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Using Capstone to Drive Continuous Improvement in the Curriculum

Dr. Mark W. Steiner, Rensselaer Polytechnic Institute

Mark Steiner is Professor in the Department of Mechanical and Aerospace Engineering (MAE) in the College of Engineering and Computer Science (CECS) at the University of Central Florida (UCF). He currently serves as Director of Engineering Design in the MAE Department. Mark previously served as Director of the O.T. Swanson Multidisciplinary Design Laboratory in the School of Engineering at Rensselaer Polytechnic Institute (RPI) and Professor of Practice in the Mechanical, Aerospace and Nuclear Engineering department from 1999 to 2015. He also worked at GE Corporate from 1987 to 1991, consulting and introducing world-class productivity practices throughout GE operations. In 1991 he joined GE Appliances and led product line structuring efforts resulting in $18 million annual cost savings to the refrigeration business. Later as a design team leader he led product development efforts and the initial 1995 market introduction of the Built-In Style line of GE Profile refrigerators. His last assignment at GE Appliances was in the Office of Chief Engineer in support of GE's Design for Six Sigma initiative. Dr. Steiner has taught advanced design methods to hundreds of new and experienced engineers. His research interests include; design education, product architecture, mechanical reliability, design for manufacture and quality. Mark graduated from Rensselaer with a B.S. in mechanical engineering in 1978 and a Ph.D. in 1987.

Prof. Junichi Kanai, Rensselaer Polytechnic Institute

Junichi Kanai received a B.S. in EE, and a Master of Engineering and a Ph.D. in CSE from RPI (Rensselaer Polytechnic Institute) in 1983, 1985, and 1990, respectively. He was an Assistant Research Professor at the Information Science Research Institute, University of Nevada, Las Vegas, from 1990 to 1997. Dr. Kanai joined Panasonic Information and Networking Technologies Lab in Princeton, NJ in 1998. He was a senior scientist developing and transferring new technologies to Panasonic product divisions in Japan. He was also responsible for managing his groups' patent portfolio. From 2002 to 2004, he was a manager at the system group of Panasonic's sales company in Secaucus, NJ providing system integration and software development for clients. He was also an Export Control officer. Dr. Kanai joined the Design Lab at RPI in 2004. He is currently the Associate Director of the lab and and Professor of Practice of in the Electrical, Computer, and Systems Engineering department. The Design Lab provides industry sponsored and service oriented multidisciplinary design projects to 200 students/semester. His responsibilities include managing the operation of the Design Lab and enhancing the experience for students working on engineering design projects.

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Abstract

Capstone is intended to be a proving ground for students to demonstrate that they are prepared for professional practice. Accordingly, this paper addresses the problem of how capstone can provide feedback and thereby continuously make improvements to the engineering curriculum. A progressive model for hierarchically prioritizing student outcomes and mapping them to direct metrics related to the curriculum is presented as a mechanism for generating feedback. The model is used to highlight areas of engineering education where significant opportunities exist for improving the preparedness of our students for capstone and ultimately for professional practice.

Keywords: engineering education, capstone, culminating experience, ABET, continuous improvement

1. Background

In the late 1980's and early 1990's industry leaders started to recognize that with globalization and advances in computer technology, the world was getting more interconnected, complex and quicker. To compete in a rapidly changing world they needed a new breed of engineering students, who could literally hit the ground running upon graduation. In addition to excellent technical knowledge and skills they also needed graduating engineering students with abilities to productively work on multidisciplinary teams. This meant that they needed to have young engineers who could effectively communicate with a broad cross-section of people [1].

In response to industry demands, ABET developed a new approach to accreditation with ABET 2000. The new approach had striking similarities to quality certification processes being implemented by the International Standards Organization with ISO 9000 [2]. ABET 2000 was less prescriptive in terms of course content. A centerpiece of ABET 2000 was a broad set of learning outcome criteria and the implementation of a culminating design course, which was established to help assess whether our young engineers met the student learning outcomes set out by the criteria and to provide students with an open ended design experience given multiple realistic constraints, much like they would experience after they took their first engineering position [3].

Most undergraduate engineering programs have now been through several iterations of the ABET 2000 accreditation process, which normally occurs in six-year intervals. After fifteen plus years of functioning under the ABET 2000 criteria it seems appropriate to reflect upon the changes and consider the results. This paper focuses on a review of the engineering curriculum, an overview of accreditation, the role of capstone in the curriculum and finally a new model for capstone in relationship to the curriculum. A hierarchical ordering of student outcomes is presented with examples of possible direct measures.

