AC 2011-2181: RE-DESIGNING CAPSTONE DESIGN: TWO YEARS OF EXPERIENCE

Cameron J Turner, Colorado School of Mines

Dr. Cameron Turner is an Assistant Professor of Engineering at the Colorado School of Mines where he runs the Design Innovation and Computational Engineering Laboratory. At CSM he teaches undergraduate and graduate courses in engineering design and is a member of the Senior Design Leadership group. Dr. Turner is currently the course coordinator for the Engineering Capstone Design program and is active in the Computers and Information in Engineering Division of ASME.

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Cameron J. Turner
Colorado School of Mines

Abstract
Circumstances sometimes provide a necessary impetus that enables change to take hold. Such a situation recently occurred within the Engineering Senior Design program at the Colorado School of Mines. CSM's program offers a general engineering degree with specialties in Civil, Electrical, Environmental and Mechanical Engineering at the undergraduate level. The cause of the change in the program was an unexpected retirement of the program leader, but the opportunity presented allowed the faculty to reinvest and reinvent the program. Years of concerns about the structure and content of the class emerged and resulted in a drive for significant and substantial changes to the course. Over the last two years and three offerings of the two-semester course sequence, a number of changes have been implemented. Some have been successful, while some continue to be modified to better serve the course goals. While our particular course structure may not be the answer at other institutions, the process of embracing change may offer insights and inspirations into how to implement desired changes within other programs. A comparison of our current course structure to the prior structure demonstrates the magnitude of the substantive and dramatic changes implemented within the program. This experience demonstrates that not all course changes need be incremental, but that revolutionary changes can be effective agents of change within engineering programs. This paper discusses the previous and current program structure, the perceived issues that led to the need for substantive changes to the program, how changes were implemented, and how the process of change impacted the program, the students and the institution. The future directions of the program and current issues and concerns are also discussed.

1. Introduction

The Colorado School of Mines Division of Engineering is an ABET accredited engineering program with specialty offerings in Civil, Electrical, Environmental and Mechanical Engineering. As such, we take particular interest in evaluating the progress of our program under ABET criterion 3 through the Engineering Senior Design Program. ABET criterion 3 specifies the following outcomes:

(a) An ability to apply knowledge of mathematics, science, and engineering;
(b) An ability to design and conduct experiments, as well as to analyze and interpret data;
(c) An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
(d) An ability to function on multidisciplinary teams;
(e) An ability to identify, formulate, and solve engineering problems;
(f) An understanding of professional and ethical responsibility;
(g) An ability to communicate effectively;
(h) The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context;
(i) A recognition of the need for, and an ability to engage in life-long learning;
(j) A knowledge of contemporary issues; and

(k) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.[1]

Senior design is a significant ABET consideration as most if not all of these outcomes are related to a senior design experience. The senior design experience is about the application of knowledge about science, math and engineering (a) to a real problem. As part of their design experience, students must apply engineering analysis to their designs, including the collection and analysis of data verifying their design (b). The design solution developed by the team may be a component, system or a process, all developed within the constraints defined by the project (c). Teams of students pursue the design (d), and generally, due to the structure of our Division are generally multidisciplinary teams. Design teams must identify, formulate and solve a real design problem (e) for a real client. In the course of the design project, and with the encouragement of the design program staff, the design teams utilize modern design tools for their analysis (k), and must effectively communicate those results (g) to their client through a design review process. Contemporary engineering issues such as ethical, legal and socio-economic-environmental considerations are a common component of senior design courses (j) and thus students often obtain an understanding of professional and ethical responsibilities (f). While not planned, a surprising number of design teams also experience these issues at some level within the context of their projects. Specific assignments with the program are used to address the broader impact of engineering (h) and the need for lifelong learning (i).

Based on these desired outcomes, the Division of Engineering faculty developed the following course goals for the senior design program.[17]

- To practice open-ended problem solving skills through a hands-on, technical project;
- To participate in a multidisciplinary design team;
- To improve written and oral communication skills;
- To interface with the “real world”; and
- To develop a professional work ethic.

Enrollment in senior design is currently around 265 students per year, with approximately 235 of these students taking the class in the FS offering. The distribution of the students by specialty is approximately 50% mechanical, 23% civil, 22% electrical and 5% environmental or other. Occasionally, students from Computer Science, Math, or Engineering Physics elect to take senior design as an elective course. Enrollment is currently growing at approximately 10% per year, and we expect to have nearly 300 students enrolled in the Engineering Division senior design program by the 2012-13 offering.

2. Prior Course Structure

These course goals predate the existing program, and are inherited from the previous program structure that was developed and operated from 2001 until the spring of 2009. This program structure was organized around a single program director, under the authority of the Division Director. The program director was assisted in delivery of the course by a group of Technical Faculty Advisors (TFAs) who were largely adjunct faculty hired from industry and a few members of the academic faculty.

The program operated through a two-semester sequence of courses. The course is a two-semester sequence, taught during the senior year. The class is offered in the Fall-Spring (FS) semesters for on-sequence students and in the Spring-Fall (SF) for off-sequence students. The course sequence is not offered over the summer semester at this time.

In the previous program, projects were sought from industry, but also from a number of faculty members and several student design competitions. Project clients provided some or all of the funding for their respective projects. Projects were often individually recruited by the program director and the TFAs affiliated with the program and so little or no project vetting occurred. Projects generally resulted in a physical prototype.

Projects were assigned at the beginning of the first semester and ran through the second semester. Teams of 2 to 25 students were assigned to the projects depending on project scope and required skill sets. Each project was required to have a civil, electrical, environmental and mechanical component so that teams could be created with students from each specialty area. Teams were selected by the TFA assigned to the project based on a job application and resume review. This often meant that teams were formed with all of the highest GPA students on a single project, which in turn led to a feeling amongst the students that their grades were predetermined.

The focus of both courses was on individual one-on-one mentoring between the TFAs and their assigned teams. However, the class met as an entity a couple of times during the year to cover the following topics: Course Administration, Documentation and Record Keeping; The Design Process; Leadership; Quality Functional Deployment (QFD); Scheduling, Gantt Charts and Work Breakdown Structures; Failure Modes and Effects Analysis (FMEA); Proposal Writing; Specifications Writing; and Ethics. Each lecture topic included an associated assignment.

Senior design is considered a writing-intensive course and as such, several significant writing assignments were expected. These included individual monthly status reports, a letter of intent, monthly team status reports, a design proposal, and a final design project report. Project presentations were scheduled for the second semester and included a broader impacts presentation, a 50% design review, and a Trade Fair poster presentation at the end of the project.

