AC 2011-1206: SE CAPSTONE: IMPLEMENTING A SYSTEMS ENGINEERING FRAMEWORK FOR MULTIDISCIPLINARY CAPSTONE DESIGN

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SE CAPSTONE: Implementing a Systems Engineering Framework For Multidisciplinary Capstone Design

Synopsis

In this paper we discuss a pilot project at Stevens Institute of Technology to develop a systems engineering (SE) framework for multidisciplinary capstone design which can be a model for broad implementation. It is part of an initiative involving 14 institutions (including all the military academies), sponsored by the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)) STEM Development Office to incorporate SE in undergraduate capstone design. The initiative is a clear demonstration of the significance placed by DoD on the need to have graduating engineers educated in the overarching significance of systems engineering for the development of large-scale and complex systems, and to have those graduates develop some foundational SE competencies.

The distinguishing features of the SE framework being developed at Stevens are: it builds on early exposure to SE concepts in core design courses; it provides a series of workshops through the course of the capstone project to teach SE concepts in what approximates to a just-in-time mode; and it engages graduate design students with the undergraduates to perform an interdisciplinary capstone of significant scope, working with external stakeholders and mentors. The goals that are addressed in the project are connected directly to primary SE Competency Areas of DoD (SPRDE-SE/PSE). Assessment is applied locally at the authors' institution and via an external assessor to the overall 14-school program, to determine the progress in meeting the institutional and consortium educational goals.

The Stevens project has involved working with various stakeholders, within and associated with the Department of Defense, to address a need for an expeditionary housing system for the military, with a major focus on integrated alternate energy sources and associated micro-grid. This has application to both forward operational units and for disaster relief missions.

This paper reports on the implementation of the project and preliminary findings.

Project Background

The project described in this paper provides an opportunity to leverage the significant graduate-level Systems Engineering (SE) education experience at Stevens Institute of Technology into the undergraduate engineering curriculum. That experience includes the development, working with INCOSE, of a reference systems engineering curriculum as a model for others[1] and associated expertise in mapping a framework of SE competencies into appropriate pedagogy. Furthermore, our systems engineering faculty have been centrally engaged with the efforts to develop the SE Body of Knowledge[2].

The imperative to find an effective means to inculcate SE into the undergraduate curriculum is embodied in the National Academy of Engineering (NAE) "Engineer of 2020" vision for engineering graduates[3]. Explicitly the follow-up report from NAE[4] states "contemporary challenges—from biomedical devices to complex manufacturing designs to large systems of networked devices—increasingly require a systems perspective. This drives a growing need to pursue collaborations with multidisciplinary teams of technical experts. Important attributes for these teams include excellence in communication (with technical and public audiences), an ability to communicate using technology, and an understanding of the complexities associated with a global market and social context."

We believe that a capstone/senior design project constitutes an ideal vehicle to introduce undergraduate engineering students, with their limited experience, to the principles, best practices and benefits of Systems Engineering. It makes what can seem foreign and abstract into a practical way of approaching a design project. The project is therefore an important opportunity to embed a **systems approach** by creating an educational and organizational framework for conducting interdisciplinary, systems engineering-based Senior Design Projects that allows us, and others, to institutionalize this type of project as the norm rather than the exception. ***Thus the goal is to inculcate aspects of systems engineering into the education of students in all engineering disciplines through their major capstone project.***

However, at Stevens the baseline for this is not zero. A feature of the engineering curriculum is that some basic systems engineering concepts are integrated in an explicit manner into the early freshmen and sophomore sequence of core design courses[5]. Experience with these teaching elements provides both an SE foundation for our students, but also experience in adapting SE for undergraduates that can be translated to broader implementation at other institutions in concert with the results of the presently described program. This approach is congruent with that being taken by a number of institutions worldwide to integrate systems thinking into the engineering curriculum under the CDIO Initiative[6], but is not associated with that group.

Capstone senior design projects at our university have been typical of most institutions in that they are primarily discipline-centric, with associated design problems, methods and tools. Although a small number of multidisciplinary projects are conducted every year, the practical and academic organization of these projects has been primarily ad-hoc. The assessment in particular of these multidisciplinary projects has been very much driven by the individual engineering program requirements, often to the detriment of the success of the overall system. This is not surprising as it places the focus for students on meeting the required deliverables and associated timetables established by each program for their discipline-centric capstone projects.

The opportunity to establish the SE project described in this paper is a result of the recognition by the Department of Defense (DoD) that it is critical for their future needs to have the engineering graduates who will work directly for DoD and for their suppliers, develop SE competencies that they can successfully apply to military systems development and deployment. In order to achieve this goal, DoD has supported a consortium of 14 universities and military academies to pilot various projects whose results can help establish a framework for building SE into the capstone design courses of engineering programs nationwide.

