

Project Management Implementation in a Capstone Design Course

Prof. Mike Simard PE, Villanova University

Mike is an engineering leader with over 30 years' experience in start-ups to Fortune 100 companies. Mike possesses both a Bachelor and Masters in Mechanical Engineering, as well as an MBA. He is a licensed Professional Engineer (PE), certified Project Manager Professional (PMP) and Certified Estimating Professional (CEP). Mike has held senior positions in engineering design, project management and operations in the power generation, biomass conversion and building material industries. He has led a variety of projects including the development of new processes & equipment, the design & build of pilot & demonstration facilities, as well as the construction and start-up of large manufacturing facilities. He has worked internationally in Europe and China. He is a published author, conference speaker and inventor with multiple patents. Mike is currently an Associate Professor of the Practice at Villanova University.

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Mike Simard, PE
Villanova University

Abstract

Project management has become a standard practice in the fields of engineering, construction, and information technology, greatly reducing the number of failed projects. While fundamental technical content takes up the bulk of the typical undergraduate engineering curriculum, the capstone design project is an excellent opportunity to teach project management principles through a project-based learning experience. While most programs include project management topics in capstone lectures few programs actively promote applied project management. A few institutions have taken a more formal approach by creating dedicated project management courses or incorporating substantial project management materials in an existing course earlier in the curriculum. Another approach is the creation of project management workshops or one-day seminars.

At Villanova University, the mechanical engineering capstone design course was revamped to include more project management activities. In addition to the standard triple constraint of scope management, schedule, and cost control, the updated curriculum includes the implementation of a communication plan, dashboard status reports, project commissioning & testing plans, and project close-out. Student teams are provided with effective templates to facilitate implementation and the activities are integrated directly into the design process. A survey of graduating students found that 57% of students considered the project management activities to be either Extremely or Very Helpful, and fully 89% found them Moderately Helpful or better. These are considered excellent results for the initial implementation and the initiative is being improved further. Students not only learn to apply basic project management techniques that improve the outcomes of their capstone projects, but they are also better prepared for entering the workforce.

Keywords: Capstone design, project management

Introduction

Project management has become standard practice for executing industrial projects and boosting successful outcomes, particularly in the fields of engineering, construction, and information technology. Studies have shown that companies that successfully implement project management practices have a project failure rate that is 75% lower than those who do not, see Table 1 [1]. Research also shows that project management regularly ranks high on the list of essential skills that experienced practitioners say new engineering graduates need [2].

Fundamental technical content takes up the bulk of the typical undergraduate engineering curriculum, leaving little room for a course that would focus on both the hard and soft skills of project management. However, the importance of developing engineering students' project

management skills should not be discounted. Standard practice is to include a one or two semester design project for senior engineering students, often referred to as the capstone course. Such courses are an ideal forum for providing project management instruction.

Table 1: Project performance based on level of project management [1].

	Organizations <u>with</u> successful project management practices	Organizations <u>without</u> successful project management practices
Projects completed on time	88%	24%
Projects completed within budget	90%	25%
Projects that meet original goals	92%	33%
Projects that experience scope creep	28%	68%
Projects deemed failures	6%	24%

The objective of this paper is to present project management modules that were implemented in the mechanical engineering capstone course at Villanova University. The paper describes the content and timeline for the implementation of seven project management modules in the two-semester capstone course starting in the 2018-19 academic year.

Capstone: Ideal for Project Management Instruction

The capstone course is a project-based learning experience that attempts to mirror a real-world problem with open-ended design projects. Thus, students are expected to combine and apply knowledge gained from previous courses and laboratory work. Often projects are sponsored and supported by industry, providing direct exposure to design problems faced by industry and inciting students to develop professional and technical skills through interactions with experienced engineers. Capstone courses are and should be used to develop students' professional skills, such as project management, communication, and teamwork [3].

The capstone project is an excellent opportunity to teach project management principles through a bona fide project-based learning experience. Student teams benefit from keeping projects on track, and stakeholders and sponsors see an increase in successful delivery of projects. Implementation of project management techniques also results in more evenly distributed workloads throughout the course, often reducing the student complaint of being overworked [4].

Various project management standards and techniques exist, such as the PMBOK framework by the Project Management Institute (PMI), the ISO 21500 standard and various Agile project management techniques. Each of these present their own advantages, but regardless of the chosen standard, project management is based on the triple constraint of scope, cost, and time (Figure 1). These parameters are interdependent since any change to one of these will impact one or both of the others.

