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Holistic Assessment of Student Performance in Multidisciplinary Engineering Capstone Design Projects*

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Capstone design courses are commonly employed in engineering schools to culminate students' learning experiences, as called for by the Accreditation Board for Engineering and Technology (ABET). Although widely considered one of the best practices of engineering education, these courses continue to challenge the field. Capstone courses are challenging not only because they involve open-ended design that may require researching untried approaches while at the same time being accountable to sponsors' particular requirements; but also due to their multidisciplinary nature and the dynamics of student teams. These challenges are reflected in the problem of giving each project the relevant advising and each student a fair final grade. In this paper we present a holistic approach to advising and evaluation of individual students in multidisciplinary teams that was developed and has proven to work at Rensselaer. The approach adopted a two-person, often multidisciplinary, instructing team design, coupled with 'mentors' from sponsoring companies, to coach the students; and developed dedicated rubrics to measure student performance concerning adherence to design process, team participation, and communication skills. These new rubrics added to the traditional methods, which include group reports and student peer evaluations. The new team teaching design also separated the duties associated with coaching and judging, to make advising and evaluation more effective and objective. Our internal reviews and students' peer evaluations showed that a high degree of consistency in grading has been achieved with the implementation of the new design. Finally, we submit that the basic structure of the holistic approach—i.e., blending objectives with due process and evaluation from multiple sources, is consistent with practices in industry that students will face after graduation.

Keywords: capstone design; pedagogy; engineering education

1. Background and outline of paper

Engineering is about design, just like science is about discovery. However, teaching design properly is a challenging task in engineering education. As practicing engineers often comment, most of the significant design problems that they encounter in practice tend to be multi-faceted challenges that involve iterative decision making in collaboration with others. Most real world problems involve conflicting conditions and ambiguities. In other words, engineering design requires empirically based judgment using a diversity of knowledge, skills, and experience. In support of this reality, the ABET calls for a capstone design experience prior to graduation that teaches engineering students about teamwork, communication, and the engineering design process that applies to any empirical setting [1, 2].

However, as noted by various authors, this empirical and multidisciplinary orientation is difficult to implement [3–5]. The problem is many-fold: Real world projects are subject to practical complexities such as sponsors' particular requirements, multidisciplinary team dynamics, and available engineering resources, which make cross-project benchmarking difficult; they are not amenable to disciplinary instruction which faculty in a university specialize to do; and are one-of-a-kind in nature while still obeying the same processes and principles of engineering design. Therefore, the critical success factor for a capstone design course is developing an educationally sound pedagogy to assure the value to students as well as the rigor of project challenges. The pedagogy has to sufficiently account for the need of project-specific advising and how these empirical complexities may complicate the assessment of student performance, and thereby allow the faculty to coach each project properly and give each student a fair final grade [6–9].

The conventional way to differentiate students' individual performance is peer review. For team grading it is the written report. The field has accumulated rich results concerning these methods and their effectiveness [10, 11]. Experience in the field [12, 13] indicates that more needs to be done. In particular, both the engineering design process and a focus on project outcomes have to be instilled in a capstone course and hence reflected properly in advising and evaluation. Since both the project quality and the process integrity are non-standardized in a capstone course, providing fair and accurate assessment of individual student performance in this context meets complexities and uncertainties. The right pedagogy needs to go beyond the measurement methods that the conventional engineering education models provide. We report in this paper a design of the pedagogy that evolved

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from an iterative process over the past decade at Rensselaer.

The capstone design course at Rensselaer falls in the responsibility of the O.T. Swanson Multidisciplinary Design Laboratory (a.k.a. the Design Lab), whose mission is to provide clinical real-world experiences that build confidence in and teach students to integrate discipline-specific knowledge with practice on challenging design projects. In the past ten years, since the Design Lab first opened, we have secured and delivered results on over 100 industry-sponsored projects from global companies. In addition to industry-sponsored projects, individual entrepreneurs, and public and private foundations have also sponsored projects, which serve to enhance and broaden the mix of possible project options for students. The projects are open-ended, technically challenging design problems that encompass a broad array of important contemporary issues such as technology innovation and entrepreneurship, manufacturing productivity and quality, environmental conservation and alternative energy, and aids for people who are physically and/or mentally challenged. In addition to defining an important problem, industry sponsors provide a significant grant as well as their direct participation with the students, faculty, and staff who work to provide design solutions. Projects typically span two semesters, but for almost all students the capstone design course is one semester long. Thus there is typically a handoff of the project to a new team at the start of the second semester.

The challenges associated with successful implementation of experienced-based learning are not new [14, 15]. For example, we note past research on expert knowledge [16] that aligns with our own experience. We are often amazed at how seemingly simple concepts to us, as experts in engineering design, appear difficult to comprehend by our students; while conversely, complex systems (to us) are sometimes viewed in rather simplistic ways by students. Various researchers have shed some light on these fascinating differences in expert versus novice perspectives in the specific context of the design process [11, 17]. The complex nature of design is further reinforced by prestigious design experts who profess the need for new ways of knowing and greater research in the area of design pedagogy that transcends contemporary approaches [18, 19]. Suffice it to say, assessment in the context of engineering capstone design is a complex phenomena with many potentially confounding factors.