The main SE learning goals that are being pursued in the project at Stevens to help develop this framework for *all* participating students are described below. These are aligned with the SE Competency Areas of DoD known as SPDRE-SE/PSE[7], which means Systems Planning, Research, Development and Engineering (SPRDE) – Systems Engineering (SE) and Program Systems Engineer (PSE) and shown in Appendix A. This was developed for the defense acquisition community and is one of a number of such competency models that have been developed in the SE domain. They are used for workforce development and education. The SE Capstone project goals listed below have the numbers of relevant competencies from Appendix A noted:

- Identify the needs and objectives of key stakeholders including the operational and life-cycle context, and how these shape and set the scope for the development program (2, 4, 5).
- Demonstrate recognition that the value of a system is largely embodied in the interaction among its components, and not in the components themselves when addressing stakeholder requirements (6, 8).
- Demonstrate an ability to produce a well thought out system design and well managed interface specifications as critical to successful system integration (6, 8).
- Use early modeling and inspection as a means to a well conceived system design (2, 6, 10).
- Develop communication skills to successfully work on interdisciplinary teams (26).
- Develop communication skills to communicate stakeholder/problem domain and solution domain content (26).
- Identify the role Systems Engineering plays on larger projects and SE career options (24).

The project is intended to embed a systems approach into the existing curriculum by creating a framework of educational and organizational components that integrates discipline-specific senior design and special projects courses at both the undergraduate and graduate level. By including graduate students as well as external advisors, we anticipate providing a level of professionalism, experience and knowledge that would not be possible on an undergraduate-only project, also giving context to the career aspects of Systems Engineering for all students involved.

Project Description

The Stevens project, which is design/build, has been conducted over two semesters and involved 4 undergraduate sub-teams from Mechanical Engineering, Engineering Management, Electrical & Computer Engineering and Civil Engineering – each team with 4-5 students, and 7 students from the graduate Product Architecture program – a total of 24 students. For the Spring 2011 semester the Product Architecture group dropped to 2 students due to programmatic constraints. For this implementation they had their “base” in their disciplinary teams, and were partly “forced” and partly self selecting into interdisciplinary working groups to perform system level activities. The graduate Product-Architecture program is one that integrates the study of Architecture, Engineering, Product Design, and Interaction. This program creates a distinctive fusion of design culture and technology through the disciplines of computation, analysis, and advanced production methodologies. The students include primarily architects but also those with science and engineering undergraduate backgrounds.

The project described in this paper, as previously noted, is part of a multi-institutional program intended to promote the development of systems engineering competence through capstone projects in focus areas of interest to DoD and sponsored by the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)), which is the DoD’s chief technology office, through the Systems Engineering Research Center (a DoD University Affiliated Research Center). The Stevens' team chose to address a green expeditionary housing focus; other schools have addressed a range of other focus areas.

In the early stage of planning the program with ASD(R&E) there had been some discussion of having a competition between institutions. However that was not pursued due to the very different implementation models used by the participating institutions: from one to two semesters; graduate vs. undergraduate; to course vs. solely project based, as well as some DoD focus areas only having limited participation.

Approach

Foundational SE knowledge

The SE capstone project builds on existing elements within the core engineering curriculum[5]. Some basic systems engineering concepts are integrated into the early design courses of the core engineering curriculum through mini-lectures linked to the major design projects in those courses. These mini-lectures address the holistic approach of SE, and the ideas of what constitutes a system. It provides a more substantial understanding than is traditionally taken in design courses on the idea of stakeholders, and situates stakeholders and their requirements within the SE context. The lectures then provide just-in-time understanding of the next stages of conceptual design and evaluation; introduces operational scenarios; and then to definition of system functionality separate from physical embodiment. The motivation for SE and the main elements of an SE process are revisited in one of the lectures integrated into a core Engineering Economics course taken by all engineers in the junior or senior year. Engineering Management students get a deeper introduction to SE principles in a required course in their program, *Innovative Systems Design,* in the second semester of their junior year. This course is structured around the main elements of a Concept of Operations (ConOps) with a strong focus on understanding stakeholder needs and objectives before selecting a high level system concept augmented by operational scenarios.

SE Capstone Pilot Project Organization

So building on this foundation, both in terms of basic SE ideas and some limited application for the undergraduate engineering students, the pilot project for inculcating systems engineering through the capstone was designed with five project phases:

1. **System definition phase:** Development of ConOps (including system concept) and system requirements. Students not directly involved with SE activities are to support with modeling and simulation as well as technology and feasibility studies.
2. **System architecture and design phase:** Development of a system architecture and related artifacts (including preliminary integration test planning). Students not directly involved are to begin preliminary design of subsystems as well as support the SE activities as needed.

3. **Detailed design and component testing phase:** The majority of the work to be at the component level. The SE team will follow up on issues with a system level impact.
4. **Integration Testing:** The SE team will lead and coordinate the effort.
5. **Demonstration:** A series of live demonstrations will be conducted to demonstrate the capabilities and suitability for the operational scenarios given.

