

A Systems Engineering Graduate Capstone Project Requirement

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Systems Engineering (SE) MS degree students at WPI are required to complete a capstone project as part of their program of study. Much like the undergraduate capstone requirement, the graduate SE capstone requirement is expected to be a “culminating experience” and draw together a student’s breadth of knowledge in a focused project environment. In this paper, I review the general SE MS program at WPI, describe the capstone requirement, and present an overview of how the requirement is generally met by program students. Sample capstone projects are also described.

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Introduction

While there are a plethora of capstone course descriptions, and indeed the ABET requirement for undergraduate engineering programs is [emphasis added];

*“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**”¹*

there are few equivalent courses or requirements at the Master’s Degree (MS) level for engineering programs. Perhaps the only *national* reference to a curriculum level requirement is that published by ABET for MS program accreditation [emphasis added];

*“The [MS] program must **demonstrate that graduates have an ability to apply masters level knowledge in a specialized area of engineering related to the program area.**”²*

The MS program statement seems to imply that all MS programs should have some type of “capstone” requirement, whether it be thesis, directed research (DR), design course or other demonstration mechanism. In fact, many graduate programs require a MS thesis or directed research (DR), but not all. As a result, for students who complete a course only MSE degree one might ask; “if a culminating experience is a *requirement* for an undergraduate engineering student, why not a similar requirement for a graduate engineering student?”

The bottom line is that there is no consistency at the graduate level for requiring a culminating experience - with two exceptions. First, graduate programs seeking ABET accreditation need to address the demonstration requirement cited above. Second, a few states (e.g. CT) require that all licensed MS degree granting programs include;

*“...at least one of the following: comprehensive examination, writing a thesis based on independent research, **or completing an appropriate special project.**” [emphasis added].³*

A quick survey of (CT) graduate engineering programs shows that there is a mix of ways in which this state requirement is met through traditional thesis and DR opportunities, as well as end-of-program courses with significant design project components.

Although a special project or research/thesis are not part of the MA higher education MS degree licensing requirements, WPI has for the past few years required a graduate capstone project as part of the MS program in Systems Engineering (SE). Below, I provide background on the WPI Systems Engineering MS degree, and then describe in more detail the required program capstone project as a model for other degree programs being considered and implemented at WPI. The link between our SE MS degree requirement and industry is also highlighted in the following material.

SE MS Degree and Capstone Course

The MS Systems Engineering program is relatively new at WPI, having been initiated in 2008 as an interdisciplinary program supported by the ECE, CS, ME and Management departments. Consistent with every other WPI MS degree programs, the new SE program was structured to include optional thesis and directed research credit possibilities.

Unlike other WPI MS degree programs however, the MS SE program was structured to include a *mandatory* three-credit capstone project which could be satisfied i) by undertaking a directed research project in a focused area, ii) by completing a Thesis, or as our experience has shown for all but one of the program students (to date), iii) by registering for our SE capstone course and

completing a project within the framework of the course structure.

SE Capstone Course

The specific course that students register for is known as SYS 585: Systems Engineering Capstone Experience with the following course description [italics added];

One of the central priorities in WPI's educational philosophy is the application of academic skills and knowledge to real-world problems. The capstone project represents a substantive evaluation and application of coursework covered in the program. Students are encouraged to *select projects with practical significance for the advancement of their company's competitive position* as well as their own personal development. The project is administered, advised, and evaluated by WPI as part of the learning experience, but *students are encouraged to seek mentorship from experienced colleagues in the Systems Engineering profession.*

The capstone course description was based, in part, on discussions with industry where strong support for a capstone experience was expressed by corporate advisory board members consulted during the creation of the Systems Engineering MS program. This support is clearly encapsulated in the course description where;

1. Students are encouraged to select a project that enhances their employer's competitive position.
2. Students are encouraged to identify and work with experienced mentors external to WPI.

Satisfying the Capstone Requirement

Given the general nature of the course description, it is natural to inquire how the requirement is met in practice. In fact, there are two general project frameworks used by faculty to manage course projects. First, however, it is important to explain, albeit briefly, the demographics of the students who are enrolled in the SE degree program.

1. The SE program is *managed* by an academic committee composed of faculty from the sponsoring departments (ECE, ME, CS, MG).
2. The SE program is *delivered* primarily by the Corporate and Professional Education (CPE) division at WPI (cpe.wpi.edu). CPE is, in turn, responsible for packaging, delivering and managing WPI graduate and professional development programs taught on-site at corporate locations.
3. As a result, the SE program is *offered* in two forms.
 - i. In one form it is packaged by CPE with other degree program courses to meet the needs of a corporate cohort group. The cohort students earn the MS SE degree over a two year period, part-time, with the courses delivered on-site and in lock step.

