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Student-Generated Metrics as a Predictor of Success in Capstone Design

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Student-Generated Metrics as a Predictor of Success in Capstone Design

Measure what is measurable, and make measurable what is not so. ~Galileo Galilei

The Capstone Design sequence in the Mechanical and Industrial Engineering program at Northeastern University has a longstanding emphasis on building prototypes to solve real-world problems sponsored by industry and research faculty. Industrial Engineers (IE), by the nature of their discipline, often work on problems that do not involve a physical object. Instead, the deliverables may be simulations, facility layouts, procedural modifications, databases, or other processes or products less tangible than a physical prototype. Previous work by one of the authors presented a validated scheme for assessing Mechanical Engineering (ME) solutions based on examination of the Executive Summary document written three weeks before the end of the Capstone course. For the present work, this same evaluation scheme was applied to the Industrial Engineering projects presented during the past seven years. The goal was to determine whether particular student skills or practices led to higher quality projects with an eye toward enhancing those skills in struggling groups.

Data shows that high performing groups tend to develop more specific and trackable metrics in the early stages of the project, by which they will define success. Quantifiable goals and specifications and/or numerical results were also evident in all of the highest performing groups. In contrast, lower performing groups –as measured by the executive summary evaluation metric– tended to have vague or ill-defined specifications, or did not apply numerical goals or evaluation practices to their design problems. This indicates that more guidance into developing numerical goals with identifiable and trackable performance metrics –particularly in the problem formulation phase– would allow groups to have a more concrete target to aim for.

Results from additional analysis showed that IE groups who worked on joint projects with their Mechanical Engineering counterparts performed at or below average as measured by the same objective rubric. Project evaluation, observation, and anecdotal evidence indicate that additional guidance is needed to guide students into working in a transdisciplinary mode, in which the students become fluent in each others' disciplines. In addition, we can encourage our IE's to be stronger advocates for the design elements related to process and interface configuration. These concerns are noteworthy as interdisciplinary projects are becoming more common and more fitting, both in the department of interest and throughout the engineering community.

Evidence from this study will be used to open a dialog and help faculty (1) develop specific a priori guidelines and in-process interventions to manage the interplay among interdisciplinary engineering students in future projects and (2) guide teams toward potential success through rigorous and timely definitions of achievement metrics, and (3) collectively with their teams develop the expectation of success through mapping performance to achievable goals. The aim is to not only avoid marginal performance, but to foster successful outcomes across the board.

Introduction

Capstone design courses are nearly universal in engineering programs, although the exact form of this program component varies widely. Past national surveys have shown an increasing number of multidisciplinary teams and a general consensus on key topics that are important to capstone design.[1,2] These surveys and additional reviews of the capstone literature point to a need for students to develop and use strong group and project management skills, to properly define their problems, and to be able to defend their work in terms of process and solution.[3]

According to a 2005 national survey of engineering faculty, writing functional specifications is specifically taught by 56% of the survey respondents. Some measure of evaluating students for how well they achieved the goals is also commonly mentioned in these wide ranging surveys. There is a great deal of variation on whether these goals and specifications are developed by the students alone, the advisors, the project's outside sponsor, or some combination. The ability of students to grasp the importance of a clear path forward for their design, as well as metrics by which to judge success, is key to the successful completion of a capstone design project.

Industrial engineering programs in particular have also been reviewed with a focus on understanding which course models are most effective for teaching industrial engineers.[4] Although no definitive model has been determined to be the best, certain common course features have been identified. Industry-sponsored projects were very common, and indeed the prevalence of these types of projects is increasing in other engineering disciplines as well.[2] In addition, most teams described were composed of only IE students. This was also seen in the national survey, as the percentage of IEs in multidisciplinary teams shrank from 17% to 4% between the 1995 and 2005 surveys.[1,2] The IE survey focused on the inclusion of professional engineering exam topics in capstone design, but did not look at the details of teaching specification writing, project management, and team functioning skills that have been discussed more generally elsewhere.