Under this structure, faculty involvement with the senior design program waned except for a small group of faculty who worked as TFAs or who provided projects in support of their research programs. The lack of faculty involvement in the structure of the program led to a silo mentality amongst those involved in the program, which manifested into a resistance to any proposed changes to the program originating from the academic faculty.

During this period, the program introduced innovations intended to increase the project satisfaction of project clients. These included an increased emphasis on project management and a focus on the delivery of design prototypes above all other considerations, and a movement towards online course instructional methods instead of large group meetings.[15]

2.1 Change Motivators

The decision to revise the program in 2009 occurred as the result of an unexpected retirement by the program director. However, rather than simply filling the vacant position, this event instigated a complete reconsideration of the program as various constituent groups, including the students and academic faculty, emerged with concerns about the nature of the course. Discussions with current students and recent graduates identified several areas of course concern from the students. These concerns included:

- A general lack of coordination between different faculty advisors leading to disparities (either real or imagined) between students working with these TFAs. Simply put, many students felt that it mattered more which TFA was assigned to mentor students, than what work they did in the course.
- A perceived favoritism by certain TFAs for certain clients, resulting in some design teams feeling abandoned by their TFA because their project was of minimal importance to their TFA.
- A course structure that led to students executing design methodologies on projects that were not useful or appropriate for the particular project; which in turn was interpreted as an inefficient utilization of the time and resources of the students on their projects.
- A lack of structure for the course that enabled teams to "crash" the project. Thus, some projects did not require a two-semester course sequence for completion.
- A significant number of graduates who either did not desire to continue to learn about design as a science, or who felt as though they were inadequately prepared to participate in the design community at a graduate or professional level and thus gravitated to other areas of engineering or even away from engineering and into project management.
- A requirement for multidisciplinary design teams that led to design projects with contrived elements to engage a disparate set of technical backgrounds.
- A lack of specialized technical support, involvement and engagement from the majority of the engineering faculty to help the students with individual projects.

Similar discussions amongst the Engineering Division faculty during a summer workshop on the future of the senior design program also revealed additional concerns with the structure of the course and the direction of the design program. Amongst these concerns were:

- An apparent focus on design as an art, without appreciation for the design with a scientific basis.
- The minimization of design methodologies in design due to the program essentially eliminating all methods except QFD, Brainstorming and FMEA.
- A lack of requirements for the application of engineering analysis in design. The use of engineering analysis being what distinguishes engineering design from craftsman or artistic design.[6] This was exemplified by a number of projects, which failed to meet the customer requirements, often due to a lack of design analysis on the part of the project team.
- A number of design projects that did not contain appropriate material for a capstone design experience and/or emphasized non-engineering aspects such as the development of marketing materials and business plans.
- Concern for the demands made by the course upon the supervising course faculty, the TFAs, the students and different program customers.

- An increasing focus of the class on project management and paperwork issues instead of on engineering design.
- Graduates who as one faculty member put it, *"could not write themselves out of a paper bag."*
- A lack of integration with the engineering curriculum and the senior design experience.

2.2 Implementing Change

The task of re-designing the program was assigned to three faculty members, representing the mechanical, electrical and civil engineering specialties (representing about 95% of the students in the course), replacing the single program director responsible for the entire program. These three faculty members, known as the Senior Design Leadership (SDL), engaged in a course redesign exercise in August 2009 that was executed for the Fall 2009 semester. A similar exercise was subsequently conducted in May 2010 to further revise the course for the Fall 2010 semester based on lessons learned during the first implementation of the course. Currently, these appointments are permanent, although a rotational structure has been proposed.

The first outcome of the 2009 summer exercises was to reconsider the course goals for the senior design program. Many of these goals were not controversial, but others revealed that the desires of the faculty were not adequately or accurately represented. For instance, the requirement for multidisciplinary design teams was often interpreted as a need to place civil, electrical, environmental and mechanical students on a design team, without sufficient concern for the technical requirements of the project. As an example, an electrical engineering major was assigned to a civil engineering project to provide a wiring plan for a light necessary for their project. The electrical scope of work in the project was not adequate in the eyes of the Division of Engineering faculty for a senior design project and was really a contrivance. In other instances, technically inferior projects were accepted because they met the multidisciplinary requirement, while superior design projects that were more discipline focused were rejected from the program.

Furthermore, some desires of the faculty were not represented within these goals. The “just-in-time” delivery style of the program of a limited set of design methodologies was not producing graduates with a sufficient breadth of design knowledge to become participants in either professional or academic design communities following graduation. The limited scope of the taught methods did not satisfy the desire of the Division of Engineering faculty to teach a broad set of design skills that supports the professional development of the students. However, the faculty also expressed concerns that teaching a broader set of design methods would require additional time-investments by both the faculty and students in the course, which was already an issue of concern for both parties.

As a consequence of this continual review of course goals, the following goals have been currently adopted (changes are shown in *italics*):

- To practice open-ended *engineering* problem solving skills through a hands-on, technical, *professional* project;
- To participate *on* a design team, *with interactions that cross disciplinary boundaries*;

- *To develop a skill set that includes a broad range of design and project management techniques enabling students to address future design challenges;*
- To improve written and oral communication skills *in different venues and to multiple audiences*;
- To professionally interface with *multiple clients* and "real world *customers*"; and
- To develop *and demonstrate* a professional work ethic.

Based on these goals, the SDL implemented a series of changes beginning with the Fall 2009-Spring 2010 senior design course sequence.

3. Resulting Program Structure - Year 1

The initial set of changes made to the program focused on implementing a new program management structure that re-involved the academic faculty of the division in the program. This began with the identification of three members of the academic faculty to serve as the SDL representatives from their individual specialties rather than an independent program director (who did not participate as a member of the academic faculty). The responsibilities of the SDL include:

1. Development of the course curriculum and schedule;
2. Recruiting, developing and selecting senior design projects for the course from external and internal clients;
3. Reviewing requests for course waivers and equivalencies;
4. Establishing grading rubrics and standards;
5. Managing and mentoring individual Faculty Advisors;
6. Identifying project Technical Consultants;
7. Organizing, scheduling and running program events; and
8. Advertizing and representing the program both internally and externally.

The SDL mentors several individual Faculty Advisors (FAs), formerly TFAs, who support the program operations. These Faculty Advisors are typically members of the adjunct faculty pool, who have been selected based on their technical design expertise. Most have real-world practical experience in design projects, although a few are current doctoral students. The job of the FA is to work directly with individual teams as a first-line manager and technical project facilitator. Their role is not to perform the design project for the design team. However, they may assist the team in staying on-schedule, on budget and often mentor teams in the professional relationship skill necessary for team projects and for interacting with clients and consultants. FAs are also responsible for grading the individual design work of the teams and individual team members. FAs are typically assigned 3-5 teams depending upon their contract. This revised description of responsibilities departed from the prior perceptions of the TFAs who saw themselves as owner/operators of engineering companies employing design students.

