AC 2012-3948: A PILOT FOR MULTIDISCIPLINARY CAPSTONE DESIGN INCORPORATING A SYSTEMS ENGINEERING FRAMEWORK

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A Pilot for Multidisciplinary Capstone Design incorporating a Systems Engineering Framework

Synopsis

In this paper we discuss a pilot project to develop an approach to multidisciplinary capstone design that incorporates a systems engineering (SE) framework which can be a model for broad implementation. It is a reflection of the growing demand for engineers educated to recognize the overarching significance of systems engineering approaches for the development of large-scale and complex systems, and to have attained some foundational SE competencies before entering the workforce. The specific project was sponsored by the Department of Defense and 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.

The SE framework provided a series of lectures/workshops through the course of the capstone project to teach SE concepts in what approximates to a just-in-time mode in an interdisciplinary capstone of significant scope, working with external stakeholders and mentors. Assessment was applied locally at the authors' institution and via an external assessor to other institutions engaged in their own pilot versions of incorporating SE into the capstone.

The initial phase of implementation 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 were associated with it being a multi-disciplinary project rather than specifically due to addressing the SE goals. In this regard student focus and assessment had been too discipline-centered in the initial phase and needed transitioning so that the systems project was 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. In a second phase of the project a new project management model was implemented to provide authentic systems level and functional modes. Some experiences and assessments associated with this pilot project are discussed in the paper.

Project Background

Systems engineering as a career has seen a very strong growth which is expected to continue. For example a recent article in Today's Engineer[1] points to a Bureau of Labor Statistics prediction of a 45% growth in systems engineering career opportunities over the next several years at a time when other fields are expected to remain relatively stagnant. As noted in the article, systems engineers do not typically start out in the field, which has a strong interdisciplinary scope. Rather they reach a position where the need to handle complex systems demands a set of competencies that systems engineering can provide. Many choose to specialize as systems engineers and support this with education at the graduate level. However as complexity and the need to function in an interdisciplinary context in the technical world of the engineer grows, there is a need for those entering the engineering profession at the bachelors level to have had exposure to SE concepts and have developed SE competencies even if they will not immediately function as a systems engineer. This recognition of the need for SE at the undergraduate level is also embodied in the National Academy of Engineering (NAE) "Engineer of 2020" vision for engineering graduates[2]. Explicitly the follow-up report from NAE[3] 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."

The capstone/senior design project provides a good vehicle to introduce undergraduate engineering students, with their limited experience, to the principles, practices and benefits of Systems Engineering. It makes what can seem foreign and abstract into a practical way of approaching a design project. The pilot project, described in this paper, is therefore an important opportunity to explore how 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. It should be noted that a valuable contribution in this area was provided by Gershenson under a 2008 NASA-sponsored program directed at capstone course development in areas of NASA interest[4]. His approach embodied some significant system engineering concepts in the design process applied.

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 sponsored, via the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)), 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. Each school chose their project(s) to address one or more focus areas identified by DoD as providing a scope for SE while addressing a need of some value to DoD. Our institution addressed the focus area of "green" expeditionary housing, specifically a forward operating base with low environmental impact. This project also evolved to include a disaster relief aspect, also a focus area of DoD as they are often called upon to be early responders to disasters around the globe.

The main SE learning goals that have been pursued in our project to help develop the SE framework for participating students are described below. These are aligned with the SE Competency Areas of DoD known as SPDRE-SE/PSE[5], 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 first phase of the project was 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 second semester the Product Architecture group dropped to 2 students due to programmatic constraints. Phase II has the same disciplines but with smaller sub teams and no graduate students.

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. The scale at our institution also did not provide the opportunity to have competing teams locally. However, this is considered a valuable motivator and would be considered for a different type of project when the program is institutionalized from the pilot.

Approach

The planned educational elements of the framework were as follows, with the primary delivery vehicle being intensive just-in-time lectures/workshops placed at the key points in the project timeline to be most effective. While a challenge, a common day/time that aligned with the discipline capstone schedules for all sub-teams was established:

- Lectures/workshops 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). These comprised:
    - Objectives, organization and deliverables
    - Introduction to SE: Focus on ConOps, stakeholders and requirements
    - Concept generation and selection: Reiteration of objectives and organization, path to concept selection
    - System Design: identification and role of subsystems, defining and managing interfaces
    - Validation, verification and test planning - guest lecture from senior project manager of BAE Systems Inc.
    - Concept evaluation through prototype testing, modeling and simulation
- Lectures on relevant aspects of project management, teamwork, etc. (guest lecturers from the faculty)
- Specific lectures from external speakers/mentors to bring domain-specific information to the team and stress how systems concepts can benefit the project at hand. In the project several DoD personnel and DoD contractors made presentations on their experience and expertise related to forward operating bases in Iraq & Afganistan during the course of the project.

