encouraged to participate in the process in five main ways: design studios, research labs and seminars, individual study and special topic courses, construction, and monitoring.

An essential requirement of delivering a Solar Decathlon entry is the ability of the student design team to function in a multidisciplinary context. The plethora of mechanical, electrical, architectural and structural systems that require integration in the house demands participation of students from a variety of backgrounds. Dysfunction within multidisciplinary teams is well known at the professional level. However, it is also very pronounced amongst student teams. In order to address this challenge, all courses offered to involve student participation in the project were organized and setup as multi-disciplinary efforts.

Moreover, as is important for all multidisciplinary design teams, all members were present at the onset of the project so that the design of each subsystem could be integrated, rather than layered, into the broader plan. This resulted in several found efficiencies that depended on the joint work of students from different backgrounds. Two strong examples include movable PV arrays for energy production and shading, and the wall systems that also functioned as part of the heating and cooling infrastructure. Both of these features required the coordinated and integrated efforts of architecture students and engineering students.

The activities offered throughout the course of the Solar Decathlon project to engage students were organized in parallel to the phases of the project:

1. Schematic Design,
2. Design Development,

3. Construction, and
4. Competition.

Three newly developed courses related to the Solar Decathlon project were offered for credit to the engineering students:

1. An interdisciplinary seminar course – *Solar Decathlon Schematic Design Phase*,
2. An engineering "special topic" course – *Solar Decathlon Design Development Phase*,
3. An engineering "special topic" course – *Solar Decathlon Construction Phase.*

The above courses will be described in more detail in the following subsections (B.2-B.4), based on the phase of the project they refer to. Furthermore, an existing co-taught civil engineering/architecture design studio course was modified to focus on the Solar Decathlon. A description of this course is presented in subsection B.1.

In addition to the above mentioned courses, a select group of the engineering students were involved in the Solar Decathlon as part of their senior design projects. Specifically, the senior design project teams focused on: 1. designing and building the energy-management, controls and monitoring systems, and 2. designing and putting together the mechanical and electrical aspects of the solar panels and the design of the mechanical systems to achieve home comfort levels. The senior design program is a two-semester course sequence. The first semester focuses on exploration of the design space and selection of the best-fit design; the second semester is used to select and order components, put the prototype together and test it. This timeline matched well with the timeframe presented by the Solar Decathlon project. The senior level engineering students involved in these two senior design projects followed the senior design course guidelines and deliverables, and at the same time reported to the Solar Decathlon Team.

Graduate and undergraduate student leaders from each sub-team – organized based on the different sub-systems in the house – were offered a research assistantship during the summer prior to the competition (construction phase).

II.B Existing Co-Taught Civil Engineering/Architecture Design Studio

In addition to the new courses, an existing co-taught civil engineering/architecture design studio course was modified to focus on the Solar Decathlon. The Department of Civil and Environmental Engineering and the School of Architecture have jointly offered this multidisciplinary design studio since 2009. Students taking the studio are presented with a green-building design challenge that requires significant collaboration between those having engineering background and architecture background. During the preliminary design phase of the Solar Decathlon project, the multidisciplinary studio adopted the competition as its design program.

The multidisciplinary studio is instructed by one civil engineering faculty member and one architecture faculty member. The exact course topics change each semester to fit the subject matter of the design tasks, however they are chosen to provide a review of both the engineering and architectural aspects of the project. From the engineering side, most semesters have included site design topics, structural engineering topics and building materials topics. From the architecture side, the studio has usually included lectures about building energy use, program design, construction detailing and the social and community aspects of the design. The group usually takes one or two field trips to visit similar projects in the local area. Evaluation of the deliverables is done in a jury format. Architects and engineers from the community come twice during the semester to review the students' work.

Several challenges routinely present during the delivery of the joint design studio. The differential expectations that faculty have for students are matched by the preexisting expectations the students have of the pedagogy within their discipline. In engineering courses, it is typical to structure grades around homework, tests, papers and a final exam. Architecture students are comfortable with establishing their grade via two or three high-stakes presentations. Engineering students are accustomed to being presented with a particular problem solution methodology during their course lectures and applying it to similar problems in a take-home problem set. They are generally uncomfortable venturing outside of the design methodologies in which they have been specifically instructed. While engineering students are encouraged to bring creativity to their design process, they are also sensitive to constraints and boundary conditions, such as economics and physical limitations. Although architecture students are also provided with formal design strategies in their curriculum, they are generally more comfortable approaching unfamiliar design challenges with confidence in their ability to solve them with brute creativity.