The educational elements planned were as follows, with the primary vehicle being intensive just-in-time workshops placed at the key points in the project timeline to be most effective. They have used a common day/time that aligns with the discipline capstone schedules for all sub-teams:

- Lectures on critical SE principles and best practices to address the learning goals and competency areas that are relevant for the system level work for the upcoming phase. (Developed by the Systems faculty member on the project)
- Lectures on relevant aspects of project management, leadership and teamwork. (Suitable guest lecturers from the faculty)
- Specific lectures that tie abstract systems concepts to the project at hand, with core principles from the involved disciplines (developed in collaboration between Disciplines/Systems Engineering faculty)
- Practical team exercises/workshops to reinforce the principles and get the students started on the systems level work that needs to be done in the upcoming project phase, as well as for team-building in general.
- Existing course material both on the graduate and undergraduate level leveraged and adapted to suit the type of students and workshop model for introducing learning elements over the two capstone design course semesters.

The project organization and management further included the following considerations:

- Organizational concepts for system level work in interdisciplinary student groups
- Organizational concepts for faculty/advisor/TA involvement in interdisciplinary activities
- Overall project plan to maximize project success and SE exposure
- Principles for the integration of graduate level design coursework (specifically Product Architecture and Engineering) to augment the competencies of the UG students with additional specialized knowledge and experience to enhance the experience of professionalism and realism in the project and ensure a more comprehensive project outcome.
- Principles for leveraging Systems Engineering graduate students as TA/advisors to help other disciplines with systems engineering concepts,

and giving themselves the opportunity to practice Systems Engineering, theories, leadership and management in a real project setting.

Project Advisors and the Relationship to the Disciplinary Capstone Requirements

Oversight of the SE capstone was through a core faculty team of three. This was lead by an SE faculty member working with the Director of the Product Architecture Program. A third faculty advisor provided additional coordination. As an interdisciplinary project it was necessary to get buy in and involvement of the disciplinary capstone advisors. The SE Capstone faculty team met during the first semester of the project with the relevant faculty members who oversee the capstone in each of the participating engineering programs.

General agreement was achieved that the SE capstone would require somewhat different focus, timelines and deliverables than were established for the disciplinary capstone projects, thus requiring some flexibility in expectations for SE capstone participants. However, the disciplines still expected the sub-teams to meet many of the deliverables of their disciplinary capstone courses. In the first semester the major portion of the grade was established in this manner leading to a lot of student frustration as the SE capstone required a lot of early activity to address SE expectations not found in the disciplinary capstone and a slower start on the technical design aspects. This placed the SE capstone students at a disadvantage and resulted in some cases to a perception that they received lower first semester grades than they might otherwise have achieved. This was of serious concern and for the second semester agreement was reached to move most of the control of grading to the SE advisors.

Disciplinary advisors for the most part were not involved in the SE capstone during overall project activities but provided input on the sub-team technical activities. For the most part all came together for significant milestone reporting at mid and end of semester reviews.

Student Products and Artifacts

The students were expected to create the following information on the system and project level:

System:

- ConOps and critical requirements: The students were attached to systems-level teams that were expected to document ConOps related information and requirements in different areas of operation/usage of the expeditionary housing as well as the logistics of deploying and assembly, commissioning and disassembly of the housing units.
- System design and interface management: The students again attached to systems-level teams to document the system design of key subsystems and develop and manage subsystem/component requirements and interface requirements.
- System Integration, Testing and validation: The students attached to systems-level teams to plan, conduct and document subsystem and system integration and testing and basic validation.

Project:

- Work Breakdown Structure and overall project plan and progress
- Budget
- Cost estimation and control

Project Implementation

Stakeholders and subject matter experts - CONOPS

A key aspect of the program is interaction with stakeholders to establish the needs and the scope of the project, i.e. the Concept of Operations (CONOPS). The program benefited from a kickoff meeting prior to the start of the academic year where participants from each of the 14 institutions involved with the program met with DoD stakeholders, both operational and technical, from the various military services and ASD(R&E). This helped establish some initial design requirements for the green expeditionary housing project based on both field experience with current operations and systems and the input of those who have been involved with technical developments in rapidly deployable housing, power systems and associate micro-grids. This kickoff established connections that led to the identification of several DoD subject matter experts plus a contractor with a business supplying base power in Afghanistan. These stakeholder connections have helped with the CONOPS phase of the project, including campus visits to discuss the student team's ideas and also to review progress at the end of the semester presentation of the project.

The design constraints for the Stevens project included: a low environmental footprint; minimized reliance on supplied fossil fuel and water as this of critical significance to military operations; and a focus on integrated alternative energy sources in an associated micro-grid.