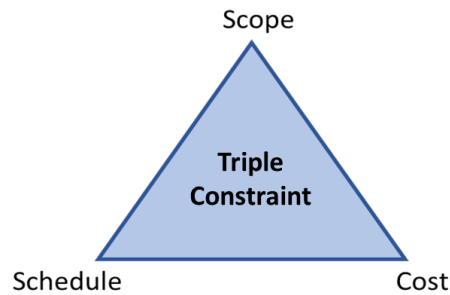


Figure 1: Project Management Triple Constraint.

The triple constraint concept is foundational to all project management activities, and even the implementation of basic project management methods yields beneficial results.

Project Management in Current Capstone Courses

Despite the evidence, few programs actively promote project management. In an online review of the top 50 undergraduate engineering programs [5], only 31% of mechanical engineering programs listed “project management” or “project planning” in their capstone course description, see Table 2. That is not to say that some project management is not included in these course curriculums, but it suggests the relative importance given to the topic and its extent of implementation. Some may argue that managing a project simply requires organization and time management skills and that students invariably develop these skills throughout their studies, but the reality is that project management fundamentals need to be learned and practiced just like any other skillset.

Table 2: Online survey of mechanical engineering capstone course descriptions of top 50 undergraduate engineering programs.

	Number (n = 51)*	
Mention “Project Management” in course description	14	27%
Mention “Project Planning” in course description	2	4%
No mention of project management activities	35	69%

* Because of ties, 51 programs are listed in the top 50.

A few institutions have taken a more formal approach in preparing students by creating dedicated project management courses [6] or incorporating substantial project management materials in an existing course [3] earlier in the curriculum. Another approach is the creation of a project management workshop [7] or one-day seminar [8]. However, it is not always possible for programs to inject yet more courses into an already congested curriculum, so including project

management topics in capstone lectures, and complementing these lectures with faculty mentoring, is an appealing option.

Implementation in the Mechanical Engineering Capstone Course

The mechanical engineering (ME) capstone course was revamped for the 2018-2019 academic year to better include—amongst other things— project management activities. The capstone projects that are offered to students are a combination of projects proposed by faculty, students, and industry sponsors. The course focuses on Design-Build-Test projects and tends to avoid feasibility or other studies that do not include a mechanical prototype.

The ME capstone course extends over two semesters. It consists of a series of approximately 18 lectures. Each team also meets with its faculty advisor once a week to discuss project progress and issues. The fall semester focuses on team development, scope definition and design. The following spring semester centers on procurement, prototyping, troubleshooting, and testing.

With this course structure in mind, project management modules were developed and implemented based on usefulness to student projects and relevance to industry practices. These modules are typically delivered in a traditional lecture using a specific fictional project example, followed by an implementation assignment directly related to their individual team project. Alternatively, most recently due to the COVID-19 pandemic, the modules were delivered via a pre-recorded lecture followed by smaller group workshops. In these smaller workshops, the student teams were required to implement that module on their respective projects. This allowed the instructor to help each team get started on its implementation.

Project management methods can seem cumbersome on smaller projects, so it is important to focus on the essentials. At its core, project management is about providing techniques to organize and track the work to meet project requirements. It is important that project management activities do not become the focus of the work but remain, instead, a tool to help the team fulfill their design project objectives. Accordingly, a limited number of impactful project management activities were implemented. Note that on these smaller capstone projects, there is significant overlap between what is formally project management and systems engineering, which will be treated conjointly.

1. Scope Definition

The most important component to project success is, arguably, scope definition. A precise scope clarifies what exactly will be accomplished, along with any limitations and assumptions. Student capstone teams are initially given a project charter, or outline. An early lecture in the course on scope development is delivered to students, with a focus on developing a quantifiable and measurable scope. For example, it's insufficient to specify that a device must be "lightweight", but rather that it must be "less than 10 kg".

Following the lecture, student teams meet with their project stakeholder to ask questions and to develop their scope. They should differentiate between performance specifications and design constraints. Note that it is important at this stage to avoid design restrictions and solutions, but simply to focus on the problem. Additionally, students are encouraged to list scope *exclusions*, as it can be helpful to list what is not included in the deliverables to avoid missed expectations.

Their final scope is reviewed by their stakeholder and faculty advisor, and becomes a central element of their project proposal assignment. Subsequently, scope management includes communicating impacts of requested changes on cost and schedule to stakeholders before accepting any scope changes. In typically short capstone projects, scope creep can easily derail a project before the end of the design phase.

