120th ASEE Annual Conference & Exposition
FRANKLY, WE DO GIVE A D*MN
June 23-26, 2013
ATLANTA

Paper ID #7464

An Innovative Two-Year Engineering Design Capstone Experience at James Madison University

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An Innovative Two-Year Capstone Design Experience at James Madison University

Abstract

Design is widely considered to be the central or distinguishing activity of engineering practice. To prepare students with a strong engineering design knowledge and skill base, almost all engineering programs integrate a capstone design experience during the senior undergraduate year. Typically, these capstone design experiences last either one or two semesters, and it is quite rare for the capstone design experience to exceed one academic year. ABET requires that capstone design be a culminating learning experience. Yet, there is no requirement for the students to apply the entire design process in these experiences. In order to prepare students with the knowledge and skills necessary to face the complex technological problems of engineering practice, we believe that it is imperative for students to have the opportunity to practice applying the complete design process at some point during their undergraduate engineering education and that a culminating capstone design experience provides an ideal context for this to occur.

In this paper, we present the two-year capstone experience of the engineering program at James Madison University. The program, which graduated its first class in May 2012,was developed from the ground up to provide students with training that emphasizes engineering design, systems thinking, and sustainability rather than focusing on a specific engineering discipline. Our vision is to produce cross-disciplinary engineer versatilists. One important place in the curriculum where this is achieved is the team-based capstone experience, which starts in the fall semester of junior year and ends in the spring semester of senior year. Our pedagogical approach in the capstone experience is for students to take ownership of their projects and their learning. The design instructors and faculty advisor(s) support and facilitate mastery learning through directed and non-directed, group-based and independent, simple and complex, structured and unstructured, project tasks that incrementally expose and reiterate the design process. In this paper, we not only describe the conceptualization and implementation of this two-year capstone experience, but also present outcomes assessment data of student learning during this experience.

Introduction

Design is widely considered to be the central or distinguishing activity of engineering. [1-2] A good education in engineering design can give students the skills required to creatively solve real-world problems and create an opportunity for them to begin the process of becoming engineering professionals.[1-2] Historically, following the Second World War, engineering design courses in a typical engineering curriculum were replaced with engineering science courses, where analysis and mathematics were the focus.[4-11] This pendulum swing left students without the hands-on design expertise required to be work-ready engineers.[11] With pressure from industry and direction from the Accreditation Board for Engineering and Technology (ABET), engineering design courses have slowly been reintroduced into engineering curricula.

Since the late 20th century, engineering undergraduate curricula have reincorporated design course(s) to "facilitate practical engineering application" and to build upon the engineering science foundation.[3] The most common way engineering programs integrate practical design application is via capstone design experiences, which typically include a project and/or related coursework. As a result of ABET accreditation requirements for capstone design and industry calling for more practically trained engineers, these capstone design experiences continue to be revered as "the most important educational component in almost all undergraduate engineering curricula."[5]

Although the structure of capstone design experiences varies widely across programs, all ABET-accredited programs must attempt to satisfy the following ABET requirement: "Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs….. Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints."[6]Although ABET requires that capstone design be a culminating learning experience, ABET does not specify what engineering design entails. For example, ABET does not require that students apply the entire design process, from planning to concept development to system-level design to detailed design and modeling to testing and refinement. This small detail is what allows engineering programs to develop their own unique models of engineering design instruction and capstone design models for their curriculum. The following paragraphs present some of the varying capstone design models that exist across engineering curricula.

Capstone design experiences vary across engineering programs and some of the differentiating features and facets include timing, duration, credit loading, amount and depth of formal engineering design instruction, project sponsorship, project solicitation and selection processes, faculty role and responsibilities, team size, team multi-disciplinarity, as well as team and project performance evaluations. Although an extensive literature review of all these differentiating facets across capstone experiences is beyond the scope of this paper, we do focus on a couple of these differentiating features and also present typical features of capstone experiences as a means of comparison to the James Madison University capstone model, which is the focus of this paper.

Across engineering programs, the vast majority of capstone design experiences involve team collaboration although some programs include individual design experiences as well in order to expose and teach students the advantages and disadvantages of both approaches.[6] Since most engineering programs are disciplinary, the resulting capstone teams represent primarily one engineering discipline. Although capstone experiences with multidisciplinary teams exist and are promoted, multidisciplinary capstone teams require more time and resources to be successful; but they are also considered better preparation for real world industrial collaboration.[8]

Many capstone experiences tend to be driven by three sources – faculty, students, and industry. Although faculty-driven capstone projects are most common and tend to align with the scholarly needs of the faculty mentor(s), programs that allow student-driven capstone experiences do exist as well.[12] Capstone experiences/courses tend to be coordinated either by a single instructor or a team of instructors.[6] While a single instructor represents the typical industry environment where one individual is in charge of the project, a team of instructors places great importance on team work, reduces the work load across the instructors, and increases motivation of the instructors to lead the capstone experience in their specific area of interest.[12] Also quite common are industry-sponsored capstone experiences. Such projects typically involve industry engineer(s) and engineering faculty member(s) and are typically financially supported by industry in the form of equipment, materials, and technical consulting.[13] Although industry-sponsored capstone experiences have shown to successfully immerse students in real world engineering problems, such experiences have been shown to lack adequate technical analysis and critical thinking often promoted and desired in the more traditional capstone experiences which require the integration of design and engineering science knowledge found in the curriculum.[16]

In regards to evaluating capstone experiences, many assessment models exist to evaluate both student performance as well as project performance in capstone design experiences.[11] Although most capstone design experiences rely on final reports and presentations for formal evaluation of performance, capstone experiences that include a traditional course component also use regular quizzes and examinations on the design content being instructed.[17] Further, many engineering programs have found it useful to include peer evaluations, which translate to a team grade as well as an individual grade to accurately evaluate student performance during these capstone experiences.[6]

Capstone models can also vary by capstone course lecture content. Many capstone models encompass both a lecture component and the applied capstone design project. While this is the most common implementation, not all capstone models include a lecture component. Rather, they focus on the applied design project. When the lecture component is offered, it involves instruction on design fundamentals and application of those fundamentals (i.e. capstone project) takes place outside of the class.[20] In some models, the lecture component also includes in-class application.[15]

One of the most significant differentiating features of capstone design experiences is the duration. In terms of timing, most experiences occur during the senior year. The following paragraphs highlight some of the key differences that exist across capstone experiences with varying durations – one semester, two semesters, three semesters, and four semesters.