Based on stakeholder input the project design is directed at a 100-person camp that can be rapidly delivered and assembled in a remote location for a 6-12 month deployment for a combat outpost (COP), and also applicable to disaster relief missions which the military is often called upon to support. Four primary areas of focus are critical to the project: shelter, energy, water and waste. Adaptability and resilience were additional considerations.

Project progress

The team has been developing an integrated "out of the box" solution that is adaptable to the local requirements and is not dependant on skilled labor to assemble. Examples of concepts that have been incorporated are shown in Figure 1. The goal is, for the most part, to integrate proven, commercially available technologies, together with the systems architecture and modeling that will provide for intelligent system design for specific missions. Furthermore, adaptability and resilience to local conditions are addressed through real-time monitoring and control within the systems approach, coupled to the ability to incorporate various adaptable, modular, alternate energy technology sources in a plug-and-play mode appropriate to the mission and to avoid single point system vulnerability.

The approach to providing energy-efficient shelter technology has involved developing systems designed to retrofit any existing tent with an enhanced insulating and airtight skin to increase R-value and air-tightness while reducing the demand on active heating and cooling systems. Adaptability and resiliency are addressed by the ability to interchangeably plug in multiple, alternate energy sources as appropriate as an integral part of the design approach. This also addresses a significant additional consideration when considering post-mission transition to the local community, which is often experienced, including in disaster relief, where temporary housing and infrastructure provided by the military can remain for an extended time in community use. In addition to shelter and power, the team has looked at water reclamation options and organic and inorganic waste minimization.

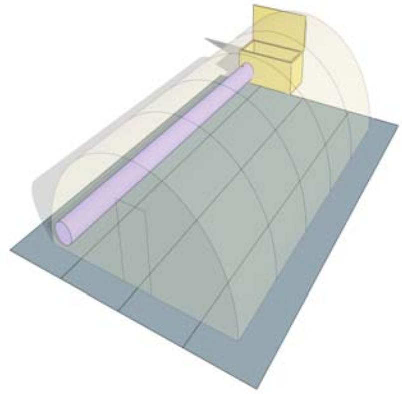

Fig. 1
(a) Transport unit doubles as on-site plug-in grid management unit
(b) Housing system in a box

In addition to hardware aspects of the project, one of the sub teams has been working on software integration associated with control to provide intelligence to the microgrid so that it can adapt top load demands and failures a well as insertion of different power sources. An additional software task is one to allow performance modeling through incorporation of data from the prototype system to refine it to establish a full base performance model . The systems framework for the interdisciplinary capstone has provided a very good vehicle for the software team to integrate their work to that of the hardware focused teams.

Analysis of the systems approach taken so far has identified significant potential reductions in both fuel and water dependency, thus minimizing both the size and frequency of supply missions. Such missions are of critical significance to DoD in combat zones.

A formal Preliminary Design Review (PDR) was not included in the project, but the final group presentation and report (including sub-team reports) at the end of the first semester served that function. The team went through all the major subsystems and their key components and assessed their performance as well as overall systems performance. Two DoD stakeholder representatives were present.

The expectation is that the project will be taken through to the prototyping stage and testing, including with the performance modeling.

Experience with Implementation of the SE Capstone Pilot Project

The project is ongoing but there are a number of preliminary outcomes and lessons learned that can be taken from the experiences to date. These are summarized below.

Concrete planning should start early to mid spring semester (of Junior year for undergraduates) in the academic year before the capstone project. This is to obtain buy-in from the appropriate faculty mentors and allow them to socialize it with their students. This way the team can largely be in place and know what to expect before the end of the spring semester. This would reduce the 2-4 week "ramp-up" time resulting from different schedules and team assignment practices in different engineering programs.

It took longer than expected for the students to leave the comfort of their own discipline and interact in an interdisciplinary way with their peers to develop a thorough understanding of the challenge at hand and develop conceptual solution alternatives at the system level. We have also had challenges in aligning the expectations of the different engineering programs with the needs of the project, which has led to some cases of student frustrations as the disciplinary programs are the final authority on their grading in the current phase of implementation. Students displayed a reluctant level of allegiance in working with the SE Project Advisors as they looked primarily to their discipline advisors.

Highlights:

- Initial student motivation as they started to explore the problem area and the stakeholder needs.
- The students' genuine interest in the circumstances of the key stakeholders (soldiers that operate out of combat and forward operating bases), and those who run the convoys to supply these.
- The interaction between the students and DoD mentors during the 2 visits they made.
- The realization that modifications within one discipline had a profound impact on the work of another discipline.

