Alternatives for Establishing Effective Capstone Design Teams

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Introduction

Universities have the task of educating student engineers such that they can provide effective and responsible solutions, both as an individual and as a member of a team, to human-social-environmental needs. For years capstone design courses have been used in single engineering disciplines and at single universities to foster the understanding of the design process and teamwork. However, more is required to prepare engineering students to interact in teams with members of different backgrounds and to meet the challenges that they will encounter in their careers. Universities and industry must work together to identify and eliminate those barriers to effective teaming and communication. This paper addresses some of the issues associated with the modification of the aforementioned capstone design activity to include multi-disciplinary teams of engineering students addressing real industrial problems.

Since 1970 over 3000 mechanical engineering seniors have teamed with other mechanical engineering seniors in the capstone design class at Clemson University to address more than 200 industrial projects proffered by 76 different industries and agencies. Beginning in August 1994, mechanical engineering students in the capstone design class at Clemson have teamed with students from five universities and six disciplines to address multi-disciplinary projects. The various combinations of students that have been used in the design teams are: (1) teams with only Clemson mechanical engineering students, (2) teams with Clemson mechanical engineering students and students from other disciplines at Clemson, (3) teams with Clemson mechanical engineering students and mechanical engineering students from other universities, and finally (4) teams with Clemson mechanical engineering students and students of other disciplines from other universities. The students have come from the disciplines of chemical engineering, industrial engineering, materials engineering, mechanical engineering, mechanical engineering technology, and nuclear engineering.

Beginning with the school year 1994-95, students and faculty in chemical and mechanical engineering at Clemson University and the University of South Carolina, and students and faculty in mechanical engineering technology at South Carolina State University participated in collaborative design efforts addressing environmental restoration and waste management needs of the Westinghouse Savannah River Company, a DOE facility. Westinghouse has sponsored twenty-one of these projects. Starting in the school year 1996-97, mechanical and nuclear engineering students and faculty from Georgia Tech. were also included in the teaming effort.[1] Since 1994-95, approximately two hundred student teams of the four combinations stated above have addressed more than fifty different industrial problems. Recently, mechanical engineering students from the Technische Universität München, the Technische Universität Darmstadt, and Clemson University teamed on a project sponsored by BMW[2].

Students in the multi-disciplinary capstone course experience benefits that exceed those received by students in a similar single-discipline course. Also the ABET "Criteria for Accrediting Engineering Programs" used during the 2001-2002 accreditation cycle states in *Criterion 3. Program Outcomes and Assessment* part (d), "Engineering programs must demonstrate that their graduates have an ability to function on multi-disciplinary teams." The best way to demonstrate that a student has this ability is to have the student actually function on multi-disciplinary teams. Hence having students successfully work on multi-disciplinary teams, not only brings additional benefits to the student, but demonstrates that ABET Criteria 3(d) has been met.

Objective

Advantages and disadvantages of the aforementioned teaming alternatives will be presented along with opinions as to the relative value of the various teaming combinations for meeting the objectives of the capstone design class. The recommendations offered are based on input from the industrial representatives, the faculty members, and the students who have participated in this course.

The objectives of the capstone design class at Clemson University are to develop and increase the student's ability: (1) to function in multi-disciplinary design groups composed of members with diverse thinking styles [Teaming], (2) to effectively communicate using conventional methods and modern technology (fax, e-mail, computer conferencing, video conferencing, phone conferencing, web pages, etc.) [Communication] and (3) to eliminate boundaries that prevent integrating course material and its application into real engineering projects [Innovative Design]. The first two of the stated objectives were identified as the two most important elements that an emerging engineer needs to know in the National Science Foundation sponsored - American Society of Mechanical Engineers' report, "Integrating the Product Realization Process into the Undergraduate Curriculum."

