ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #31982

An Engineering Capstone Course From Multiple Perspectives

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Introduction

An engineering capstone course serves as the culminating experience of an engineering student's undergraduate curriculum. The EPP Projects course, the capstone for the Engineering and Public Policy additional major program, has provided decades of students – both undergraduate and doctoral students, with a unique learning opportunity. In this paper we describe the Engineering and Public Policy undergraduate program and curriculum leading to this course, and the structure of the course itself. We provide perspectives on the course from the undergraduates taking the course and doctoral students serving as project managers. The lessons learned beyond the direct learning objectives contribute to the success of our graduates, and the long-lasting success of the course itself.

The Engineering and Public Policy Undergraduate Additional Major Program

Engineering and Public Policy in Carnegie Mellon University's College of Engineering is a unique department that works to solve problems at the interface of technology and society. Academic programs include a highly regarded research-oriented doctoral program, Masters programs in EPP as well as Engineering and Technology Innovation Management (a technical MBA-type program), and additional major and minor undergraduate programs. Faculty in the department often have joint appointments with other engineering and non-engineering departments. Research and teaching span the gamut of problems, with a focus on energy systems, climate and environment, information and communication technology systems, cybersecurity and privacy, technological innovation, and risk assessment and communication.

The Engineering and Public Policy additional major is offered in conjunction with each of the five traditional engineering departments. Students complete all of the requirements of the traditional engineering degree programs (all ABET accredited), as well as a set of courses in for the Engineering and Public Policy program (also ABET accredited). Established in 1970, from the beginning, the additional major undergraduate program was not intended to create a different kind of engineering graduate but rather to add some additional dimensions and skills in the education of traditional engineering students who will go out into conventional engineering careers. Its core mission has always been to deepen a student's understanding of the interaction of their traditional engineering field with the broader society. The program emphasizes the requisite non-engineering knowledge and skills to navigate the interface and understand the mutual impacts of engineering and policy at various levels. The department offers a corresponding additional major program in Science, Technology and Public Policy for non-engineering technical majors. These programs serve as extensions to the traditional technical

programs of engineers and scientists to provide this perspective. And, unlike completing a minor or additional major in a different field, our approach to teaching students is to continually emphasize the connections among the technical and non-technical issues.

Students can complete the additional major in the typical eight semester timeframe. The curriculum includes an introductory course in engineering and public policy basics, a set of core area courses in economics, statistics, decision making and technical writing, three technology-policy electives, and a three course capstone series. The first course in the series provides students with highly scaffolded assignments to practice skills learned in both our program and their technical programs while also learning project management skills. The last two courses are the EPP Projects course where students work to structure and solve a large complex problem with multiple dimensions in an interdisciplinary group. The EPP Projects course is taken in addition to the design requirement course of the traditional engineering program. All EPP students take the EPP Projects course twice, typically once in the Junior year and once in the Senior year, or twice during Senior year. Each EPP Project is a separate project completed within that semester (not a project that continues from one semester to the next).

The EPP Projects Course

Course Description, Learning Objectives, and Project Topic Features

The primary goal of the EPP Projects course is to teach the students to work in interdisciplinary groups to solve complex societal problems that involve science or technology. In each project course, students work in multidisciplinary teams on a project topic of current interest with very little in the way of prior analysis or solutions. Students are given a general statement, some background materials and are then expected to self-organize to work in groups each of which addresses a different aspect of the larger topic. As a team, they are required to structure their approach to investigating and solving the problem by recognizing key areas of relevance to the topic and organizing in groups and subgroups appropriate to solving the problem. The students are expected to discover existing knowledge on the topic, to examine and assess existing policies relevant to the topic, and to analyze alternatives that make society better off. Using this background research, and their technical and social analysis education as appropriate, the students then create new knowledge on the subject. This knowledge is communicated to an external advisory panel, selected from experts and constituencies of importance to the issue. Students make at least one interim progress report during the semester, after which the advisory panel may make suggestions on data and other resources and on the direction and scope of the work. A final oral report is presented to the panel along with a written report (~200 pages) at the end of the semester. The course also serves as a project management learning course for doctoral students in the department.