Although IE seems to be somewhat absent in the larger surveys, there are nevertheless a number of researchers discussing best practices in industrial engineering capstone design. Daniel *et al.* focused on ABET outcomes, rather than professional engineering exams, as a means of improving their capstone design course.[5] This particular program both required their students to *identify measureable objectives* and specifically included the "*ability to state the problem and the constraints*" in the rubric by which the projects were assessed. It was found that the scores on this particular measure were acceptable, but not exemplary based on their data. This may indicate that requiring objectives alone may not always translate to producing quality objectives. Other schools have attempted to use IE tools such as project management, Lean, and Six-Sigma as means to teach and improve their IE capstone design process and outcomes.[6] Although this research is ongoing, they did find that weak objective creation in the early stages of the project led to groups being disconnected from their sponsor, leading to poor performance.

Measureable goals and targets seem to be particularly important when it comes to interfacing with industrial partners. With the majority of industrial engineering capstone initiatives featuring partnership with industry, best practices for working with industry have been studied by numerous authors. Needy and Bidanda discuss how they managed their industrial partnerships by requiring a *statement of deliverables* to be produced by the students and signed by the advisor.[7] However, they did not specifically outline how objectives for success are generated, and it seems that the student teams are primarily tasked with satisfying the industrial customer, rather than developing independent metrics. Another paper discusses a longstanding IE capstone design course, with an emphasis toward securing industry funding.[8] A key point is that all involved need to have a *clear stake in the project*. Outside consultants, whether they are other students, a shop to build a prototype, or some other source of information, can sink a project if it is not their priority. This uncertainty in working with industrial partners is addressed in a number of ways in the literature. It seems that in many cases that rigid definition of scope is used to help mitigate the uncertainty.[9] However, this can potentially lead to a lack of innovation and diminished creativity among the students, or not allow much leeway in case of unexpected changes.

As noted, industrial engineering projects are not as likely to result in a physical prototype as mechanical or electrical engineering projects would. Because their 'prototypes' are more likely to be plans, processes, or data mining/simulation results, it can be difficult for IE students to easily integrate into multidisciplinary teams. Kroll *et al*. discussed two different scenarios, one successful, one less so, in which IE students partnered with non-engineering students.[10] IEs who partnered with physical therapy students were generally successful, which the authors attributed to *good advisor communication* and *clear guidance to define roles*. The successful groups demonstrate what Park and Son refer to as '*transdisciplinary*' behavior[11], whereby the students learned new information outside of their discipline to synthesize a solution that encompassed both disciplines. IEs who partnered with Teacher Education students, on the other hand, had a less successful experience due to poor role definition, marginal communication between the disciplines, and a lack of positive interdependence. Each discipline did not seem to know why the other was there, and saw no real need to synergize. Given the unique challenges of IE projects, it is clear that guidelines are needed to not only foster success for IEs in isolation, but also to promote successful interactions between IE students and other disciplines in the capstone design arena.

Capstone Design in Mechanical and Industrial Engineering (MIE) at Northeastern University

At Northeastern University, the Senior Capstone Design program consists of a two-semester sequence which is required for all senior students in MIE. Students work in self-selected teams of 3-5 students, each with an assigned faculty advisor. Project problems can originate from faculty members or from industrial sponsors. In Industrial Engineering, the projects tend to fall into one of four primary categories: healthcare (either office or hospital based), industrial (manufacturing or process-related), service learning, or educational systems. A small number of projects over the past several years have been expressly designed to be multidisciplinary. This may take the form of IE and ME students joining forces on the same team, or an IE team and an

ME team working in parallel on different aspects of the same project. For example, in the most recent offering there were 17 strictly ME groups, 8 strictly IE groups, and 4 groups that contained multiple disciplines. One ME team and one IE team were working in parallel on different aspects of a common project. This project intentionally focuses on the IE and IE hybrid teams, as the ME teams have been studied previously.[12]

During the first capstone term, the students are expected to conduct background research on the company and relevant IE tools, search the literature for related problems, and come up with a detailed problem statement and project management plan. At the end of the first semester, students produce both a written and an oral report outlining the problem and laying out their plan for the remainder of the project and their own goals and metrics for success.