2. Schedule

The typical project schedule is a tool that outlines the work that needs to be performed, the resources that are needed, and the timeframe in which the work will be done. It is useful in guiding the work, tracking progress, forecasting completion and communicating with stakeholders. When thinking of schedules, Gantt charts invariably come to mind, with a long list of activities created from a work breakdown structure or a waterfall.

Generally, student teams may lack the experience to prepare sophisticated schedules, so a preferable approach that is easier to manage could be milestone tracking, activities planning, or key events listing. The project should be broken down into specific actions due every 3 – 6 weeks. Maintaining a simple list at a reasonable frequency can be just as effective on smaller projects as a complex Gantt chart.

Following the lecture on scheduling, students are given a template to prepare a list of project milestones, which they subsequently develop based on course deliverables in the syllabus and stakeholder input. Project milestones are another important element of the project proposal assignment.

3. Cost Control

Cost estimating is an important step in defining a project but can be difficult for students at the proposal or even conceptual stage. A more practical approach is to require a detailed cost estimate with the detail design. Student teams must then focus on cost controls, which consists of monitoring expenditures and taking effective actions to minimize these costs. While accounting departments can report regularly on project expenditures, typically they do not have the granularity of specific student projects to provide each team with their current costs. Additionally, accounting reports record expenditures after the fact, on a cash-basis. It benefits the team to track costs, for example in a spreadsheet, that includes all accrued and committed purchasing costs, even if payable in the future. This allows the team to have a better sense of actual project costs and thus be proactive if costs rise, instead of reacting to an accounting report after it is too late.

The cost estimate is required in the team's design report and forms the basis for the project's budget. Cost tracking begins as soon as expenditures are incurred, which in the capstone environment is with the procurement stage as design costs (i.e. student's time) is not accounted for. Teams must report on their cost tracking versus estimate in their regular status report assignments as well as in their final report.

In addition to these triple constraints, the additional following project management activities were also implemented.

4. Communication Plan

Lack of communication within the project team and with stakeholders can threaten the success of a given project, but different stakeholders (team members, industry sponsors, faculty advisors, course instructor, etc.) require different forms of communication, from informal face-to-face working sessions to formal written reports. Likewise, different stakeholders require communication at different frequencies, from daily scrum meetings to annual results reporting. Therefore, a communication plan should be written that outlines the who, what, when and how of communication activities for the duration of the project.

Communication planning is covered along with other project management basics in an early course lecture. The students must consult each project stakeholder, and develop their communication plan accordingly so that all stakeholders understand the type and frequency of communication they can expect throughout the project. This plan is also included in the project proposal assignment.

5. Status Reports

Project status reports are regular, formalized, short reports on project progress against the project plan. They communicate project status as well as provide a documented history of the project. Most often they are in the form of a one-page dashboard report with visual charts, graphs, and color codes to provide an at-a-glance status of project metrics. These metrics include scope tracking, milestones review, and cost tracking, as well as a list of issues and concerns.

Completing monthly status reports helps teams stay accountable and on track, as well as assuring communication with stakeholders. A review of the purpose and format of status reports is included in a project management lecture. The teams are then assigned to develop their own dashboard status reports from provided templates.

6. Commissioning & Testing Plan

Commissioning is a process that ensures the safe and effective start-up of a project by verifying compliance to design specifications of each component, each sub-assembly, and finally the full assembly. Specifically, it involves the inspection and testing of each operational component of the project as it is being built, as well as the complete system upon completion. Commissioning of large projects is a complex and sophisticated technical specialty, but design teams can benefit from having to plan and outline the sequence of their prototype build, think through the commissioning of sub-assemblies, and plan in advance how the project will be tested to ensure it meets the project scope.

To this end, lectures are provided after the detail design is completed but before prototyping begins. These lectures cover health and safety training, as well the commissioning and testing process. The objective is for the teams to plan the sequence of their prototype build, and to inspect and test components as it is being assembled. The testing portion must also describe the methodology used to demonstrate that their project meets their scope requirements, including the tools, instruments or equipment that will be needed.

The commissioning & testing plan is an assignment prepared early in the second semester of the course, and due before prototyping begins.

7. Project Close-out

Project close-out is an often overlooked project management process. It basically verifies that project deliverables are complete and concludes project activities. Notably it transfers project ownership from the project team to the stakeholder. Close-out is also an opportunity to determine lessons learned and best practices to be applied in the future.