By the end of the course, both students and the project managers should gain skills in the following areas:

1. Decomposing, structuring, and formulating solutions to unstructured, complex, real-world problems.
2. Interdisciplinary problem solving: Data collection, analysis, and synthesis, formulation and evaluation of policy recommendations.
3. Developing professional oral and written communication skills through participation in oral presentations, and preparation of the final written project document.
4. Developing the ability to function on multidisciplinary teams, including handling group dynamics, goal selection, distribution of labor and conflict resolution.
5. Assessing what can be done and delivering a product on time, including insuring that steady progress is made, setting milestones and deadlines, meeting deadlines, and synchronizing work with others inside and outside the project.

These course objectives are independent of the content and topic, or what specific activities and responsibilities a particular student takes on.

Project faculty attempt to choose topics with both technical and social dimensions, requiring multi-dimensional analysis, and of current importance. The general features of project topics include:

1. Technical in nature, with social and economic ramifications.
2. "Hot issues" of current relevance to society or where issues are just beginning to surface.
3. Cannot be resolved by application of engineering principles alone but must be combined with social and economic analysis in order to provide a useful set of recommendations.
4. Size and effort are enough to be interesting for 20 to 30 students and a semester timeframe, while keeping it manageable.
5. Has facets that can be broken up and worked in parallel, while retaining connections. Since all groups are working on the entire problem at the same time, one part of the problem cannot rely on the results of another part. However, it is expected that the different parts inform and support the work of other parts.
6. Experts and administrators from a range of organizations – government, non-government, communities, non-profit, private, etc. have an interest in the research and analysis outcome and will be willing to serve on the advisory panel.

The biggest difference, perhaps, in this course versus other engineering capstone experiences is reflected in point 5 above. Other capstones often provide a single design goal to the class, with the groups effectively competing to create the “best” design; or groups are following the same process and procedures but tackling different and unrelated product issues. Here, the entire class is working toward a singular goal on a common topic, with subgroups focused on different

aspects of the problem. The subgroups' work informs the work of other subgroups, rather than subgroups working in individual silos.

As an example, the Spring 2018 EPP Projects course topic was addressing lead (Pb) exposure in Allegheny County. The County had established a Task Force that released a report in December 2017. A faculty of EPP was a member of the Task Force and suggested the topic for the project course. The Task Force report provided the County with a list of potential strategies to directly remove lead hazards, reduce childhood exposure to lead, and improve education and monitoring of lead hazards. However, the report did not provide any prioritization of the strategies nor assessment of effectiveness or cost. In the EPP Projects course, students formed into six sub-groups that tackled the following areas using the listed tactics:

1. Benchmarking perceptions of lead risk and behaviors to reduce lead exposure – survey design and deployment, survey response analysis (validated by 6. below)
2. Identifying high-risk lead areas in the region – collection and geo-coding of ~20 databases including historical industrial locations, homes with lead-based-paint, locations of vacant lots likely to have high soil lead levels
3. Measuring soil lead levels in Pittsburgh – completed a background soil lead level sampling study using EPA methods, used to validate GIS-models in 2. above.
4. Evaluating options for mitigating lead hazards on both reducing blood lead levels and cost – extensive literature review of existing studies and modeling to rank different lead reduction strategies
5. Evaluating cost of implementing various policy solutions – cost modeling (using estimates from 4.) and regional data (from 2.) to determine range of costs for Allegheny County.
6. Examining media coverage on lead issues as it pertains to educating residents – database search and coding of over 4,000 articles printed in local newspapers
7. Assessing availability and usefulness of lead information to the public and high-risk populations – review of websites and interviews with local community groups (informed by 1.)

The Interdisciplinary People Involved

The EPP Projects course involves four groups: students, doctoral students serving as Project Managers, faculty instructors, and the professional Advisory Panel. Typically, the course is taught by two faculty with different backgrounds to provide sufficient breadth of knowledge in the areas for investigation. The advisory panel serves as the "client" for the work, attend and give feedback on the presentations and report, and support students with data or background. We focus, though, on the students and Project Manager roles for the remainder of the paper.