Capstone experience duration is often an indicator of how the capstone experience is structured to ultimately provide the students with a real-world opportunity to apply their engineering knowledge. Projects of a longer duration are typically used when a working, physical prototype is needed, while shorter durations are used to teach and apply design fundamentals in an environment where construction and testing is not the focus. Therefore, the foremost challenge for any capstone design experience is to fit all instructional and experiential aspects that the program wishes to accomplish within a given timeline.[18] According to the 2005 National Survey of Engineering Capstone Design Courses, course duration has ranged from a few weeks to three or more semesters.

One-semester capstone experiences/courses are the most common in engineering undergraduate education programs, and they require students to apply the accumulated knowledge from other engineering courses in the curriculum. Such models rely heavily on previous coursework and students properly integrating previous knowledge to inform the capstone project. For example, both Auburn University's Biosystems Engineering and Software Engineering programs are one semester capstone experiences incorporating design topics, written and oral communication, and a capstone project.[19] Due to the one-semester time limitation, these capstone experiences tend to be conducted according to a strict timeline. A 2010 report describing the curricular model of a one-semester capstone course stresses objectives the instructor, faculty, industry, and the student must accomplish such as conducting research, grading proposals, evaluating team performance, and collaborating with the industrial component partner.[21]These are all important steps that have to be taken for the one-semester course to be successful.

Two-semester capstone design experiences/courses are often organized to include design instruction during the first semester and design knowledge application during the second semester. For example, at Mississippi State University, the Chemical Engineering Program follows a two-semester model with the first semester class, "Process Design," containing four design team projects requiring a formal report at the end of each project.[15] Each project focuses on a different portion of the design process, ranging from research and data collection to systems analysis and applying process optimization. Design process skills are reinforced in one final report at the end of the semester.[15] Then, the second semester course, "Plant Design" focuses on one project.[15] Similarly, Southeast Missouri State University implements a similar capstone course package in their Computer Science and Engineering Physics programs with the first course focusing on "the early stages of design procedure, defining of the design problem, evaluation of alternative solutions, and system-level design" which prepares students for the formal senior capstone project in the spring semester.[22] As a result of heavy instructional emphasis and application in the first design course, these courses can then build upon the design skills in the second semester capstone course via a real world engineering problem.

Three-semester capstone experiences/courses, though uncommon in undergraduate programs, tend to be used when testing and prototyping are required. This approach is in place at the United States Military Academy (USMA) where the three-semester capstone model begins with a course that does not include an official senior capstone project.[23] Instead, the course emphasizes the "soft" sciences, including "design process, methodology, project management, communications, economics and ethics."[23] Students are introduced to the engineering design process and methodology, and they apply this knowledge to their junior projects before being immersed in their senior capstone project. A significant advantage of the three-semester capstone model is its earlier introduction to the design process through a course project that covers the entire breadth of capstone design without the concurrent pressure of being a capstone project.

Even more uncommon, the four-semester capstone model is useful when a more thorough design process and more progress on the project is expected (i.e. testing, evaluating, and refinement of a prototypes). For example, the Mississippi State University Electrical and Computer Engineering Departments collaborate with NASA on a four-semester capstone design project. This model involves an initial capstone design team taking on the project one semester with subsequent transfer to another capstone design team the following semester for a total of four semesters. This multi-team model and the staggered project start dates "forced inter-team cooperation, project management" and ultimately produced a testable prototype.[24] This model, while covering a span of four semesters, does not provide students with a true two-year capstone experience. The James Madison University Department of Engineering has implemented a four-semester capstone design model via a four-course design sequence during junior and senior year which provides students with four concurrent semesters working on the same design project. The decision to design a four-semester capstone experience at James Madison University was driven by the fact that a longer duration capstone project would enable our students to apply the engineering design process more thoroughly in both breadth and depth. A previous publication details the course content coverage of these courses, while the rest of this paper details the capstone project aspects of these courses.[25]

Is there a single ideal capstone model for undergraduate engineering programs? The models that exist each have advantages and disadvantages. ABET requirements, industry needs, and practicality of engineering knowledge and skills in each program/curriculum should be the driving factors for the chosen capstone design model. Ultimately, every engineering program seeks to provide a hands-on capstone experience with practical skills of "system design, integration, and synthesis to meet industry needs." [26]

Design Experience at the James Madison University Engineering Department

In order to better understand the capstone design model at James Madison University, it is important to understand the overall curriculum and overarching engineering design focus of the program. This section briefly outlines both of these elements.

The Department of Engineering at James Madison University, which graduated its inaugural class of engineering students May 2012, has been developed from the ground up to provide an emphasis on engineering design, systems thinking, and sustainability.[24] Offering a bachelor's degree in engineering without discipline-specific majors or concentrations, our goal is to train and produce engineering versatilists. The term was popularized by Friedman and defined as individuals who can "apply depth of skill to a progressively widening scope of situations and experiences, gaining new competencies, building relationships, and assuming new roles".[26] Through an innovative curriculum and a variety of pedagogical approaches, we train students to have the cognitive flexibility to solve engineering challenges that transcend disciplinary boundaries. We provide a holistic curriculum through the integration of a campus-wide liberal arts core, several sequences of engineering courses on technology management, engineering science, sustainability, and systems analysis, and a six course design sequence that represents the spine of the engineering curriculum. ***Figure 1*** provides a general overview of the curriculum.