Starting with such knowledge we have engaged in a continuous improvement process that is ongoing and whose previous phases have been reported in earlier publications by some of the authors of the current paper [20–23]. The present state is a new pedagogy featuring a holistic approach to support project-based learning and equitable assessment of individual student performance. The new pedagogy entails a team teaching approach at its core, where two faculty members share advising and evaluating tasks, while also specializing to assume dedicated responsibility of coaching and grading, respectively. They collaborate with company 'mentors' to achieve project quality, and implement rubrics to assure process integrity as well as measure individual performance. These rubrics include team and individual deliverables such as memos and project forum participation on the individual side, and work statement, project management, and mid-term and final reports and presentations on the team side. Traditional methods such as reports, peer reviews, and end of semester reflective memos are enhanced with Rensselaer's institute-wide communication-intensive requirements, which provide even more content as student input to the assessment process. The pedagogy is multifaceted from the standpoint that a variety of assessment methodologies are employed in combination, and its evolutionary nature, such as the feedback in the form of students' end-of-semester reflective memos, makes the 'assessment of assessment' ideal a work in progress. The new pedagogy, since implemented fully in 2008–2009, has consistently been associated with improved student evaluations and industrial sponsors' praises. Our internal reviews and feedback from participating faculty also showed consistent grading and satisfaction.

The outline for this paper is as follows. The next section provides a broad overview of the pedagogy employed, including a brief discussion of some of the factors that influence capstone projects, an overview of the characteristics of our program and student grading policy, and a process timeline for our capstone design course. Integration of these factors defines the holistic approach. The following section, then, elaborates on three major course design changes implemented in 2008–2009 and how they improved understanding of student assessment. These changes include project level administration; separation of mentoring and assessment roles; and grading rubrics for engineering communication assignments. The last and concluding section attests to the consistency of assessment inputs in our current approach and summarizes lessons learned.

2. The new pedagogy

2.1 Factors influencing capstone design courses

The design of multidisciplinary capstone courses starts with the learning objectives that ABET

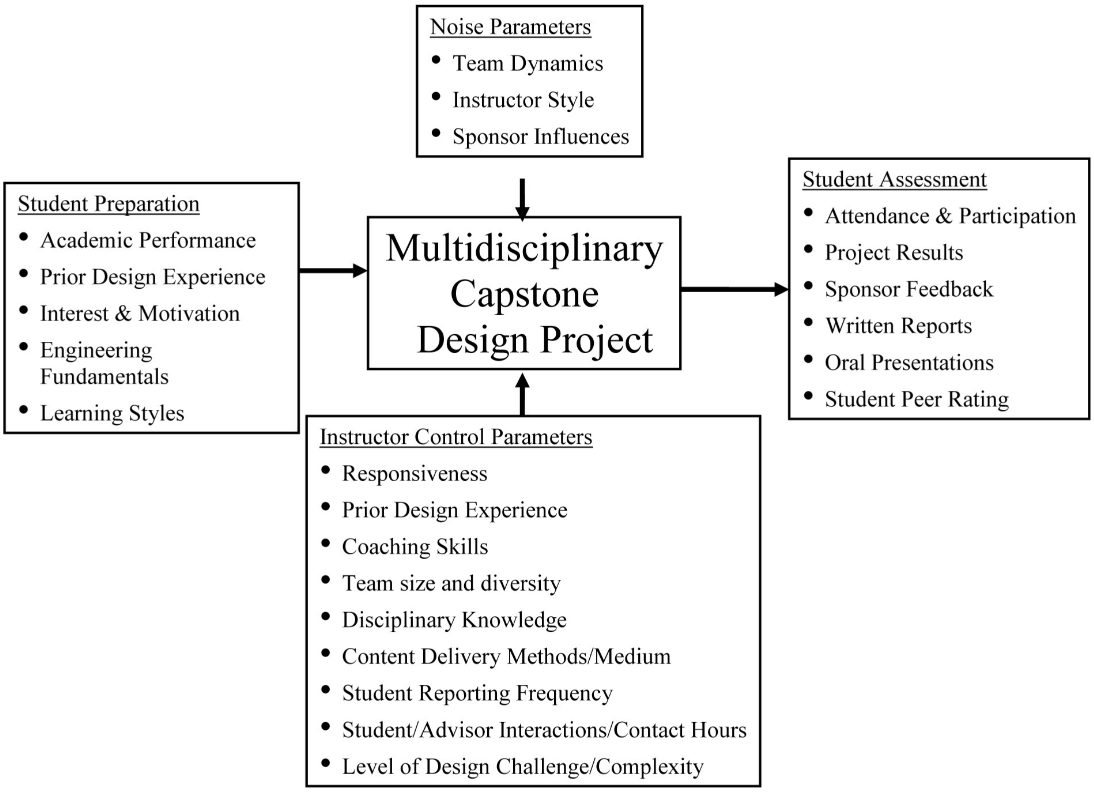

Fig. 1. Factors that influence multidisciplinary capstone design project outcomes.

recommends: teamwork, communication, and the design process. Figure 1 identifies the causal-effect relationships of factors that capstone design projects influence.

The pedagogy entails three levels of control for the factors that influence capstone design courses, as discussed below.

2.2 Course level administration

Based upon our experience with capstone design courses, we have found that, given the many potentially interacting factors, it is essential that a foundational set of processes, milestones and infrastructure be in place to guide the student experience and monitor progress. At the course level it is important to have policies, procedures, and guidelines for such matters as safety, purchasing, shop practices, travel requests, and meeting practices. For example, we have implemented extensive safety policies with a compulsory on-line assessment [23]. Likewise, a web-based projects forum is used by students, instructors, and sponsors to share common course policies and procedures, while also serving as a collaboration space for documenting and sharing information in a secure fashion among project participants [21]. Pre-project preparation includes scoping of project parameters, identification of technology study areas, and student team formation. While predefined processes are important, it is also true that both instructors and students need to be flexible and able to appropriately respond to changing situations. Support systems must be in place that can respond on-demand to individual project needs.