During the second semester, the students are expected to carry out their plan with the goal of developing a deliverable solution by the end of the course. As described above, these solutions may include facilities layouts, database schemas with user-friendly interfaces, product development of medical devices, methods for reducing queue times, and other IE outcomes as appropriate. The solution is expected to be verified by real world testing and/or simulation. Two update presentations and reports are required during the course of the second term. In addition, a five-page executive summary is due two weeks prior to the end of the course which provides a snapshot of the completeness of the project at that point. The final presentation consists of an oral presentation and a poster session judged by an alumni jury. The final grade is determined by the advisor, course coordinator, and technical writing consultant based on technical communication skills, how well the design satisfies the specifications, attendance and weekly progress reports, project management, and demonstration of a clear design process. This course model is consistent with similar courses reported by the literature.[2]

Motivation and Methods

The motivation for this study came from a realization that there was a diversity of outcomes in terms of the IE projects in the capstone design course. Some projects were clearly runaway successes, while other teams clearly struggled. In particular, there seemed to be difficulties when it came to IEs working in interdisciplinary teams. A review of the team composition, gender, cultural background/nationality, and GPA revealed no clear patterns in student capabilities in terms of previous success in coursework. It was hoped that by examining factors and outcomes of these past projects, it would be possible to zero in on the unique challenges posed by IE projects, and come up with recommendations for interventions that would set the IEs up for more certain success. There is also a need for guidelines to allow multidisciplinary groups to take advantage of the unique capabilities and skill sets of IEs without the IEs being overshadowed.

In order to study these concepts, past projects were examined going back to 2007. The executive summaries were scored based on a modification of a rubric developed previously by one of the authors.[12] This modified rubric allotted 5 points for the design solution and 5 points for the testing and verification of this solution, as show in Table 1 below. A solution that was fully developed and tested would receive a score of 10. Because the executive summary is due two weeks prior to the end of term, in order to send it out to the alumni jury in advance of the final presentations, it also provides a check on how well the groups are managing their projects. Well managed projects are generally closer to completion, and have time to do last minute improvements. Scoring was accomplished by detailed review of the executive summaries.

Table 1: Capstone Executive Summary Scoring Rubric.

Solution Score	Verification score
5 = Fully developed solution	**5** = Fully verified and validated
4 = Solution partially developed	**4** = Verification substantially done
3 = In progress, solution expected by course end	**3** = Verification planned and in progress
2 = Solution in progress, unlikely to meet all specifications by end of course	**2** = Verification planned, unlikely to be complete by end of course or not started
1 = Working solution unlikely by course end	**1** = Verification not discussed or planned

In addition to the executive summaries, the final reports were evaluated to determine which groups developed clearly defined measures for success. This was done in order to see if there was a correlation between high executive summary scores and well-developed specifications and metrics. The results were also examined to look for patterns based on type of project (healthcare, industry, service, or education) or type of group (IE only vs. multidisciplinary).

Results

Team Composition. A total of 46 projects were examined. The team composition in terms of IE only vs. multidisciplinary is shown in Figure 1 at 89% versus 11%, respectively. This number of multidisciplinary teams is slightly less than the 14% average found by Bauer *et al*.[4] According to a chi-square analysis, this is a representative ratio in accordance with the established profile of IE-related capstone, as shown in Table 2.