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 Graduate 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. In Phase II it was agreed that the schedule and all deliverables and grading was ceded to the SE Capstone Pilot faculty.

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 (power, water, waste, shelter) 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 helped with the CONOPS phase of the project, including campus visits to discuss the student team's ideas and also for project reviews.

The design constraints for our 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 developed an integrated solution adaptable to the local requirements and not dependant on skilled labor to assemble. It integrated where possible 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.

Shelter

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. Fig. 1 shows an example of a multi-layer wall system that was designed to be attached to a range of currently deployed DOD tent structures using simple, rugged fastenings. A prototype tent with this system was constructed as part of the demonstrator for the project – it can be seen connected by ducting to the tri-generation cooling unit in Fig. 3 inside the main display tent during the annual Senior Projects Day in April.

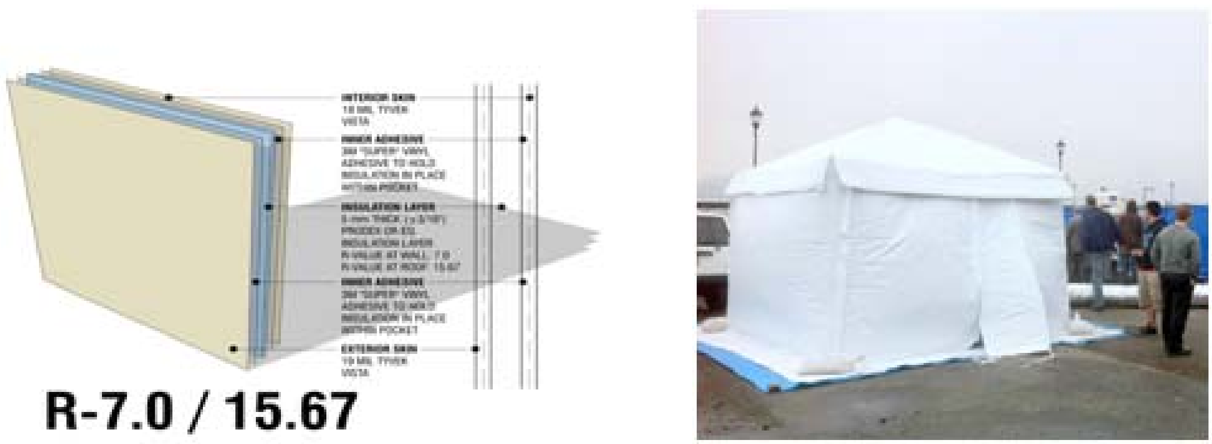


Fig. 1. Example of a Wall System to Provide High R-Value in a Flexible Approach to Tent Structures.

ConOps Document

Three constraints were developed in this document: Stakeholder needs and requirement, overall system concepts and logistical and support aspects. This document served as the basis for all subsequent design work. This was the primary focus of the students for the first two months of the Fall semester and was continuously updated and developed throughout the remainder of the project.

Energy
For the energy supply, adaptability and resiliency were addressed by the ability to interchangeably plug-in multiple, alternate energy sources as appropriate as an integral part of the design approach. A micro grid and generation system were designed to be delivered in modular form in shipping containers. Fig. 2 shows a schematic map of a generic Combat Outpost (COP) with a power micro grid, a thermal grid to supply HVAC to the tents as well as water and waste flows.