2.3 Project level grading

While most academic institutions operate at a course section level, for capstone design we argue that student assessment should be at a project level. In this way, project-level reporting on factors such as teamwork, progress on relevant objectives, project challenge level, resource requirements, and sponsor interaction can be monitored on a regular and continuous basis. Project level reporting of team grades facilitates consistency of delivery across the entire course. We have noticed that a dichotomy also exists in terms of the roles that instructors must play while advising project teams. In one case instructors will act as 'coach' and 'mentor' in support of the team, but in another case they need to monitor progress and ultimately assign a grade. These conflicting roles can have an emotional impact on the instructor, when the same person who is at one point supporting team success must now change roles and act like a 'referee' or 'judge' to make assessment.

2.4 Individual student level assessment

A major challenge for instructors is the difficulty involved with making individual assessments when students are working together as members of a team in the context of a capstone course. Even when the overall team grade for the project is clear, it can be difficult to discern the contributions and participation of one team member compared to the other members of a team. Use of student peer evaluations is very helpful in this regard. Another dimension for assessing individual student contribution and participation occurs through communication intensive requirements, which in our case accounts for 25% of the individual student final grade. Our experience with implementing the communication intensive requirement is consistent with those reported by Paretti [9]. While we have generated rubrics to provide guidance using an activity theory framework, our implementation has been situational, resulting in improved communication and understanding among all parties (i.e., students, faculty and sponsors). One example includes student posting to an on-line project management website [21] that is a course requirement and provides a useful calibration point for individual contributions. We have also found that student teams who follow a disciplined process of regular and efficient communication via the on-line project management website have a better success rate overall in delivering results according to their project objectives and plans (i.e., statement of work)

3. Characteristics of the multidisciplinary capstone design course

3.1 The educational program

The capstone course possesses the following characteristics:

- The program operates with the infrastructure at a private research university.
- All projects are approached in an authentic 'clinical' real world fashion.
- A single semester multidisciplinary capstone course involving electrical, materials, mechanical, computer systems, industrial and biomedical engineering students with a common syllabus across all participating departments.
- Projects come from a combination of industry, service, or entrepreneurial sources with over 60% of projects from industry sources, each funded by an annual grant of $40,000.00.
- Average team size: seven to eight students
- Approximate number of project teams each semester: 25

The capstone course builds on training that the students receive on teamwork, communication and the engineering design process in an earlier sophomore level 'Introduction to Engineering Design' course.

3.2 The overall design of the evaluation framework

As will be described in more detail in section 5.2 our instructional team for each project consists of two people, a 'mentor' or project engineer and an 'evaluator' or chief engineer. The chief engineer is the person who is ultimately responsible for determining team and individual student grades.

The final grade is determined by two basic factors: the grade for the project and the adjustment for individual contributions. The grade for the project is assigned by the chief engineer based on the sponsor's input (including the written evaluations of the project's output and the team's presentations to the sponsor); the team's group deliverables (including statement of work, midterm report, and final report); and the sponsor and the project and chief engineer's evaluation of the team's design process. The chief engineers may use their discretion to adjust the grade for some extreme cases (e.g., unusual events), including facilitating the team to undertake additional tasks, and dealing with cases where it is difficult to get the attention of sponsor representatives when critical guidance is needed.

The individual grade for each student is, in essence, an individual adjustment from the project grade in accordance with the student's individual deliverables (including technical memos, participation in project meetings, and self assessment), peer reviews, and the chief and project engineers' evaluation of their individual performance and contributions. While self-assessment, peer reviews, and instructor reviews are all subjective; the collection of them provides a mosaic of the student that is as objective as any traditional metric. Coupled with the written records in the form of individual deliverables, these reviews substantiate an appropriate adjustment to the final grade for a student. Although we have not done exhaustive quantitative studies of consistency between the various raters in this process, we have never experienced a complaint about a team grade. We do have occasional (less than 2%) questions about individual grades, particularly when a student is graded well below the team grade.

4. Major course milestones, assignments and grading

Since 2001 we have iteratively refined our syllabus, course assignments, and support processes that are common to all students and participating depart-

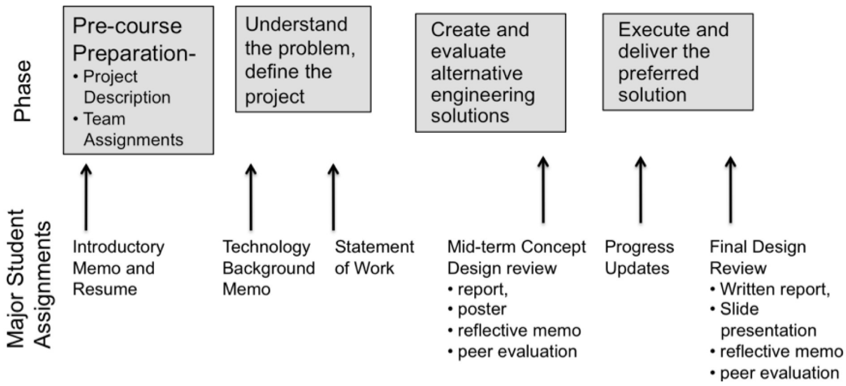

Fig. 2. Course structure and major student assignments.

ments. Figure 2 shows the structure of the course at the present time.

The syllabus includes the following major course milestones and assignments:

Pre-course Assignment—Introductory Memo and Resume: Each student submits this assignment in the semester prior to project team formation. The information provided by students is used to understand their interests and capability and ultimately to match them to appropriate projects.

Project Team Formation: Just prior to the first week of classes students are informed of their project assignment. On the first day of class, students are engaged in a variety of introductory team forming (i.e., building) activities.