In addition to the FAs, each project also is assigned a Technical Consultant (TC) from the Engineering Division Faculty. The role of the TC is to provide technical expertise to the team and thus to encourage them to work at a technically high level as well as to provide them access to appropriate technical tools that may not be available to the general student population (e.g. specialized simulation software, laboratory equipment, reference materials, etc). TCs are generally assigned 1-2 teams depending upon their other service obligations. The Division Director makes final decisions regarding TC appointments.

Both the TC and the FA attend design reviews and meet with teams regularly. However, the TC does not have a formal grading responsibility, and acts as an external consultant to the team. This lends additional weight to the results of the design team in the eyes of the client, and assists the FA and SDL in ensuring that the team is applying adequate design rigor to the project. This is especially important if the FA is not well versed in the design project area. In essence, the role of the TC is to ensure that the students practice engineering design through the use of analysis, rather than craftsman design, which is purely experience based.[6]

These roles are obviously distinct from the role of the Client on the project. While the Client is the originator of the project (or a representative of the originator) and is thus primarily interested in a successful outcome, the SDL and FA act as clients for the course and seek to ensure that the team uses an adequate process to demonstrate the course learning objectives, and the TC acts to ensure technical rigor is applied as a representative of the profession. Because these roles are not always compatible, for instance a Client may not value the preliminary design review otherwise required by the class; thus the roles of Client, TC, and SDL/FA are kept separate. (Note that the SDL also may act as FAs for a limited number of design teams.)

Figure 1 shows the schematic relationship between these roles.

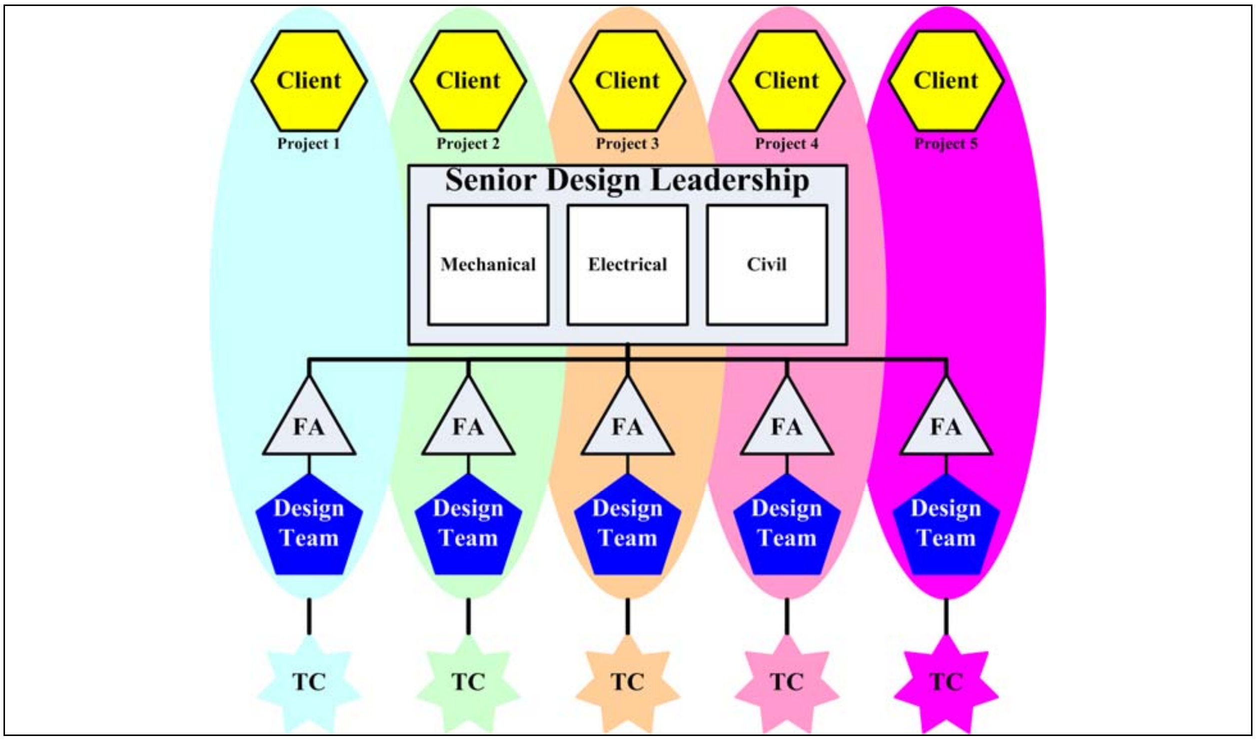

Figure 1. Senior Design Roles and Relationships.

By separating the roles of the FA, TC and Client, design teams are also faced with the real-world task of balancing different demands upon their work. The FA is primarily concerned with the design process used by the team. The TC is primarily concerned with the quality of the engineering analysis performed by the team. The Client is primarily concerned with the product produced by the team. Successful teams must combine process, with engineering analysis to produce a product in order to satisfy all three entities. Teams that choose to ignore one or more of these elements may succeed in satisfying one of their customers, but ultimately are not successful in the class.

With a clear program structure in place, the SDL was able to address the concerns for the academic rigor of the course, the selection and quality of course projects, the process of assigning students to projects, enhancing professional client interactions with student design teams, improving the quality of engineering analysis within the course, and providing grade transparency.

3.1 Curriculum Changes

In the academic curriculum, the SDL set aside the first eight weeks of the course to teach a broad ranging set of design methodologies, including techniques and results recently published in the research literature [such as those identified below]. These methods include customer needs, functional analysis, ideation methods, decision-making approaches and project management techniques. During this portion of the class, students are assigned to a multidisciplinary design team to engage in a reverse-engineering project. During the course of the reverse engineering project, they are introduced to and apply a number of design methods. These methods include:

- Project Scheduling and Budgeting[13]
- Team and Leadership Skills[13]
- Customer Identification
- Customer Surveying and Interviewing
- Customer Needs Analysis (determining the significance of the needs expressed)[21]
- Functional Decomposition and Analysis
- Black Box Modeling
- Functional Modeling[9]
- Quality Functional Deployment (QFD)[16]
- Force/Energy Flow Analysis
- Subtract-and-Operate
- Exploded View Analysis
- Disassembly/Assembly Procedures
- Requirements Generation
- Ideation Methods (Brainstorming, Brainball, 6-3-5)[11]
- Morphological Matrices
- Design-by-Analogy and Innovation[14]
- Decision Methods (Pugh and Decision Charts)

These methods were selected by the senior design leadership as being relatively common tasks in a wide variety of design problems, independent of discipline. And in reality, it is difficult to conceive of a design problem where there is not some level of problem identification, problem abstraction, problem analysis, requirements documentation, ideation and decision making required.