In capstone, this often consists of a final project presentation and final project report. Just as importantly, student teams must assemble and file all relevant documents (drawings, CAD models, etc.) in a central location for future access. Finally, the team delivers any prototype to the stakeholder for their use.

The above seven project management activities are covered in four lectures: three early in the first semester and another (commissioning & testing planning) at the beginning of the second semester. Furthermore, there are frequent references to project management activities in other lectures, such as when discussing the design process.

Integration of Project Management in the Design Process

Most, if not all, engineering design follows the engineering design process. While there is no formal definition, it is generally accepted that the engineering design process is comprised of (1) defining a problem clearly, (2) generating ideas and selecting a solution, and (3) testing and evaluating the final design [9], [10].

Often, the design process is shown graphically as an iterative loop that continuously looks to improve the design. This can often be the case for a product with incremental designs that add new specifications or features. However, by definition a project has a defined beginning and end [11], so that in a project-based design, the engineering process is more linear, which is not to say that the process doesn't include design iterations.

Figure 2 depicts the author's view of the project-based engineering design process, which includes three phases. In Phase I, the team is focused on understanding the problem, completing background research and developing a scope of work. Phase II is a traditional design sequence, from conceptual to detail design, that includes stage-gate reviews to ensure project objectives are being met as the design progresses. Phase III consists of the actual project build and assessing if the technical objectives are being met. If there are gaps in performance, the team would iterate on the design, at the appropriate level depending on the outcome of troubleshooting analysis. Finally, the project is closed and the project deliverables are transferred to its owner.

I. PRE-DESIGN → II. DESIGN → III. APPLICATION

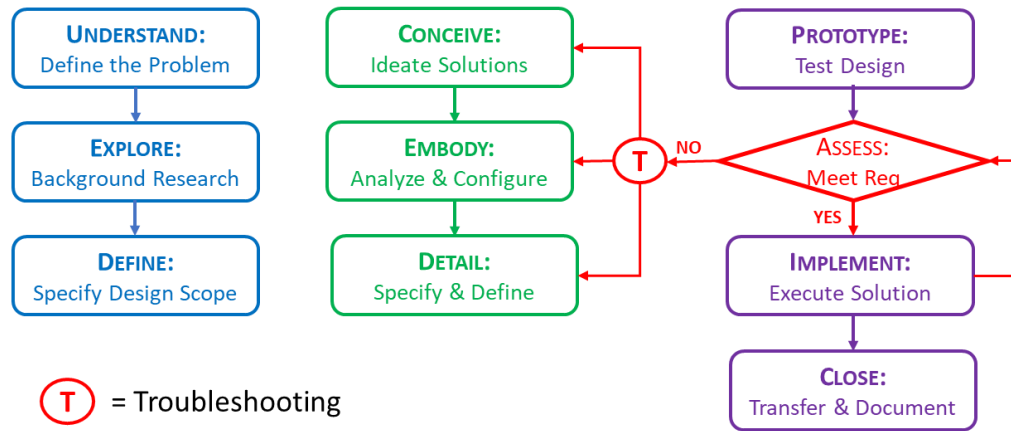


Figure 2: Project-based Engineering Design Process.

Again, it's important that project management activities do not become the focus of the work but remain a tool to aid in meeting project objectives. To facilitate implementation, the previously listed seven project management activities are integrated into existing work as much as possible.

Specifically, they are completed and assessed as part of five distinct assignments:

- Project Proposal: includes amongst other things project management activities of scope definition, schedule or milestones, and communication plan.
- Design Report: in addition to the technical design work, includes a detailed cost estimate that is the basis of the team's approved budget.
- Commissioning and Test Plan
- Final Presentation and Report
- Status Reports: these dashboard reports are issued monthly, starting at the end of the second month of the course, and update stakeholders on general progress, tracking of project management's triple-constraint (scope, schedule and cost), and highlight any issues or concerns with the project.

Faculty prepare and distribute effective templates to student teams for project milestones, dashboard status reports, cost tracking, and commissioning and testing plans. Teams are also provided with examples of past project proposals and design reports, along with each assignment's grading rubric.

Importantly, these assignments are integrated into the project-based design process, as depicted in Figure 3, thus incorporating project management activities seamlessly to the course objective.