Technology Background Memo: After classes begin the first assignment for each student is to conduct background research in an area of interest related to the project. This assignment is an individual writing assignment due during the second week of classes.

Statement of Work (Milestone 1): This assignment is the first significant team milestone where students are expected to clearly and concisely communicate the project objectives, plans, and deliverables for the semester in a one to two page write-up due in week three of the semester.

Mid-term Concept Design Review (Milestone 2): At this major milestone student teams are expected to have fully defined the problem and identified viable solution paths. This design review is conducted as a poster session that includes a combination of student, instructor and external reviewer feedback and assessment. In addition to a poster presentation, student teams also prepare a written mid-term technical report that provides a comprehensive documentation of the team's project.

Progress Updates: After the mid-term design review and until the end of the semester each student team works to implement their project plan and ultimately demonstrate results. During this time instructor and sponsor mentors support team efforts, while evaluators observe and monitor progress through postings on the project forum, conference calls with customers, and impromptu project updates by individual students.

Final Design Review (Milestone 3): The final semester design review is an intensive one to two hour session where a student team makes a comprehensive presentation and is expected to demonstrate their expert knowledge of the project before a panel of judges. In addition to the formal design review, students prepare a final technical report, demonstrate project results through system models and/or physical prototypes, and deliver a comprehensive documentation package to their sponsor.

The statement of work (M1), mid-term concept design review (M2) and final design review (M3) represent major project milestones. The composite project milestone grade is back-end weighted using the following point distribution:

Milestone 1 (M1) = 10%
Milestone 2 (M2) = 35%
Milestone 3 (M3) = 55%

For each major milestone we have developed templates, rubrics and feedback forms to provide guidance and assessment. For example, the grading rubric for the statement of work includes the following elements:

1. Objectives that reflect customer needs and expectations (4.0 points): The long-term objectives and customer payoff are well written and reflect a clear understanding of customer needs. Usually this understanding is based on multiple effective communications with the customer. Current semester objectives are well written, measurable and consistent with the long-term objectives and with what the team can accomplish in one semester.

2. Technical approach, strategy and special resource needs and issues (1.0 point): The technical approach section is written clearly and succinctly captures the team's strategy and any special resource needs and issues.
3. Major tasks and dates to deliver on project objectives (2.0 points): The deliverables and dates list corresponds to the high level tasks needed to meet the semester objectives. Tasks are written so as to be associated with a concrete deliverable. Dates reflect a good first approximation to the project schedule.
4. Team effectiveness (3.0 points): This item is not explicitly part of the statement of work document. Rather it reflects the judgment of the project mentor and evaluator on the team's overall progress to date. This judgment is based on interactions with the team during class and on the quality of postings on the online projects forum.

For milestones 2 and 3 oral presentations, a common design review feedback and evaluation form is used to collect comments and ratings from team instructors, other faculty, and external invited reviewers. Questions for reviewers include:

1. How well did the team communicate the assigned problem and their design objectives/specifications?
2. Did the team apply appropriate design methods?
3. How well did the team deal with technical and non-technical challenges?
4. How well did the team communicate their design(s)/solution(s) and open issues?
5. Would you please provide any additional comments?

For questions 1 through 4, reviewers assign ratings based upon a 4.0 scale identical to the university grading system.

Although we have not done exhaustive quantitative studies of consistency between the various raters in this process using the design review feedback and evaluation form, we have found that over the past ten years it has provided valuable feedback for instructor assessment purposes. Rating variances and comments often highlight possibly overlooked insights and perspectives, while rating consistency often serves to reinforce instructor observations. Sharing external reviewer ratings and comments (anonymously) with a project team further helps to calibrate student understanding of their performance, while allowing the chief and project engineers to serve as impartial third parties. A random sampling of reviewer feedback and evaluation forms for five mid-term project teams during the Spring 2011 semester indicates a range of ratings from 1.8 to 4.0 across all reviewers and questions (see Fig. 3). With three to four reviewers for each team we found average ratings for all four questions fell into a relatively narrow range of 2.8 to 3.14 with small variances (ranging from 0.0 to 0.29).

Three quarters of an individual student's final grade is based upon their contributions to the team project. A team project grade is first developed for the major project milestones to which a contribution factor is applied to arrive at each individual student grade. The remaining 25% of a student's grade is based upon individual communication assignments that occur throughout the semester. The communication component of the grade is based upon individual deliverables and contributions to the major course milestones. Individual deliverables include:

1. Cover Letter and Resume (Pre-course assignment).
2. Technology Background Memo.
3. Impromptu Oral Presentations.
4. Mid-term Reflective Memos and Peer Evaluation.
5. Team Progress Memo.
6. Design Documentation.
7. Final Semester Memo and Peer Evaluation.

Over the course of a semester, each student is required to compose, at a minimum, the equivalent of 15 pages (typed, double-spaced) of writing. In determining the extent to which an oral presentation meets this requirement, one rule of thumb is that it can take speakers approximately two minutes to present the amount of information contained on one page of typed text. We have estimated that that individual deliverables used to fulfill the communication intensive requirement are equivalent to well over 30 pages (typed, double-spaced), giving instructors multiple repeated opportunities to observe, evaluate and provide direct feedback to students on how they can make improvements and refine their communication skills.

Major project milestone grades are based upon progress on relevant objectives that include teamwork, design methodology and project management. For each major project milestone, project teams are provided with a written narrative assessment by the chief engineer (in consultation with the project engineer) that provides a rationale for the team grade and opportunities for improvement. These written narrative assessments do not follow a predefined template or rubric, but instead are written to provide customized feedback and direction that is relevant to the unique aspects of the project and provided to student teams in the interest of facilitating their success.