- ii. Individual students can register for nearly any SE course offered on- or off-campus. Individual students work with an advisor to plan a course sequence that best meets their needs and also meets the SE program requirements.

When it comes time to complete the SE capstone requirement, cohort groups register for the capstone course together, generally work on projects (below) in small teams, have an assigned course instructor, and participate in course activities that are similar to those of an ABET undergraduate capstone course.

Individual students who are not part of a cohort group typically sign up for individual course credit with a capstone advisor, another name for a faculty course instructor with a single project student or, less common, with a small team of (non-cohort) students.

Whether a cohort course instructor or an individual project student advisor, the faculty advisor sets the standard for the project(s) much like a faculty member would set the standards, goals and objectives, and desirable outcomes for a directed research project or an ABET capstone project.

Project Formats and Selecting a Project

While the guidelines for a project selected as part of the capstone course are relatively general, the following capstone project themes are the two most common employed by faculty who advise projects and students who select a project.

- If a systems development project the project topic must be sufficiently complex so as to allow the student(s) to demonstrate a broad range of systems engineering principles.
 - The selected project should obviously describe various aspects of system development, needs identification, risk assessment and management, system partitioning, work breakdown structure and management planning, architectural views, test and measurement plans, and so forth.
- Alternatively, for systems engineering research topics, the topic selected should address some aspect of the management, implementation, operations, or development of systems engineering principles.
 - For example, the topic could address a weakness or evolving need for the application of systems engineering techniques, provide a solution and justify it with peer reviewed research, and provide examples of applications and best practices.

Course Organization and Schedule

A typical evening graduate course at WPI meets for three hours, once a week for 14 weeks. With this in mind, a systems engineering capstone project will typically progress as follows.

Week 1: Initial meeting with students; discuss expected project scope and bounds, work effort, desirable outcomes, deliverables and schedule; discuss project ideas and, particularly for industry cohort groups, consider projects that would benefit the company; identify candidate project mentors.

Week 2: Detailed project proposals due; in-class presentation and defense of proposals (ppt); class critiques of goals and outcomes; discussion of needs assessment, conops and stakeholders; approval of project proposals and deliverables.

Weeks 3-6: Continuous refinement of: detailed project statement, goals and objectives, methods, research topics, and identification of peer reviewed and other pertinent publications; development of background chapter material; development of needs statement, conops, requirements and traceability, management and work breakdown structure; regular submissions of updated reports; formal (ppt) oral presentation and critique of project activities.

Weeks 7-10: Emphasis on risk assessment and management, test and measurement plans, preliminary system architectures, and key performance parameters; continued refinement and submission of material; formal oral presentation and critique of project activities.

Weeks 11-12: Emphasis on detailed architectures, life cycle planning; integration of all previous material into a draft project report; development of final oral project presentation.

Weeks 13-14: Final oral presentations; in-class critique; final project reports due.

For students working in industry, supervisors and colleagues are invited to critique the development work to insure that it is aligned, as appropriate, with the SE processes and methods of the supporting organization. For both corporate cohort and individual student projects, peer graduate students and other faculty and colleagues are invited to presentations and encouraged to critique material presented. In other words, much like a DR project or a thesis, SE capstone project students are required to present and defend their work to an audience of their peers.

Capstone Projects

It is instructive to provide examples of capstone projects that have been completed by program students. Such projects range from general to specific topics based on student interest and the guidelines offered previously. Examples of research focused projects include the following.

- *Systems Engineering vs. Project Management* - This student was interested in an in-depth exploration of the roles and responsibilities of a Systems Engineer

vs. a Project Manager, focusing on their individual roles, how they work together and separately to manage the development of complex engineering systems to insure a collaborative and well managed leadership environment.