2. Status of the Engineering Curriculum

Beyond the addition of the capstone course and how we measure student outcomes, relatively little has changed in the general sequence of courses from the traditional engineering curriculum established prior to ABET 2000. The first year of the engineering curriculum at most universities continues to focus on providing a foundation in the abstract concepts of math and science. Calculus, physics and chemistry remain as staples of the engineering curriculum. In the second year, most programs offer a variety of general engineering courses, such as statics, materials science, and/or circuits. In the third and fourth years, curriculums offer core engineering courses specific to a particular engineering discipline. In addition, a variety of humanities and social science electives are interspersed throughout the curriculum, intended to provide students with knowledge of contemporary issues and the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context. Many programs also offer variations of introductory engineering courses sometime during the first two years to expose students to the real world aspects of how engineers think and what engineers' do [4].

While examples of engineering curriculum reform exist it appears that except for the addition of the capstone course the basic structure of the engineering curriculum has not changed appreciably at most institutions [5]. Certainly greater emphasis on teamwork and communication is a notable improvement that has been motivated in part by ABET 2000 [1]. Meanwhile, the style of teaching has generally remained the same. For most courses, instructors lecture and students take written tests to show that they have mastered the content [6,7].

An underlying assumption of the engineering curriculum that is still in use today is based upon the premise that engineering students attend college to learn about the fundamental principles of engineering. After graduation, students take a job to actually practice and learn how to be an engineer. This sequence of abstract principles first, and actual practice second, seems to make sense on the surface, but is peculiar, from the standpoint that research and understanding in the area of education indicates that the learning process is best accomplished based upon a sequence of concrete experiences followed by abstract principles [8,9].

3. ABET Quality Assurance

Prior to ABET 2000 engineering curricula generally worked as an open loop system (figure 1). Students entered an engineering program and courses were taken according to a prescribed sequence. Upon successful completion students graduated and found employment. Quality assurance of an engineering degree was in part based upon a regular ABET accreditation process occurring in six year intervals, at which time external evaluators reviewed every aspect of an engineering program.

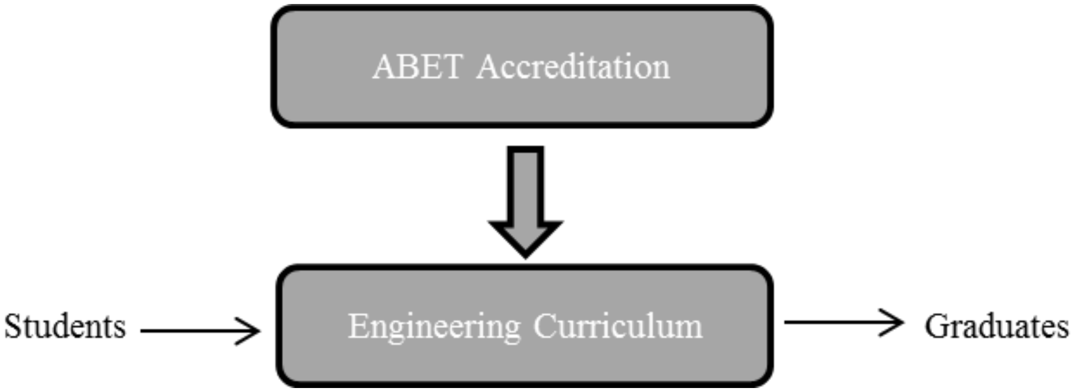

Figure 1 – Pre-ABET 2000 Open-Loop Curriculum Model

With ABET 2000 a set of outcome criteria was added that significantly changed the accreditation process. The new process provided a broad set of criteria by which an engineering program must show that it is making appropriate direct and indirect measurements with associated assessment and evaluation to demonstrate that the student outcomes are being met. In addition, ABET 2000 mandated that engineering programs add a capstone course into the curriculum as a culminating experience for students (figure 2).