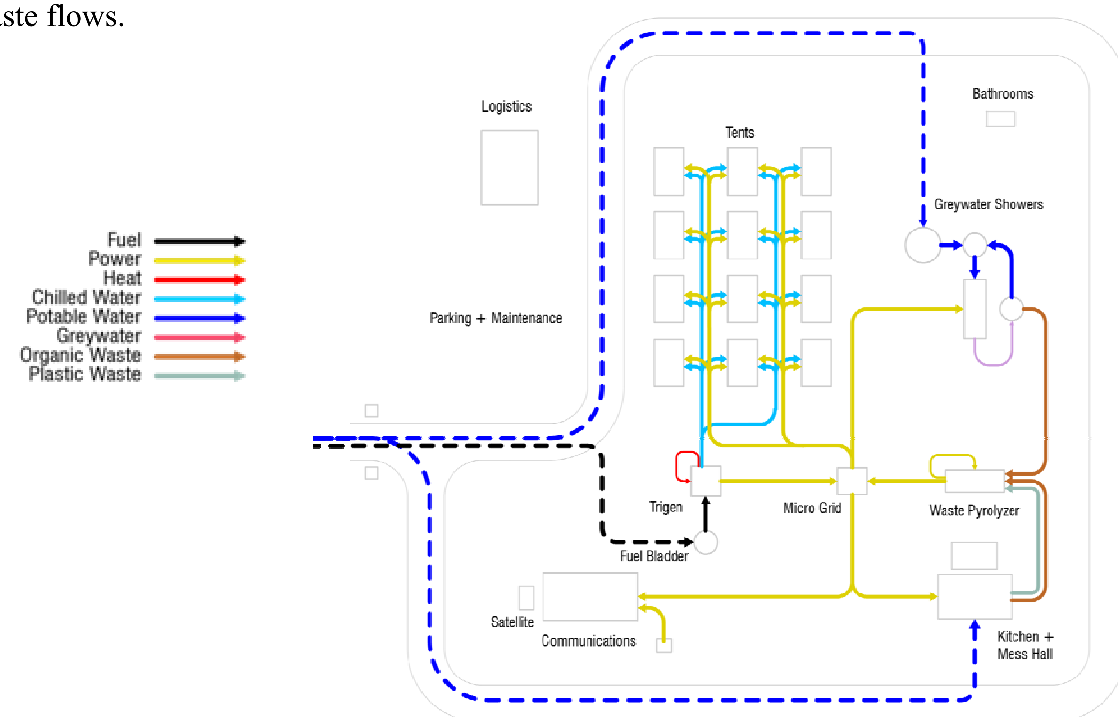


Fig. 2. Camp Schematic Showing the Various Systems for Energy, HVAC, Water and Waste.

The design maximizes energy efficiency while providing power and heating/cooling to the tents through use of tri-generation systems (combined heat, power,cooling), utilizing the waste heat from diesel generators and reducing the demand for fuel. The system is also adaptable to plug-in various alternate energy sources such as solar. Fig 3. shows the prototype mobile tri-generation system feeding the tent prototype on Senior Projects Day.

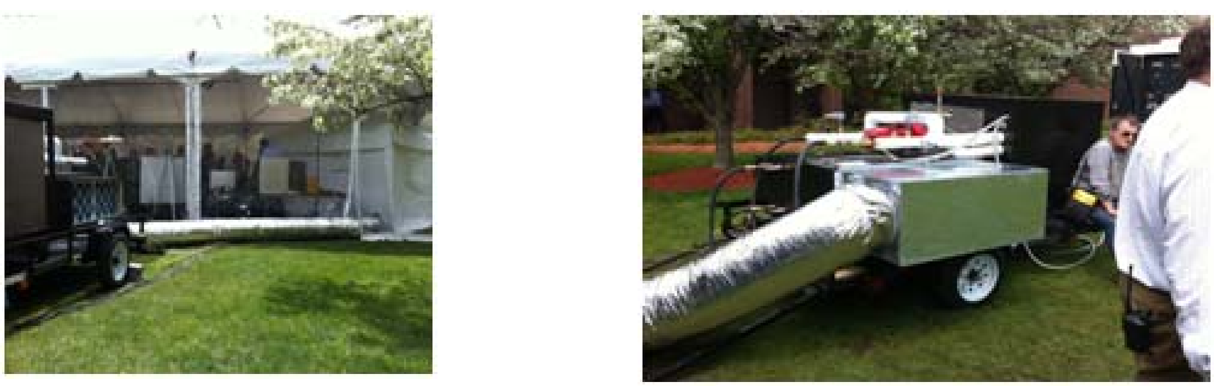


Fig.3. Mobile Tri-Generation System Cooling and Powering an Insulated Tent Prototype
Water & Waste

In addition to shelter and power, the team has looked at water reclamation options and organic and inorganic waste minimization. The primary focus was on minimizing water use for showers. A recycled grey water system was developed using a biofilm/sand filtration approach that can be packaged in shipping containers. The prototype system is seen in Fig. 4.