One result of these observed differences is a dynamic that frequently develops in the studio teams of the architecture students presenting the "what" of the design and the engineering students being charged with determining the "how". Because of each student group's relative lack of facility with their disciplinary knowledge base, it is often the case that the "what" represents an unintendedly grand design feat and the "how" lies outside of the abilities of student engineers. This manifests in frequent collisions of egos and frustrations. The role of the instructor is to reframe the design tasks with an appropriately difficult scope. Frequent meetings between the student teams and the faculty are key to avoiding tensions and maintaining progress.

The positive outcomes of teaching the joint studio have been well worth the difficulties of delivering it. Students gain a fresh perspective on the design process as well as an appreciation of the purview of allied professionals. It also gives them an opportunity to gain confidence in their knowledge by frequently being in a teaching role as they interpret aspects of their discipline to their peers. Students are able to cross pollinate presentation techniques and communication strategies that are typical of their profession. As the students enter the workforce, the experience of working in teams and the soft skills learned in the design studio add significantly to their marketable skills.

The prior experience that the Civil Engineering and Architecture departments had with multidisciplinary design studios was a great asset during the Solar Decathlon project.

II.C Schematic Design Phase

The project plan was developed and organized in order to respond to the competition requirements, defined by the DoE series of deliverables. Several design charretts were held to define the design concept. Therefore, the development of the house design proceeded under the fundamental design intent of exploring modular, urban infill and strong connection between indoor and outdoor living areas. This goal was articulated into the overall design of the house and defined the theme for the integration of the systems. During the schematic design phase, the initial design concept was proposed by the design team. The engineering team was simultaneously doing parametric energy simulation in order to make a better decision on choosing the insulation and wall assembly.

In order to achieve these goals and to form a strong multi-disciplinary team that worked well together, the first course was offered during the summer of 2012 and co-taught across all departments involved (engineering, architecture, and business) – See Figure 3. The course, listed as an independent study course for engineering students, focused on the schematic design (first) phase of the Solar Decathlon project and engaged students and faculty from all involved schools and departments, as well as external invited guests. This integrated multi-disciplinary course was broken into several main stages: introduction to sustainable design principles, study of prior work /precedents, climate evaluation for our area as well as for the competition site, and design iterations focused on clarifying the program and formal elements of the design. The course was offered in a vertically integrated format, where graduate and undergraduate students came together as a learning community with the faculty and professional industry. Students were assigned responsibilities and contributed to the project as a function of their respective interests, capacities and skillsets, so as to foster self-motivated learning as well as development of leadership skills. Multiple invited external lectures were conducted, in order to tap into existing expertise and research interests of the faculty at our university, as well as on local supporting professionals. The final assignment was the development of the schematic design phase of the Solar Decathlon (feeding into the actual deliverables to the DoE).

Figure 3. Team brainstorming session during the Schematic Design Phase

II.D Design Development Phase

After finalizing the initial design, the integrated design team focused on developing the details and the initial construction drawings. During the design development phase, the materials and details were finalized. In parallel, the students were developing a Building Information Model (BIM) to integrate the systems within architectural design of the house.

The second course offered to engineering students (cross-listed among all engineering departments) during this phase of the project was the "Special Topic: Solar Decathlon Design

Development Phase" in the fall of 2012. This course focused on the design development phase of the Solar Decathlon project and engaged students from all engineering departments. Topics covered included: electrical load estimation, photovoltaic system design and integration, power conditioning systems and appliances, mechanical systems and thermal comfort achievement, HVAC and plumbing, heat pumps and refrigeration cycles, limiting thermodynamic performance and heat transfer within buildings, design overview of sensors and dashboard systems, and preliminary structural calculations. Students were then split into groups based on their expertise and interest. Active brainstorming and collaboratively working with architecture and business students was encouraged.

II.E Construction Phase

In the spring of 2013, during the construction phase of the project, another course was offered: "Special Topic: Solar Decathlon Construction Phase" as continuation of the previous one. This course again engaged students from all engineering departments and focused on the construction phase of the Solar Decathlon project, as well as on preparing the team for testing and commissioning of the house (which occurred over the summer into competition time – October 2013).

