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The Development of Engineering Project Curricula that Emphasize Design Cycles

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1 Abstract

As engineering educators, our role is to prepare students for careers in engineering. As such, we aim to develop our students' engineering capabilities in accord with the expectations of the modern engineering work force. ABET EC2000 identifies many of these capabilities, the so-called "(a) through (k) student outcomes." Much has been written about curricular tools and teaching methods that focus on building engineering career-related capabilities. We too are motivated to develop new curricular tools to address these capabilities. As such, this manuscript details the structure and assessment of our design-centric engineering projects. These design-centric projects emphasize teamwork, independent learning, formulating engineering problems, communication, and modern engineering techniques. Through our interactions with students and assessment of deliverables, we have developed an understanding of the value such projects have on the development of these professional engineering capabilities within our engineering students.

2 Introduction

In order to adequately prepare students for careers in engineering, their engineering capabilities should be developed to meet expectations of the modern engineering work force. ABET's Engineering Criteria 2000 (EC2000) identifies a suite of these capabilities in its list of recommended student outcomes, commonly known as the "(a) through (k)" outcomes, or "SOs." However, many of the traditional curricula tools that engineering educators employ do not adequately address these capabilities.

As such, a significant body of research has been developed around the use and assessment of curriculum tools and teaching methods that focus on building enigneering career-related capabilities. For instance, the work by Felder, *et al*, describe instructional methods relevant to developing the critical skills required of modern engineering graduates.[1–3] As well, Feisel and Rosa's work describe the functional role of laboratories in engineering education, including the ability to meaningfully assess the objectives set forth by EC2000 in the laboratory setting.[4] Dym, *et al*, describe the role of design in the engineering curriculum and explore project-based learning as a method for developing these engineering capabilities.[5] And, Prince and Felder describe inductive teaching and learning methods that include both problem- and project-based learning approaches.[6]

This manuscript compliments that body of research by describing design-centric engineering projects (DCPs), which we have developed and are in the process of refining. Our DCPs emphasize context-oriented, design-focused coursework, with a strong focus on teamwork and collaboration. We feel that development of professional "soft" skills and design expertise are achievable through project-based learning (PBL). Our development efforts draw from the current pedagogical literature on PBL, particularly that pertaining to electrical and computer engineering education.[7–10] We are especially interested in efforts related to electrical power engineering.[11,12]

For PBL, instructors introduce a relevant problem at the beginning of an instruction cycle, which is used to provide the context and motivation for the learning that follows.[13] We have observed that students often lack an understanding of context, unable to comprehend the “big picture” surrounding technically-focused curricula. Our DCPs present open-ended problems within a design-centered context. Intentionally, we present each DCP without adequate background information, thereby forcing students to learn on their own outside of the course curriculum. Consequently, this provides more freedom and flexibility for students to work through engineering problems on their own without being told specifically what they must do and learn.[14] This is a fundamental structural change to our teaching, one that we feel is especially important for students during their junior year, a time in which they are first applying engineering principles to solving design problems. These experiences aid students in developing the abilities to understand engineering within a wider context, provide them with experiences that build their confidence, and help them to understand that success in engineering requires a lifetime of independent learning.

3 Design in Engineering Curriculum

As recognized within ABET EC2000, design is a fundamental learning outcome all engineering students should be familiar with, noted specifically within SO (c), *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*. The concept of design is open to multiple interpretations, and education researchers have created detailed abstractions to define it and charactize how it is conducted.[15–17] But fundamentally, design is recognized as essential to the engineering profession.

Design-focused coursework is of particular importance for electrical and computer engineering education; Passow, *et al*, score *design* within their high cluster of ABET SOs for electrical and computer engineering populations.[18] Design-focused coursework has been shown to be particularly hard to learn and teach, but it improves retention, student satisfaction and student learning.[19] Design begins with contextualizing a problem by presenting students with incompletely-defined engineering specifications that employ social constraints. These contraints may include, for example, codes and standards, budgets, and regulations. Students then undergo a series of design reviews during which they refine their proposed solution through instructor feedback. And finally, students evaluate their implementation, which helps them to understand the value of the experience.[14] In doing so, students use contemporary techniques and tools common in engineering practice, thereby providing them with professional capabilities they will use throughout their careers. Mastery of this technique is achieved through repeated practical application.