YEAR 1	Calculus 1	Liberal Arts Core	Liberal Arts Core	Liberal Arts Core	Physics 1
	Calculus 2	Liberal Arts Core	Introduction to Engineering	Liberal Arts Core	Physics 2
YEAR 2	Calculus 3	Liberal Arts Core	Engineering Design 1	Liberal Arts Core	Chemistry 1
	Linear Algebra & Different Eq.	Statics & Dynamics	Engineering Design 2	Engineering Management 1	Chemistry 2
YEAR 3	Thermal-Fluids 1	Instrumentation & Circuits	Engineering Design 3	Engineering Management 2	Liberal Arts Core
	Thermal-Fluids 2	Materials & Mechanics	Engineering Design 4	Liberal Arts Core	Liberal Arts Core
YEAR 4	Sustainability Fundamentals	Systems Analysis	Engineering Design 5	Technical Elective	Liberal Arts Core
	Sustainability & Design (LCA)	Technical Elective	Engineering Design 6	Technical Elective	Liberal Arts Core

Figure 1: The engineering curriculum places engineering design instruction at its core.[26]

The design experience in the Engineering program consists of 7 semesters of coursework beginning in the first year of the curriculum with ENGR 112: *Introduction to Engineering* and followed by a six-course sequence of design courses that include ENGR 231*: Engineering Design I* andENGR232: *Engineering Design II* during the sophomore year **Error! Reference source not found.**-**Error! Reference source not found.**, ENGR 331*: Engineering Design III* and ENGR 332: *Engineering Design IV* during the junior year, and ENGR 431: Engineering Design V and ENGR 432: *Engineering Design VI* during the senior year. In all these courses, students receive instruction on design theory (thinking, process, methods, and tools), which they apply in the context of projects The following paragraphs detail examples of the balance between theory and practice as well as describe our overarching vision and philosophy of engineering design in the curriculum. The next section focuses specifically on the capstone design projects. For more details on the specific course objectives and content please refer to an earlier publication entitled *A New Vision for Engineering Design Instruction: On the Innovative Six Course Design Sequence of James Madison University*.[25]

In ENGR 112, students gain foundational exposure to the engineering design process and an introduction to tools and methods as well as engage in design projects and activities such as reverse engineering exercises, a water filter design project, and conceptual design exercises. Through these reverse engineering and redesign activities, students begin to develop early application skills, recognizing how to apply the design process to solve engineering problems. Such activities are meant to provide students with basic knowledge and comprehension of the engineering design process.

During the sophomore year, in ENGR 231 and 232, students build upon the design knowledge gained during ENGR 112. In ENGR 231 and 232, students learn about the design process with a primary focus on the planning, concept development, system level design, detail design, and testing and refinement phases.[30] In alignment with our vision for these courses, students learn design theory, but also apply this theory through project work. Woven into the design theory and methodology instruction is a year-long design project requiring students to design, build, and test a human-powered, pedaled vehicle for a client with cerebral palsy is. Through this sophomore design course sequence, students gain knowledge of the engineering design process as well as begin to develop the application, analysis, and synthesis skills necessary to begin their capstone projects. The year-long, real-world design project with an actual client from the local community is integral to students developing such higher-order problem solving skills. The project also facilitates students' development of interconnections between engineering science coursework, engineering design coursework, product testing, and sustainability. Further, the project provides a service learning experience for students as well as an opportunity for them to produce a working prototype of their selected design for the client.

During the junior and senior years, in ENGR 331, 332, 431, and 432, students continue to build upon the design knowledge and skills gained in previous design courses, but also integrate knowledge and skills gained in the other engineering courses (engineering science, engineering management, sustainability, and systems courses). As was the case for all previous design courses, we work towards balancing theory and practice in the junior and senior design courses. This is achieved by meeting with the students for one hour per week for the lecture portion of the course and allowing students to work on their capstone project with their teams and faculty advisors for the remaining class sessions. In these four upper-level design courses, there are several topics that are developmentally covered to advance students' engineering design knowledge and skills, which also apply to diverse problem solving contexts and experiences (e.g., workplace, team management, project management); thus, there is a the strong focus on also building professional skills in these courses. A list of the topics that are developmentally integrated in the upper-level design courses include:

(a) *Advanced Design Thinking, Principles and Methods* – to advance students' engineering design knowledge, we introduce them to tools and methods such as Design for X(ENGR 332 and 431), Embodiment Design and Evaluation (ENGR 332 and 431), TRIZ (ENGR 332), Failure Modes and Effects Analysis (ENGR 432), User-centered Design(ENGR 431), Holistic Design (ENGR 431), Design Aesthetics (ENGR 431), SixSigma and Lean Management (ENGR 431 and 432), Psychology of Design and Cognitive Engineering (ENGR 431), Sustainable Design (ENGR 431 and432), Creativity Principles and Practices (ENGR 431 and 432), Innovation (ENGR 432), and Intellectual Property and Patents (ENGR 332).
(b) *Ethical Awareness and Understanding* – to advance students' ethical awareness and understanding, we expose them to many case studies with ethical implications in varying contexts including professional code of ethics (ENGR 332), personal values and ethics (ENGR 431 and 432), and team management ethical scenarios (ENGR 432).
(c) *Technical Communication Skills* – to advance students' written and oral communications skills, we cover several relevant topics including technical writing style and form (ENGR 331), presentation delivery (ENGR 331), presentation slide design (ENGR 331), proposal

writing (ENGR 331), progress memo writing (ENGR 332, 431, and 432), design report writing (ENGR 332, 431, and 432), and design presentations (ENGR 331, 332, 431, 432).

(d) *Professional Career Planning* – to enable students to have the knowledge to plan and decide on their future career plans, we deliver material to them on finding and seeking out internships (ENGR 331), finding and seeking out Research Experiences for Undergraduates (REUs) (ENGR 331), understanding the graduate school experience and application process (ENGR 332), interviewing tips (ENGR 331 and 432), preparing resumes, cover letters, and personal statements (ENGR 331 and 432).

(e) *Professional Team Work and Team Management Skills* – to prepare students to enter be effective team members and team leaders, we cover topics and have discussions on team building (ENGR 331), team performance evaluation (ENGR 331, 332, 431, 432), and conflict resolution (ENGR 432).

During the past four years, the faculty teaching the engineering design courses have worked collaboratively to develop these courses so that the content will be developmental with seamless integration and transitions over the seven semester sequence. This was achieved by having weekly or biweekly meetings to discuss the execution of these courses as well as many meetings during summers, before the start and after the completion of each semester to reflect and identify areas of improvement in content, delivery, and assessment.

Our pedagogical vision in teaching these engineering design courses is to enable *mastery learning* through directed and non-directed, group-based and independent, simple and complex, structured and unstructured, problem-based learning experiences that incrementally expose and reiterate the design process. Our overarching goal is to teach our students to be adaptive problem solvers. Several key attributes are integral to and are accentuated by the pedagogical framework of this design experience:

- *Developing a balance between design theory and practice*.
  A combination of directed, in-class instruction covering topics such as design theory, professional skills, systems thinking, and ethics in addition to out-of-class, non-directed application and practice is given particular attention.