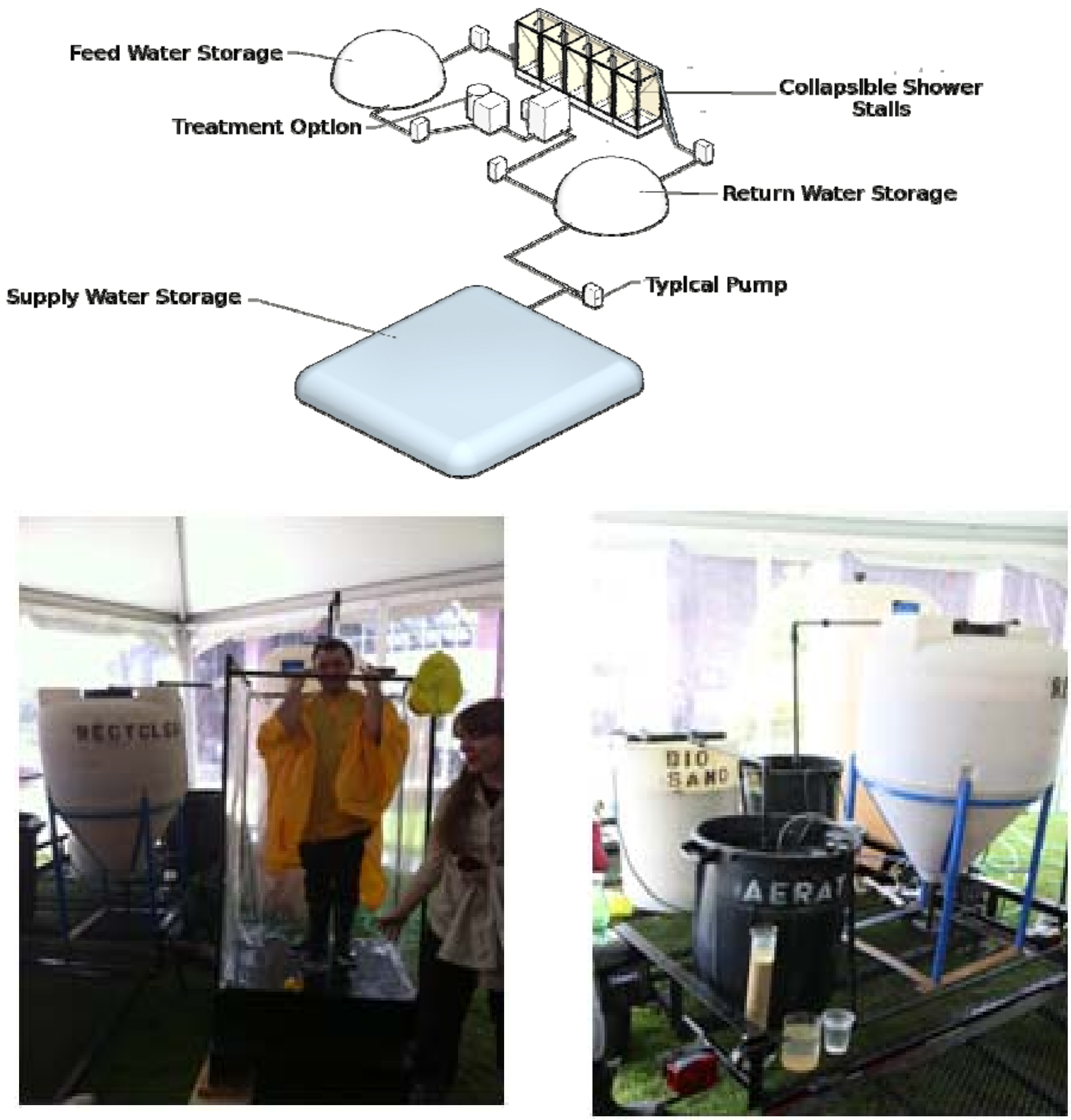


Fig. 4. Grey Water Management for Showers – Design and Prototype for Design Assessment