4 Design-Cycle Project Description

In this section, we describe the structure and implementation of our 300-level project DCPs. We implement our DCPs as term-long projects within our electrical power systems and rotating machinery courses. These assignments require students to design, build, troubleshoot and demonstrate an asynchronous motor soft-start controller and a generator synchronization controller, respectively. Designs for both projects are implemented using Programmable Logic Controllers (PLCs). These design projects require students to apply and physically demonstrate the concepts being presented in lecture. More importantly though, the projects run students through a design cycle process.

The project begins with the assignment of a set of deliverables. These include system specifications consisting of *must*, *should* and *might* requirements; an operator’s manual describing the system operation as well as notes on relevant codes and standards; a demonstration of realized specifications; and, a bill of materials (BoM).

Deliverables are due at four milestone points (Tasks) throughout the project timeline, thereby providing a sequence of firm deadlines, opportunities for feedback, and chances for mid-project assessment. Each successive Task builds upon past ones. As such, iterative feedback is provided regularly and improvements are made. The students' work is "red-lined" (reviewed), specifically their PLC ladder logic diagrams and electrical panel plan view CAD layouts. Their use of codes and standards are scrutinized, and their BoMs updated to reflect design changes. In this fashion, feedback is provided to the student groups at each critical phase in the design process.

By the end of the term, students have designed and built a system in accord with a set of specifications. They have written a vetted user's manual. They have applied and justified the use of relevant codes and standards. And, they have demonstrated their project via a verbal explanation and demonstration of the project design. All of these the course instructor may use to assess the students' mastery of the course SOs.

5 Assessment Methods

In this section, we demonstrate the assessment of the design-cycle projects, and the DCP alignment with ABET EC2000 SOs. Assessment results come from two DCPs, one from Spring term 2014 and another from Winter term 2015 (on-going).

We employ two methods of assessment for these projects. One, we use a rubric to assess the project deliverables and design specifications, which are related to the project SOs. And two, students complete an on-line survey at the end of each Task, which consists largely of qualitative feedback.

5.1 SO Assessment

In addition to SO (c), our design-cycle projects addresses several other SOs, particularly (a), *an ability to apply knowledge of mathematics, science, and engineering*, (d) *an ability to function on multidisciplinary teams*, (e) *an ability to identify, formulate, and solve engineering problems*, (g) *an ability to communicate effectively*, and (k) *an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice*.

We assess these SOs using rubrics. Details of the project deliverables are assessed using a three-column rubric, with column headings *Developing*, *Accomplished*, and *Exemplary*. Rubric rows relate to deliverables, for example *Prototype Demonstration*, *Engineering Drawings*, and *Operator's Manual*. An example rubric row is shown in Table 1. Within each row are a set of numbered assessment items, which are evaluated by an instructor. Each assessment item links to one or more SOs. The links between the assessment items and the SOs are noted in the leftmost column of Table 1.

After evaluating each student group using the assessment rubric, the results are compiled into tables, one for each SO. An example SO table in shown in Table 2, specifically demonstrates assessment of SO (c). Each SO is assessed using assessment items from multiple rubric rows. For instance, SO (c) is assessed using items from three different rubric rows, *Prototype Demonstration*, *Ladder Logic Circuit Diagram*, and *Operator's Manual*.

Results for all SOs are summarized in Table 3. An SO is deemed to have been satisfied if greater than 80% of assessment items score within the *Accomplished* or *Exemplary* columns. Those that do not meet this objective merit attention via an assessment review process.

Table 3 shows results from Task 1 of the design-cycle project. The project consists of four Tasks

Criteria	Developing	Accomplished	Exemplary
Prototype Demonstration Relevant SOs: a(3), c(1), d(2,3), e(1,2), g(2,3)	1) Physical prototype meets some or all *shall* specifications. 2) Team members cannot effectively explain the system operation or design; 3) do not demonstrate their engineering knowledge during discussions.	1) Physical prototype meets all *shall* and *should* specifications. 2) Team members can explain the system operation and design, and 3) demonstrate their engineering knowledge during discussions	1) Physical prototype meets all (*shall*, *should*, *might*) specifications. 2) Team members effectively explain the system operation and design, and 3) effectively demonstrate their engineering knowledge during discussions.