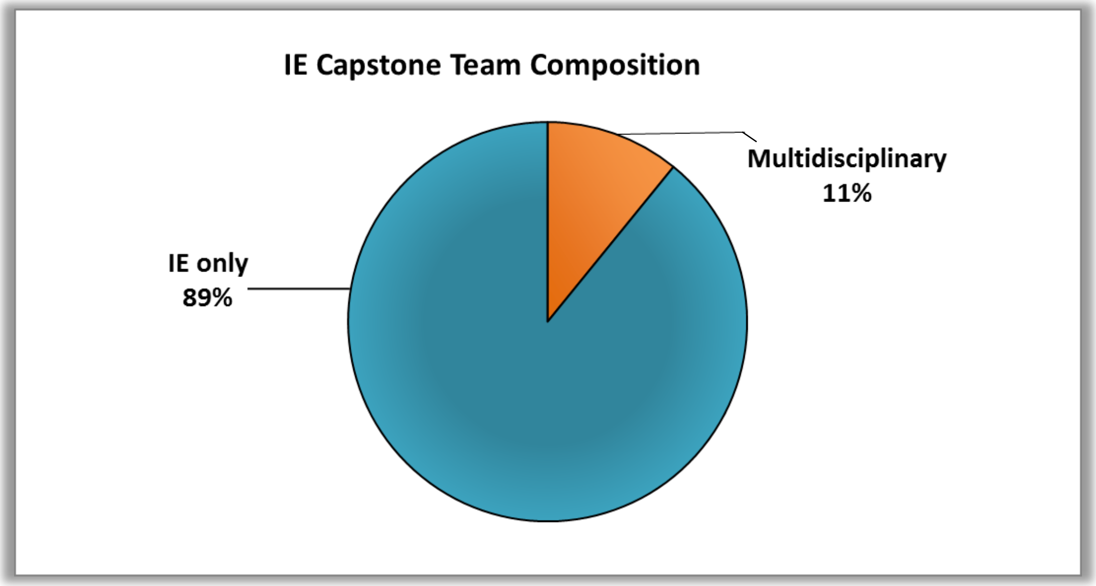

Figure 1. Percentage of multidisciplinary teams in Industrial Engineering Capstone since 2007.

Table 1. Team Composition in Industrial Engineering Program, recent and established.

TEAM PROFILE*	IE Only	Hybrid	Total
Observed, Current Set	41	5	46
Expected, Established	39.6	6.4	46
**Chi-Square calculation: $\chi^2 \rightarrow 0.3873$ - Sample is representative in composition*			

Project Type. Figure 2 shows the percentage of projects in each of the general IE categories. The ‘Healthcare’ category can include both hospital-based processes and individual office practice as well as data mining problems. The ‘Industry’ category encompasses both traditional manufacturing and process/service-oriented industries. ‘Service learning’ projects are generally working for local nonprofit organizations. ‘Education’ projects may involve designing laboratory experiments for IE classes, assisting with scheduling and resource allocations for various university clients, or other education-related problems.

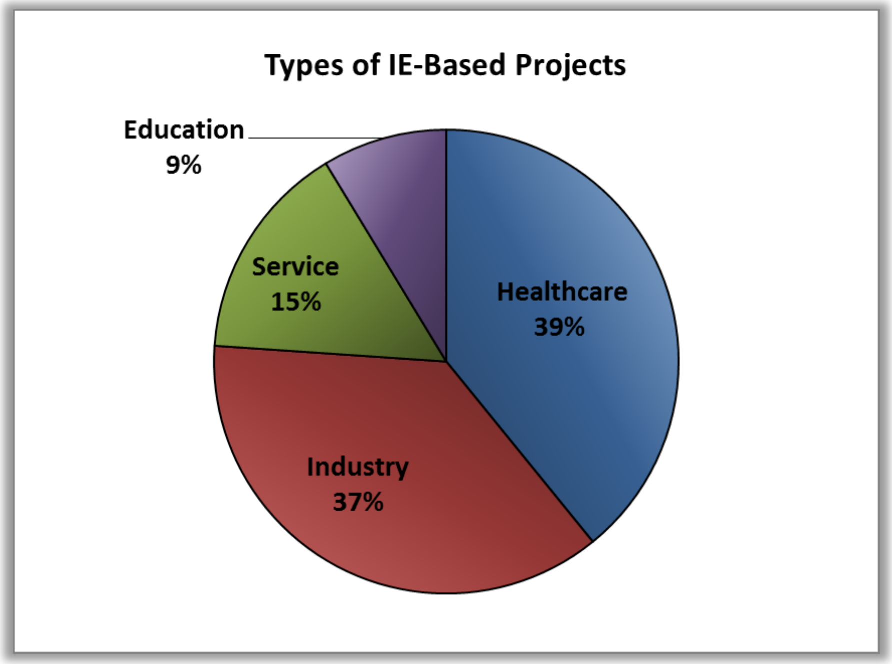

Figure 2. Breakdown of Industrial Engineering project categories since 2007.