Challenges:

- The reluctance/fear of students to engage in system level conceptual design and analysis across disciplines
- The reluctance of many students to engage in discussions that went outside their own discipline – especially when it came to apply their discipline specific knowledge to interdisciplinary research and analysis to quantify and be more specific on findings from the problem/stakeholder analysis
- Misalignment of departmental expectations vs project expectations, which led to "busy work" for the students, and loss of motivation towards the project.
- In the first semester of implementation we had to abandon our initial schedule of SE lectures after the first one on SE in general and ConOps in particular. Due to the challenges listed and relatively slow progress we chose instead to engage more actively with the students in a more mentoring/facilitation mode during the weekly all-hands meetings. It may be beneficial to include an intensive workshop at the start of the project to provide an overview of the SE concepts that need to be considered as a foundation for the students in knowing where they are headed and to reinforce what they had learned in the Freshman/Sophomore SE content delivered in early design courses.

On a day to day basis, the project has been supervised by two SE Project advisors, one from SE and one from Product Architecture, assisted by an additional professor from the Product-Architecture program. The faculty advisors from the other departments have shown moderate interest in contributing as they already have a heavy load advising other senior design projects.

A more formal course structure and framework for departmental/faculty/external resources involvement has to be developed based on the experiences from this pilot.

Assessment

The organizational aspects of the framework were planned to integrate some of what is already done in the individual engineering disciplinary programs, but much of the overall project management and organization needed to be developed. The competency elements from the DoD SPRDE-SE/PSE Competency Model, that were to be addressed in the project, are listed in Appendix A. The major emphasis is on the competencies highlighted in bold.

The general tool for assessing student learning through the above deliverables is through the use of scoring rubrics. These are complemented by a set of student presentations. The progress of the project is demonstrated through a physical prototype of a representative sub-set of the overall design to be displayed prominently on-campus. The integration of critical subsystems is showcased at the Senior Projects Expo that takes place at the end of April each year to which stakeholder representatives are invited and at a summer conference for all participants in the overall SE Capstone Program along with DOD stakeholders. As noted, the 1st semester review is effectively a PDR, the final review associated with the Senior Projects expo will be emulating a Critical Design Review (CDR) at the prototype stage.

Rubric Development
The SE concepts and competencies addressed in the project for the most part do not lend themselves to simple quantitative assessment measures, such as through quizzes that can be directed at knowledge accumulation. Rather, they represent higher-order conceptual and performance skills and are carried out in the context of teamwork which adds a further dimension. For this reason an appropriate assessment methodology is through the use of rubrics. Therefore, a key component of the assessment task is the development of appropriate rubric measures that address the targeted SE conceptual learning and its application.

Assessment of capstone design is an active area of engineering education research because of the challenges of capturing the higher-order attributes that the capstone is intended to develop. We are guided by the extensive work of the NSF-funded TIDEE consortium[8] in this regard as we extend this to specific SE elements in the proposed capstone project and in particular to the rubric development process. The framework for assessment is through performance tasks associated with a set of performance criteria that align with the competencies listed in Appendix A. The rubric development is being done in association with this framework. Students' artifacts are the primary source for evaluation. Reflective essays will also be required at the end of the project. In addition the teamwork and communication aspects are assessed through existing assessments[9].

Rubric development is an iterative process involving the faculty advising the multi-disciplinary team, together with the input of systems engineering faculty members with extensive industrial experience in the systems field. This is to ensure that the learning objectives are appropriately addressed and that the rubrics are constructed to effectively and reliably capture the range of performance in meeting the objectives. Allen and Knight[10], as example, provide a methodology for such a collaborative approach to constructing and validating rubrics.

The timescale of the project provides for only limited iterations in rubric validation; however this project is effectively the pilot for broader implementation in capstone design at the host institution and further validation can follow through the several multidisciplinary projects which will represent the next phase in institutionalizing SE into the capstone across the engineering programs.

A first design for a rubric to assess the SE aspects of the project has been developed and shown in Appendix B. This is being applied in the second semester and so no results are included here.

Teaming

An existing teaming assessment instrument developed at Stevens[9] (shown in Appendix D) was used for the sub-teams to obtain peer assessment and feedback approximately two thirds of the way through the first semester. The results of the latter were for the most part not revealing of teaming problems at that point of the project. It should be understood that the undergraduates had received prior design teaming experience, teaming skills development, and assessment with a version of this instrument in their freshmen/sophomore year core design courses[9]. The assessment will be reapplied at the end of the project.

External Assessment

An overarching external assessment process was established for the multi-institutional, SE Capstone program to supplement the assessments of the individual institutions, which naturally are tailored to their projects and associated goals. This external assessment process is administered by program leadership sponsored directly by the Systems Engineering Research Center. The common set of assessments include: (1) pre- and post-surveys to gauge knowledge of systems engineering, interest in systems engineering careers, and awareness of a spectrum of Department of Defense systems engineering problems; (2) a pre- and post- case study analysis of a systems engineering problem; and (3) analysis of student activity such as through blog posts, to measure student progress toward more sophisticated systems engineering analysis in the context of their own Capstone projects. Surveys are also included of the faculty involved and the mentors supporting the projects at the various institutions. The external assessment will also analyze artifacts developed by the program participants as part of overall evaluation. These elements are more extensively described along with the overall multi-institution program, in a paper at this conference[11].