- *Developing a balance between qualitative and quantitative reasoning*.
  An emphasis on the fuzzy front-end concepts of the engineering design process as well as quantitative reasoning typically highlighted in engineering science classes. Students are given exposure to the reality of dealing with uncertainty in the design process.

- *Implementing an integrated and developmental approach*.
  Each course builds upon prior ones, providing instruction over a long period of time and developmentally reinforcing prior learning outcomes. The skills and attitudes students learn and practice over time (with regular support from and collaboration with faculty) are ones that they will take ownership of and tailor to their own abilities and design habits.

- *Applying project management skills*.

Concepts and tools learned in the management courses embedded in the curriculum are applied in design projects. Students also have the opportunity to work across disciplinary boundaries with business students who ideally have a vested interest in the successful organization of the project.

- *Practicing professional skills*.
  Students learn to work and communicate in small (2-4), medium (5-7), and large (10+) engineering teams. As effective members of these teams, students work on the design process as well as learn to develop and execute a design plan incorporating the types of constraints typically encountered in engineering workplace environments. Students learn to compose a proposal, memo, report, technical paper, and technical presentation as well as how to project their professional image through a resume.

The Capstone Design Model at the James Madison University Engineering Department

Overview

As previously mentioned, the capstone design experience includes Engineering Design III (ENGR 331), Engineering Design IV (ENGR 332), Engineering Design V (ENGR 431), and Engineering Design VI (ENGR 432). During ENGR 331, the students begin a two-year, four-semester long capstone project in groups of four to five with one or more faculty advisors. ***Table 1*** illustrates the vision of the James Madison University engineering capstone model in terms of project attributes and deliverables semester-by-semester as well as integration of classroom design topics with capstone projects. This capstone design vision was inspired by an industry design model summarized in terms of five design reviews: systems requirement review, preliminary design review, critical design review, testing readiness review, and production readiness review. Overall, the first semester of the project is focused on problem formulation, research, and planning with some teams being able to start on the concept development design phase. Most capstone teams focus on concept development in the second semester with initial efforts towards prototyping and modeling, both of which continue into the third semester. Detailed designs are the culmination of efforts in the third semester and accompany testing and evaluation efforts. For several teams, the fourth semester focuses on testing and evaluation as well as redesign processes.

***Table 1**: Vision for the two-year James Madison University capstone design model.* [25]

<table>
<tr><th colspan="3">Ideal Attributes and Deliverables for the Capstone Design Projects</th></tr>
<tr><th>Capstone Projects Should:</th><th>Typical Project Focus and Deliverables Each Semester</th><th>Each Team Will Focus on Conducting:</th></tr>
<tr><td rowspan="4">(1) Be designed to span a two-year duration and meet the deliverables described (to the right).
(2) Address a real-world need or problem (and ideally have a specific client in mind).
(3) Involve the design of a specific system or technology (whether that system is a product, a process, etc.)
(4) Apply design thinking, principles, and process.
(5) Incorporate a balance between theory and practice.
(6) Incorporate modeling, which may include physical, theoretical, computational, experimental, etc.
(7) Integrate engineering science content.
(8) Apply systems thinking and systems analysis to evaluate designs from a sustainability perspective to assure a sustainable design.
(9) Encourage and seek cross-disciplinary collaborations or consultants (within and outside of engineering).
(10) Be conducted in a team setting where both individual and group contributions are critical.</td>
<td><u>Design III-ENGR 331</u>
Planning and Conceptualization

<u>Deliverables</u>
Midterm and End-of-Semester Reports and Presentations</td>
<td>System Requirement Review (SRR) will focus on addressing: problem identification and statement, project goals, literature review, market analysis, stakeholder analysis, analysis of available resources, feasibility study, project management plan (budget, timeline, team member roles and responsibilities), list of consultants, etc.</td></tr>
<tr><td><u>Design IV-ENGR 332</u>
Conceptualization, Modeling, and Prototyping

<u>Deliverables</u>
End-of-Semester Report and Presentation</td>
<td>Preliminary Design Review (PDR) will focus on the evaluation of the conceptual design and planning of the project to ensure that teams are meeting the necessary requirements.</td></tr>
<tr><td><u>Design V-ENGR 431</u>
Prototyping, Testing and Evaluation

<u>Deliverables</u>
End-of-Semester Report and Presentation</td>
<td>Critical Design Review (CDR) will focus on the evaluation of the detailed designs, prototyping models, and planning of the project to ensure the design implementation plan. Testing Readiness Review (TRR) will focus on the evaluation of testing preparations, readiness, and procedures.</td></tr>
<tr><td><u>Design VI-ENGR 432</u>
Evaluation, Redesign, and Production

<u>Deliverables</u>
End-of-Semester Report and Presentation</td>
<td>Production Readiness Review (PRR) will focus on the evaluation of the design to ensure that it is completely and accurately documented and ready for formal release to manufacturing. Marketability and commercialization of the design could also be evaluated.</td></tr>
</table>

Students work on capstone projects collaboratively with the design course instructors and faculty capstone advisors. Each group of faculty members plays a key supporting role for the projects. The design course instructors coordinate the project selection process, provide the overarching design structure for the projects, and provide design and professional development instruction. Students are given a rubric outlining the overarching design process that should be followed as well as an overview of the design tools taught through the six-course design sequence. Students are encouraged to develop their own design process nuances, but generally, they are encouraged to follow a process beginning with planning and client identification and ending with prototype development, testing, and refinement. Additionally, course instructors coordinate capstone project deliverables (memos, reports, and presentations), score the progress of students, and work to maintain consistent rigor across design projects. The instructors give students homework assignments that are both independent from and dependent on their capstone projects. Thus, course instructors are placed in a role which allows them to monitor the status of all capstone projects, and consequently, they are able to monitor the progress of a class, identify outliers, and work with teams to mitigate conflicts.

The faculty capstone advisors are responsible for one or multiple capstone teams per academic year. Faculty capstone advisors provide technical advising to the team. Faculty capstone advisors meet with teams weekly or biweekly to ensure that technical goals are being achieved and may give a team assignments and goals as well as formal or informal instruction. The faculty capstone advisors also help their teams work with or establish connections to clients and/or stakeholders. The flexibility of interfacing with at least two different advisory groups on projects is important because all projects have different technical needs that tend to evolve as projects evolve.