- *SE Workforce Development* - This student undertook a survey based study (at a very large multi-national company) of two aspects of SE workforce development. The first survey sought to determine the types of project assignments, and roles and responsibilities that would, over time, lead to the development of well rounded, career focused systems engineers. The second survey was focused on career tracking methods that would help supervisors make engineering assignments that would lead to the development of a “seasoned” systems engineer. A key to the development and interpretation of these surveys was a detailed understanding of the roles and responsibilities of systems engineering professionals.
- *Logistics Readiness Levels (LRLs) and Integration Readiness Levels (IRLs)* - Two students undertook research projects to develop definitions for readiness levels for integration assessment (IRLs) and logistics assessment (LRLs). Based on extensive literature reviews, matrices of readiness levels were proposed that were consistent with industry practices. Examples were provided to show how to apply the new RLs.
- *Best SE Practices for Small Organizations* - Small companies (~<100 employees) have a desire to implement best SE practices when developing complex systems, but usually do not have the dedicated staff to manage a project in the same way a large (~ >1000 employees) company does. The question this student explored was; what are key core SE practices that should be followed by smaller systems development organizations?
- *Compare Current Corporate Development Practices to INCOSE Standards* - This student was interested in comparing his company’s practices for the development of a specific product to the INCOSE SE handbook standards. After a detailed comparison between the corporate approach and the INCOSE life cycle model⁴, it was determined that the corporate process was appropriately implemented but that there were opportunities for modernizing the process based on the most recent INCOSE standards.

Systems development projects that have been completed and that were selected with the support of, and at the recommendation of corporate leadership, include the following.

- Developed and recommended a system design for processing video data that included requirements, staffing plans, trade studies, architecture, and test.
- Developed a systems engineering method framework to test engineering prototypes as part of the product design process focused on reducing development time and risk.
- Described a software development and evaluation system based on commercially available and internally developed business models, development frameworks, and simulation and test environments.
- Developed a SE test and evaluation planning guideline to minimum risk and maximize utilization when using national test facilities (e.g. radar ranges, test aircraft, etc.).
- Based on a customer identified need, described how to develop a new networking system. The plan included needs assessment and stakeholder analysis, conops, requirements development and traceability, risk identification (especially including the business development perspective) and management, testing, architectural frameworks, life cycle planning (and so forth) - essentially all of the classical SE life cycle topics.
- Performed a detailed review of how a large company should manage subsystem outsourced subcontracts from a SE perspective. There had been some issues with SE methods compliance when outsourcing select subsystems. The result of the project was both an analysis of current SE, Project Management, and general contracting business practices, and recommendations for improving SE oversight of outsourced sub-systems development.

What is particularly important to note in many of the projects completed by industry cohort teams is that the projects are enthusiastically supported by the corporate cohort sponsors. Indeed, in most cases the industry sponsored projects have two notable results; first, the project outcomes directly benefit the company sponsor and, second, the student takes the first steps in becoming a seasoned systems engineer by completing a useful and meaningful project under the guidance of both a faculty and industry mentor expert.

Program Lessons Learned

All students are strongly encouraged to provide instructor and course feedback at the end of every course and/or project. The form used is common to all courses and projects whether at a graduate or undergraduate level. The first part of the student evaluation is ranking focused (for example, on a scale of 1-5 rate a course/project/instructor attribute) while the second part is open ended (“what did you learn”, “what would you change” and so forth).

For project based activities the rankings based evaluation is perhaps less valuable than the student open ended feedback. General student open ended comments generally include the following;

- The capstone experience is considered “intensive”. The standards are set very high and students need to invest significant time and effort in their selected project, make a very high quality final oral presentation and turn in a comprehensive final project report and presentation.
- The experience is highly valued, in part because the projects are not assigned, but rather negotiated based on student interest.
- Through critique of drafts and individual discussions with mentors and instructors, students often comment that they learned how to perform literature research better, how to integrate previous course material into a real-world project, and even how to critique other student’s presentations and material.

Finally, while not part of the student survey data, it should be noted that corporate supervisors and mentors often comment on the value of the capstone project experience, particularly when the student project has a direct bearing on corporate operations.

Summary and Conclusions

The capstone requirement, while faculty time and effort intensive, is well received by SE program students and cohort corporate sponsors as a valued culminating experience. Further, because of the experience gained with this program, a capstone course has been proposed for the power systems engineering MS program at WPI.

It is anticipated that as new MS level programs are created or existing programs are modified, that MS level capstone courses will be incorporated as an alternative to a Thesis or DR culminating experience. Whether a culminating experience will be required for all new and/or modified existing programs, however, is not yet certain.

References

1. ABET General Req. 5: Curriculum - - <http://www.abet.org/engineering-criteria-2012-2013/>
2. ABET General Criteria for Masters Level Programs - - - <http://www.abet.org/engineering-criteria-2012-2013/>
3. CT Department of Higher Education, Section 10a-34-17 - - www.ctdhe.org/regs/RegsAcad.htm
4. International Council on Systems Engineering (INCOSE), Systems Engineering Handbook - - - <http://www.incose.org/ProductsPubs/products/sehandbook.aspx>