The assessments to date have been through the normal disciplinary capstone course grading within each contributing engineering program. These have for the most part included interim reports and presentations by disciplinary sub-teams to disciplinary faculty advisors/panels with a grade set by these for the first semester. It is clear from the initial experience and anticipated for the next phase as disciplinary advisors have become involved, that the center of gravity for grading needs to be with the overall systems capstone rather than at the sub-team assessed within the disciplinary programs. The discipline capstone advisors are working with SE Capstone leaders to establish the grading approach in association with the rubric development, so that all educational outcomes that the individual disciplinary program capstone courses must address are adequately covered and assessed.

A questionnaire was administered approx. one third into the second semester to assess certain aspects of the SE goals not included in the rubric of Appendix B. The questionnaire is seen in Appendix C. Some results are shown in Fig. 2. The students generally embraced the value of the contributions from the other disciplines participating in the interdisciplinary projects although as noted they were most comfortable working with disciplinary partners on the detail project work. The course does seem to have been effective in providing insight into the role of system engineers and to a lesser extent on career options. The last set indicates that stakeholder needs were well recognized and one might have hoped so based on the Freshman/Sophomore design class emphasis in this when first introducing SE concepts.

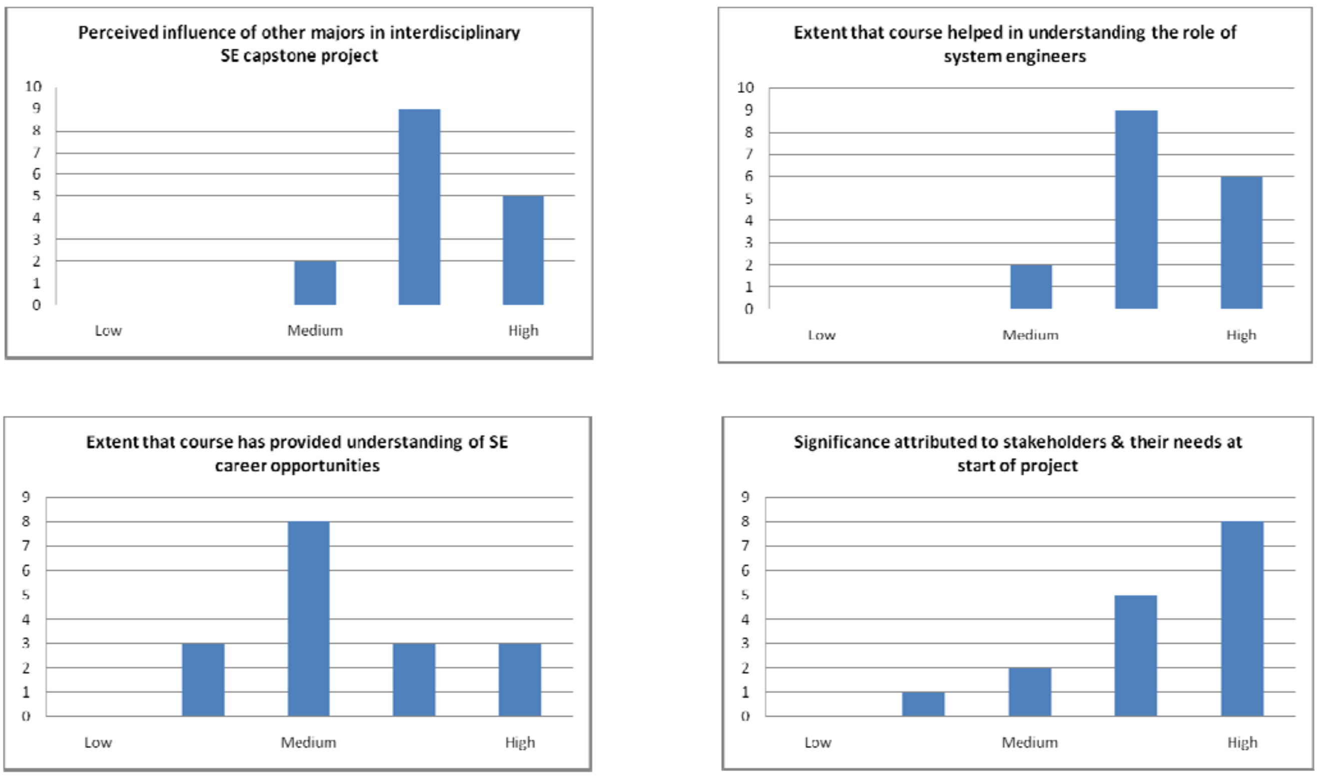

Fig. 2 Results from survey of student perceptions related to SE capstone goals

Conclusions

- The initial phase of implementation has revealed both some immediate benefits of introducing systems engineering into the capstone for a major multi-disciplinary project, but also the challenges.
    - some of the latter are associated with it being a multi-disciplinary project rather than specifically due to addressing the SE goals.
    - in this regard student focus and assessment has been too discipline-centered in the initial phase and needs transitioning so that the systems project is accepted by all

stakeholders as the focus and assessment base while still meeting disciplinary engineering capstone educational outcomes.