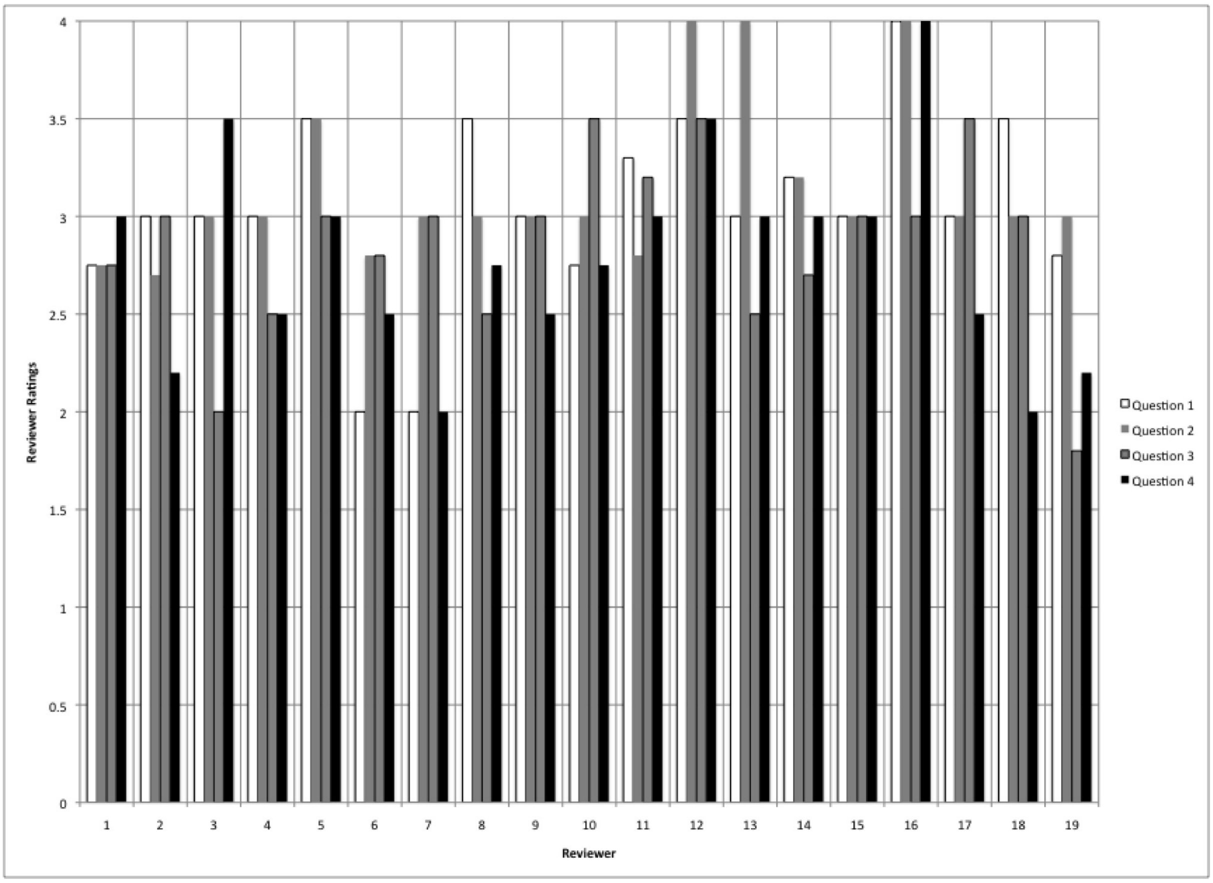

Fig. 3. Reviewer ratings for each question across all projects.

5. Analysis of changes with the 2008–09 academic year results

During the 2008 and 2009 academic year we introduced the following changes:

- Implemented Project Level Course Evaluations: Instead of organizing course and instructor ratings at a 'section' level we chose to do so by project team. This way we would be able to discern and compare consistency of team grades with team performance at the project team level and potentially account for why one team may have performed differently from another.
- Introduced Roles of Project Engineer and Chief Engineer: We assigned two instructors per project team. One instructor as project engineer would primarily take on the role of mentor and coach. The other instructor as chief engineer would primarily take on the role of evaluator and be responsible for assessing team performance and assigning a final grade for each student.
- Implemented Communication Intensive Requirements: We implemented an Institute level 'communication intensive requirement' in to the Design Lab capstone course syllabus that called for each student to compose, at a minimum, the equivalent of 15 pages of writing and for instructors (i.e., the chief engineer) to conduct individual student assessments.

Rensselaer is a participant in the IDEA program for teaching evaluation by students every semester. To gain a baseline understanding, we conducted supplementary course surveys at a project level in Fall 2008 and Spring 2009, as measured by the IDEA Diagnostic Form Report [24]. We obtained results for 15 teams in Fall 2008 and 20 teams in Spring 2009 where the average IDEA Survey response rate was 70% for a total of 168 students reporting across both semesters. As discussed next, we have used these survey data together with information from student reflective memos, to gain insights into the effects of the three course changes.

5.1 Project level course organization

Conducting course evaluations at a project team level has provided additional insight on the importance of teamwork as a learning objective for multidisciplinary capstone design [13]. Depending upon the personalities of various team members, we have found that teamwork can easily become con-

For this assignment you should reflect upon your participation on the project and comment on your key strengths and how it has contributed to the overall effort. You should also describe possible weaknesses and opportunities for improvement, the major challenges and issues faced, and what you have learned from the experience. Comment on what might have been done differently to make your learning experience more productive.

