Graduate Systems Engineering Capstone Projects

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A standard project format is described for graduate systems engineering capstone projects. Each section of the outline is described and references provided to supporting material given to the students.

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Introduction

Graduate capstone projects are becoming more common[e.g.,1,2,3] and are required in some states as a terminal experience for the MS degree. In a previous Capstone Conference paper[4], I described the WPI Systems Engineering (SE) MS degree program[5] and a few completed capstone projects.

In this paper, I describe a standard SE capstone format guideline I have used now for more than 20 recent graduate MS SE capstone projects, and provide some examples of the capstone professional development value students have noted in their summary comments.

SE MS Capstone Experience

The graduate SE capstone[4,5] supports one of the central priorities in WPI's educational philosophy, specifically the application of academic skills and knowledge to real-world problems. The SE capstone project represents a substantive application of graduate coursework covered in the program and 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 course is managed and evaluated by WPI faculty, but students are encouraged to seek a project mentor from among their professional colleagues who have systems engineering experience. The selection and support of a mentor is, however, entirely at the discretion of the student.

Capstone Learning Objectives

The learning objectives of the capstone project can be generally stated as follows: *At the completion of the SE capstone project, students should be able to*:

1. Demonstrate detailed knowledge and application of SE methods to design a system, component, or process to meet specific stakeholder needs.
2. Demonstrate an understanding of the language and the processes of systems engineering and the SE Body of Knowledge[20] (SEBOK) through group discussions, arguments and decisions.
3. Demonstrate effective engineering communication skills through oral project presentations and a written final capstone report.

Capstone Project Framework

The generic framework I have used for the past few years is described below in terms of nine specific SE topics (§2-10), and four additional sections (§1, §11-13) that add structure to the final project report. During each week of a typical capstone course students make short in-class formal presentations on the section(s) due that week. In addition, students are expected to act as professional systems engineers and to critique the presentations made by others.

Brief descriptions are provided below for each of the capstone project report sections.

§1 Introduction

Most new systems are a result of a specific customer need, a technological opportunity, or in response to a specific RFP (which can of course encompass one of the previous opportunities). The introduction section is where a student is expected to make a compelling and, to the extent possible, realistic case for the development of the selected system. It should be noted that this section is included in the capstone to allow a student to develop their argument for proceeding with the selected capstone project and, with help of the course instructor, to adequately frame and bound the selected capstone design problem.

§2 Needs Analysis

A detailed capstone Needs Analysis section is not expected to be a complete and professional needs statement, but rather a representation of a Needs document in sufficient detail to illustrate the most important system needs and, from the faculty advisor perspective, that the student understands the structure, importance and nuances of the Needs section. At a

minimum, this section typically includes the following subsections;

i. Brief System Overview
ii. Needs Solicitation - how?
iii. Stakeholders - including a discussion of the role of each stakeholder (proxy, passive, oversight, primary, regulatory, customer, negative, etc.).
iv. Detailed Needs Descriptions - including a discussion of the category of each need (operational, standards, customer request, etc.).
v. Needs Validation - which stakeholder(s) "own" the need, and an assessment of the priority of each need (e.g. identifying and validating "key" needs).
vi. Gap Analysis - a description and critique of similar systems as a way to identify critical development efforts (where the gap is… breadth and depth) and to make a case that the proposed system can actually be built. When possible, a cost comparison is included.

Throughout the classroom mentoring of the graduate capstone students, detailed references are provided to guide students in terms of templates, subject matter tutorials and other material pertinent to writing, documenting and justifying a particular phase of the system development life cycle. For example, during the development of the Needs section, references are provided to material developed by the MITRE Corporation[6] and the Federal Highway Authority[7]. To the extent possible, students are encouraged to use standardized forms, such as the Needs forms from the FHWA[8].

§3 Concept of Operations - CONOPS

A CONOPS is a description of how a system is used and operates from the user's perspective. Since a complete and well developed CONOPS is beyond the capability of a project student, students are asked instead for an abbreviated CONOPS, focusing in particular on:

- A description of the operational environment and operational needs that will, in turn, drive operational requirements and requirements discovery.
- Context Diagrams - particular system environmental boundaries, data exchanges and human operator interfaces.
- Use Cases - a few that are well written, singular and realistic.

By focusing on these three key areas, students learn the value of the CONOPS, and the value of Use Cases to discover requirements and overlooked or even unforeseen operational needs of the proposed system.

The FHWA web site on CONOPS provides an excellent check list which students are directed to and are asked to follow[9]. Students are also directed to a CONOPS tutorial by W. K. Day[10].

§4 System Requirements

Requirements describe what a system must do and how well (but *not* how). Learning to properly document requirements is not easy, even professionals can struggle with the language associated with writing unambiguous, singular, necessary, feasible, testable, technology independent and complete requirements[11].

This report section provides an opportunity to remind students that there are many categories of requirements, including operational, functional and non-functional, environmental, performance, legal, regulatory, standards and so forth. Further, while even a moderately simple system can have hundreds of requirements, students are asked to thoroughly document, validate and describe the verification methods for only a small subset of requirements that represent a few different categories of requirements. The emphasis is on writing a few good requirements, not on writing many poor requirements.