This integrated multi-disciplinary class was organized into several working groups (WG) based on their system of focus:

1. *The Photo-Voltaic (PV) system WG*
   This WG focused on the PV panels and power electronic, as well as the mechanical adaptable mounting system. It was composed of electrical engineering, mechanical engineering and engineering technology sophomores to senior level students.
2. *The HVAC WG*
   This WG focused on the active elements needed to maintain comfort level (the mini-splits, the humidifier and the ventilation systems). It was composed of mechanical engineering and engineering technology students.
3. *The Plumbing WG*
   This WG focused on the hot water system, as well as the innovative radiant cooling capillary tube system embedded in the walls and ceiling of the home. It was composed of mainly mechanical engineering and engineering technology students.
4. *The Structural WG*
   This WG focused on the structural load calculations and structural drawings. This group was composed of civil and environmental engineering and engineering technology.
5. *The Lighting, Appliances and Cabling WG*
   This WG focused on everything to do with the lighting system and appliances in the house, as well as all the wiring and cabling. The group was composed of electrical engineering and engineering technology students.
6. *The Controls & Dashboard WG*
   This WG focused on the home energy management system for monitoring and control purposes. It was composed of electrical engineering and engineering technology students.

Each WG had a student lead and a student liaison to other groups. Communications among the various WG as well as with the Architecture students was of paramount importance, as all the systems in the home are highly interdependent. A design decision on one system would affect the others. The student liaison was tasked with this important communicator and exchanger of information role. In support of a smooth sharing of information, the course also regularly met with a corresponding studio class in architecture. During this construction phase, the students also obtained safety training. Figure 4 below shows pictures of a group of students working on the house construction.

Figure 4. The team during house construction

II.F Competition Phase

All the students who were involved in the design and construction phases participated in the competition. Students reported to the competition sites two weeks before the competition to put the house back together and test to make sure it was in the working and excellent condition for the showing (Figure 5). For the engineering students, the key experience to gain was in the grid connection of the PV system. This was done with the help of the qualified technicians on site. Once the house was powered, all the engineering designs were tested. There were some challenges in the workings of some of the appliances such as the refrigerator due to the insertion of the thermocouple for monitoring. Thus the first two days of the competition our team was losing points as a result of that. This was quickly fixed after a brainstorming meeting.

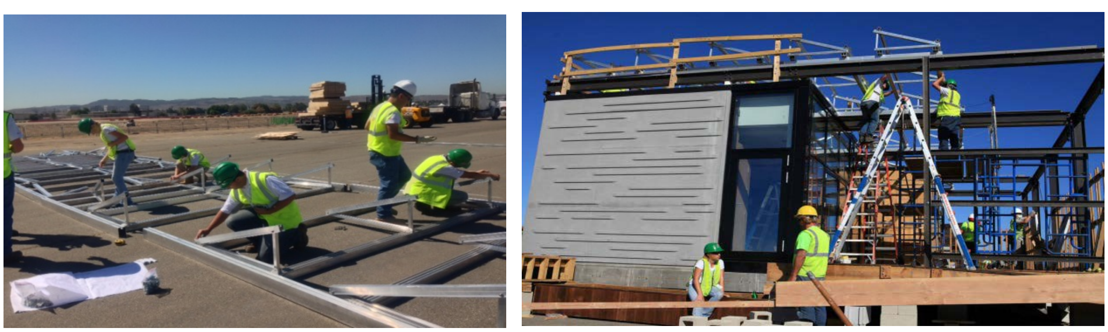

Figure 5. The team outing the house back together on the competition site

Overall the team was very satisfied with the performance in the competition; our design achieved the goal of being net zero, it won the People's Choice Award. Moreover, the team won 3rd place in the engineering contest! Figure 6 shows the team accepting this award.

Figure 6. The team accepting the "3rd place in engineering" trophy

III. Assessment of Student Learning

At the end of the design development phase, students were asked to rate their understanding of the eight areas of this phase according to the following (i) not improved, (ii) improved, (iii) improved and (iv) greatly improved. The outcome as shown in Figure 7 indicates students were very strong in three areas: Energy efficient strategy, Engineering design process and Design of net-zero energy house after the design development phase. Home management systems, passive and active heating and cooling strategies were adequately covered as majority of the students indicated their understanding improved or greatly improved. However, in the design of the solar pv system and generation there was a small percentage (9%) that did not grasp the concept and 18% got slight improvement. Whereas the rest student's population had a grasp of the concept and this is the population of the students that partook in the competition phase. The result of this survey is reflected in the class evaluation shown in Table 1.

The construction phase transitioned smoothly as the students had learned about the project in greater detail at the end of the design phase as indicated in students' evaluations of Table 2. In each area of the construction, professionals were invited to coach students in the execution of their design. This was very beneficial in the competition phase because the students reconstructed the house and bring down after the competition.