In addition, the reverse engineering aspect of the project is common to many design experiences. Engineers are rarely tasked with designing a completely original system, but are in fact more often tasked with improving upon an existing system, in essence re-designing the system, which is very much a reverse engineering process.[12]

By introducing this material in advance of the senior design project, students are more willing to use the methods during the first portion of the course, knowing that the assignments are intended to develop skills that they may use in the senior design portion of the class. A consequence of this model is that the time for the senior design project itself is reduced from approximately 30 weeks to 21 weeks. However, during this time, students are expected to use methods appropriate to their particular design problem to support their design efforts. The students have positively received this reduction in "busy-work", and the clients have been positively receptive to this change as well. However, there is an element of client education that also is necessary, as new clients do not always understand the process that the students execute during the project.

There are two additional by-product benefits observed from this change. First, the course now requires the students to develop a proposed plan for how they will apply design methods learned in the first 8 weeks of the course to their senior design project (which begins in week 9 of the course). This is much like a real-world design activity where an engineer needs to tailor their approach and methods to the specific design problem. Students develop and propose this plan in a new writing assignment due about 12 weeks into the first semester. As a part of the same assignment, students also are asked to explain how their engineering coursework will be used to execute their design process. This activity provides a strong link between the content of the course, the degree program, and the engineering design project. This in-turn reinforces the idea that continuous learning will be an element of their engineering careers.

The second benefit observed from the new first semester course structure is that the students obtain two design experiences. The first is through the reverse engineering project, which is a unique design activity in its own right, but also uses teams formed using Myers-Briggs-Test Indicator (MBTI) results and techniques advocated by Wilde[22].This team experience teaches students to work in assigned teams, and students often have a realization that their peers "see" problem solutions differently. These teams are also often multidisciplinary (even though this is not required), and thus reinforce the ABET criteria and program goals without the problems associated with forced integration of multidisciplinary content into projects.

We have adopted a different team formation strategy for the senior design project compared to the reverse engineering project where the students are assigned by MBTI results. For the senior design project, students self-identify design teams and competitively bid for their choice(s) of design project. To be competitive, students need to identify the necessary skill sets for the project(s) that they intend to bid on, and recruit from their peers students with the necessary skill sets. This is a promising entrepreneurial experience for the students and brings a real-world aspect to project selection.

3.2 Project Selection Changes

Projects vary significantly. All projects, including internally sponsored projects have a formal client identified. The client is distinct from the other personnel involved in the course. Some projects are entirely paper projects, others are paper and experimental testing/evaluation projects, some are reverse engineering projects and others are original prototyping projects. Table 1 categorizes the projects from the FS 2009-10, SF 2010, and FS 2010-11 Senior Design Program Offerings.

TABLE 1. Senior Design Projects in FS 2009-10, SF 2010, and FS 2010-11.

Project Type	Project
Paper	Pedestrian Bridge Design, Passive Solar Home Design, Solar Energy Camp System, Hydro Energy Camp System, Survey Field Shelter, Basketball Court Design, Cooling Tower Recovery System, High Peaks Drainage, Vertical Axis Wind Turbine, Bolivia Solar Heating, Landing Pad Stabilization
Paper + Experimental	Alaskan ATV Bridge Design, Mechanical Rural Gate Design, Rural Berm Kicker Design, Biomass Briquette Manufacturing, Wind Energy Camp System, Low-head Hydro Generation Design, Rail Wheel Attachment System, Tunnel Girder Attachment System, Ultra-Filtration, Residential Energy Efficiency, Bridge Details, Experimental Bridge Decking, Diving Trainer, Reverse Osmosis Membranes, Biodigester Facility, Clean Water Disinfection, Portable Potable Water, EMI Instrumentation
Reverse Engineering	BD-5 Aircraft, Biodigestion System, Biodiesel Production, Open-front Refrigeration System, Shot-crete Depth Indicator, Snow Pack Measurement System, Low Volume Chiller, Smoke Removal System
Original Prototype	Solar Energy Hardware-in-the-Loop Simulator, Vacuum Casting Lift Design, TGA Fuel Cell Design, Avalanche Threat Detection System, Lunar Astronaut Tool, 1/6 G Lunar Excavation Testbed, Lego Part Sorter, Street Glider, Automation Course Prototype, Modular Work Platform, Automated Linear Storage Array, Spinal Implant, Shaker Table, Organic Rankine Cycle Power Generation, HydroGo, Antarctic Logistics System, Sunglasses Automation, Snowboard Press, Foot Cooling System, Wind Power Control System
Competition Projects	ASCE Steel Bridge, ASCE Concrete Canoe, Shell EcoMarathon, WERC2010 Reverse Osmosis Filtration, NASA Lunar Excavator Robot, MiniBaja, Low Gravity Flight

Some projects are derived from student design competitions. However, these competition projects must meet the standards imposed upon other projects, including the identification of a client. In the case of competition projects, the client either is a society mentor or is an experienced veteran of the competition who can provide experience to the team about the competition. Unfortunately, not all design competitions are compatible with our design program requirements, either due to prohibitions concerning the interactions with clients and faculty and the design team, or due to calendar issues with respect to the course. Regrettably, we have had to learn by experience that some competitions are not compatible with the design program. Unfortunately, students on these projects often have difficulties remembering that the senior design course is not designed around their competition and thus the students often lament the perception that the senior design class does not benefit their competition chances. Descriptions of these projects can be found on the CSM senior design website.[2]

Because sponsored projects are a significant component in the Senior Design Program, a number of steps are taken in order to develop a robust portfolio of projects.

Today, all clients meet with a member of the SDL to outline the program, its educational objectives, and the "business" issues of a senior design project. The goal is to ensure that the Client understands their roles and responsibilities as well as the nature of the Senior Design Program. While several Clients initially expressed doubt at the changes being made to the program, most leave the meeting with a feeling that the program is based on a solid premise, to teach a flexible design process to the students, even though it is not the same program that they had become accustomed to in previous years. Following this meeting, the Client is invited to submit a project proposal. The senior design leadership reviews each project proposal for several areas of project concern, including:

- Is the nature of the project a design project (i.e. are there multiple potential solutions that could work)? This eliminated a number of projects that were focused on product marketing that had appeared in the program in recent years.
- Is the problem and scope adequately and clearly defined by the Client? This requirement helps the program and Client understand what the design team should accomplish and helps the design team accomplish the project.
- Is the scope appropriate to the level of the students (seniors) the number of students on a typical design team (5-6), the time available (21 weeks) and the available resources (both budget and technical)? This suggests a project requiring approximately 1000-1200 hours of engineering work and eliminates projects that are too simple or complex for a single design team.
- Is the design project likely to garner interest and enthusiasm from the students? This factor is important, as student interest and enthusiasm can overcome a number of challenges that would otherwise derail a project.