Issues to be resolved by faculty members

The faculty members who participate in the multi-disciplinary design activity must be devoted to this effort and work to overcome the impediments to teaming. The faculty members should participate in the multi-disciplinary capstone activity because they believe that the students receive benefits that cannot be obtained in a single-discipline design experience. These faculty members facilitate the work done by the students, ensure that the required electronic communication systems are accessible, and serve as coaches and as technical advisors for the student teams. The faculty members never tell the students what or how something should be done, but ask leading questions to help the students consider other approaches to the solution.

The coordination of a multi-disciplinary capstone design course requires that the faculty members resolve issues that often do not arise in the single discipline, single university activity. Some of these issues are now listed. Recommendations based on how the listed issues were resolved in the Clemson program then follow.

(1) An industrial project must be selected by the faculty members that contains meaningful components from all of the disciplines that are involved in the design activity.
(2) The composition of the student teams by discipline and the number of teams required to efficiently address the project must be determined**.**
(3) The faculty members must establish the beginning and ending dates of the project.
(4) The reporting requirements for the students, both written and oral, must be specified.
(5) The faculty members must decide what hardware and software the students will use for communication and ensure that these tools are available.
(6) Meeting dates and acceptable communication with the industrial sponsor (both when and how) must be established.
(7) The financial resources available to student teams for communication, travel, building prototypes, etc. must be determined. The industrial sponsor should provide these resources.
(8) Since different engineering students may have been taught different design methodologies, a single methodology must be established for use by the student teams.
(9) Since different disciplines may offer different course credit for the design activity, the students should be assigned individual responsibilities in proportion to this credit.

The following suggestions as to how the aforementioned issues may be handled are based on seven years of actual experience with multi-disciplinary design teams at Clemson University, on the data from surveys completed by the students, faculty members, and the industrial representatives relative to the design activity, and on individual reports written by each student.

Selection of an industrial project that meets multi-disciplinary requirements. If students of various disciplines are to work on the design team, then the project must contain elements in the domain of each of these disciplines. In this way each student can see where he or she can make a contribution, and they can also see the value of the contributions made by the students of the other disciplines. Projects that work best require nearly equal contributions from each discipline. Four to six months prior to addressing a multi-disciplinary project, the faculty members request several candidate projects from industry. The industrial liaison establishes broad statements of need for each of these specific projects. Then the faculty members from the various universities, in coordination with the industrial liaison, modify and select from the candidate projects those projects that may be addressed most effectively by the multi-disciplinary student teams in the time allocated for the project. The industrial liaison represents the industry in all interactions with the teams.

*Required composition of team and number of teams to efficiently address the project***.** The number of students from each discipline should be in proportion to the effort required in that discipline area. Input from the students and faculty members indicate that the total number of students on a team should be three to five, with the best number being four. Teams with as many as sixteen students per team have been assembled; however, the students in these teams subdivided themselves into smaller sub-teams to address different tasks associated with the project. Also, the discipline, gender, and ethnic makeup of the team should not isolate one student as being different in more than one measure. That is, try not to have the only female on the team being the only student of her discipline. Being a uniquely different team member may lead to isolation of that member or the reluctance of that member to fully participate in the team.

At Clemson, typically sixteen students are divided into four competing design teams of four students per team to address the industrial project. It has also been found that industrial liaisons often feel overwhelmed if they are asked to work with more than four teams. Hence, the maximum number of teams addressing a single industrial project at Clemson is four. All student teams working on the same project attend the final oral presentations of the competing teams to the industrial client. From the final presentations of the competing teams the students learn that even though all teams began with the same objective statement, valid criteria, constraints, and solutions other than theirs exist. Recognition of this fact leads them to be more innovative and open to new and different ideas.

Scheduling beginning and ending dates. Typically, the beginning and end dates of the semester (quarter) are not the same at different universities. Thus to maintain team unity, either the time period available to address the project is shortened to fall entirely within the time constraints of all universities, or some students must work outside their semester timeframe. Also, the duration of the capstone design class can vary from university to university and from discipline to discipline within a given university. It is difficult for students who take a one-semester capstone design class to team with students who take a two-semester capstone design class. In mechanical engineering at Clemson, the one semester capstone design class is taught every semester. However, in chemical engineering the capstone design class is taught only in the spring semester. Therefore, teaming of Clemson mechanical and chemical engineering students on a capstone design project works better during the spring semester. Coordination of timing on multi-disciplinary design projects is easier within a single university; whereas, coordination of multi-university teams is very difficult and requires cooperation of all involved students and faculty members.