Average compound executive summary scores (solution and verification combined) for the four general project types are shown below in Figure 3. A single-factor ANOVA detected differences among the project categories on compound executive summary score, [F (3,41)=10.65, p=0.039]. Sheffé's *post hoc* method was applied for pairwise comparisons[13]. The lowest scores were found in the Education category, statistically different from all other project types at or below p<0.02. These were the only statistical differences detected when comparing project classification scores. The Service Learning projects tended to score the highest, very similar in score profile to the Healthcare and Industry categories.

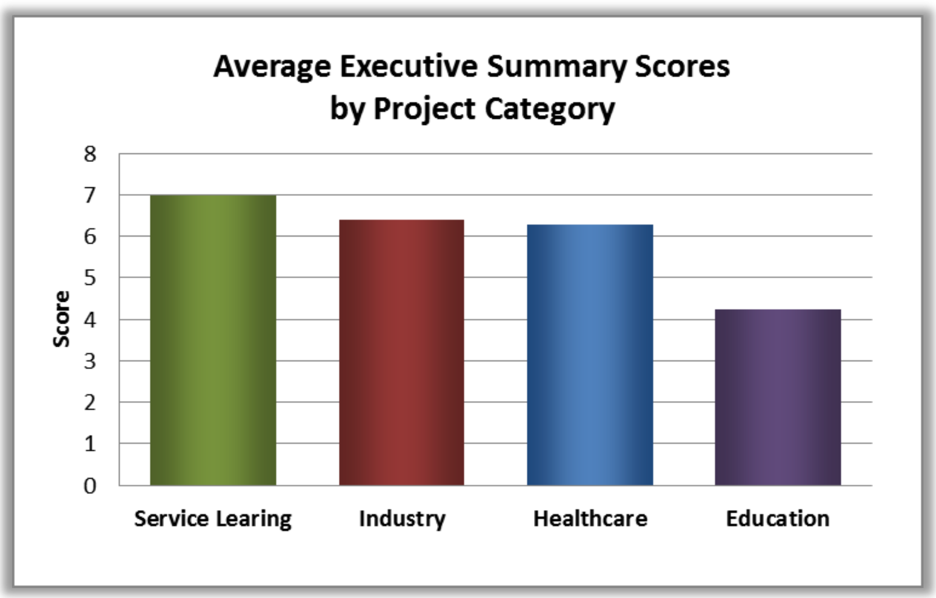

Figure 3. Average Executive Summary Scores by Project Category

Established Success Metrics. As stated previously, the reports were examined for evidence of clear metrics outlined for project achievement. Successfully specified metrics had outcomes that were measurable, numerical specifications where appropriate, clear schemes for quantifying more qualitative results, and mapping of the final results to the originally specified goals. Table 2 below shows the results of this examination. The average score for the groups that failed to develop clear metrics was statistically lower than those that did develop strong metrics. It was encouraging to see that more than half of the groups examined did develop clear metrics, and that this contributes to in more complete projects that fulfill the established goals.