The EPP Projects course is cross listed in 3 different colleges, serving as a capstone course in each program, and thus attracts a diverse audience of students. Students in Project Courses include:

- Engineering and Public Policy additional major undergraduates from the five traditional engineering programs (chemical, civil, electrical & computer, materials science, and mechanical)
- Science, Technology and Public Policy additional major undergraduates (includes computer science, information systems, biology, chemistry, math, physics, statistics, and economics among others)
- Social and Decision Science policy and management or decision sciences undergraduates
- Heinz College public policy and management Masters students
- Technology and Policy minor undergraduates (includes mostly business students, but open to entire undergraduate population)
- other students when interest in the project topic merits their participation

Students in the EPP additional major must take this course twice, in different semesters. During the first experience in the course, students are learning how to use their skills from prior EPP courses in solving complex, unstructured problems and developing skills for effective project completion. The second experience in the course serves as the student's capstone design course. In this second experience, students apply their skills and knowledge from the first experience, demonstrating project framing, decomposition, and developing analyses. Since students follow their own curriculums, they take the course during different semesters in their studies, therefore a project usually involves students who are taking it for the first time as well as second timers. Students in this second course are expected to be course leaders, assisting students taking the course for the first time in navigating project communications and tasks.

Doctoral students in the EPP department serve as Project Managers, a required practicum assignment for graduation. These students enroll in a separate course number and are graded on their acquisition of project management skills and effectiveness in the position. These students come into the course with a range of prior experience in project management from earlier career positions (or lack thereof), and technical skill sets. When possible, the project manager assignment is given to a particular doctoral student because of their expertise in the project topic or potential analysis. For example, for the project addressing lead hazards, one project manager was doing dissertation work on water distribution systems involving lead policy and brought a wealth of information on lead regulations, while the other project manager was skilled with GIS and data management skills (but knew nothing about lead). However, it is often the case that the assignment is "random" – a student needs to complete the requirement in a particular semester due to upcoming ABD status or extensive field work and travel in a future semester. Regardless, the assignment serves for them to learn skills needed for their future careers which will in all likelihood involve project topics tangential to their core research area.

Course Flow and Structure

We run the course as a "consulting firm." We received a problem from a client (the Advisory Board), and the principles, the faculty instructors, must assure that quality work is delivered on time. The Project Managers are responsible for organizing the work tasks, arranging logistics and administration for the project, and leading the workers. Students are the front-line employees. They are tasked with the day-to-day work tasks – research, analysis, interfacing with each other, preparing deliverables, etc.

The course is completed in a single semester timeframe. In some semesters, enrollment dictates that two project sections are held. In this case, the first day of class is used for the faculty and PMs to pitch their project to the class, enticing them with a fascinating problem area and the potential analyses that students will be needed to do. Students then rank project interest and are divided among the sections, with an aim to balance interest but also expertise and disciplinary background. The typical semester timing for tasks is given in the table below.

TIMING	TASK
~2 months before 1st class	Select a project topic (*see above for details*)
	Specify roles for PMs (including division of labor)
	Prepare advance materials for early pickup by students
	Arrange introductory lectures
	Outline tentative operation schedule
	Create a list of potential Review Panel members
1st day of class	Both sections meet, students choose topics
~1st week of class	Introduce topic
	Form working groups
	Begin preliminary problem structuring and formulation (typically requires several iterations)
Week 6 or 7	Initial presentation to Advisory Panel
Week 7 or 8 (prior to mid-semester break)	Compile first half semester activities in report form Incorporate feedback from Advisory Panel into plan for 2nd half of semester Student performance meetings
Second half of semester	Each week, working on research, analyses, and report writing. Quick group updates provided in class. Drafts of report chapters updated weekly.
Final week of classes	Final presentation to Advisory Panel Final draft report completed and shared with Advisory Panel

The initial task is to get the students up-to-speed on the dimensions of the topic. A set of introductory readings and a bibliography of the literature that forms the basis for various aspects of the project should provide foundation and motivation for the project. Articles forming introductions to various aspects of the project are read by all students. The initial few weeks of class are often filled with short structured tasks to have all students exploring the topic overall and determining smaller problems that could be tackled during the semester. This can be done individually or in small groups. If needed, guests with essential knowledge may be invited to come to class to present or answer questions. These have included faculty with expertise in the project topic area or advisory panel members with background knowledge of the project. Once those smaller problem areas are identified, students (re)form into groups to identify research goals and tasks for the initial exploration.