*Reporting requirements, both written (log books, etc.) and oral***.** Engineering capstone design courses in different disciplines often have different requirements for the students in reporting their work. To maintain the working relationship in the team, all members of the team must have the same reporting requirements as determined by the faculty members involved with the project. Typically design teams make formal biweekly oral reports to the faculty jury, in addition to, submitting interim and final written and oral reports to the jury and industrial sponsor.

To ensure the quality and consistency of the student's reports and work, a document should be written by the faculty members and distributed to the students. This document would define what should be contained in the team's interim written report, the individual final written report, the team's final written report, the log book, etc. This document helps ensure that the goals of quality are met, and that the students operate in a professional manner. Also, the faculty members and students should discuss teaming issues, and the students should be provided written information on teaming (how teams should work, problems typically encountered, etc.).

Hardware and software used as communication tools. Multi-university teams must communicate using electronic means that are available to all students on the team. Hence, the faculty members must ensure that the chosen means of communication are available at their respective universities. Computer conferencing is extremely desirable for multi-university teams and allows regular face-to-face meetings of the team members, as well as oral reporting to all faculty members. Thus, if the faculty would like the teams to computer conference using ISDN lines, then it is the responsibility of the faculty members to make that resource available to the students. The lack of compatible hard and software at the various universities is often difficult to overcome.

It is strongly suggested that all teams (single-university, etc.) develop and use a web site. The web site should have a public portion where such things as the project title, objective statement, industrial liaison, faculty members, team members, e-mail addresses, and phone numbers are listed. Also, the web site should have a password-protected portion where team members would keep, among other things, their logbook, a listing of their criteria and constraints, communication with vendors, etc., and written statements about the project in a form that is easily incorporated into the oral and written reports.

Meeting dates and acceptable communication with industrial sponsor. The times and dates for student meetings (either face-to-face or computer) and for student reports to the faculty members and industrial liaison must be established. Even though the students are updated on the progress of their teammates via the web site, the students must meet at least weekly as a team to discuss their progress, make modifications of their objective, criteria, schedule, the selection of their solution, etc. It is suggested that the student teams meet biweekly with the faculty members, in addition to meeting with the industrial liaison on a mutually agreed schedule.

To reduce the number of questions going to the industrial liaison from the students, it is recommended that the students first pose the questions to the faculty members involved in the project. If a faculty member does not know the answer, then the liaison is asked, typically via e-mail. The liaison responds to both the student team that asked the question and the faculty members. When a student from a second team asks the same question, the faculty members can provide the answer without bothering the liaison.

Financial resources available to student teams for communication, for travel, for building prototypes, etc. Each student team needs to be given a specified dollar amount for addressing their project. The students then must work within their established budget in making long-distance phone calls, ordering materials, traveling, making copies of reports, etc. The budget will depend on the deliverables as determined by the faculty members and industry and is typically paid by the client. Currently at Clemson, the industrial client pays all out-of-pocket expenses of each student team up to a maximum of $500 per team and contributes $5000 to the departments involved in the project. Only with the written approval of the industrial client may the budget of any student team exceed the $500 maximum.

Design methodology to be used. The student team must use a single design methodology with the definitions of items well understood by all parties involved. As an example, the faculty members must agree as to what is meant by and what is included in the "Design Objective." After the industrial liaison makes a single presentation of the problem statement to the students addressing the project, all students, as a group, write a design objective that is consistent with the faculty's definition. First the design objective is approved by the faculty members and then by the industrial liaison. After the objective statement is approved by the liaison, each four-student team independently develops the criteria and constraints and then proceeds to address the project.