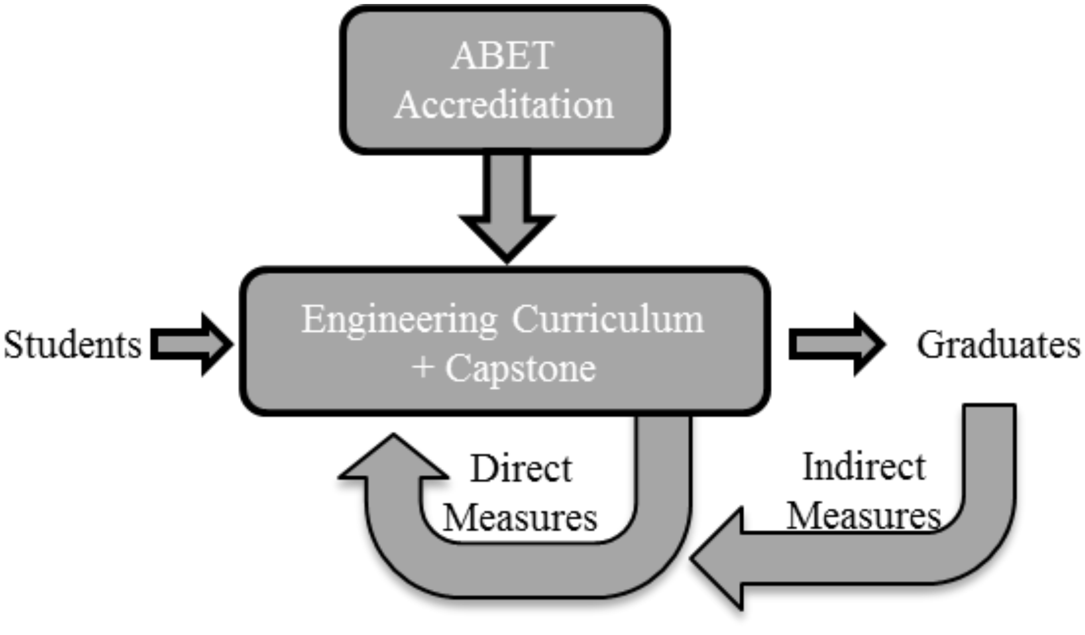

Figure 2 – Post ABET 2000 Closed-Loop Feedback Curriculum Model

These changes were intended to provide the necessary elements for establishing a form of feedback control system to identify and monitor curriculum improvement opportunities. The correspondence between outcome criteria and what knowledge and skills were learned in the curriculum was left for each program to define.

4. The Role of Capstone in the Engineering Curriculum

The addition of capstone into the curriculum by ABET 2000 forced many engineering programs across the nation to address the need for providing a new form of experiential learning for students. Instead of focusing on the knowledge of abstract principles, analysis, and engineering fundamentals, the introduction of the capstone course meant that educators also needed to address synthesis and consider the skills needed for engineering graduates to actually use their newfound knowledge in practice [10]. As engineering programs implemented the capstone course a host of pedagogical issues surfaced. These issues included how to best teach multidisciplinary teamwork, professional communication, and design methodology. Other issues associated with the overhead of teaching capstone included the identification of suitable projects, attracting industry sponsorship, sponsor relationships, intellectual property, and much more [11,12,13].

Of all these issues, one of the key challenges has involved fair and accurate student assessment and the resolution of how we might view an open-ended engineering design problem versus the student perspective [14]. As capstone instructors, 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 as instructors 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 engineering and design [7,15]. The consensus among researchers appears to be that we must provide more opportunities to strengthen the connections (i.e., synapses) in the brain between concrete application of skills and abstract knowledge [9].

To address the challenge of student assessment at a practical level we have developed, implemented and reported on a methodology that we have used since 2008 which has provided a well-tuned system for evaluating student progress on engineering capstone projects [16]. We have also implemented a web-based collaboration system for students, faculty, staff and sponsors to communicate [17,18]. This system allows us to track project status and monitor basic analytics about student participation, while continuously monitoring the quality of their work.

5. A New Model for Capstone

Up to this point in time, most of our efforts as instructors have been to establish a robust capstone course. Relatively little effort has been put forth to explore and use the intelligence gathered from capstone as a means to reduce the gap between the skills and knowledge students need to hit the ground running versus what they actually possess. Our experience indicates that it may be possible to use capstone to assess the preparedness of graduating engineering students for professional practice and in turn use this as feedback to the curriculum to affect change [19].

Our approach to capstone is based on the premise that as a culminating experience there should be little or no formally prepared content delivered to students. Engineering faculty and experienced engineers provide mentoring to each project team. The basic assumption is that students should be prepared and ready to work on an open-ended real world project at the culmination of their undergraduate academic careers and demonstrate an ability to apply the knowledge and skills learned in prior courses to solve a practical problem. Of course, in practice we find that this assumption is not always true. Nevertheless, we maintain that a capstone project is in essence a semester long exam that provides direct measures of how students will perform as practicing engineers.