Parallel tracks of Capstone Projects and Design Courses

The first year of the 2-year capstone experience (ENGR 331 and ENGR 332) builds upon the processes, tools, concepts, and experiences in ENGR 231and ENGR 232 and incorporates concepts and tools from ENGR 322: *Engineering Management II* which is a co-requisite for ENGR 331. In ENGR 331, students are in the planning phase of their design, and directly apply the knowledge gained in ENGR 322 to develop a project management plan. During ENGR 332 students are involved in the concept development phase of design, which involves concept generation, evaluation and selection. Students apply the tools and methods learned in their prior design courses, but are also exposed to advanced concept development tools and methods. Additionally, they can integrate newly-obtained knowledge from the engineering science courses in which they are enrolled. Design challenges included in the course foster the application of newly-acquired knowledge to a design problem. These challenges aim to improve students' ability to think critically and make engineering decisions. Sustainability and systems thinking are revisited in more depth to continue broadening the students' perspective.

The second year of the capstone experience, ENGR 431 and ENGR 432, builds upon previous design courses and also incorporates concepts and tools from mathematics courses and ENGR 413: *Systems Analysis*. In ENGR 431, students are in the embodiment phase of design, and ENGR413 is a co-requisite for this design course. Students can apply the systems thinking concepts gained in ENGR 413 to their capstone projects to develop analytical prototypes that verify design parameters, trade-offs, and components. The content in ENGR 413 is aligned with the projected design phase of the capstone projects and integrates well with the design course. ENGR 432 is when students are in the testing and refinement phase of design. Students apply the tools and methods from prior design courses and are also exposed to advanced testing and refinement tools and methods. In both ENGR 431 and ENGR 432, students continue to integrate knowledge from the engineering science courses. The four sustainability contexts—environmental, social, economic, and technical—of engineered systems are also evaluated. This aligns well with content acquired in the sustainability courses. The continued incorporation of design challenges in these courses helps to reinforce the application of newly-acquired knowledge to design problems.

Not all students in the capstone courses take the engineering science courses in the same sequence. Rather than detract from the overall experience, this provides a unique opportunity for dynamic interaction among capstone team members. The team members can share their particular knowledge areas in the project setting and different members could bring in various knowledge areas at different stages in the project. This scenario would mimic team interactions in a real-world setting, where not all members on a project have the same initial level of information or knowledge to contribute to the process.

During the four-semester capstone design course sequence, students apply the engineering design process and design tools and methods learned during the sophomore design sequence to their new capstone projects. A typical design process showing the design steps for a project is shown in ***Figure 2***, which also maps to the Capstone Design Process Guide [29] used in both the instruction and assessment of capstone design projects. The guide is comprised of three key parts: (1) a typical design process-to-semester mapping for capstone projects, (2) a design process rubric applicable to engineering design projects in the curriculum, and (3) a mapping between the design process and engineering design tools taught within the curriculum. Please note that Figure 2 does not imply that the design steps are to be carried out in the linear format in which they are presented. The visual simply serves to show the typical design steps for a capstone project.

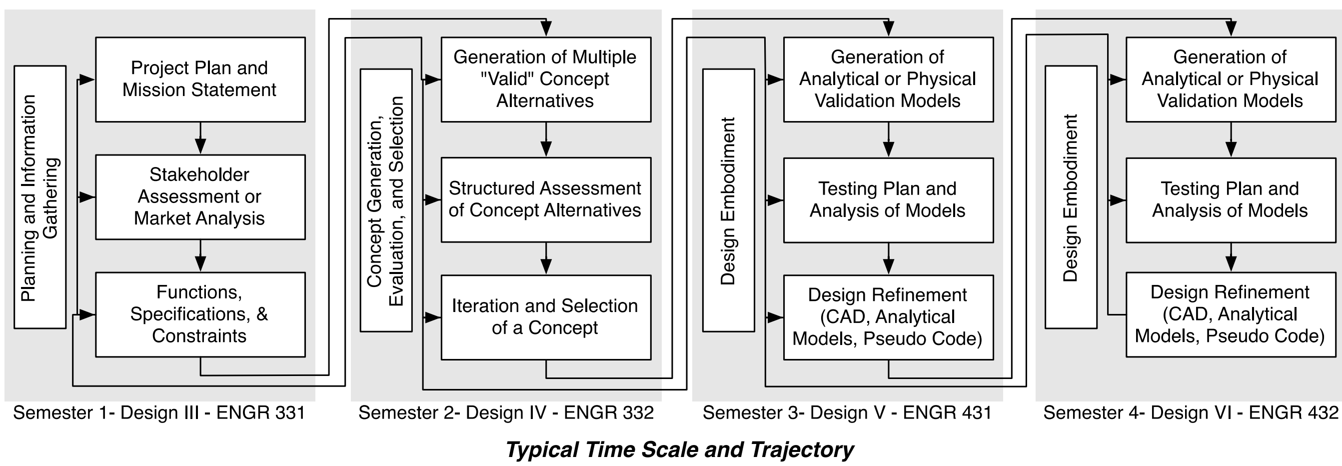

Figure 2*: A typical design process timeline for completing capstone design projects.*

As is evident herein, via design process content, rubrics, report templates, etc., there are clear expectations and requirements for our students to document and justify the design process and the steps used in completing their capstone projects. In preparing students for the workplace and engineering practice, this is a standard in which we strongly believe. We also encourage our students, where applicable, to apply engineering standards in executing their capstone projects. Some projects, which have industry sponsors, have such standards embedded in the projects. For projects which do not have an industry sponsor, we encourage the capstone team to identify and apply engineering standards where applicable.

Projects used for the capstone design experience cover diverse topics and are designed to enable students to utilize knowledge across multiple areas within their formative course preparation. The content for the projects contain sufficient depth and breadth to allow iterations within the design process. A listing of the capstone projects offered during the first two runs of the capstone model are provided in ***Table 2***.These capstone projects include and highlight all the essential attributes required for professional engineering practice, thereby providing students with the opportunity to hone their engineering skills using a real-world approach. Capstone projects are culled from engineering faculty as well as from industry representatives or collaborators, from faculty in other departments, or from proposals by student teams. Students are required to give presentations and submit reports at major milestones during the project timeline.