Table 1: An example row from the assessment rubric. Rows relate to project deliverables. Assessment items in each row are evaluated by the instructor. These items related to one or more ABET SOs.

Performance Criteria for SO (c)	Developing	Accomplished	Exemplary	% $\geq$ Accomplished
Prototype Demonstration: (1) Physical prototype meets *shall*, *should* and/or *might* specifications	0	1	3	100%
Ladder Logic Circuit Diagram: (4) Logical circuit topology	0	4	0	100%
Ladder Logic Circuit Diagram: (5) Efficient implementation of specifications	0	4	0	100%
Operator's Manual: (1) Operator instructions are clear and easy to follow	1	3	0	75%
Operator's Manual: (2) Design specifications shown to have been achieved	2	1	1	50%

Table 2: An example summary table for SO (c). Each SO is assessed using assessment items from multiple rubric rows. Note that assessment item (1) of *Prototype Demonstration* is found with in the *Prototype Demonstration* rubric row of Table 1.

(three of which had been assessed by the time of this manuscript submission). After assessment and grading, the rubrics are returned to students, which provide them with feedback on completed Tasks. Students also receive feedback from the instructor from red-lining of engineering drawings and during demonstrations of their project prototypes. As students progress through the project, we hypothesize that SO assessment values will improve because of these design review and assessment processes.

5.2 Survey Assessment

The student surveys are administered on the due date of each Task deliverable. These provide opportunities for the students to express their opinions, frustrations, and exaltations about the project. As such, they are *qualitative* assessments, from which we infer the students' opinions of the project. Questions pertain to *project difficulty*, *prerequisite preparation*, *team work*, *concerns* and *further comments*.

Regarding *project difficulty*, all of the respondents noted the difficulty associated with the knowledge ramp-up of learning the PLC software and the PLC hardware I/O configurations. These were not subjects of discussion in the course lecture. For *prerequisite preparation*, most respondents noted they had very little preparation for this PLC-based project, other than familiarity with 8-bit addressing, and evaluating circuit schematics. But as one student noted, "*that's what makes it a great engineering project.*"

The *team work* portion of the survey was rated on a five-point scale, five indicating excellent

SO	Developing	Accomplished	Exemplary	% ≥ Accomplished
(a)	0%	0%	100%	100%
(c)	15%	65%	20%	85%
(d)	0%	0%	100%	100%
(e)	0%	13%	88%	100%
(g)	18%	45%	38%	83%
(k)	50%	25%	25%	50%

Table 3: A summary SO table. The target is to have greater than 80% of assessment items scored within the *Accomplished* or *Exemplary* columns.

teamwork. Half the respondents scored *teamwork* as a 2 or 3, and the other half as a 4 or 5. Student *concerns* and *comments* enlighten these ratings, with respondents noting that the group sizes are too large (five), greater care should have been taken to select groups, balancing the assignment against other course requirements, uneven teamwork distribution, and difficulty finding time for the group to engage with the project.

Within *concerns* and *comments*, students noted nervousness about their own capabilities to complete the project, the vagueness of the specifications, and not understanding how the whole system will work as they progress through successive Tasks. Other respondents expressed enthusiasm for the project, noting it as a "*good experience so far*," and that their team was going to "*knock it out of the [expletive] park.*"

These comments were collected at the end of Task 1 of our 2015 DCP, and as such we read of apprehensions and frustrations, as well as some enthusiasm. Comments collected at the end of our 2014 DCP reveal the students' appreciation of the experience after they had finished their projects and developed a sense of accomplishment. Characteristic comments include:

- "*Projects like this help students become better engineers. Going through the process was both time consuming and difficult, but this project made me think differently. When the project was done I felt a real sense of accomplishment.*"
- "*This project was extremely difficult and time consuming, but to have a complete working system at the end was one of my most satisfying experiences in school.*"
- "*The project as a whole was a great way to 'drive home' some of the more mundane, but real world, aspects of motors.*"
- "*[This project] better prepares you to work in industry and gives you a heads up on other graduates.* "
- "*... it is critical to the future of education that projects mirror industry standard practices, methods and format. Student projects should result in something they can add to their portfolio of work and present to a potential employer.*"

... and finally,

"*Tell me, I forget.*
Show me, I remember.
Involve me, I understand."