Using these assumptions as a starting point, we propose a progressive model (figure 3) for capstone in the engineering curriculum. In this case the engineering curriculum prepares students for the capstone culminating experience. Students must meet basic requirements and show that they are prepared for a capstone project. If not they may be required to retake courses or engage in independent studies to get ready and be prepared for capstone. Capstone in the new model serves as the "final exam" for all ABET 2000 student outcomes. Student outcomes are mapped to direct measures from assignments in the capstone course.

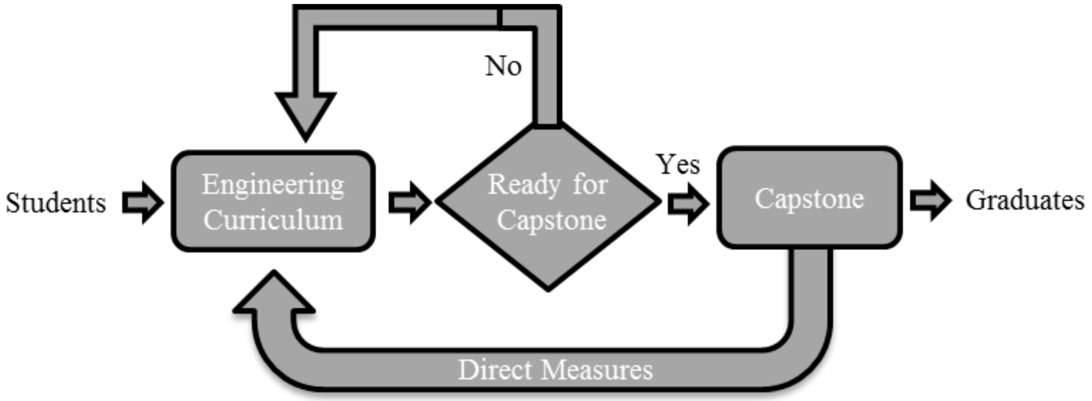

Figure 3 – A New Model for Capstone in Relation to the Engineering Curriculum

6. Mapping Direct Measures of Student Outcomes to Knowledge and Skills

To help implement the new model, we hierarchically prioritize the ABET criteria to guide the design of direct measures [20]. The hierarchical prioritization is shown in Figure 4. Criteria 3c of the ABET 2000 program outcomes calls for students to demonstrate an ability to "design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability". We view this student outcome as paramount to engineering practice and encompassing of the remaining student outcomes [21]. In support of criteria 3c the remaining ABET student outcomes call for a foundation of knowledge that facilitates, enables and essentially supports the practice of engineering design, which by definition includes systems thinking. At a secondary support level this includes the ability to, (3e) identify, formulate, and solve engineering problems, (3d) function on multi-disciplinary teams, and have, (3h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.

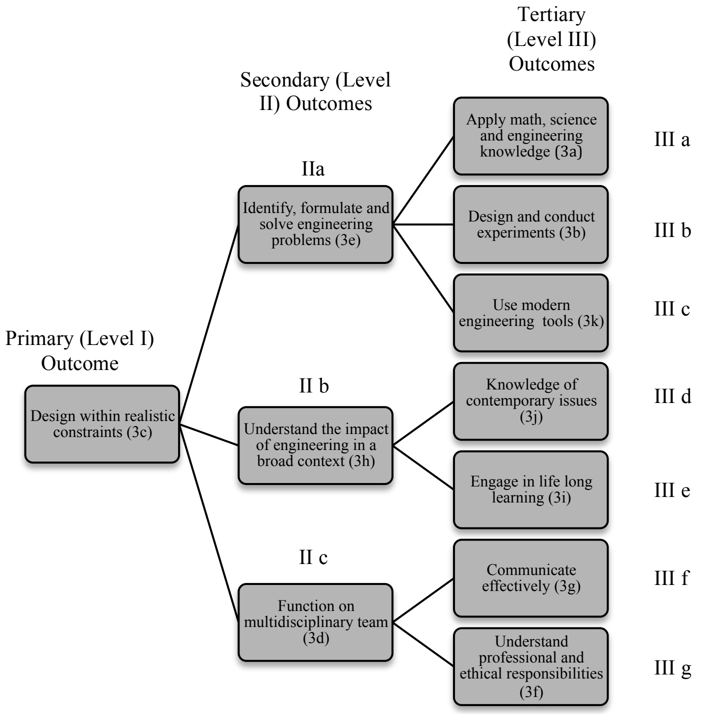

Figure 4 – Hierarchy of ABET 2000 student outcome criteria 3a through 3k

It follows that in support of the secondary outcome (3e) to "identify, formulate and solve engineering problems" students must be able to (3a) "apply the knowledge of mathematics, science, and engineering," (3b) "design and conduct experiments," and (3k) "use the techniques, skills, and modern engineering tools necessary for engineering practice." To (3h) understand the impact of engineering in a broad context students must possess (3j) knowledge of contemporary issues and (3i) engage in life long learning. Finally, if students are to properly (3d) function on multidisciplinary teams they must (3f) understand professional and ethical responsibilities, and (3g) communicate effectively.