***Table 2**: Selected Projects from the First Two Rounds of the James Madison University (JMU) Capstone Experience*

Project Title	Brief Description	Sponsor
Autonomous Fire-Fighting Robot	Design of a robot to find and extinguish fires.	Internal
Biomimicry on the Road	Design of a surface structure to reduce aerodynamic drag on a tractor trailer.	Internal
Design and Development of a Campus Composting Facility	Design of a reactor for recycling waste from JMU dining halls.	Internal with EPA grant
Designing a Sustainable Health Care Center for Sub-Saharan Africa	Creation of a health center design to address the needs of this African community.	Internal
Electric Commuter Scooter	Design of a scooter to meet the needs of JMU off-campus commuters.	Battery Mart, NuGen Mobility
Energy Modeling Project	Design of residential wall system structure for use in construction of residential houses.	The Gaines Group, PLC
Redesign and Construction of a Piezoelectric Oligonucleotide Synthesizer and Micro-arrayer (POSaM)	Design of a micro-arrayer for use in bacteriophage and gene expression investigations at JMU.	Internal with NSF grant
Resource Recovery Facility Centralized Vacuum System	Design of vacuum system to mitigate ash buildup at local municipal solid waste incineration plant.	City of Harrisonburg
Testing Apparatus and Procedure to aid in the Characterization of Semi-Conductor Photo-electrodes	Design of testing apparatus for use in solar hydrogen production.	Internal with Dept. of Energy grant
Aero Team	Design of an add-on device to enhance the aerodynamic performance of a Volkswagen race car.	Mid Atlantic Motorwerkes
Building Energy Optimization	Development of system for intelligent analysis of building energy data.	2RW Engineering
Converting Waste Cooking Oil to Biodiesel	Design of a portable continuous-flow biodiesel reactor.	Internal
Electric Assist Bicycle Trailer	Design of a bicycle trailer capable of pulling its own weight.	2RW Engineering
Energy Modeling Project	Design of residential wall system structure for use in construction of residential houses. (Both juniors and a senior member)	The Gaines Group, PLC
High Energy Battery Development Team	Design of a high-voltage, high amperage battery pack for a motorcycle.	Outlier EV
Storm Water Filtration System	Design of a filtration device to improve efficacy of removal of contaminants from storm water runoff.	Internal
Wind Harvesting Capstone Project	Design of a system to convert wind energy produced by tractor-trailers under overpasses into electrical energy.	Internal

Assessment of ABET-based Learning Outcomes

To accompany the capstone design model, the James Madison University Engineering Department has also set forth a detailed assessment plan which has been shaped through two NSF-funded projects (included in the acknowledgements) and the strong University assessment culture requiring all academic programs to develop extensive assessment plans and submit annual reports providing evidence of how well students are meeting the program goals (in our case ABET outcomes "a-k"). The James Madison University Engineering assessment plan includes numerous measures, both direct and indirect, to evaluate the extent to which program outcomes are met. The measures that are of particular importance to the capstone design experience include the National Engineering Students' Learning Outcomes Survey (NESLOS), a project evaluation survey, achievement goal orientation, creativity scales, etc. In this paper, we focus on NESLOS results, which measure students' perceptions of ABET-based learning outcome gains. Students' learning outcome ratings correspond to students' self-assessments on their abilities to achieve the specific learning outcome as a result of completing design projects.[31,32]NESLOS, a reliable instrument, has been administered to seniors engineering students (n=47, response rate 91%) at the end of their capstone experience (i.e. end of ENGR 432) as well as their capstone faculty advisors (n=10, response rate 80%). NESLOS construct reliability indices (Cronbach's alpha) ranges from 0.70 to 0.90. [31,32] NESLOS was administered as an online survey where faculty rated the extent to which her/his capstone design students demonstrated an ability to achieve the learning outcomes, and capstone students self-rated the extent to which he/she demonstrated an ability to achieve the learning outcomes during their capstone experience. Faculty and student responses were based on a five point scale where a rating of one corresponded to "1-low ability or no experience" and a rating of five to "5- high ability." NESLOS contains fifty items—twenty-five related to technical engineering skills and twenty-five related to professional skills—with most aligning with ABET learning outcomes 'a-k'.

In analyzing the NESLOS items, it seemed most relevant to gauge the degree of attainment for each learning outcome as assessed by the capstone senior students (i.e. self-assessment of their learning during the capstone experience) as well as by the capstone faculty advisors (i.e. assessing students' attainment of the learning outcomes). Table 3 provides the percentages of these attainments for the fifty NESLOS items across the two groups. For each NESLOS item, percentages of faculty advisors rating his/her students as having "adequately" attained the outcome are shown as well as the percentages of students' self-assessment of their "adequate" attainment of the learning outcome. The difference between the percent attainments across students and faculty is also shown to provide insight into the degree of agreement between faculty advisors and students. Also included in Table 3 are Cohen's d values, which are a measure of effect size (standardized difference between means to reveal the magnitude of the difference present between the two groups) and are derived from comparing the mean and standard deviations of each learning outcome across average faculty and student ratings. Cohen's d values below 0.2 suggest a negligible effect size (non-significant differences), values between 0.2 and 0.5 suggest a small effect size, values between 0.5 and 0.8 suggest a medium effect size, and values over 0.8 suggest a large effect size. Cohen's d values in Table 3 for the fifty NESLOS items suggest that the magnitude of difference present between faculty and student ratings tend to be either negligible effect sizes or small effect sizes, which suggests that there is fairly good agreement between faculty and student ratings of learning outcome attainment.

Table 3*: Student and Faculty Advisor Assessment of Learning Outcome Attainment of Student Achievement at the End of the Two-Year Capstone Experience. Learning Outcome Assessment Corresponds to the NESLOS items.*