The second part of the class is filled with the smaller research groups completing research and analysis. Scheduled course meetings are used for two tasks – all-class coordination activities and small group work. All-class coordination activities include presentations by the working groups, discussion of progress to date or trajectory of work, reminders of timelines and deadlines, and decision making that impacts the entire class. The majority of class time is for working within the smaller working groups, and for any efforts that need to be coordinated among groups. Individual faculty and PMs will meet with the smaller groups during those times.

The class meets as a whole for two hours, twice a week. The assigned class time is essential to the progress of the work, and students are required to attend. This is time for communicating, planning and organizing. The majority of the research and analysis work is done outside of class time. Presentations for the advisory panel are scheduled during this time on campus. Video conferencing is available to allow non-local panel members to join remotely.

The course lacks traditional homework assignments or tests. Instead, the focus is on meeting intermediary milestones towards achieving the final goals of the project. Milestones include regular submission of written report drafts as students build up the research materials and complete analysis. Students receive regular feedback on these drafts to guide the next round of work and to improve the writing. As the advisory panel presentations approach, parallel milestones of submitting presentation drafts for feedback are added.

As described above, the structure of the work is divided into smaller areas that all serve to answer the overarching project issue. These smaller areas are addressed independently by groups of 4-6 students, but at the same time are informed by the work of the other groups. This integrated format allows students to identify the interactions of different facets of the problem (how public perception might influence technology deployment, for example). Often as the work progresses, a single group member from the different original working groups form into a new

working group to address common issues (how various policy options proposed would impact their original focus, for example). Group members also serve as representatives on two functional groups – groups who complete common administrative tasks. One is the synthesis group, tasked with writing the introduction, conclusion, and executive summary of the final report, and preparing accompanying slides for the final presentation. The other is the editorial board, tasked with creating the templates for the paper and presentation, compiling the group chapters into the final report, creating the front matter for the report, and doing any final editing.

The Student Experience

The EPP Projects course is an eye-opening experience for students. The fluidness of the work, the integration of the topic areas, and the evaluation process work together to give students a unique experience of how their future careers will be structured, and the expectations they will have as workers. Here we describe situations in the course and the lessons learned from students over the years.

1. Balancing tasks and time

By the end of the semester, each student should have one area of substantive responsibility for the project topic where they are the expert, have completed some analysis, and have created the corresponding section of the final document and presentation, one area of functional responsibility where they have done a specific task to get the project to completion, and contributed overall to the collaborative project process and product. It is very much a transition to their post-college workplaces and the various aspects of "real" work – balancing both the concentrated effort for the research with the administrative burdens of making that work presentable to others.

Students learn quickly the importance of setting aside time to complete work outside of class time, and the idea of working toward semi-defined milestones. It is very easy for students to neglect work for this course since the body of what is to be accomplished is ill-defined, whereas other courses have structured assignments with clear completion outcomes. Students also recognize the balance across the substantive research work and the administrative work. A regular response from students of a lesson learned is to set personal micro-goals in conjunction with planning for the class and group goals and milestones. And, to hold those micro-goals as non-negotiable so that the necessary time is allotted to the course. We inform students early on that "I'm busy" is not an excuse here – we are all busy. So, a main lesson learned is how to be effective in allocating their time and effort.

2. Receiving feedback is both painful and constructive

Unlike other courses, students receive regular feedback on submitted materials (report drafts and presentation drafts) and are expected to iterate on analysis and improve the communication

materials. This idea that submitted work is returned with comments *and* the expectation to put additional time and effort to make it better often paralyzes students. Rarely have they been asked, or permitted, to improve upon their writing. Since this process repeats itself for the last six weeks of the course, they (eventually) learn to accept the criticism and suggestions and edit their work accordingly. The lessons learned here are resilience and self-motivation. The groups who do allot the requisite time to improving their report chapters have far less work to do at the end of the semester but motivating that can be difficult. The most received advice for future students of the course is to write earlier and write often.