Projects that meet these criteria are accepted into the program. Projects that elicit concerns from the SDL are returned to the Client with feedback. Often the SDL and Client can then refine projects to better serve the needs of the Client and the Design Program. The review process is essentially continuous, with cut-off dates in the spring and fall semesters that coincide with the release of potential projects to the student design teams.

3.3 Assignment of Students to Projects

The second portion of the course sequence begins with the students being provided with a set of project descriptions. Project descriptions are released after approximately the sixth week of the course, which allows several weeks for the students to complete the next step of the course. Based on the project descriptions, students form design teams with appropriate skill sets for the design projects on which they hope to work. To facilitate the formation of the design teams, a "jobs" discussion board is used. Students will post advertisements seeking teams and teams post advertisements seeking students. The teams then submit bids for the projects upon which they want to work. The SDL and FAs evaluate bids and the teams with the best bids are awarded their top project choices. In some cases, more than one team is assigned to a project.

In essence, the student formed teams act as individual engineering companies. Despite the fact that many of the reverse engineering teams are composed of individuals that have not previously worked together, nearly 60% of the senior design project teams include a core group of 3+ students from the reverse engineering teams. Some of the change is due to personality conflicts within the reverse engineering teams, and some is due to the requirements associated with the particular projects upon which the team wants to bid.

The bid assignment asks the design team to identify the required technical capabilities of the project and the available technical capabilities of the design team. Thus, the project bid resembles a technical competency bid such as that used in professional practice. Teams are encouraged to bid on multiple projects, and the bids are evaluated in a competitive bidding process. Consequently, not all teams get their first choice of project.

3.4 Integration of Clients into the Design Process

All projects in our senior design program have clients that teams with whom teams must interact. Teams are given three high-level milestones as an initial schedule for their project. In week 15, a Conceptual Design Review (CDR) of the project occurs with the client present. In week 19, a Design Analysis and Verification Review (DAV) for concept selection occurs. Finally, in weeks 28 and 29, a Final Design Review (FDR) and the Senior Design Trade Fair allows an opportunity to display the final project design to the client and to the campus community. Several of these presentations are formal design reviews, and Trade Fair is a standard poster session presentation. Thus students are exposed to several presentation types and ultimately interact with peers, clients, faculty, and the general public.

Leading up to the CDR, design teams meet with their client and generate a concise yet complete problem statement including a scope of work, schedule and budget. Within the schedule, the design team is expected to define a project-specific design process, which includes an appropriate subset of the design methods taught in the first portion of the class. In addition, during this timeframe, teams are introduced to additional sets of design methods, including:

- Failure Modes and Effects Analysis (FMEA);
- Design for Manufacturing and Assembly (DFMA);
- Design for Environment (DFE);
- Robust Design;
- Design Optimization;
- Design of Experiments/ANOVA; and
- Physical and Analytical Prototyping techniques.

Obviously, not every design project requires each and every one of these approaches. However, many design projects require at least one of these methods in order to be successful. In general, these methods also are deployed during the detailed design process, so these methods would be used during the second semester of the course sequence.

The CDR precedes the winter or summer holidays. The holiday break is a chance for the design teams to reconsider the concepts that they have generated thus far and facilitates the design team decision-making process at the beginning of the next semester, ultimately leading up to the DAV Review.

The DAV Review is a chance for the design team to defend their concept selection process and decision, as well as a chance to define the scheduled detailed design and prototyping work through the remainder of the semester.

During the second semester of the course a number of additional design related topics are discussed. The discussed topics are generally valuable in professional practice, if not immediately valuable to the project at hand, regardless of discipline. These topics include:

- Professional Ethics;
- Licensure;
- Intellectual Property;
- Torts and Contracts;
- Entrepreneurship and Innovation; and
- Professional Design Experiences.

During the final portion of the course sequence, the design teams complete a detailed design and prototyping process. The results of this work are presented to the client during the FDR, and publically the following week at an organized Trade Fair exhibition (which was retained from the original course structure). A few photographs from the Spring 2010 trade fair are included in Fig. 2. Teams also prepare a final design report due the final week of the semester.

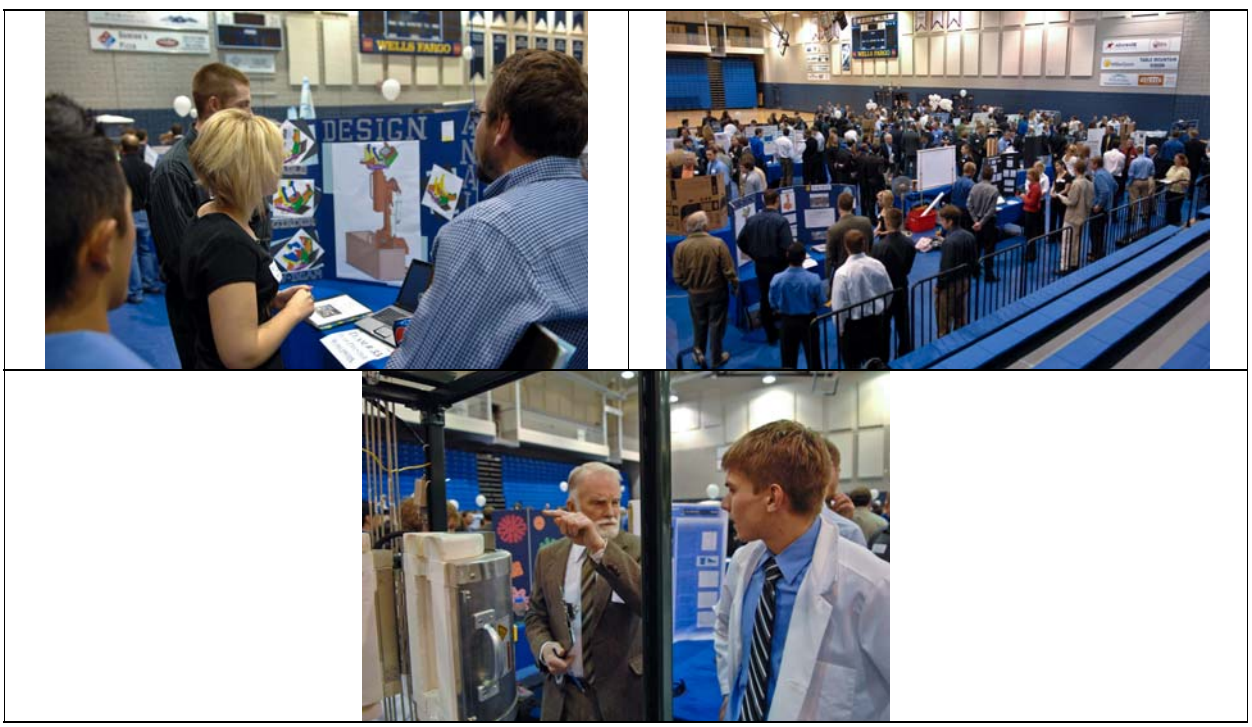

Figure 2. Spring 2010 Trade Fair Photographs.