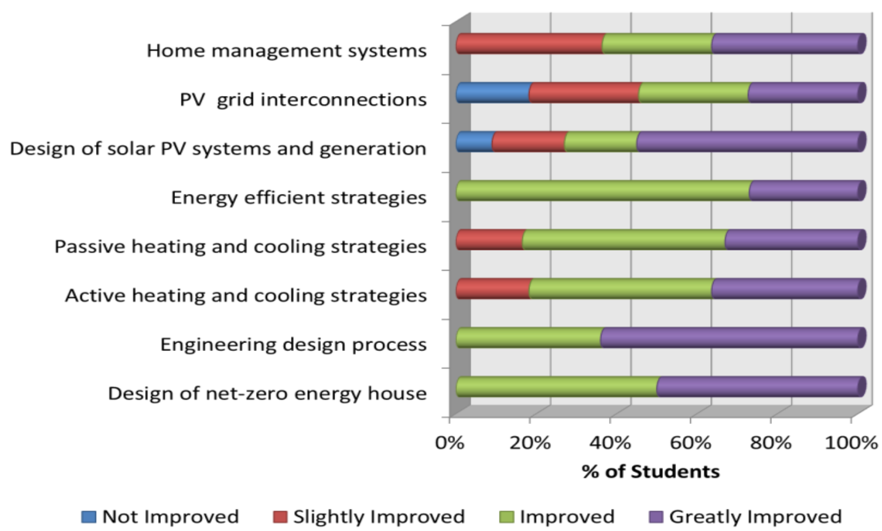

Figure 7. Class survey outcome on how students understanding improved in the eight areas of the design phase.

Table 1. Student evaluations for the Solar Decathlon Design Phase course (12 students enrolled)

Question: level of agreement with following statements (5: completely agree – 0: completely disagree)	Mean	Standard Deviation
Overall, I learned a lot in this course.	3.9	1.47
This course has effectively challenged me to think.	3.4	1.67
The climate of this class is conducive to learning.	3.8	1.79

Table 2. Student evaluations for the Solar Decathlon Construction Phase course (12 students enrolled)

Question: level of agreement with following statements (5: completely agree – 0: completely disagree)	Mean	Standard Deviation
Overall, I learned a lot in this course.	4.78	0.67
This course has effectively challenged me to think.	4.50	0.93
The climate of this class is conducive to learning.	4.75	0.71
I can apply information/skills learned in this course.	4.75	0.71

Some of the students' comments as part of the course evaluations included:

- "Great project to be associated with."
- "For clarification purposes, the focus of this class was to coordinate the effort between engineers for the Solar Decathlon research project. The instructor for this class merely set the groundwork for the Engineering students to work with one another. Valentina always worked hard to keep interest and motivation high and produce a working environment for us. She was effective in this role."
- "Awesome experience. Learned a lot on this project. This project for sure prepared me for real world more than any class that I took at ***, as it is involved with real companies and real world problems."
- "A nice window into real world practice and construction."
- "This course was really interesting and very broad. We were learning about green strategies and at the same time working on graphic designs. It was never the same thing twice."
- "It was nice being able to do some of the background work for the solar decathlon. It will be interesting to see if the test we have run will match the actual built design."
- "I learned a lot about how the building comes together. Applying sustainable concepts learned in previous semesters was interesting."
- "Great semester. The opportunity to participate in Solar Decathlon has been great and I have learned a lot over the course of the semester. It has been fun to work with Engineering and instructors from the Business department."

IV. Conclusion

Our engineering philosophy/strategy was to leverage long-standing, even ancient, design principles, construction methods and materials to achieve a greater level of energy efficiency, livability, and comfort, while simultaneously minimizing carbon footprint. The final design didn't just use those ancient design principles, but improved on them with the use of innovative technologies developed by students and faculty at our university.

The project provided an opportunity for the development and implementation of new educational materials focused on energy efficiency, sustainable building design, solar energy, and power conversion and conditioning technologies. Being part of a large and varied team seeing a project from the preliminary design phase to construction and commissioning, the students were provided with a true multi-disciplinary hands-on opportunity. The opportunity proved to strengthen their technical skills, acquired in the regular curriculum, via integration of theoretical knowledge and practical experience. Identifiable and valuable additions to classroom-based education was brought by the involvement in this project. Moreover, the students were exposed to the perspective and educational styles of professors and students in each represented academic department (electrical and computer engineering, mechanical engineering, civil and environmental engineering, architecture, marketing and communications). Organized in a multi-disciplinary format, students were then able to share their strengths across disciplines and contribute to a synthesis of process and product.

Faculties were able to interact freely through discussions and agree on issues that promoted the success of the project. This led to the team being the recipient of the "Peoples' Choice Award" in the competition. The engineering team winning 3rd place in the engineering contest confirmed the knowledge and experience gained by students through the course of the project.

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