3. Integrating individual work into the larger whole

As noted above, the projects are specifically designed to have distinct workflows. Individuals take ownership of one small aspect, working groups combine those efforts into a single facet of the problem, and those facets integrate into the larger full project. Students navigate across several domains to integrate the work completely. The class meetings are essential for communicating the tasks being completed, so a lesson learned is to pay attention to what other groups are doing. It can be easy to slip off during class to do other work or use social media since "my group" is not presenting their work. But catching potential overlaps of effort is crucial. Students also learn to use citation management software, and to cite the various data they may have found. Many a presentation practice has been lengthened upon seeing the same piece of information (e.g., total carbon dioxide emissions) reported by different groups as different values because of different sources and years of reference. Again, pay attention to what other groups are doing!

4. Evaluating performance no longer involves numerical grades

Perhaps the most difficult shift in the course design for students to adapt to is the lack of regular feedback through numerical grades on assignments. Students are evaluated on their individual contribution to the project, but also to their contribution to the functioning of their working group, and ultimately on the outcome of the project as a whole. The faculty and Project Managers will use materials submitted throughout the course, interactions with the student, and peer evaluations and self-reports as the basis for mid-term and final grades.

This process is similar to a "performance review" for a job: would this be someone we want to keep at our firm, give additional responsibilities, and reward them for their contributions, or, would we want to fire them? We use weekly work logs, group reports in class, peer evaluations, and communications as evidence. Interactions with students are important as well – faculty and project managers take into account how receptive students have been to comments, how self-motivated students have been to take on tasks, do students and groups complete work on time, and what level of task(s) students have taken responsibility for. A main lesson learned for students with respect to this aspect of the course is to take ownership. For some, it means taking on leadership or positions that are outside of their comfort zones. For others, it means stepping

aside to let others do their share of the work. Students often marvel at the end of the course at all they have accomplished and learn to take pride in that work and taking credit for their efforts.

5. Communicating is key

Perhaps the single most important lesson learned through student's experience in the class is communicating, on all the levels that it is needed. As said above, students learn through the many report and presentation revision cycles the importance of clear written and visual communication. But, to some degree given earlier coursework, this area of communication is already known to be important. Student's consistently report that communication was key success or failure point of previous project work. This could be among group members or across groups, or between faculty instructors or between instructors and students. Maintaining clear lines of communication and responding within a reasonable time frame are quickly learned.

Throughout the course, students find themselves in awkward stages:

- Not knowing what to do next.
- Not knowing where to find needed material.
- Not knowing how to do a kind of analysis.
- Having difficulty coordinating or getting along with other group members.
- Not knowing how to respond to faculty comments on preliminary analyses or report drafts.
- Dealing with pressure from other classes, or non-class life.

These are no different than the stresses of the work settings that project courses are meant to simulate. Perhaps the single biggest risk students face is doing nothing because they do not know what to do *and* hesitate to ask. We regularly remind students that one of our responsibilities is to help them execute their initiatives to the highest professional level possible. Once they communicate their issues with us, we can figure out together how to proceed. This is often a difficult lesson to learn.

To help students articulate these lessons learned, the "big picture" outcomes of the course, we end the course with some time for reflection on the process as well as the product. One exercise for the last day of class is to have students write a "letter to their future self." In this letter, they remind themselves of challenges and issues in the course, consider what worked well and what did not, and suggest strategies to employ for future project work to make everything run more smoothly. We retain these letters and mail them out after some time (maybe a year, perhaps more depending on when they surface during an office cleaning!). This is an excellent way to connect with the alumni of the program, and responses to reading their long-forgotten letters invoke laughter, fond memories, and the recognition that they truly had learned so much from the course.