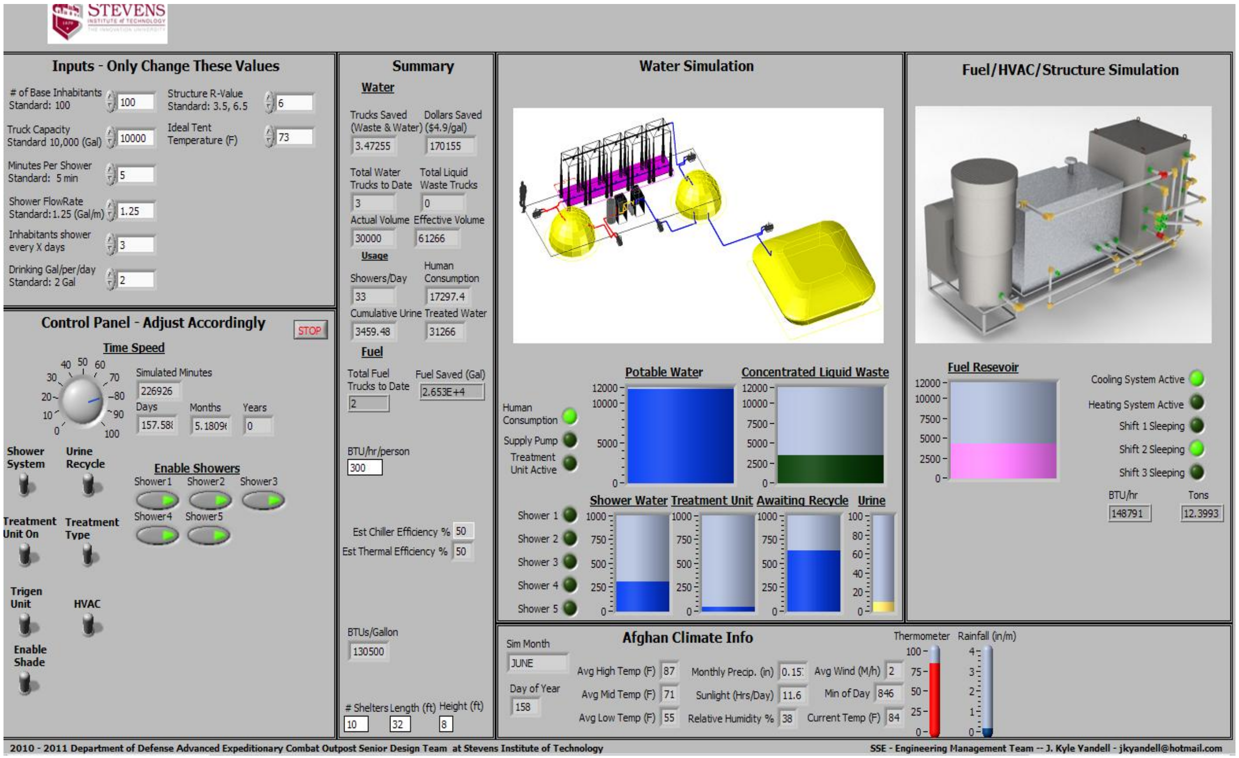


Fig. 5. Performance Simulator

Systems Performance Simulator

One of the sub-teams developed a camp operations performance model through incorporation of data from the prototype systems. The model can be used for design refinement and base planning. The graphical interface is seen in Fig. 5. The simulator allows for camp operations and climate etc. to be input for a given camp configuration and the impact on energy and water use determined. The systems framework for the interdisciplinary capstone has provided a very good vehicle to integrate software and hardware-focused teams. Analysis of the systems approach taken has identified significant potential reductions in both fuel and water dependency, impacting the size and frequency of supply missions.

Phase II

The concept that was developed and demonstrated during Phase I left many opportunities for technical maturation as well as extensions that are the focus for Phase II in the second year of the project:

- An evolved prototype that allows better performance data to be collected for all major subsystems
- Enhanced studies of logistical aspects to assess viability for deployability and operations in the field
- Enhanced modeling and simulation capabilities to support camp configuration and deployment logistics
- Add monitoring capabilities to monitor and forecast camp consumption of critical resources like water and fuel to improve operational logistics

Experience with Implementation of the SE Capstone Pilot Project

Taking an interdisciplinary approach to engineering systems is inherently complex since the behavior of and interaction among system components is not always immediately well defined or understood.

There are two major findings from our experience that stand out with respect to the teaching and assimilation of SE knowledge:

Students can grasp the SE concepts intellectually, but:

1. they have a hard time internalizing and recognizing the value of them without experience from the "trenches".
2. they have a hard time applying that knowledge into practical, interdisciplinary work at the system level.

Based on these findings there are strategies that we will consider for future implementation:

- An initial intensive simulation exercise that exposes the problems of not doing foundational SE work. This exercise could be based on the combat outpost concepts and data previously developed and also give the students a head start in understanding key stakeholder requirements and critical internal interdependencies between subsystems. Defining and characterizing such systems and subsystems and the interactions among them is critical.
- A set of "all-hands" workshops with a mix of lecture followed by practical project related exercises in interdisciplinary teams to give the students a solid start and direction on system level work-products