Given the hierarchy of student outcomes described above and depicted in figure 4 it is possible to develop a one to one mapping of all ABET student outcomes versus the direct measures used in capstone. Table 1 shows examples of possible direct capstone measures for all ABET learning outcomes.

Hierarchical Order		ABET Learning Outcomes	Example Capstone Direct Measures
1		(3c) Design within realistic constraints	Final Project Team Grade Final Individual Course Grade
2a		(3e) Identify, formulate and solve engineering problems	Final Individual Course Grade
3a		(3a) Apply math, science and engineering knowledge	Individual Technology Study Memos

3b		(3b) Design and conduct experiments	Validation of Project Results
3c		(3k) Use of modern engineering tools	On-line Collaborative Tool Statistics
2b		(3h) Understand impact of Engineering in Broad Context	Team Project Statement of Work Team Project Final Report
3d		(3j) Knowledge of contemporary issues	Team Project Statement of Work Team Project Final Report
3e		(3i) Engage in lifelong learning	Individual Resume and Cover Letter End of Semester Reflective Memo
2c		(3d) Function on multidisciplinary teams	Individual Peer Evaluations
3g		(3g) Communicate effectively	Individual Technology Study Memos
3f		(3f) Understand professional and ethical responsibilities	Individual Peer Evaluations

Table 1 – ABET 2000 Outcomes versus Example Capstone Direct Measures

As a general guideline, engineering programs should not rely solely on capstone for all student outcome direct measures. Instead, direct and indirect measures should be monitored from a variety of vantage points, both from coursework (direct measures) and using post-graduate surveys (indirect measures). The model presented here shows that it is possible to monitor all of the ABET student outcomes from capstone. Given this model, it may be prudent to monitor student progress throughout the curriculum in such a way to insure that students are indeed prepared for capstone and in turn, better prepared for professional practice. Unfortunately, as discussed below, this aspect of capstone learning is often overlooked in the engineering curriculum.

7. Preparation for Capstone

Most papers on engineering education focus on teaching of specific content relevant to engineering. Relatively few focus on the broader topic of learning what it takes to become an engineer [22]. In the paper by Stevens, and others, the authors conducted an ethnographic study and analysis of the navigational pathways students take to attain the requisite disciplinary knowledge and personal identification associated with becoming an engineer. They conducted the study over four years at four universities that included a large public university, technical public institution, suburban private university, and urban private university. The major observation from their work was that the engineering curriculum focused excessively on the navigational pathway or “pipeline” and needed to take a more “people-centered” approach. In the spirit of “returning to the field work” as recommended by their study to “recover the person” the observations reported here are based upon over fifteen years of direct personal contact with thousands of engineering students at all stages in the navigational pathway from an ABET accredited urban private university. While some structural and cultural differences with other engineering programs may exist, we believe our observations about engineering students are representative of the whole.

Based upon the introductory memos and résumés submitted by thousands of capstone students, one overriding interest that students consistently ask for from capstone is to gain practical real world engineering experience. At this point in their academic careers students have spent countless hours acquiring knowledge in prior courses, but with relatively little opportunity to actually apply concepts to a real problem. We know that learning and building confidence in engineering design is an iterative process that is best learned by repeated design experiences [23]. From this perspective we agree with others who have called for curriculum reform, starting in the first year and continuing into the second and third years, to give students more opportunities to practice and learn about engineering design prior to their capstone experience [4]. Practical real world experiences motivate understanding of more abstract principles. By strategically integrating more concrete skill-based instruction into regular coursework, understanding and retention of basic principles and engineering fundamentals can be improved.

Our experience and success with assessment processes provide insights into the likely success level for students entering capstone [16]. We assign students to teams based upon promoting the overall likelihood of project success. The process begins when we receive a student's first assignment, which consists of their résumé with cover letter. Similar to industry practice we match students with projects that align with their interests and capabilities.