NESLOS ITEMS *Items Relevant to Technical Engineering Skills in Bold and Italics* Items Relevant to Professional Skills not in Bold or Italics	**CAPSTONE FACULTY ADVISORS** N=8 **% Attainment**	**CAPSTONE SENIOR STUDENTS** N=43 (2012 Class) **% Attainment**	**Difference** (Students-Faculty)	**Cohen's d**
Recognize their strengths and weaknesses	38%	98%	***60%***	0.41
Locate and reference scientific/engineering textbooks, journal	38%	93%	***55%***	0.23
Recognize the need for diverse perspectives in solving problems	50%	100%	***50%***	0.36
Reach beyond oneself (challenge himself/herself to new limits)	50%	100%	***50%***	0.31
Recognize intrinsic interest in learning/intellectual curiosity	50%	98%	***48%***	0.38
Set and pursue her/his own learning goals	50%	98%	***48%***	0.31
Operate in the unknown (open-ended problems)	50%	98%	***48%***	0.29
Recognize contemporary scientific, engineering, and technology issues	50%	95%	***45%***	0.22
Engage in critical, reliable, and valid self-assessment	50%	93%	***43%***	0.28
Recognize connections between and within different disciplines	50%	93%	***43%***	0.27
Identify potential ethical issues and dilemmas in problems	50%	91%	***41%***	0.31
Understand the impact of engineering solutions in societal and global contexts	50%	91%	***41%***	0.28
Understand the ethical responsibility associated with the your profession and projects	50%	88%	38%	0.29
Recognize the need for lifelong learning	63%	100%	37%	0.39
Demonstrate a strong work ethic	63%	100%	37%	0.37
Take new opportunities for intellectual growth or professional	63%	100%	37%	0.32
Demonstrate strong organizational skills	63%	100%	37%	0.33
Demonstrate originality and independent thinking	63%	100%	37%	0.33
Manage planning and organization of project tasks and processes	63%	100%	37%	0.23
Create and follow a timeline when managing projects	63%	100%	37%	0.17
Use evidence to draw conclusions or make recommendations	63%	98%	35%	0.29
Evaluate problems and solutions in local and global social	63%	98%	35%	0.23
Recognize knowledge transfer between real-world engineering/scientific problems and coursework	63%	98%	35%	0.23
Understand assumptions needed to solve a problem	63%	95%	32%	0.30
Conduct or simulate an experiment	63%	95%	32%	0.23
Create and follow a budget when managing projects	63%	95%	32%	0.17
Demonstrate strong leadership skills	63%	93%	30%	0.24
Evaluate the ethical dimensions of professional practice	63%	91%	28%	0.34
Design a product, process, or system to meet desired needs	75%	100%	25%	0.25

NESLOS ITEMS *Items Relevant to Technical Engineering Skills in Bold and Italics* Items Relevant to Professional Skills not in Bold or Italics	**CAPSTONE FACULTY ADVISORS** N=8 **% Attainment**	**CAPSTONE SENIOR STUDENTS** N=43 (2012 Class) **% Attainment**	**Difference** (Students-Faculty)	**Cohen's d**
Work independently to complete project tasks	75%	100%	25%	0.24
Formulate and justify the need and relevance of a problem or project	75%	100%	25%	0.24
Identify and establish requirements and constraints to solve a problem	75%	100%	25%	0.22
Formulate a range of solutions to a problem	75%	100%	25%	0.19
Identify and define problems	75%	98%	23%	0.29
Effectively manage conflicts that arise when working on teams	75%	98%	23%	0.27
Analyze and interpret data	75%	98%	23%	0.23
Demonstrate leadership skills in managing project tasks and project	75%	98%	23%	0.17
Recognize the need to consult an expert from a discipline other	75%	98%	23%	0.15
Apply basic scientific principles to analyze the performance of products, processes, and systems	75%	95%	20%	0.20
Design an experiment	75%	95%	20%	0.21
Use feedback from an experiment or simulation to improve solutions to a problem	75%	93%	18%	0.18
Apply experimental tools (e.g. machining, instrumentation, laboratory equipment, etc.) to solve engineering/scientific problems	75%	88%	13%	0.04
Work in a team setting during engineering/scientific projects and problem solving	88%	100%	12%	0.26
Apply interpersonal skills when working with others	88%	100%	12%	0.27
Collaborate with others when working on engineering/scientific projects	88%	98%	10%	0.23
Convey technical ideas in formal writing and other documentation	88%	98%	10%	0.16
Apply computational and numerical tools (e.g. programming, modeling, simulations, other software, etc.) to solve engineering/scientific problems	75%	84%	9%	0.15
Communicate effectively with others	100%	100%	0%	0.24
Generate multiple and alternative solutions/concepts	100%	100%	0%	0.15
Convey ideas verbally and in formal presentations	100%	100%	0%	0.12

Important differences noted in Table 3 are the learning outcomes that show a 40% difference when comparing percent attainments assessed by faculty and students. These learning outcomes, denoted in red, bolded italic numbers in Column 4 of the Table 3 are primarily related to professional skills and are outcomes where the students self-assessed as having attained at a much higher percentage than faculty assessed the students to have attained. In terms of students' technical skill attainment during this capstone experience, there appears to be good agreement between faculty advisors and students, and many of the outcomes related to problem identification and formulation, engineering design, engineering analysis, experimentation skills, and project management skills were adequately attained during this two-year capstone experience. In general though, and perhaps to be expected, the students self-assessment their learning outcome attainments higher than faculty advisors rated the students.

Continuous Improvement

The engineering faculty at James Madison University is committed to continuous improvement of the two-year capstone model and attempts are already being made to evaluate and improve the capstone experience. As evidence of some of the changes being considered, the following table shows a mapping of some of our assessment findings with ABET student outcomes "a-k." As for most engineering programs, ABET is a driving standard that guides the continuous improvement efforts. ***Table 4*** thus includes derived average ratings from NESLOS items that map to ABET student outcomes "a-k" and compare faculty and student ratings. The table does not include the full assessment but rather examples of how the mapping of NESLOS items to ABET student outcomes is used to guide the continuous improvement process. What one observes from reviewing Table 4 is that the James Madison University capstone experience being intertwined with four engineering design courses during junior and senior years means that good coordination among these two facets (capstone experience and engineering design instruction) is essential to this model. These intertwined facets are not unique to the James Madison University engineering program. Many engineering programs nationwide are challenged by balancing these two facets. In moving forward, these are some of the layers of the James Madison University capstone model that the engineering faculty are working on and continuously improving.