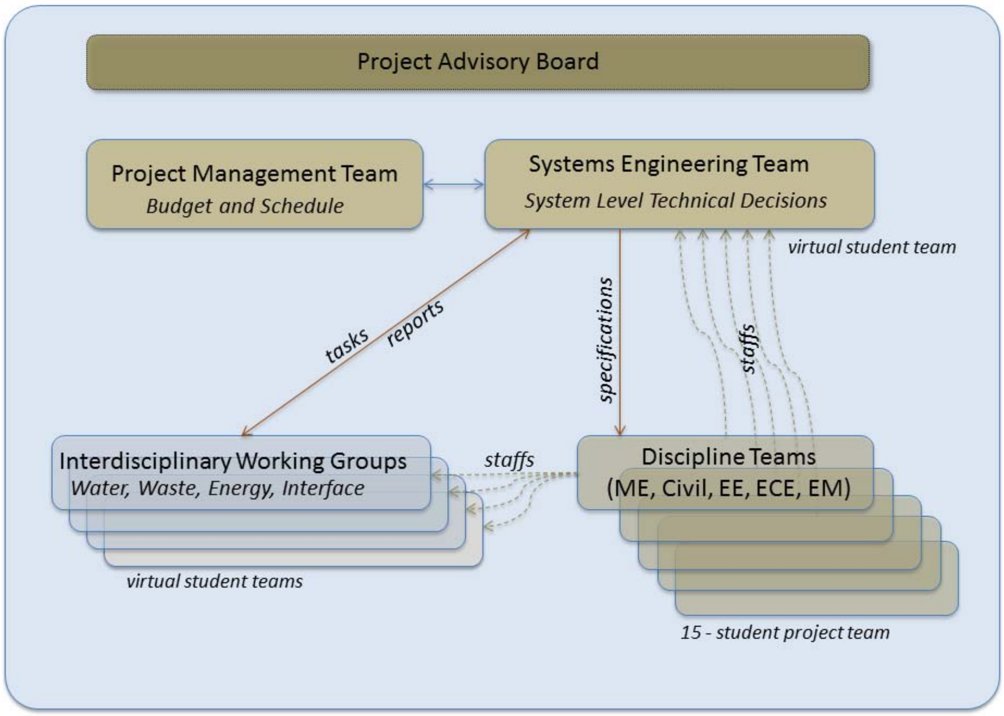
A key pedagogical challenge involved the dissolving of process and cultural departmental boundaries ingrained in both the individual advisers and student groups. It is important to note that ultimately, the individual departments retained grading "supremacy" in Phase I with less than optimal influence from the SE capstone pilot project advisers during the first year of implementation. As a consequence, the grading was largely based on disciplinary/departmental criteria which led to split "loyalty" and motivation for many of the students.

Establishing a seamless and aligned collaborative relationship between departmental advisers and project advisers is key to institutionalization of the SE framework. The development and implementation of a single set of project deliverables, schedules and grading, while seemingly obvious and straightforward, was a primary obstacle but overcoming this will allow for better transparency back through individual departments.

Specific recommendations:

- The creation of an **active interdisciplinary advisory and evaluation board** as the upper most layer of a project organizational chart is an idea that we have been attempting in Phase II of the project. This advisory board interacts directly with the project management team and a virtual systems engineering student team populated with representatives from the discipline teams.
- The school-wide coordination of weekly academic schedules among engineering departments for the capstone will establish and ensure a sufficient allocation of common class time (~3 hours) to satisfy teaching, coordination and administrative needs for cross-departmental endeavors. This initiative is being currently addressed as a precursor to wider adoption of the SE Capstone from the pilot.

- A formal grading policy has to be developed for this type of project that balances the academic requirements at the department level with the contributions to the project and systems level work products while maintaining the overall academic rigor of the senior capstone design course.
- Identify industry mentors to take a domain-specific role in the mentoring of students, i.e. sustainability, tri-generation. The external mentors, subject matter experts and client representatives should be integrated into the overall advisory board.



Assessment

The assessments in the first semester of the project included the normal disciplinary capstone course grading within each contributing engineering program. These for the most part included interim reports and presentations by groups to their disciplinary faculty advisers/panels with a grade set by these for the first semester. It was clear from the initial experience that the center of gravity for grading needed to be with the overall systems capstone rather than at the sub-team assessed within the disciplinary programs. In spite of the initial discussions that had tried to lay the groundwork for the project with the discipline capstone advisers, there was resistance to cede assessment control without an approved and robust process across all engineering programs to do assessment that incorporated the interdisciplinary and systems aspects. An attempt was made, as the project progressed into the second semester, to engage the discipline capstone advisers to work with project leaders to establish a grading approach such that all educational outcomes that the individual disciplinary program capstone courses needed to address were adequately covered and assessed while also meeting the SE competency goals. It proved difficult to make the desired headway at this point and grading remained heavily discipline centered. This is being addressed for future interdisciplinary projects as previously described.