Individually, each student also is asked to write an essay concerning the broader impacts of engineering design in an economic, environmental, societal or global context. This assignment provides an opportunity for each student to internalize the role of engineering in a professional context and to demonstrate an understanding of the broader role of engineering in the bigger world.[8] This assignment directly relates to the ABET evaluation criteria, as discussed in the next section.

3.5 Enhancing Engineering Analysis

The lack of engineering analysis in senior design projects is probably one of the most commonly heard comments within the senior design community in the opinion of the authors. It is also one of the first comments most faculty seem to make about design programs. The increasing involvement of TCs with design teams is intended to improve the use of analysis in design projects, as is the use of design methods based in analytical analysis (such as decision methods, specifications development, etc.). By no longer relying on the FAs to be the sole expert in all the projects under their direction, the SDL hoped that faculty and students would improve the use of analysis within design projects.

Observations at the 2010 Trade Fairs indicated that some progress has been made in encouraging some design teams to base their designs upon engineering analysis. Unfortunately, this progress is not consistent - some design teams still do not embrace analysis as a design tool. Also disappointing to the SDL in the first year was the lack of involvement of some TCs with their teams, and of some teams with their TCs.

3.6 Grade Transparency

Of significant concern to the students was the grading in the course. Students repeatedly expressed concern that their grade was predetermined by who they were assigned as a TFA. Several TFAs exacerbated this perception by publically declaring that the average GPA of their team told them all they needed to know to grade the team. Students with lower GPAs were thus discouraged from applying themselves in senior design, as they fate had been determined by their GPA. In the end, it became a self-fulfilling philosophy.

The SDL took an active role in attempting to bring grade transparency to the course. The individual grade component in the class is significant, which ensures that students cannot ride on their team's coat tails. The SDLs developed specific grade rubrics for every assignment in the course which were provided to both the students and FAs before the assignment is due. Furthermore, the mentoring process of the FAs is intended to help provide a uniform grading basis. As a final check, statistical comparisons of each FA are used to identify FAs with unexpectedly high or low grades. In these instances, the grades issued by FAs can be questioned and if necessary brought into line with the other sections.

The results from the first year of implementing these practices have been promising, as shown in Fig. 3 and Fig. 4. Figure 3 demonstrates that there is a significant correlation between individual performance and an individual's final grade. Figure 4 demonstrates that there is no consistent pattern where students of one FA outperform those of other FAs.

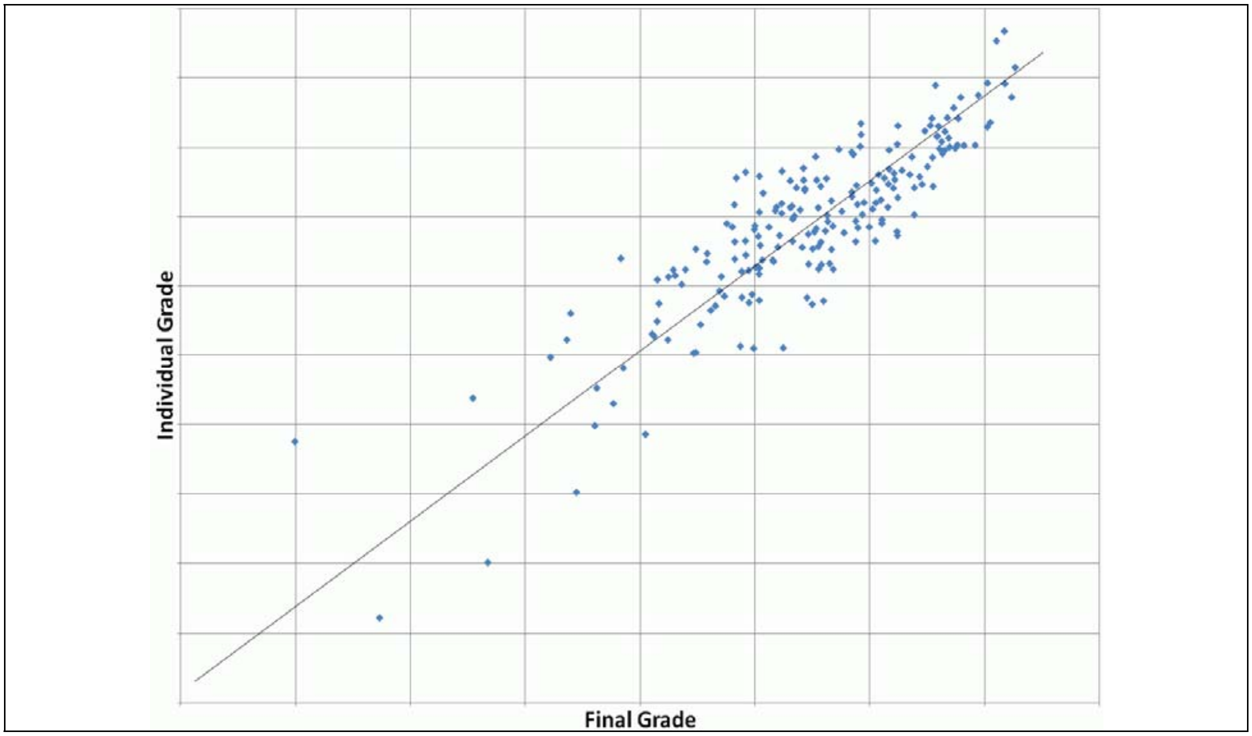

Figure 3. Individual Grade versus Final Grade demonstrating the importance of individual performance above the team assigned.