In addition, you should prepare a peer evaluation for everyone on your team. List the names of each member of your team, including yourself. For each team member you should describe their performance and contribution to the overall team effort. For each team member identify a key strength, identify an area for improvement for each team member, and suggest how this might be achieved. Finally, if you were in a position of assigning a grade to each individual on the team based upon what you have observed to date, what would the grade be? Please use the following grading system: A=4, A-=3.67, B+=3.33, B=3, B-=2.67, C+=2.33, C=2, C-=1.67, D+=1.33, D=1, F=0.

Questions that you should consider for each team member include:

1. Did they attend meetings, follow through on their commitments, and meet deadlines?
2. Were they open to the ideas of others and treat others with respect?
3. Did they share ideas and make a fair contribution to the team effort?
4. Did they have a positive attitude and conduct themselves in a professional manner?
5. Did they support the goals of the team and stay focused on project objectives?

Fig. 4. Reflective Memo and Peer Evaluation Assignment.

founded under various situations, such as, 1) No one emerges as a leader, 2) Students sit back and wait for instructor to lead, and 3) Difficult personality on the team. Using a combination of regular bi-weekly interactions during scheduled team meetings, student peer evaluations and monitoring postings in an on-line collaboration tool, we have learned over time to be very attentive to teamwork issues, especially during the first few weeks of the semester.

Using questions adapted from NSF sponsored research in assessing capstone design [6] students prepared peer evaluations at both the mid-term and the end of the semester. Concurrently with peer evaluations, each student was also asked to write a reflective memo. Both the reflective memo and peer evaluation questions were designed to force the student to think critically about their team experience. The words used for the assignment are shown in Fig. 4.

The mid-term evaluations were used to assess whether any team dynamic issues exist among students, as well as calibrating the sponsors' requirements and detecting any needs for mid-term adjustments. At the end of each semester when students were asked to reflect upon their project experience, we found strong correlations (0.78) between average team peer evaluations and instructor project milestone assessments for 20 projects across Fall and Spring semesters in which we were able to collect representative data (see Fig. 5). Data from past and future years have indicated similar correlations between team milestone grades, external design review ratings, and final semester student peer evaluations. We can also observe from the data that students tend to rate their performance higher than the milestone grades they received. However, four out of the top five teams under-estimated their performance (milestone grade > peer evaluation). The data also show that weaker teams (those receiving lower milestone grades) over-estimated their performance more than the stronger teams. These results are consistent with well-known studies about human self-assessment [10].

In the cases where student teams peer evaluation grades differed by greater than a half letter grade from their final milestone team grade, there was always a mitigating factor that inhibited teamwork. While students sometimes express concerns about team size, using IDEA [24] ratings for teams across the two semesters, we found little significant correlation (-0.1) between instructor ratings (on a 1 to 5 scale) and team size, which ranged from five to nine students per team (see Fig. 6). Our findings are consistent with prior work on the impact of team size [25].

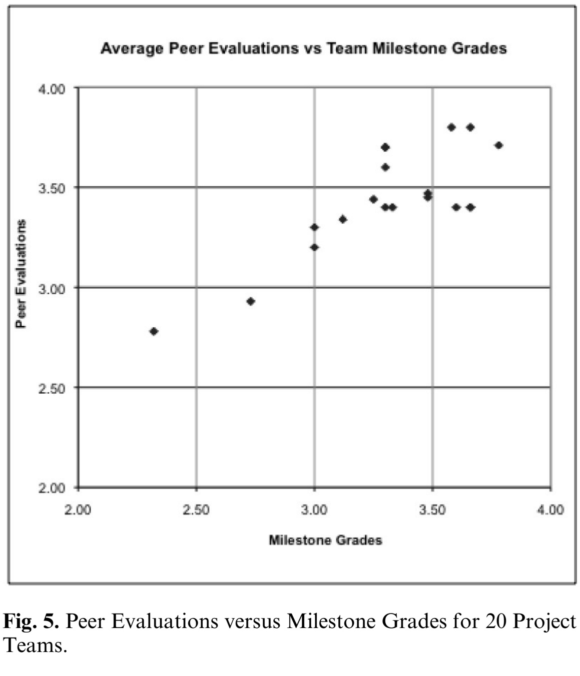

Fig. 5. Peer Evaluations versus Milestone Grades for 20 Project Teams.

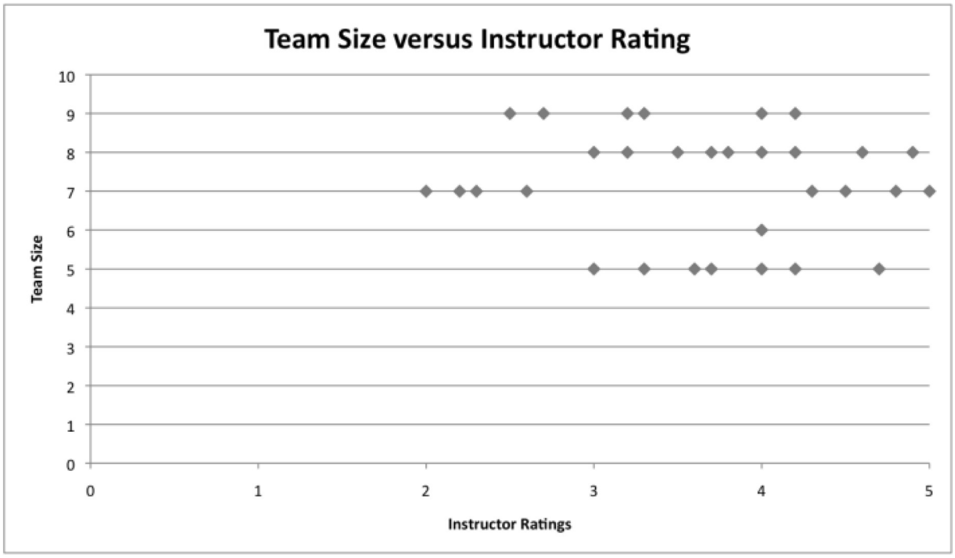

Fig. 6. Team Size versus Instructor Ratings.