§5 Trade Study

Regardless of the capstone project selected, it is inevitable that there will be multiple ways in which the detailed design of a subsystem, component or algorithm can be implemented.

For this section, students are asked to fully document and defend one trade study that includes:

- a concise description of the trade study to be performed, the need for the trade study, and the different options that will be compared
- a clear statement of the trade study parameters and their scaled value(s)
- a clear explanation and justification of the weights associated with each of the trade parameters
- the results of the trade study
- a sensitivity study of the results
- a discussion of the meaning of the results (do they make sense, should the study be refined, were the best alternatives actually analyzed, etc.)

Several references and tutorials are provided to the students, include a FHWA reference[12], a well written chapter from a Middle East Technological University (METU) book[13], and a Space Grant Space Systems Engineering undergraduate tutorial module[14].

§6 Risk Management

Risk Analysis (RA) and Risk Management (RM) are processes that are normally embedded throughout the system development lifecycle. For the purpose of the capstone project however, it is easier to require students to document and evaluate the risks associated with a

select number of system components, subsystems, technologies, schedules and so forth. The FHWA framework and templates are recommended for use by the students[15].

Key subsections of the report that students are directed to include:

- RA/RM Organization Structure and Responsibilities
- RA/RM Process - described within the context of the systems life cycle
- Risk Identification and Documentation
- Risk Statements - clear statements of each risk
- Analysis and Prioritization
- Mitigation and Responsibilities
- Communications Plan

§7 Systems Engineering Management Plan (SEMP)

One of the more difficult capstone project sections for most students is the SEMP. Few students have management experience, fewer still have practical SE project skills or experience. As a result, for this section students are asked to develop only broad statements related to the following topics.

- Project Organization Structure and Staffing
- Executive Management and Responsibilities
- Core Development Team and Responsibilities
- Business Management Team and Responsibilities
- SE and PM Statements of Responsibilities
- Core Integration and Test Plan
- Production and Sustaining Engineering
- Work Breakdown Structure
- Communications and Change Management

It is noteworthy that students will often expand on one or a few sections in which they have some experience or interests (a common one is change management).

§8 Test and Evaluation Master Plan (TEMP)

What is typically emphasized here is the need to clearly articulate Measures of Effectiveness (MoEs) and Performance (MoPs) and other "acceptance" standards, as well as (as appropriate for each capstone project system) compliance with national standards, the need for long range test and evaluation planning, the possibility that test equipment will need to be developed, traceability requirements during test (e.g. to a NIST standard), testing to mitigate risks and related issues. The emphasis is not on identifying every test process, but fully documenting a few representative tests, outcomes and alternatives, and contingencies.

§9 Architecture

Architecture has always been a difficult section for capstone students and is one of the few areas that is not covered in the core FHWA documents. For this section, students are asked to develop the following views based on the Department of Defense Architecture Frameworks[16,17] (DoDAF):

AV-1 Overview and Summary Information
OV-1 High Level Operational Concept Graphic
OV-2 Operational Node Connectivity Description
OV-3 Operational Informational Exchange Matrix
SV-1 System Interface Description

§10 Life Cycle Management Plan (LCMP)

Much like the SEMP section, students are asked to provide a general overview of the LCMP. To guide them in the development of this section, the students are directed to two excellent references[18,19]. Unfortunately, it is not easy to find a standard template for a LCMP. As a result, capstone students are asked to address the following general attributes of their system, many of which can be referenced to previously developed report sections.

- program management plan
- risk management plan
- cost, performance and schedule management plan
- test approach and management plan
- product support, including training, maintenance, warranty service, etc.
- configuration management
- end of life planning, planning for upgrades, planning for retirement/recycling
- any other special needs planning (e.g., if hazardous materials or wastes are an issue, how will they be managed? or even if on-going maintenance is requirement to maintain system effectiveness, how will that be managed?)

§11 Project Summary

The project summary section is included to help tie the capstone report together.

§12 Lessons Learned, Experiences Gained, Reflections

The capstone project course is usually the first time an MS SE student has been asked to complete a system design encompassing many of the classical SE life cycle phases of a system design. Further, this course has other aspects that challenge capstone course students such as:

- The course is writing intensive and the writing is expected to be at a post-graduate level.
- Students are required to professionally present and defend their work after completing each section.

A short selection of paraphrased student reflection comments includes the following.

- I really learned how to write and make an excellent, concise and well structured presentation.
- This was the an excellent opportunity to learn how to apply the SE life cycle to a full project from beginning to end.
- Learned a lot about standards and regulatory issues.
- Learned a lot about how important it is to write accurately and professionally.
- For the first time in five years at my job, my boss wrote back and said my report was really well written and documented (after applying what I learned about writing in this course).

§13 Bibliography

This section is of the capstone project report is self-explanatory. Students are expected to follow either the IEEE or MLA citation standard.

SUMMARY

Clearly, no single SE capstone class format will work for all faculty. Further, when a student selects a project that is different than a design project, for example a case study, this format can not be applied. However, my experience has been that this format, coupled with directed references to standards and tutorials for each section as a way to help students remember their coursework, provides a solid foundation for a well organized capstone project experience.

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