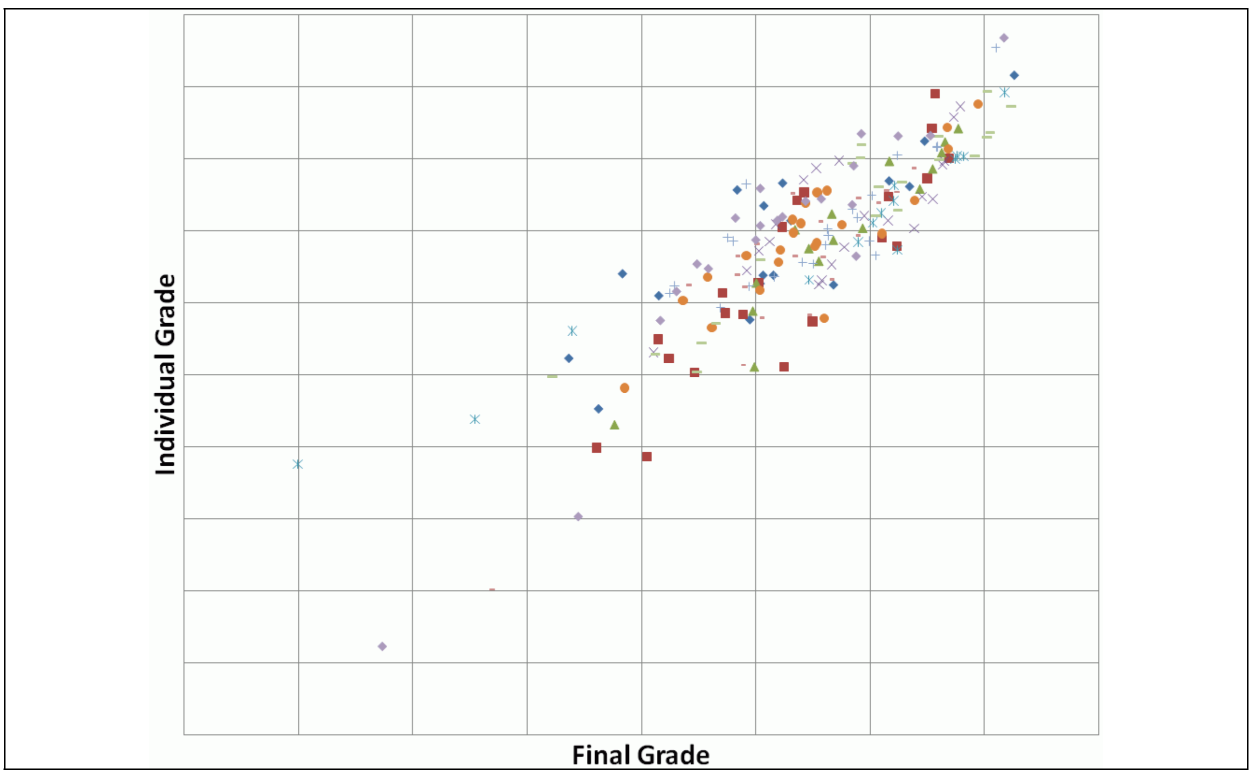

Figure 4. Grade Distribution by individual FAs (each symbol corresponds to an FA).

3.7 Evaluating Year 1

Considering all the changes made in the first year, the faculty and administration were generally pleased with the program. While clients initially expressed reservations at the changes, project clients who stayed expressed general approval of the changes. However, the students as a group were generally unhappy. As one student put it *"You took a class that I was looking forward to as a blow-off class and put some rigor into it!"*

Admittedly, not everything worked. Several assignments were too closely spaced to allow teams to make progress between reports. Other assignments lacked a clear purpose in the class. One of the most successful guest lecturers in the class was an alumni panel discussion where former students talked about their design experiences in the professional world. Just as the faculty expected, they emphasized many of the aspects that the program focused on improving such as writing skills, the use of calculations, and the use of design methods in a flexible design process. However, this lecture was scheduled late in the second semester, long after the students in the class had decided that these aspects existed only for academic purposes and had no real value. This lecture should have been given early the first semester.

In addition, in the rush to redesign and implement the new class, adequate supporting materials and examples were often unavailable on a timely basis to the students. Lecture handouts were often being completed just-in-time for lecture, and examples of finished work were not available.

Finally, the rush to produce the class did not allow the faculty sufficient time to incorporate internal assessments into the course with which to obtain early evaluations of our own progress towards the course goals we had laid out. While several approaches were used, including formal surveys, focus groups and individual informal interviews, the course faculty were rarely able to process the data in a timely manner so as to be useful. By the time feedback was obtained, it was often too late in the course to respond to areas of apparent weakness. As a result, several faculty and FAs took these areas of weakness as an opportunity to declare the changes a failure and advocate a return to the prior structure. This led to several unfortunate instances where students were party to these discussions and further damaged their confidence in the course. The lack of timely and substantive assessments affected the course.

4. Resulting Program Structure - Year 2

The changes made for the fall 2010 semester were much less substantial than those made initially in the redesign of the program. But, as not every element introduced into the class was a success, they were no less significant. Structurally, the program remained the same, with the same organization and leadership in place. There was considerable changeover in the FA positions, some of which was deliberate and some was due to normal changes in the adjunct faculty pool. In general, the goal became to staff the course with individuals willing to give the new structure a chance, and willing to work to improve it rather than to propose a return to the policies of the past. Achieving buy-in from those involved in the course was a strong consideration in developing the second year of the class.

4.1 Curriculum Modifications

The alumni guest panel lecture was moved to the first day of class. It remains one of the most popular lectures of the semester and often has the effect of putting the students in a position where they realize that the course assignments do have a purpose and correspond to real-life engineering tasks. Several assignments were consolidated and a clear purpose was identified for each assignment. Assignments without a clear purpose were eliminated. In addition, a new structure was adopted for the assignments that better mimics the style of many professional engineering reports was adopted replacing a more traditional and formal report style. This style change also significantly reduced the work burden assigned to the students.

The only assignment added to the curriculum was the reintroduction of periodic individual status reports, submitted electronically. This assignment enabled students to individually develop a professional writing style and enhanced the value of their individual course grades. The team submits a similar status report after any meeting with the Client or TC to their FA.

4.2 A Design Textbook

At the request of the students, the SDL spent the summer of 2010 in search of a suitable course textbook. The SDL had originally followed the practice of the previous course and had not adopted a text based on feedback that the students found the existing texts too discipline specific. This often turned off the disciplines not used as a focus of the textbook. The available texts are generally written from a electro-mechanical engineering perspective. Popular texts such as Ullman's[18] "The Mechanical Design Process" are acceptable reference authorities to mechanical engineers, but students in other disciplines do not see them as connected to their own field because of the title. Similarly Ford and Coulston's[7] "Design for Electrical and Computer Engineers: Theory, Concepts and Practice" does not seem to appeal to engineering students outside of electrical engineering for the same reason. More generic titles such as Otto and Wood's[12] "Product Design: Techniques in Reverse Engineering and New Product Development" seem to appeal more to mechanical and electrical engineering students, but do not appeal to civil and environmental engineering students who do not consider the results of their design work to be "products" in a classical sense. Even more generic titles, such as Dym and Little's[5] "Engineering Design: A Project-Based Introduction" can quickly turn off students because many of the initial examples are electro-mechanical in nature.