The Project Manager Experience

For some project managers (PM), this may well be their first time organizing this many people for a semi-professional project. PMs are expected to juggle project management with their own research and other course work outside of the project course. PMs correspond between students and faculty and is crucial in delivering general concerns regarding the project from both sides.

In preparation for the project course, PMs will set up an online course website, in our case, Canvas, to keep track of personnel and student progress. The students are expected to submit weekly logs of what they accomplished that week, challenges, and plans for the next week. Students are also encouraged to write down any difficulties they may be facing, may it be conflict within their group, or personal circumstances they find themselves in. PMs will read these logs and report to faculty if anything requires more attention.

During class meeting time, PMs assist faculty in guiding groups of students through their research direction and analyses, and address any questions that arise. In developing the midterm and final presentation to the review panel, PMs are expected to help students edit slides and practice presenting. During the presentations, PMs are to present introduction and conclusion slides, as well as run the subsequent Q&A session. PMs may also help with editing and proofreading draft reports.

Seemingly straight forward responsibilities of project managers can lead to challenging situations. It can be difficult to balance the interest of students and the wishes of faculty. Students sometimes push back on analyses faculty wish to see performed due to some difficulty in data collection or difficulty of analysis. It can be hard to gauge whose side to be on in situations like this. On the one hand, PMs are also students and can relate to the level of stress of a full time education. On the other hand, suggestions or requests from faculty often stem from decades of experience and insight and may significantly improve the quality of the project. A PM's role as a mediator is crucial in striking a compromise between students and faculty.

Another situation a project manager may find themselves in is doing the students' work for them. It can be frustrating to see students stray too far away from their goals and not delivering satisfactory results. PMs may also have knowledge and skills to complete a task quickly and effectively that would take the students a long time and several false starts. PMs will need to judge how and how much to help students get through an obstacle, and when to complete tasks for the sake of moving forward versus letting the students learn through failure.

When classes are larger, or when faculty advisors feel there is a need, one project may have two managers. In this case, PMs not only have to manage above and below, but will also need to practice communicating with a peer. This requires establishing a working relationship that will

benefit the class as a whole. Sometimes there will be an uneven split of duties, as is natural in all teamwork, but being understanding of the other and taking initiative when needed can help set things straight.

Setting boundaries and expectation is another important lesson learned. PMs may want to be overly helpful and answer emails at 2 am. This sets poor examples of time management and self-care for students and blurs boundaries between working and non-working hours. PMs must also put forward the initiative both administratively and in terms of group intervention to bring the project tasks to completion. They can have high but reasonable expectations for both students and faculty advisors. They need to remember that the students are undergraduates, not their doctoral student colleagues, so they have different skills and that the purpose of the course is to develop them further.

A final lesson for PMs is finding ways to motivate students. Especially as the semester wears on, student morale can dip. Analyses may not be providing the expected outcome, survey responses are few, group tensions are high, demands of other courses start to interfere. Finding ways to motivate students to work through these challenges is essential. PMs have succeeded in motivating through various ways – from simply bringing a snack to class, posting a message to highlight recent successes, or digging into a spreadsheet to find the error that has been plaguing a group.

Epilogue

This course has been a primary component of the program since its inception in the 1970s, so we are now celebrating 50 years of EPP Projects. With courses running both fall and spring semesters, and offering usually two project sections each semester, the EPP Projects course has a history of over 180 individual projects. Throughout this time, little has changed in the course design. In many cases, it lacks many best practices of student learning. We have no rubrics, no homework or tests. We do not have a pre-conceived approach, structure, or answer for the project at the beginning of the course. Individual faculty and PM teams may structure details of the project design and execution in different ways. Yet, the course has endured and has been successful in training both undergraduate and doctoral students to address the complex problems they will face in their careers. Alumni point to the course as a defining moment in their undergraduate experience, a fulfilling course to round out their technical path. “Every day of my work now is an EPP Project,” is a common refrain. Doctoral students are thankful for the opportunity to practice managing a team, to fail at “herding the cats” in this experience rather than in their post-doctoral positions. We look forward to the next 50 years of this course, and the lessons that will be learned over and over again.