The projects presented by industry often address designing a particular piece of hardware to solve their problem. However, using a different approach may lead to a better solution of the problem. As an example, the students might be asked to design an end-effector for an operator-controlled robot with better tactile feedback, such that a weld plug can be more easily placed in a canister. Since the real objective is to get the plug in the canister, a new design of the plug may provide a solution that is more cost-effective and performs better. This illustration is based on a real project addressed by the student teams. Therefore, the students often need to change the problem statement as provided by industry and develop an objective statement that does not say how the problem will be addressed.

Assigning individual responsibilities in proportion to course credit. The weighting of the capstone project in determining the student's final course grade may be different in various disciplines. Also, what is considered as graded material may vary from discipline to discipline. Therefore, the motivation of each student to actively participate in all parts of the project may be different. To reduce this problem, it is suggested that the faculty members adopt a grading plan for the capstone design course that is uniform for students of all disciplines.

Another problem that arises is caused by the difference in credit earned in the capstone design course by students of different disciplines. Since the course credit is tied to the particular curriculum, it is not easy to change. To maintain team unity, it is suggested that the faculty members tell the student teams that some students are getting more or less credit than others for participating in the course, and that the workload assigned to each student should be in proportion to the course credit received. This difference in contribution to the project is typical of what happens in industry and is something to which the students need to become accustomed.

Procedure for start up and termination of the projects

Multi-university teams. At the beginning of the semester, the students from the various universities are divided into multi-university teams. These students and their faculty advisors then travel to the industrial site where the student teams are assembled, and industrial personnel present the projects. After the presentation of the project to the student teams, all of the students jointly develop a specific objective statement for their problem and confirm with the faculty members and industrial liaison that their objective is appropriate. Then the students divide into teams, select a team leader and the keeper of the team's logbook, develop time-task charts, assign specific tasks to team members, and select times for their scheduled electronic communications during the remainder of the semester. The student team members then return to their universities where each student addresses his or her team's problem.

Each week, all members of a multi-university student team have a scheduled hour-long telephone conference and also a scheduled hour-long computer conference using ISDN lines. In addition, twice each semester, all teams have a one-half hour conference where they make formal interim reports to the faculty members. Each team also practices for their final oral presentation to the industrial client via computer conferencing. The students transfer files, CAD drawing, etc., from one university to another using e-mail, fax, and computer conferencing.

At the end of the semester, the students travel back to the industrial site where the solution for their project is presented by each team in both written and oral format with appropriate proof-of-concept models. Industrial representatives and the faculty members judge the solutions and reports. After the presentation of the final team report, each student submits a written critique of the techniques and communication procedures used in addressing their problem, offers suggestions as to how their experience could have been improved, and evaluates the contributions of each team member. After the individual report is received, each student is asked to complete a course survey that has been prepared by the faculty members.

When Clemson students teamed with the German students, the Clemson students met with their German counterparts at a BMW facility in Germany. The meeting in Germany proceeded as described above. The final presentation was made at Clemson University in South Carolina, with the German students traveling to South Carolina.

Single-university teams. The procedure used for single-university teams is quite similar to that described above for multi-university teams, except that the industrial liaison travels to the university to present the project and to receive the final report. Typically within the first few weeks of the project, individual student teams travel to the industrial site to meet with industrial representatives and to view where their project solution will be implemented. During these visits, students often see constraints to their solution that were not disclosed by the industrial liaison. The single-university teams have face-to-face meetings instead of the conferences described for multi-university teams. However, both the single and multi-university teams develop and use web sites.

Advantages of the various teaming configuration

The students in the multi-disciplinary capstone design teams develop skills and learn lessons that their counterparts in a single-discipline design class do not. The students in a multi-disciplinary capstone design class develop a vocabulary that recognizes differences in engineering terminology as used by various disciplines. They learn and practice new design methodologies with students of a different technical background. In previous courses they may have been working with stronger students in their discipline, while in the multi-disciplinary course they now see bright students of a different discipline that do not know some of the things that they know. Thus, they become more confident in their technical ability. These students develop skills in various electronic communication tools (developing web sites, etc.) and learn to communicate using modern technology. All of these advantages are present in a single or multi-university capstone design program.