- The timeline to bring the project and students up to speed is longer than for a traditional capstone, including multi-disciplinary ones, as the SE foundation has to be established
    - first, in terms of SE knowledge acquisition
    - second, for socialization to and the buy in needed from the students to work on the project in a meaningful systems engineering mode.

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Appendix A DOD SPRDE-SE/PSE Systems Engineering Competencies[7] (those addressed in current project are in bold).

Competency	Competency element description
1. Technical Basis for Cost	Element 1. Provide technical basis for comprehensive cost estimates and program budgets that reflect program phase requirements and best practices using knowledge of cost drivers, risk factors, and historical documentation (e.g. hardware, operational software, lab/support software).
2. Modeling and Simulation	**Element 2. Develop, use, and/or interpret modeling or simulation in support of systems acquisition**
4. Stakeholder Requirements Definition	**Element 4. Work with the user to establish and refine operational needs, attributes, performance parameters, and constraints that flow from the Joint Capability Integration and Development System (JCIDS) described capabilities, and ensure all relevant requirements and design considerations are addressed.**
5. Requirements Analysis	**Element 5. Ensure the requirements derived from the customer-designated capabilities are analyzed, decomposed, functionally detailed across the entire system, feasible and effective.**
6. Architecture Design	**Element 6. Translate the outputs of the Stakeholder Requirements Definition and Requirements Analysis processes into alternative design solutions. The alternative design solutions include hardware, software, and human elements; their enabling processes; and related internal and external interfaces.** **Element 7. Track and manage design considerations (boundaries, interfaces, standards, available production process capabilities, performance and behavior characteristics) to ensure they are properly addressed in the technical baselines.** **Element 8. Generate a final design or physical architecture based on reviews of alternative designs.**
7. Implementation	Element 10. Manage the design requirements and plan for corrective action for any discovered hardware and software deficiencies
8. Integration	**Element 11. Manage the technical issues that arise as a result of the integration processes that feed back into the design solution process for the refinement of the design.**
9. Verification	Element 12. Design and implement a testing process to compare a system against required system capabilities, to link Modeling and Simulation (M&S), Developmental Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E) together, in order to document system capabilities, limitations, and risks. **Element 13. Verify the system elements against their defined requirements (build-to specifications).**
10. Validation	**Element 14. Evaluate the requirements, functional and physical architectures, and the implementation to determine the right solution for the problem.**
18. Requirements Management	Element 23. Use Requirements Management to trace back to user-defined capabilities and other sources of requirements, and to document all changes and the rationale for those changes.
19. Risk Management	**Element 24. Create and implement a Risk Management Plan encompassing risk identification, analysis, mitigation planning, mitigation plan implementation, and tracking throughout the total life-cycle of the program.**
21. Interface Management	**Element 27. Ensure interface definition and compliance among the elements that compose the system, as well as with other systems with which the system or system elements will interoperate (i.e., system-of-systems (SoS)) by implementing interface management control measures to ensure all internal and external interface requirement changes are properly documented in**

	accordance with the configuration management plan and communicated to all affected configuration items.
24. Systems Engineering Leadership	Element 40. Lead teams by providing proactive and technical direction and motivation to ensure the proper application of systems engineering processes and the overall success of the technical management process.
26. Communication	**Element 42. Communicate technical and complex concepts in a clear and organized manner, both verbally and in writing, to inform and persuade others to adopt and act on specific ideas.**

Appendix B – Assessment Rubric for SE Capstone

Learning Goals	Performance Criteria	Level of Achievement			Score 1: poor thru 5: excellent	Weight %	Weighted Score
		1	3	5			
PROJECT ASSESSMENT							
Identify the needs of key stakeholders and how these shape the scope of a project	System scope and design clearly addresses key stakeholder needs and concerns	Little influence of stakeholders in project scoping and development	System scope and design choices show a moderate consideration and understanding of stakeholder needs and concerns	System scope and design choices reflect an intimate understanding of the core needs and concerns of the key stakeholders	☐ ☐ ☐ ☐ ☐ 1 2 3 4 5		
Demonstrate recognition that the value of a system is largely embodied in the interaction of its components rather than the components themselves when addressing stakeholder needs.	Synergies across subsystems and components have been identified and utilized to address stakeholder needs	Main focus on component/subsystem design	Potential synergies have been identified and exploited to a reasonable degree in the system design	Synergies have been identified and exploited in an innovative way to maximize system performance w.r.t stakeholder needs and concerns	☐ ☐ ☐ ☐ ☐ 1 2 3 4 5		
Demonstrate an ability to produce a well thought out system design and well managed interface specs. as critical to successful system integration	System integration is facilitated through: system elements that are clearly identified & specified interfaces are specified and managed in a central place	Integration is performed mainly by "trial and error"	Integration is to a certain extent planned and performed based on a reasonable system design and interface specifications	System integration is driven by well documented system design and interface specifications. Findings during the integration are fed back into the system design.	☐ ☐ ☐ ☐ ☐ 1 2 3 4 5		
Use early modeling and inspection as a means to a well conceived system design	System design trade-offs and sizing are guided by modeling and inspection	Design decisions on elements are based on superficial insights into the impact at the system level	A reasonable set of models and simulations are used to assess key design decisions	A set of models and simulations based on facts and well-founded assumptions are used to guide all critical design decisions.	☐ ☐ ☐ ☐ ☐ 1 2 3 4 5		