The progress on the project is demonstrated through a physical prototype of a representative sub-set of the overall design. The integration of critical subsystems is showcased at the Senior Projects Expo that takes place at the end of April. The first semester final review is effectively a Preliminary Design Review (PDR), with a Critical Design Review (CDR) coming early in the second semester prior to prototype fabrication. The Final Review is given at the end of the second semester.

A questionnaire was administered approx. one third into the second semester to assess certain aspects of the SE goals. The questionnaire is seen in Appendix C. Results are shown in Fig. 6.

The students generally embraced the value of the contributions from the other disciplines participating in the interdisciplinary projects, although from comments in the survey 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.

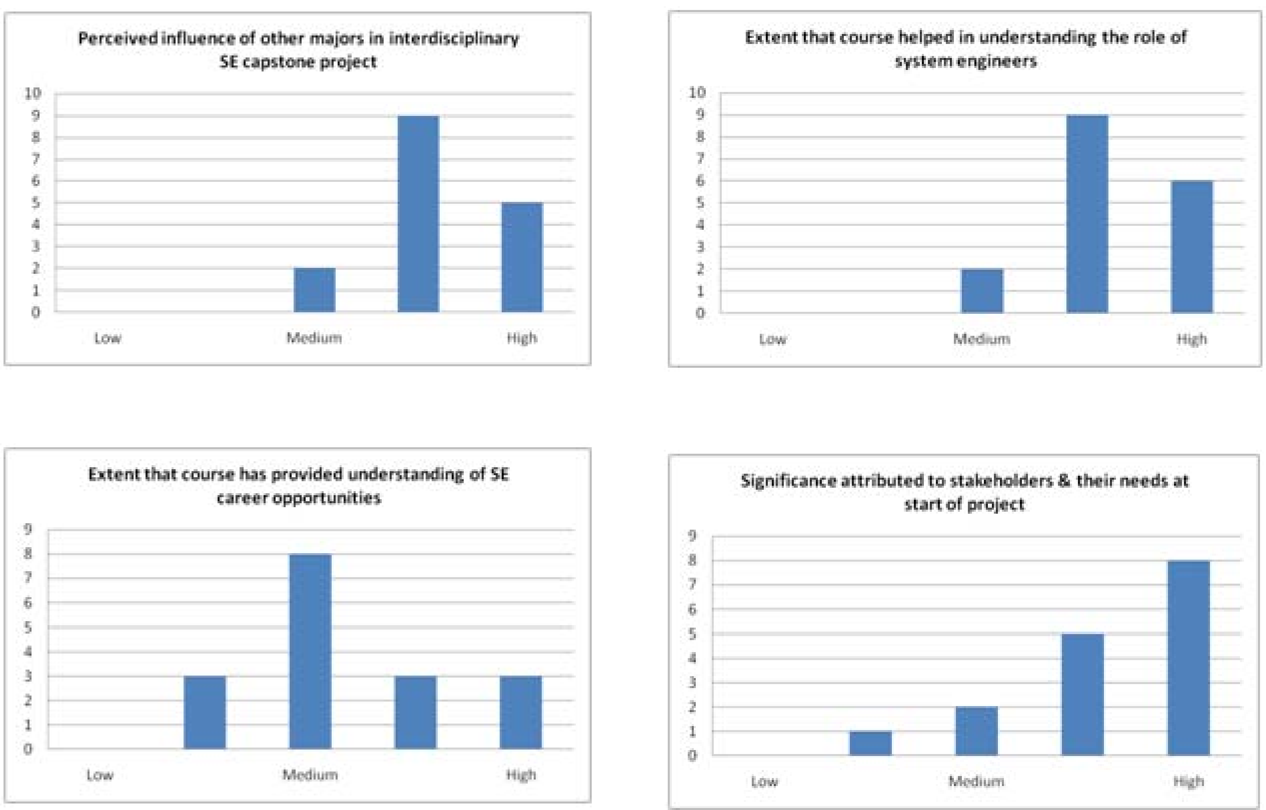


Fig. 6 Results from Survey of Student Perceptions Related to SE Capstone Goals.