6 Closing the Loop

Performing assessment after each of the four Tasks of a DCP allows us to track how student performance changes as the project progress. And, assessing DCPs from year to year and in different courses will provide us with a thorough understanding of how effective DCPs are at preparing students for their engineering careers.

These efforts are part our process of "closing the loop." Our DCPs provide us with measurable outcomes that map to program SOs. We have an assessment method and instruments to provide us with feedback. And, our assessment method includes a benchmark target. With these, we may then "close the loop" by analyzing data and using results to improve our teaching and the students' learning.[20] In other words, results of the assessments are used as input to inform the continuous improvement of both teaching and learning.

As of this printing, we had assessed three of the four Tasks of our most recent DCP. Table 4 shows our assessment results for each of the SOs. Our results show scores on all SOs improving as the project progressed. Scores for most SOs exceeded the 80% threshold after the first Task, and in most cases, scoring in the *Exemplary* column improves with each successive Task. By Task 3, all of the SO were meeting the 80% threshold. Even before the fourth Task was completed, students were turning in deliverables that demonstrated high achievement on almost all of these career-related capabilities. These data indicate that the iterative nature of the project resulted in students making progress towards achieving the SOs benchmark, likely due to the feedback provided to each student after each iteration.

In closing the loop, we feel that this project has provided students with opportunities to develop career-related capabilities, as indicated by the assessment scores in Table 4. We conclude that the project is proving to be successful. Students have been exposed to a design cycle process and are engaging in tasks expected of practicing engineers. Yet there is always room for improvement. We have already begun developing the next DCP, which features greater technical complexity and therefor more independent learning. Our current cohort of students will take on this next DCP, so they will have an opportunity to further refine their design capabilities and engage in more professional practice. And, we will continue to improve our rubric-based assessment instruments, as these provide the detailed quantitative assessments that allow us to close the loop.

SO	**Task 1**		**Task 2**		**Task 3**	
	Acc	Ex	Acc	Ex	Acc	Ex
(a)	0%	100%	0%	75%	0%	100%
(c)	65%	20%	29%	67%	8%	92%
(d)	0%	100%	0%	75%	0%	100%
(e)	13%	88%	0%	75%	0%	100%
(g)	45%	38%	23%	59%	16%	82%
(k)	25%	25%	13%	50%	33%	67%

Table 4: For purposes of closing the loop, we summarize our assessment results for each SO after the completion of each DCP Task. Noted are the percentages of criteria in which student groups scored *Accomplished* (Acc) or *Exemplary* (Ex) per SO for the first three Tasks of our current DCP.

7 Future Work

We intend to expand this design-cycle project concept to other electrical engineering courses. Specifically, we have begun conceptualizing how to design a DCP for a 300-level feedback & control course that would involve PLC-based PID control systems. Such a project will involve conducting step and/or frequency response characterization of a plant; developing a plant model and validating that model within a computer simulation environment; tuning and modeling a PID compensator according to a set of design specifications that describe the desired dynamic and steady-state system response; implementing the PID compensator within the rungs of a PLC ladder logic program; and finally, testing the control system to validate the specifications.

We see possibilities for expanding in future to other power-related courses, such as power systems design and power systems protection (PSP). For a PSP course, students could use a PAC (programmable automation controller) specifically designed for substation automation, rather than a general PLC, to create control strategies for substation-level power systems protection schema. And of course, other possibilities for PLC-based DCPs lie outside of electrical engineering, such as within HVAC, pneumatic systems, logistics automation, chemical processing, etc.

8 Conclusion

Our design-centric projects provide students with hands-on learning experiences where, through an iterative process, they explore the engineering design cycle. Ultimately, we would like students to have gone through three DCPs during their junior year. These experiences will give students opportunities to become familiar with the engineering design cycle and to develop meaningful design skills before they graduate. In addition to design, these projects will reinforce SOs pertaining to application of engineering knowledge, team work, solving engineering problems, communication, and using modern engineering techniques. If we can demonstrate that students are able to achieve these outcomes through DCPs, we may infer that they will be adequately prepared for starting careers in engineering; their engineering capabilities should be developed enough to meet the expectations of the modern engineering work force.

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