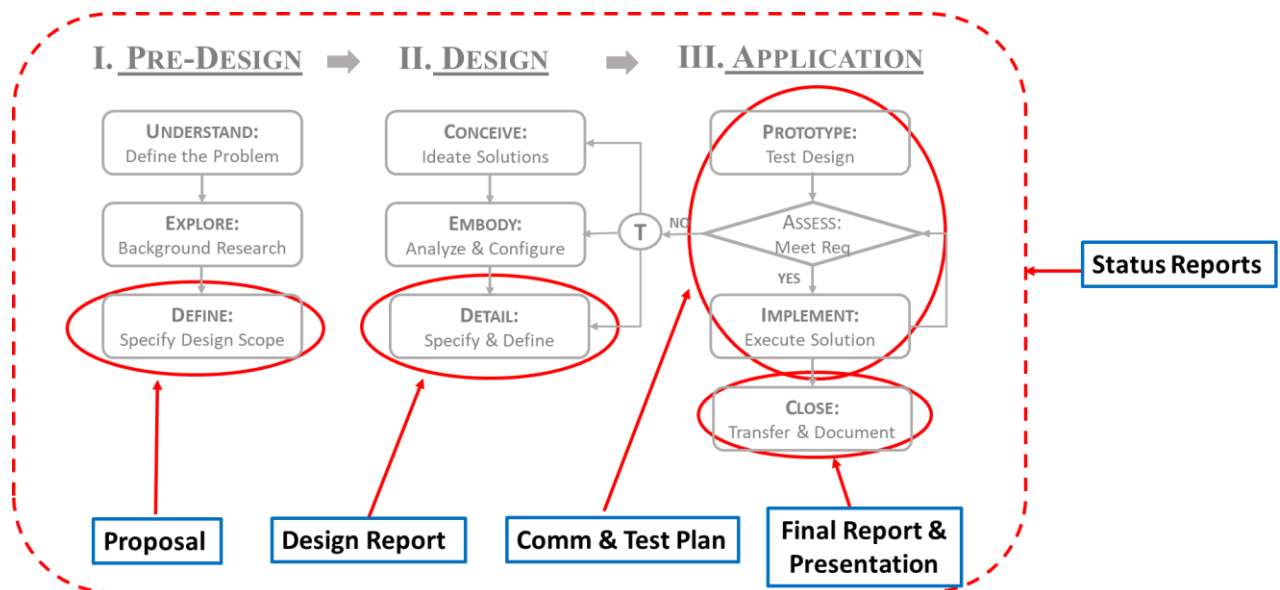


Figure 3: Integration of Project Management into the Design Process

Results

In order to evaluate the impact of the changes to the senior capstone course, a student survey was executed to the entire class in the spring 2020 semester. Surveys were conducted online and administered by Villanova’s Survey Research & Evaluation department. Of 69 students surveyed, 43 (62.3%) responded, though some students failed to respond to all questions. This may be due in part because the Covid-19 pandemic interrupted late semester activities.

As the results of Figure 4 illustrate, the majority of students found that all of the implemented project management tools were helpful in the execution of their project. Overall, 57% of students found the activities to be either “Extremely helpful” (24%) or “Very helpful” (33%), and fully 89% of students found them “Moderately helpful” or better. In particular, “Developing a quantifiable & measurable scope” and “Preparation of monthly status reports” scored the highest, with 26% of students indicating both of these activities were “Extremely helpful”. Although many projects’ prototyping activities were interrupted by the pandemic, 70% of students still found the “Preparation of a commissioning & test plan” to be either “Extremely helpful” or “Very Helpful”. This activity may have been rated even higher had the students been able to complete their prototyping.