It was observed that the multi-university teams tend to make a more uniform and consistent progress toward a solution than the single university teams. Members of multi-university teams seldom allowed other activities to take priority over their conference meeting. When a conference was scheduled, they were there with their assigned tasks completed. Whereas, single university teams did not always have team meetings at the scheduled times, and on occasion meetings were canceled. However, they never missed a meeting with the faculty member or industrial representative. There was no discernable difference in the quality of the final product from the multi-university and single-university teams. The main advantage of a multi-university design effort is that it increases the self-confidence of the students, for they see that they can compete with students from other universities.

Disadvantages of the various teaming configuration

Some of the disadvantages of the multi-university program have been discussed above in the section entitled "Issues to be resolved by faculty members." These disadvantages are now summarized. Different beginning and ending times of semesters and schedules at different universities make scheduling of the multi-university capstone activity more difficult. Differences in the curriculum at various universities as to when the capstone course is offered, the duration of the course, and the course credit are more difficult to overcome in multi-university design activities. Technology, such as computer conferencing, can be difficult to use when crossing institutional boundaries. These difficulties are a result of differences in, or the lack of, systems at the various institutions. Another difficulty in developing a multi-university design program is the cost, which includes extensive faculty time in planning and coordinating the activity, the cost of travel, the cost of conferencing equipment and the associated hardware & software, and the cost of long-distance phone time.

Closure

The multi-disciplinary capstone design course was judged best to meet the objective of developing the student's skills in teaming, communication, and integrating the application of hard engineering science with safe, ethical, and innovative design. The multi-university design activity developed a higher level of self-confidence in the student's technical ability. However, the additional cost of the multi-university may make it impossible to implement. Achieving the objectives for the students as stated above were weighted against the cost of the various teaming combinations as measured both in dollars spent and faculty members' time. The various teaming combinations are now ranked in the order of value (benefits/cost) as determined by the author, with the best of these alternatives listed first.

Ranking of team composition to meet objectives:

(1) Multi-disciplinary - single university,
(2) Multi-disciplinary - multi-university,
(3) Single-discipline - multi- university, and finally,
(4) Single-discipline - single university.

The multi-disciplinary design effort has been highly successful, and the students, faculty, and industrial liaisons all feel that they have benefited from the program. A typical student comment is, "My experience with the Senior Design Project has been extremely beneficial to me in gaining a complete education. I can clearly see the relevance of an innovative team of different engineering disciplines working together on a project that has many different parameters." A professor involved in the project stated, "I think that the program was extremely beneficial for the students. The projects showed the students how they can work with other disciplines to get things done. Also the students had their confidence boosted by seeing students from other schools and seeing that they can hold their own." In a letter to the author of this paper, the manager of the process chemistry and control section at the Westinghouse Savannah River Company stated, "During this time we have realized benefits from the student designs in several areas. Last semester their contributions to the Counter Current Decantation project for sludge processing and the designs for the remote placement of the canister weld plug were particularly helpful. ····· It appears that the senior projects program is very beneficial to the students. If you agree and would like to continue the program next fall, we would welcome the opportunity to work with you again." In the words of the Westinghouse manager quoted above, you should "welcome the opportunity to work…" in a multi-disciplinary capstone design class.

This project has received the major portion of its funding from the South Carolina University Research and Education Foundation (SCUREF) with additional support coming from the Southeastern University College Coalition for Engineering Education (SUCCEED) and from the industries involved in the projects.

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Biography

Marvin Dixon is Alumni Distinguished Professor Emeritus of Mechanical Engineering at Clemson University. For fifteen years he was the coordinator of the capstone design course at Clemson University. He established the multi-university, multi-disciplinary capstone design activity that is the subject of this paper. Prof. Georges Fadel is now coordinating this effort in mechanical engineering at Clemson.