Table 2. Comparison of groups with and without metrics

PROBLEM FORMULATION STATUS	Number of Capstone Groups	Average Executive Summary Score*
Groups with clear metrics	27	7.3 $\pm$ 2.28
Groups without clear metrics	19	4.8 $\pm$ 1.71
**Significantly different, p<.001*		

Team Composition. The average compound executive summary score for teams that were comprised solely of only IE students was found to be 6.4, while the average total score for multidisciplinary teams was 5.2. This difference was found to be statistically significant, $p<0.05$. This aligns with the observation that these teams typically struggle to finish their projects successfully. Table 3 below provides a closer look at these interdisciplinary projects. The patterns seen across this sampling are as follows: (1) lack of defined metrics, (2) educationally based projects, and/or (3) hybrid teams, with the two lowest performing groups having IE and ME students combined on the same team.

Table 3: Multidisciplinary projects. Projects labeled as 'parallel' were working on one aspect of a larger project in parallel with an all-ME team.

PROJECT TITLE/Topic	Project Type by Category	Executive Summary Score	Clear Metrics?	Combined or Parallel	Ratio: #IEs/#MEs
Energy Efficient Room	Industry	6	No	Parallel	5/0
EC Window Energy Optimization	Industry	6	No	Parallel	4/0
Advanced Vehicle Seat Design	Education	6	Yes	Combined	2/2
Classroom Lab Flexible Mfg System	Education	4	Yes	Combined	2/2
Photodynamic Therapy Delivery System	Healthcare	4	No	Combined	3/2

Discussion with Select Case Examples

Team composition and project classification have been shown to have an observable effect on the success of Capstone projects, What is remarkably clear, however, is that guiding students to generate specific, measurable goals for their projects is key to success for teams regardless of their membership profile and project type. This begs the question: *What prevents groups from doing this*? All teams are exposed to the same curriculum and project management information. All teams have been held to the same Capstone milestones and all group members have had practice in design in their freshman curriculum and through the Engineering Program. Observation and deeper inquiry has revealed that much of the difficulty can be traced to the primary issues described at the outset of this paper. Namely, issues are created by (1) the process-based nature of many IE problems when goals are not addressed creatively and assertively, and (2) the challenge of balancing multidisciplinary alliances when multidisciplinary team synergy is not addressed creatively and assertively.

The intangible nature of IE projects is well-established. What is also becoming clearer is that IE problems possess a less structured solution path in terms of steps and requirements as compared to other majors in which a nearly universal design progression and specification outline can be applied and followed. Case examples below illustrate this feature in which the outcomes were affected by the goal-setting approach.

Case Examples. To illustrate the "IE challenge", take the example of a particularly low scoring team which was charged with developing an inventory management system for an electronic distribution company. The goal was to provide tools for a growing company to manage expanding inventory through the use of a redesigned system that was user-friendly and adaptable. The design requirements were fairly generic such as 'provide accurate inventory traceability'. There was, however, no indication of what this accurate inventory traceability would look like or how they would know it had been achieved. There was a desire to have a system that could be accessed by multiple users, but no indication of how many at once. They wanted to 'provide data metrics' without ever specifying what data was to be gathered. In the end, they did come up with a basic barcode system for the clients, but never verified that the system would work as intended, either physically or with simulation. This group would have benefited from additional interventions to prompt them to emphatically quantify their measures for success earlier in the process.[14]

In contrast, one of the highest performing IE groups was tasked with optimizing patron flow at Terminal C of Boston Logan Airport. This group did an excellent job of innovatively measuring qualitative information. For example, the subtask of reducing passenger misorientation in the terminal was quantified by counting the number of times customers stopped to ask directions before and after various changes were made. Designs for queue layout had clear requirements and boundaries, and were numerical wherever possible. The group came up with a multifaceted solution with several options based on various contingencies. The solution was verified both by simulation and by physical observation at the airport. This was a group that consisted of highly motivated and driven students, which may have been a factor. However, it was noted that their clear metrics allowed them to have sound and readily available answers to "Have you considered…?" questions in presentations, and allowed them to narrow down a very large and messy problem to one that was solvable.[15]