INDIVIDUAL ASSESSMENT							
Demonstrate the communication skills to succeed on interdisciplinary teams	Demonstrate effective communication organization, content (accuracy & depth) and verbal interaction (language and tone) that promote the success of an interdisciplinary team in meeting project goals	Passive role taken with little contribution technically or organizationally	Provides competent contributions and is able to interact with team members with different skills/background to the benefit of the team	Demonstrates excellent communication organization, content and varbal interaction in an interdisciplinary team to promote its success	☐ ☐ ☐ ☐ ☐ 1 2 3 4 5		
Demonstrate the communication skills to communicate stakeholder/problem domain and solution domain content	Able to effectively communicate, both orally and in writing, the project scope, design architecture and implementation to technical & non-technical audiences	Communicates information and ideas with limited clarity and does not engender confidence	Communicates information and ideas with reasonable effectiveness	Communicates information and ideas with a high degree of clarity and with confidence	☐ ☐ ☐ ☐ ☐ 1 2 3 4 5		
TOTAL							

Appendix C - Questionnaire for SERC RT-19 Systems Capstone Project

			Score (low:1 to high:5)
To what degree have other majors influenced your design concepts and actions in the project?			☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
More specifically please rate the contribution of each major to your project. Also check against your major	Major	My major	
	ME		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
	Comp E		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
	EE		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
	EM		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
	Civil		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
	PAE		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5

The course/project has provided me with an understanding of the role of systems engineers in the successful design & implementation of large/complex projects. (1: disagree to 5: agree)		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
The course/project has provided me with an understanding of the career opportunities available for systems engineers. (1: disagree to 5: agree)		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
What significance did you attribute to identifying stakeholders and their needs at the start of the project? (1: low to 5:high)		☐ ☐ ☐ ☐ ☐ 1 2 3 4 5
Looking back what would you have done differently, if anything, to organize the CONOPS (Day in the Life) at the start of the project?		
Looking back what would you have done differently, if anything, to organize the project and teams?		
Looking back do you think that having the team leaders meet separately on a regular basis was a positive for the project – comment?		
Are you a team leader?	Yes _______ No_______	

Appendix D

<u>TEAM MEMBER CONTRIBUTION RATING FORM</u>

Use the form below to provide your assessment of the contributions *<u>you and each of your fellow team members</u>* made to your design project. This information may be used by your instructor to make adjustments to individual final course grades. **The information you provide will remain confidential. No individual ratings will be identified or discussed.**

First, write your own name on the top line of the chart below. Then write the names of each of your team members in the spaces below. Next, rate each team member by circling a number corresponding to the following rating scale:

3 = Meets or exceeds expectations: Is fully deserving of the team grade
2 = Marginal: Questionable as to whether performance warrants an equal grade
1 = Below expectations: Should be graded lower than the rest of the team

Team Member	Contribution of Time, Effort, and Technical Expertise			Cooperation w/ Other Team Members (In and Out of Class)			Timely Completion of Individual Assignments			Overall Contribution to the Team		
(Use top line for your name)	1	2	3	1	2	3	1	2	3	1	2	3
	1	2	3	1	2	3	1	2	3	1	2	3
	1	2	3	1	2	3	1	2	3	1	2	3
	1	2	3	1	2	3	1	2	3	1	2	3

PLEASE ANSWER THE FOLLOWING:

- Indicate the **<u>one person</u>** on the team who you think contributed **the most** to the project:
  ____
  And Why? (Include yourself)

- Indicate the **<u>one person</u>** on the team who you think contributed **the least** to the project:
  ____
  And why? (Include yourself)

- Some of **<u>my</u>** key contributions to the project were:

- Overall, I was <u>happy with the composition and performance</u> of my team (Circle One).

1	2	3	4	5
Strongly Disagree		Somewhat Agree		Strongly Agree

- Overall, I was <u>satisfied with the efforts that my team members and I made</u> to collaborate and work together.

1	2	3	4	5

Please include any thoughts you have for making future team projects more successful and rewarding.