In an attempt to maintain a level playing field students are generally assigned to projects such that the average GPA is at or above 3.0 for each team. Albeit, in some cases we will cluster students with higher GPAs together and assign them to more challenging projects and conversely cluster students with lower GPAs on projects that may be equally if not more "open-ended", but perhaps not as technically challenging. Our observations indicate that while GPA may be a parameter for engineering job placement, in isolation of other factors we have not found GPA to be an adequate measure of student performance on open-ended design experiences with real constraints [24]. For example, over a period of four semesters (Fall 2013 to Spring 2015) we compiled data for 679 capstone students [25]. Our data indicates that individual student GPA has a weak relationship to individual student capstone grade ($r = .28$). These results are consistent with our findings from prior semesters.

In general, we have found that a diversity of knowledge, skills, past experiences and personalities provide for the most successful capstone teams. One critical factor that we have noticed that has an impact on team success has to do with maturity and past experience. Students with internships, cooperative education, military service, or other comparable life experiences often will have an edge over students with only coursework. Students with significant maturity and life experiences will often stand-up and take on leadership roles on projects and be well respected by their peers [26].

As capstone instructors, we have compiled our observations from our regular interactions with students over the past fifteen years and believe that our insights are representative of the broader population of engineering capstone instructors [19, 27]. We find that significant gaps exist between the knowledge and skills that some students demonstrate versus what an employer might hope for from them as engineering graduates. The observations that we have identified and compiled fall into five general categories of 1) critical thinking, 2) resourcefulness, 3) project management, 4) technical communication, and 5) basic technical skills.

8. Discussion

At this point, an integrated approach has emerged to combine capstone results as feedback to the engineering curriculum for its continuous improvement. The direct measurement process consists of a set of instruments and actions. The conventional instruments used to monitor student performance include project reports, peer evaluations, technology study memos, design reviews, and validation of project results. Less conventional feedback may include a combination of qualitative and quantitative feedback from students, faculty and project sponsors. Feedback from student résumés and cover letters, project website postings, course surveys, sponsor design review evaluations and student reflective memos have an important role in monitoring what individual students have learned from the curriculum and its applicability to professional practice.

For example, a section could be added to student reflective memos indicating the course(s) most directly useful relative to the project tasks and that enabled students to learn more as required by the project; and the conflicts between the project tasks and specific courses where both address the same topics but present contradicting results/contents. Compilation of such results from all memos, sorted by discipline and courses provide invaluable insights for continuous improvement. Annotation augmented to these results that include student performance and other relevant comments from the instructors provide further context for interpretation of these results.

Departmental meetings also provide an important forum for conferencing between the capstone instructors and departmental faculty to present and discuss student performance, as well as, to improve the direct measurement process. Each discipline decrees the continuing improvement actions on its own, based on the above results ultimately leading to proposals for departmental curriculum improvement. Meetings at the school or college level are used to review, coordinate, and/or mandate improvements on engineering curricula across disciplines. The cycle for this process could be a term/semester or an academic year.

9. Conclusion

This paper suggests a new paradigm for capstone, which highlights its unique role in the engineering curriculum for continuous improvement. As such, the progressive model presented in this paper, coupled with references cited, suggests opportunities for improving the preparedness of students for professional practice. A major opportunity lies in sharpening the focus on the engineering curricula and providing guidance for updating teaching methods and content. As pointed out here and by others, beyond the capstone course, relatively little has changed in the curriculum in decades. There is a need to make more substantive changes to the curriculum, particularly in the second and third years [28].

While the process of improving student preparedness has clearly begun, as evidenced by the emphasis of capstone in the curriculum, much more is required and the process of curriculum reform must continue. Clearly, conducting meaningful experimentation in this area is challenging. However with a robust process for collecting and monitoring learning outcomes using a progressive model that uses capstone to drive continuous improvement like the one presented here in this paper, it will be possible as we move forward to make meaningful changes based upon data analysis and knowledge.

Our assessment processes and web-based collaboration forum have allowed us to better gauge opportunities for student and curriculum improvement. We believe that once students have reached the capstone level that all students should have the opportunity to perform well, if not excel. From this vantage point, our observations provide insights as to how well prepared graduates are for professional practice and what we might do better to accelerate their progress and smooth their transition into professional practice.

The paper presents how the culminating engineering design course and accreditation criteria can be used to identify gaps in students' knowledge and suggests remediation strategies. A model for hierarchically prioritizing student outcomes and mapping them to direct metrics related to the curriculum is presented as a mechanism for generating feedback. A systematic and thorough analysis framework is presented that can be useful to other institutions and programs.

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