Interdisciplinary groups involving IEs are growing in number, but have been problematic in the past. In the authors' experience, this seems to be a combination of *problem framing*, *group management*, and *goal-setting* difficulties. An example was a group charged with developing a flexible laboratory for teaching manufacturing systems. This involved two IE students and two ME students. The idea was that the IE students would use their expertise to determine what type of experiments and layout of machines would best teach the IE principles, while the ME members would design and build machines in the specified configurations to demonstrate the principles. In the end, the IE students' recommendations were to purchase existing machines, restricting the ME portion of the design to a conveyor 'bridge' between machines. Because the specified off-the-shelf machinery was well beyond the price range of the project, the group felt that in the end there was nothing they could do to implement any portion of the project. Moreover, although it was meant to be a multi-phase effort, there was no clear or measurable description of what success for this particular phase would look like.[16] Both sets of students ended up feeling hamstrung and unable to make any meaningful contribution to the problem. This desire to have an impact and make difference is a driving force for many teams, but the problem seemed amplified by the lack of synergy and communication between the two disciplines.

Curricular Considerations. In examining the past projects, a disconnect has been identified between the curriculum and the projects assigned. The main focus of the curriculum tends to be geared toward traditional manufacturing industry. Students take courses on manufacturing systems, logistics, supply chain concepts, and quality assurance. However, only 37% of the IE projects typically fall into the typical manufacturing category. Some exposure to service learning occurs during the freshman engineering sequence. Healthcare systems are covered in some electives, or used as an example in some of the more general courses such as simulation and modeling, but make up 39% of the capstone projects. This lack of domain exposure to the unique problems of healthcare and service organizations may make it more difficult for some groups.

Conclusions and Recommendations

The recommendations which have come out of this study can be applied to a wide range of capstone groups, IE, hybrid, and otherwise. These include:

- Mentoring students to develop numerical, specific metrics for success including plans to quantify qualitative elements of their solution.
- Developing detailed rubrics for evaluating the student generated metrics and evaluating these early in the design process.
- Encouraging students to be creative and assertive in the early stages to own and outline the process and its measurable milestones and to measurably define what success will look like.
- Providing additional domain-specific seminars and orientation sessions to address project types that do not get extensive coverage in the standard curriculum.
- Developing guidelines for interdisciplinary groups involving IEs that take advantage of IE's unique skill sets.

Student metric generation is taught in the first-year design course, but may not be specifically required throughout the curriculum. This skill could be included and emphasized with term projects in a number of courses in the IE curriculum, and efforts should be made to do so. However, in the context of capstone design, providing students and advisors with detailed rubrics that demonstrate what 'good' metrics could guide more groups toward a clear path forward for their projects. This type of information could benefit capstone projects in almost any discipline.

Multidisciplinary projects involving IEs can benefit from their knowledge of process development, designing for human factors, designing for quality control, their expertise in simulating stochastic outcomes, and their knowledge of design for manufacturing. However, a successful hybrid IE project needs to foster interdependence and transdisciplinary thinking between the IE students and their partners. It is not enough to have the ME's, for example, design a physical prototype in one room while the IEs develop protocols for using this device in another room. MEs must be introduced to the key relevant IE principles, and IEs must learn what can and cannot be built. Both disciplines must become proficient at jointly generating and adopting measurable design specifications.

The challenge of fostering transdisciplinary learning and the problem of projects that are not well represented in the curriculum can both be addressed by developing targeted domain-based seminars on these less familiar project types. A seminar on working in the healthcare industry, for example, would lay out requirements for understanding the metrics of medical practice, working with patient data, learning typical expectations of healthcare professionals, outlining FDA regulations and limitations, and other information that could bring both IE and ME students onto the same page. Similar short seminars could be developed for service learning and product development, both of which are only nominally served in the curriculum. Currently an IE professor is already responsible for presenting Project Management information to both groups, but having ME professors teach the IEs about beneficial topics such as rapid prototyping would open new channels of inquiry that would allow IEs to speak the ME language more effectively. Similar cross-disciplinary seminars or presentations could be imagined for a large number of disciplines and combinations of disciplines to set up our capstone teams for more certain success for all constituents: their organizational clients, the university, the program, and themselves.

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