In reviewing many of the applicable texts, the SDL decided that there is a decided bias towards electro-mechanical design methods texts. Equal treatment of civil, mechanical, electrical and environmental engineering problems are difficult to find. Yet, students from all disciplines ask for a textbook reference in support of the class that is specific to their particular point of view. It is clear that before this class, students do not come to the realization that design is not discipline specific and that the disciplines are much more closely related by design methods than the students suspect.

As a solution, the SDL developed a custom textbook that incorporated parts of six different engineering texts[3, 4, 7, 10, 19, 20], into a two-volume textbook for the class. One volume focuses on project management issues, while the other volume focuses on design methods. This text was adopted for the Fall 2010 semester. The chapters adopted are shown in Tables 2 and 3.

TABLE 2. Senior Design Program Project Management Text.

Chapter	Topic	Source	Source Chapter
1	Engineering Design	Dieter[4]	1
2	Why Study Engineering Design	Ullman[19]	1
3	The Design Process & Product Discovery	Ullman[19]	4
4	The Design & Construction Processes	Davis[3]	1
5	Planning for Design	Ullman[19]	5
6	Developing a Project Plan	Larson[10]	6
7	Estimating Times & Costs	Larson[10]	5
8	Scheduling Resources & Costs	Larson[10]	8
9	Cost Evaluation	Dieter[4]	16
10	Managing Risk	Larson[10]	7
11	Reducing Project Duration	Larson[10]	9
12	Teams & Teamwork	Ford[7]	9
13	Team Behavior & Tools	Dieter[4]	4
14	Leadership: Being an Effective Manager	Larson[10]	10
15	Legal & Ethical Issues in Engineering Design	Dieter[4]	17

TABLE 3. Senior Design Program Design Methods Text.

Chapter	Topic	Source	Source Chapter
1	Product Development Process	Dieter[4]	2
2	Identifying Customer Needs	Ulrich[20]	4
3	Gathering Information	Dieter[4]	5
4	Understanding the Problem & Developing Engineering Specifications	Ullman[19]	6
5	The Requirements Specification	Ford[7]	3
6	Concept Generation	Dieter[4]	6
7	Decision Making & Concept Selection	Dieter[4]	7
8	Embodiment Design	Dieter[4]	8
9	Detail Design	Dieter[4]	9
10	Modeling & Simulation	Dieter[4]	10
11	Materials Selection	Dieter[4]	11
12	Product Evaluation: Design for X	Ullman[19]	11
13	Quality, Robust Design & Optimization	Dieter[4]	15
14	Industrial Design	Ulrich[20]	10
A	Factor of Safety as a Design Variable	Ullman[19]	App. C
B	Component Failure Rate Data	Ford[7]	App. C
C	Human Factors in Design	Ullman[19]	App. D

Unfortunately, the text has not been a complete success. Many students chose to do without the text, even after requesting it. Others quickly returned the text deciding that it was not of sufficient value given the price. Obviously, the price of the text is a significant issue, but so too was the lack of an index for the text that would truly make the text useful. This issue will remain a work in progress.

4.3 Assessment Strategies

The first year of the course relied on end of semester course assessments (evaluations and exams) to provide feedback to the faculty. These tools were clearly inadequate for this course. Instead, the SDL adopted a strategy, which incorporates iClickers into course lectures and design presentations. These tools forced all the lectures in the course to be reworked, and have led to some issues with guest speakers who are generally not familiar or fluent in using these devices. However, they do provide immediate feedback to the faculty on points of misunderstanding, and also keep students actively involved in the class. With this new feedback, the SDL expects to identify areas for further improvement in the class and to be able to defend the structure of the program much more effectively.

4.4 Preliminary Evaluation of Year 2

At the time of writing, year 2 of the re-design of the senior design program is underway. Far fewer complaints were received from the students during the fall 2010 semester by the SDL and the students seem to be much more invested in the current structure of the class rather than in trying to facilitate a return to the old class structure. To date, the course seems to be much improved over year 1. Mid-course evaluations improved nearly 50% over the first year. Preliminary evaluations from the new assessment tools suggest that the course objectives are being better met this year as compared to the prior year. We hope to present quantitative results from these assessments in future publications once a complete analysis can be completed.

5. Current Issues and Future Directions

The SDL is generally pleased with the progress in re-designing the senior design program. Client interest continues to grow, and the Division faculty are increasingly involved in the program as a track record of successful and impressive projects is developed. However, several issues still remain to be addressed by the SDL. These include:

- The program has recently been allocated Teaching Assistants for the first time. How can TAs best be used within the program?
- Publicity remains a challenge as the program still operates under a website developed for the previous program. Resources and time need to be allocated to revamp our web presence.
- Issues related to intellectual property, handling non-disclosure agreements, a more formal contracting and project accounting process need to be addressed in coming years as their importance continues to grow from our client base.
- Turnover amongst FAs needs to be managed better. Part of this is a training issue, and a portion of this is a recruitment issue.
- Achieving a sustainable staffing model remains an issue. Half of the faculty involved in the transition to the new curriculum have retired or announced their intention to do so in the last year, leaving fewer faculty involved in the program operations. Replacing these faculty member has proven to be a significant issue given current economic considerations.

6. Conclusions

Change is never easy, but when faced with change, an opportunity exists for truly transformative change at little additional risk. Embracing such opportunities for grand and sweeping change may inspire new enthusiasm for changes that would be difficult to sustain if implemented in a more incremental manner.

Change in a senior design program is a complex process with many interconnected customers ranging from project clients, to academic institutions, invested faculty, students, and even departmental resources. Substantial changes can be achieved in these complex programs, but only if careful consideration and recognition of the needs of all of the involved parties are considered. While dramatic changes can be made, ultimately dramatic change must give way to a community of continual change and improvement. Rapid, transformative change is a rare event that can be used to dramatically shift the status quo to a new state.

The shifts in the program at CSM from a project management model to a design process model supported by design methods has produced a spirit of renewal in the program amongst the faculty and has enabled new goals and a deeper understanding of the relationship of a design program to the department to emerge. This exciting development has been supported by a number of energetic and committed leaders whose efforts have led to a newly respected design program that is paying benefits to all of its constituent parties.

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