Table 4*: Examples of evaluation of JMU Capstone Experience via Assessment of ABET Student Outcome Attainments Using NESLOS Items.*

ABET Student Outcome	**Capstone Project Survey (NESLOS)**	**Attainment** **Target**	**Measured**	**Evaluation and Action**
A. Apply knowledge of mathematics, science, and engineering.	Faculty	80%	75%	**Student Outcome Adequately Met.** **Evaluation** - There appears to be a mismatch between faculty and student ratings of Student Outcome A learning outcomes as related to the capstone design projects. Students think that they are adequately applying knowledge of mathematics, science, and engineering, yet faculty advisors believe that students can be doing better. **Action** – Faculty (capstone advisors and design instructors) plan to continue to encourage adequate application of knowledge of mathematics, science, and engineering in capstone design projects by showing more and better design examples integrating design thinking with mathematical, science, and engineering knowledge.
	Student	80%	95%	

ABET Student Outcome	Capstone Project Survey (NESLOS)	Attainment Target	Measured	Evaluation and Action
D. Function on multidisciplinary teams.	Faculty	80%	70%	**Student Outcome Adequately Met.** **Evaluation** - There appears to be a mismatch between faculty and student ratings of Student Outcome D learning outcomes as related to the capstone design projects. Students think that they are adequately and effectively working in their capstone teams, yet faculty advisors believe that students can be doing better. The major issue is that, for some teams, not all team members are committed and contributing to the capstone projects consistently and equally. **Action** – The use of the national online tool Comprehensive Assessment for Team-Member Effectiveness (CATME) during the past year has been useful and will continue. A strength of this existing online tool is that students receive formative and confidential feedback on how peers are evaluating their performance. Design instructors, with feedback from capstone advisors, are also considering the implementation of individual "contracts" to be completed by each capstone student for accountability purposes.
	Student	80%	98%	
E. Identify, formulate, and solve engineering problems.	Faculty	80%	64%	**Student Outcome Somewhat Adequately Met.** **Evaluation** - There appears to be a mismatch between faculty and student ratings. Students think that they are adequately and effectively identifying, formulating and solving engineering problems related to their capstone project, yet faculty advisors believe that students can be doing better. **Actions** – The integration of design challenges in the junior and senior design courses (ENGR 332, 431, and 432) during the past year did help in illustrating to students the integration of design thinking and systems thinking with engineering science thinking. These design challenges will continue to be enhanced and advanced in the design courses, but also in other engineering courses (ENGR 313, 314, 411, 413). The design instructors will implement design activities to help students identify engineering design problems of interest in the hope that such skills of problem identification and formulation will translate to the capstone project. More detailed formative and formal feedback to the capstone teams by the capstone advisors will also be encouraged.
	Student	80%	98%	
G. Communicate effectively.	Faculty	80%	90%	**Student Outcome Adequately Met.** **Evaluation** - There appears to be agreement between faculty and student ratings of Student Outcome G learning outcomes as related to the capstone design projects. Faculty advisors and students are in agreement that written and oral communications skills are effectively and adequately met in the context of the capstone projects. **Actions** – The implementation of two individual progress memos during the 2^{nd}, 3^{rd}, and 4^{th} semesters of the capstone experience in ENGR 332, 431, and 432 helped a great deal with design instructors providing each student feedback on their writing style via use of a rubric. Such a practice will continue and will also be improved.
	Student	80%	99%	

ABET Student Outcome	Capstone Project Survey (NESLOS)	Attainment Target	Measured	Evaluation and Action
H. Have the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.	Faculty	80%	58%	**Student Outcome Somewhat Adequately Met.** **Evaluation** - There appears to be a mismatch between faculty and student ratings of Student Outcome H learning outcomes as related to the capstone design projects. Students think that they adequately understand the impacts of their capstone project in the larger societal, economic, environmental, and global contexts, yet faculty advisors believe that students can be doing better. **Actions** – Although topics on sustainability, systems thinking, environmental, and economic impacts, as well as social impacts are adequately addressed and attained in the curriculum, it appears that students are not translating these principles to their capstone project. To address this, the design instructors plan to formally include a section in the capstone report template addressing sustainability principles and related impacts.
	Student	80%	95%	

Conclusion

This paper presented the two-year or four-semester capstone design model that exists at James Madison University, which is a newly established undergraduate engineering program. The vision and approach for this capstone model was presented as well as some evidence to suggest that students are gaining important technical and professional skills as a result of this experience. Almost all engineering programs integrate a capstone design experience during an undergraduate engineering education to prepare students with a strong engineering design knowledge and skill base and to meet ABET requirements for a culminating learning experience. Although there are many capstone design models in existence, the majority last either one or two semesters and there is no requirement for the students to apply the entire design process. Capstone design experiences that exceed one academic year are quite uncommon and previous publications show that these capstone design experiences tend to result in students progressing through the design process in more depth and breadth. Through the James Madison University engineering capstone model, students experience a real-world design project from planning to concept development to system-level design to detailed design and modeling to testing and refinement. Through this design project, students are challenged to apply the engineering analysis learned in their engineering science, environmental sustainability, and technical elective courses. While preliminary assessment of the capstone model suggests that students are achieving many of the desired ABET outcomes, the JMU faculty are exploring ways to bring faculty and student attainment scores in alignment with one another and continuously improve the capstone learning experience. The continuous improvement described in this paper provides an example for how other capstone experiences, two-year or otherwise, could be assessed.

Through implementing and assessing the two-year capstone model, this paper can provide lessons learned for other engineering programs considering changes to their model. As cited in the literature, multi-semester capstone models take more time and coordination to execute. In particular, successful implementation of this two-year model requires:

- Proper scoping of projects so that students can progress through the design process in two years and integrate knowledge from science, mathematics, and engineering coursework;
- Alignment of design course instruction (theory) and the capstone project work (practical application) to help students draw connections;
- Coordination of faculty teaching engineering design, engineering science, and other engineering topic courses to help students identify knowledge pertinent to their capstone project and view all engineering problems as sustainable design problems;
- Flexible assessment that allows student teams to progress through the design process at an appropriate pace for their project;
- Coordination of project advisors and design course instructors to provide consistent assessment across projects; and
- Monitoring and assessment to ensure student outcomes are being met.

While there are resource and coordination challenges involved in implementing the innovative two-year capstone model, it provides an opportunity for students to experience real-world engineering design problems in a realistic timeframe and integrate knowledge and skills from across the curriculum.

Acknowledgments

The authors would like to acknowledge the support of the National Science Foundation Awards #DUE-0837465 (NSF CCLI – "Design and Implementation of an Innovative Problem-based Learning Model and Assessment Tools in Undergraduate Engineering Education") and #EEC-0846468 (NSF CAREER – "Characterizing, Understanding, and Integrating Complex Problem Solving in Engineering Education"). The views expressed in this paper are those of the authors and do not necessarily represent those of the National Science Foundation. We would also like to thank the students and faculty who participated in this study.

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