We found a relatively large positive correlation (of 0.565) existed between instructor ratings and how much students felt they learned about teamwork (see Fig. 7). The implication here is if instructors emphasize teamwork (regardless of team size) and support students in this regard, this should enhance student team performance and the opportunity for them to be successful.

Teams generally focus on their own work and have little time to see what other teams are doing. In the 2008–2009 academic year we introduced project poster sessions at the midterm. The motivation was primarily to train and evaluate students on stand-up presentations using a poster as a visual aid. But this also gave students an opportunity to visit other team's posters and see how other teams performed and thereby calibrate their own relative standing among teams. In theory at least this should contribute to students getting a perspective outside of the confines of their team on what the expectations are for superior performance.

5.2 Separation of the roles of project engineer and chief engineer

As mentioned earlier, we have established two-person instructional teams consisting of a 'mentor' or project engineer and an 'evaluator' or chief engineer. The chief engineer is the person who is ultimately responsible for determining team and individual student grades. The chief engineer has a

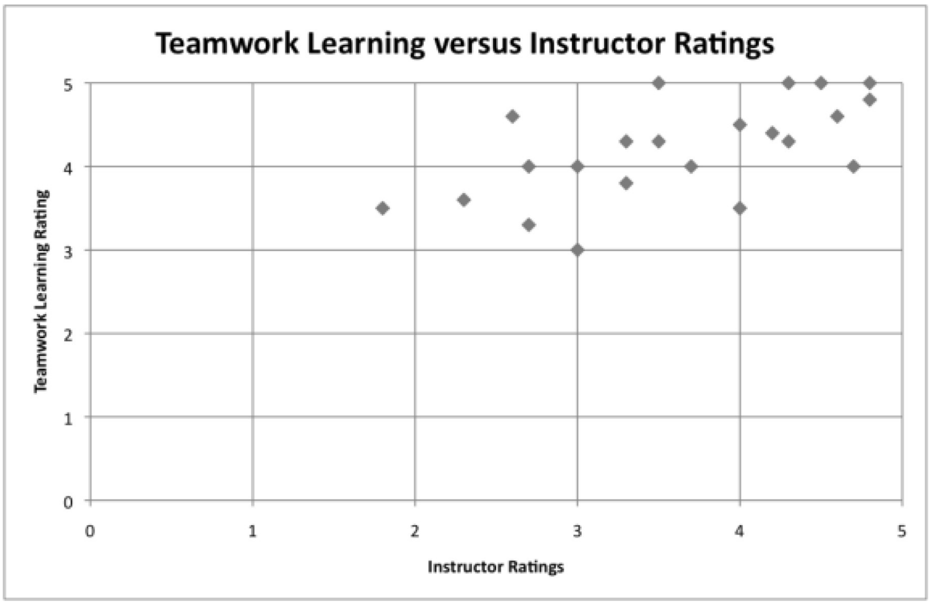

Fig. 7. Teamwork Learning versus Instructor Ratings.

teaching role, in addition to being primarily responsible for assessment. But the chief engineer performs this teaching role from a position similar to that of the professor in a conventional course. By contrast the project engineer dedicates a greater portion of their time to supporting student success and virtually no time to assessment, other than to share insights with the chief engineer. The project engineer is freer to assume the position of a key team player, rather than an outside judge.

The chief engineer provides feedback on both team and individual course assignments. In addition, the chief engineer conducts regular one-on-one project update reviews with individual students throughout the semester. In addition to providing an opportunity for feedback on performance, these give students practice in summarizing project progress and their own contribution for visiting upper level managers as frequently occurs in real-world organizations.

Having these two-person instructional teams achieves two basic goals: 1) Offering multiple perspectives and experience backgrounds to share with students, and 2) Minimizing conflict of interests between working with students and evaluating them. A basic concern about this design is that having multiple 'faculty advisors' in a team teaching environment could be confusing to students and potentially present a conflict of views between the advisors. However, our experience over the entire period and since the change was implemented has been that this new arrangement has worked well for students and confusions rarely occurred. We would like to attribute the success to the spirit shared by both the faculty and the students that they make necessary adjustments to achieve the project goals, including both educational and sponsors' objectives.

The students' team spirit of project success generally set the tone for all grades. This single, common measure helps faculty advisors cultivate team spirit and promote teamwork. Sidebar discussion is a technique commonly used by the faculty to bring individual students on board if they are being observed as lacking in their performance and/or teamwork. However, peer pressure has proven to be really effective in this regard. Faculty only needs to steer and smooth out rough edges when they are observed, rather than having to carry the whole team on their shoulders.

A major benefit of the team teaching approach becomes the opportunity to have multiple perspectives and a larger experience base to share with students and to collect assessment data. The introduction of the evaluator role facilitated our ability to implement our communication intensive requirement thus permitting focused assessment on individual students. To date, there have been no student comments about the team teaching arrangement in end-of-the-semester-course surveys and few students contesting their final grades. Because of the multiple inputs used to arrive at final student grades, it has become a relatively easy matter to explain grading rationale, look back upon the factors contributing to an assessment, and obtain resolution when questions arise.