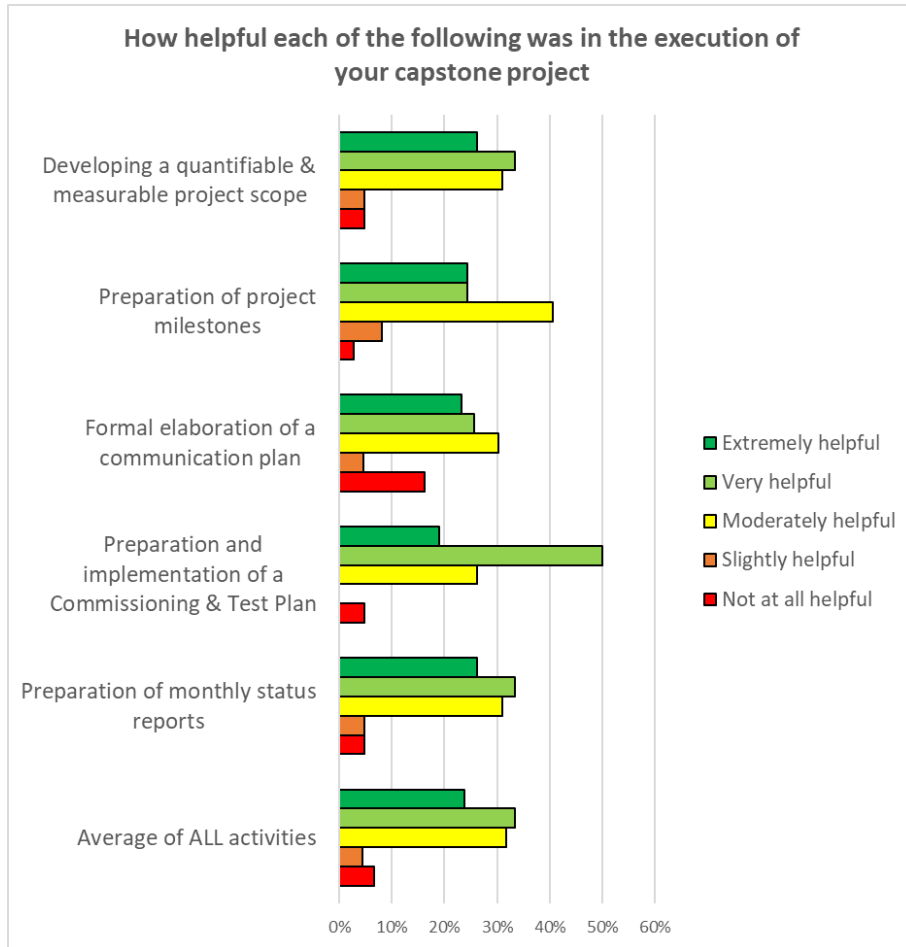


Figure 4: Helpfulness of project management techniques in executing capstone projects.

Just as importantly, students report having gained practical knowledge of project management techniques throughout the course, with 88% of students feeling “Extremely knowledgeable” or “Very knowledgeable” in project management techniques, versus only 13% before their capstone course. See Figure 5.

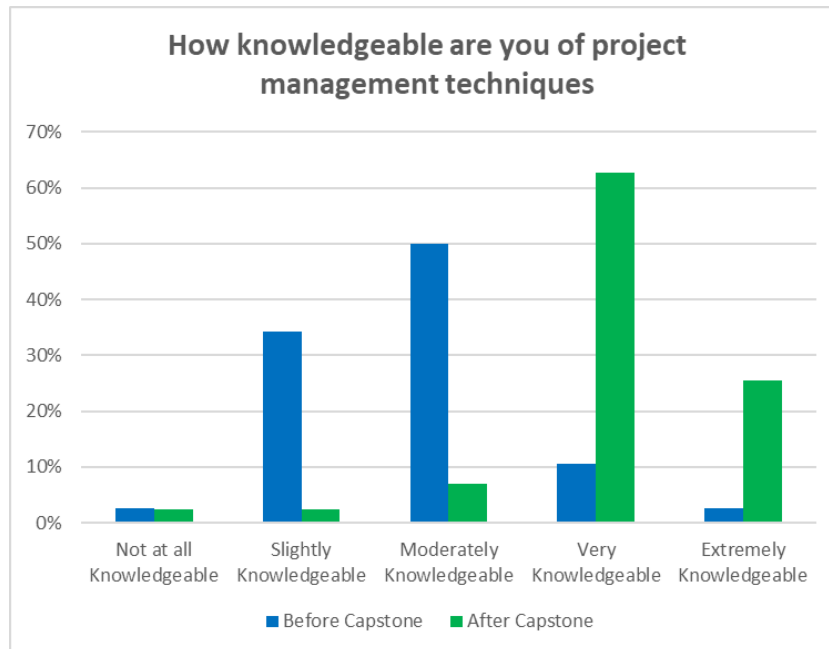


Figure 5: Knowledge gained in project management during the capstone course.

Conclusion

It is not expected that students become expert project managers during their capstone experience, but rather that they apply basic techniques that yield improvements in capstone project results. As the program matures, there are several other project management activities that can be implemented, such as work breakdown structure (WBS), risk management and management of change. Given the importance of developing project management knowledge and basic competencies in graduating engineers, educators should take advantage of the capstone design course to teach project management through active learning situations.

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