5.3 Communication intensive requirements and grading rubrics

Rensselaer instituted the campus-wide communication intensive requirements, which the capstone course adopted, to help ensure that students are able to communicate effectively in a variety of media (written, spoken, visual, electronic) and in a variety of genres (reports, proposals, etc.). The communication intensive requirements were accompanied by a set of guidelines that were developed almost ten years ago by faculty in Rensselaer's Department of Language, Literature and Communications based on their research of the field. The guidelines are a synthesis of work in rhetoric and composition, filtered through the faculty members' own experiences as teachers of writing. Whatever the medium and genre, the communication intensive guidelines insisted that students should be able to:

1. Understand the context in which they are communicating:
   (a) Identifying the goals of and audience for their communication.
   (b) Using their understanding of goals and audience to choose appropriate media, language, and content.
2. Organize their work:
   (a) Establishing a clear structure or principle of organization.
   (b) Creating effective introductory and concluding passages in which they identify their main point and set their work in a larger context.
3. Develop content appropriately:
   (a) Displaying a clear ethical sensibility (e.g., reporting data accurately, citing sources of information).
   (b) Asserting and elaborating on claims using evidence and reasoning that are appropriate for their audience and their discipline/profession.
   (c) Addressing the questions and/or topics that are essential for success with a given assignment.
   (d) Understanding, and, as appropriate, applying principles of visual communica-

tion (graphs, charts, animations, pictures) in their written or spoken work.

4. Edit their written work carefully:
   (a) Observing the conventions of Standard English (e.g., correct usage, sentence structure, spelling, and punctuation).
   (b) Observing the conventions (e.g., terminology and page format) of a particular discipline or workplace.

From these general guidelines we created grading rubrics for each specific individual assignment that reflected the intent and satisfied the objectives of the communication intensive requirement. Table 1 shows an example of such a rubric for the technology background memo.

Overall results from implementation of the communication intensive requirement were greater insight into individual student performance on the part of instructors. The grading rubric facilitated consistency in grading, clear feedback to students and grading productivity for instructors. With five instructors reporting their average grade for the technology background memo for a total of 141 students in Fall 2010 we had an average grade of seven out of ten points and standard deviation of a half point (0.5). We have noticed over the past couple of years since we implemented the communication intensive requirements that overall project results have improved, which we believe can be attributed in part to real time monitoring of artifacts posted on our on-line forum.

6. Summary: Observations and recommendations

A continuous improvement effort is reported which redesigned the pedagogy of a multidisciplinary capstone design course implemented at Rensselaer over the past ten years. This effort expands and improves upon the previous works reported in the field [20–23]. The pedagogy embraces a 'holistic' approach, signifying the focus on teamwork, communication, and the design process. However, 'holistic' here also signifies multidisciplinary instructional teams evaluating students on the whole of their performance. The paper elaborated on how this holistic approach is implemented in the new pedagogy, including in particular how our assessment methodology employs a broad spectrum of inputs from a variety of sources. Collectively these inputs provide confidence in our final grades with regard to student understanding, application of appropriate use of the design process, teamwork, communication, and overall contribution to project success.

The new pedagogy was monitored and analyzed since its introduction in the 2008–2009 academic year, and all indications so far (over four semesters) have pointed to its success. Empirically, there have

Table 1. Grading rubric for the technology background memo

	Excellent	Good	Fair	Poor
Structure, Style and Editing	The work is well structured, including introduction and conclusion sections, with appropriate style and is free of errors in language. (2.0)	The structure and style are appropriate with few errors in language. (1.5)	The work includes all elements of a memo but contains distracting style and editing problems. (1.0)	The work is not written in an appropriate memo format and contains numerous style and editing problems. (0.0)
Useful information content	Contains much useful information critical for moving forward with the project. (4)	The memo is thorough and contains useful information. (3)	The memo contains some useful information (2)	The memo is not useful and/or too brief. (1)
Organization and logic	Information is well organized with insights and implications for project decisions clearly defined. Appropriate visual elements, such as Tables and Figures, are used. (2.5)	Information and implications are there, but require some effort to discern the implications for the project. Appropriate visual elements, such as Tables and Figures, are used. (1.5)	Information and implications misinterpreted or very difficult to discern (0 .5)	Poor organization of information; project implications unclear (0.0)
References and Citations	All information is cited in text, and the sources are correctly documented so that follow-up to the original sources is straightforward. (1.5)	All information is cited in text, and some information sources, such as information obtained from the Internet, are not correctly documented. (1.0)	Some information sources are not documented. (0.5)	No information source is presented. (0.0)

been few (if any) complaints from students or the faculty— at least much less than before the implementation of the new program. Anecdotally, many sponsors as well as students and faculty have praised the quality of work that these projects have delivered under the new pedagogy. We are continuing our effort of data analysis in the spirit of continuous improvement.

Overall, we would recommend that a similar approach be considered in other engineering programs for multidisciplinary capstone design courses. In this spirit, some lessons may be worth mentioning: We have found that project level course administration is important, since it offers the opportunity to maintain greater consistency and share lessons learned from one project team to another. Separating mentor and evaluator roles is effective in maintaining clarity in technical advice and in performance evaluation in the context of multidisciplinary project-based learning. Communication intensive assignments provide insight and resolution into the critical thinking of individual students.

Looking forward, we note that the current design as presented herein could and should be further improved. First, as the ABET continues to up the ante on the broader issues facing engineering education, such as social awareness and the cultivating of an 'analytical mind' in a liberal arts sense, the design of capstone design courses needs to strive toward a new level in these areas. Next, as real world engineering design problems become increasingly cutting edge, as evidenced by the advanced nature of design projects bestowed on the Design Lab in the past two years, capstone projects offer an opportunity to better align with faculty research. In this way, capstone projects may provide the so-called undergraduate research experience in the same time they instill engineering design.

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