A survey (Appendix D) was also administered at the end of Phase I of the project to ascertain

- the students' perceptions on the percentage of the efforts of their disciplinary team and also of their individual efforts in the project that were interdisciplinary versus just involving/applying their discipline
- the extent to which students considered their knowledge of SE, and its value to interdisciplinary projects, had increased by working on the pilot project

The results are seen in Fig. 7. The participation in the survey was not as comprehensive as hoped with only eleven respondents. This can be attributed to the fact that the students were graduating seniors with the associated end of college distractions. The responses were anonymous but students were asked to identify if they had been a team leader of not. This was considered important as in the second semester, as a result of the experiences in the first semester, the team leaders had met separately in addition to meeting with their disciplinary team. The results show that almost all students responded that their team spent at least 50% of effort or more on interdisciplinary work. When individual work was considered the spread was to lower numbers, especially among those who were not team leaders. The latter point likely reflects the fact that the team leaders were the ones most connected to the systems-level issues when they met separately in semester 2, while the other team members primarily focused on the disciplinary work. In addition to the data, comments were collected to gauge how the students thought the project might have been organized to enhance the systems-level outcomes. Team leaders generally liked the fact that they had met separately from this perspective and recommended this strategy. So we are presented a challenge to both manage the larger project where having a systems team of sub-team leaders appears effective, while also keeping the non-leaders connected to the systems issues and application of SE knowledge.

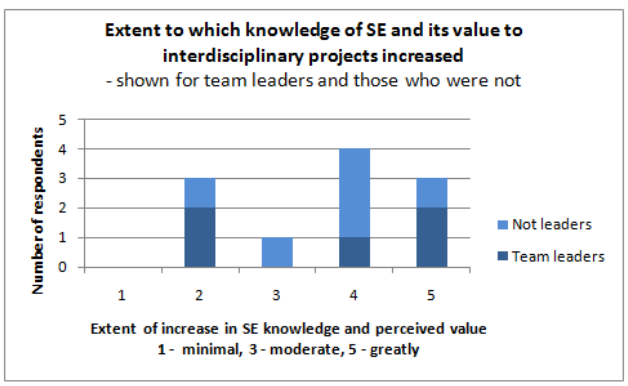
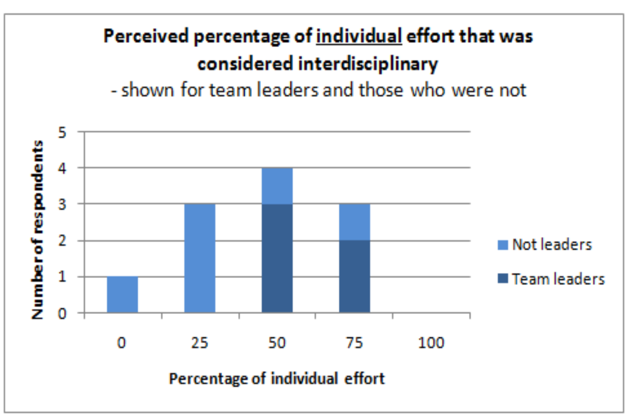
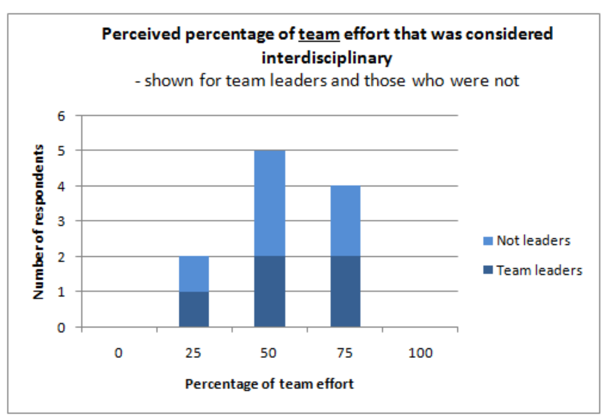


Fig. 7 Survey of student perceptions of the level of interdisciplinary engagement and their increased knowledge and value of SE from SE Capstone pilot project participation





Rubric Development

The SE concepts and SPRDE-SE/PE competencies addressed in the project for the most part do not lend themselves to simple quantitative assessment measures. 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 one of the goals of the project was development of a rubric to assess SE competencies. The rubric was developed with input from the project faculty and an assessment expert with experience in rubric development. It was also reviewed by one of the DOD mentors.

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[6] 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 and presentations are the primary source for evaluation. In addition the teamwork and communication aspects are assessed through existing assessments[7].

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[8], 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. The rubric was used for guidance by the faculty in the final presentation in helping guide them with grading of the project but it did not prove possible to apply the rubric in the manner for which it was intended, to provide assessment of the achievement of the individual SE competencies. The result was that a common assessment protocol could not be achieved and connected to student grading which in the end is the key. This is being addressed in the Phase II 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 the multi-institutional program leadership sponsored by DoD directly. 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. Surveys are also included of the faculty involved and the mentors supporting the projects at the various institutions. The external assessment also analyzed artifacts developed by the program participants as part of overall evaluation. These elements have been described along with the overall multi-institution program[9].

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[4] (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 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 - End of project survey of student perceptions

DOD Advanced Expeditionary Housing Project
End of project survey

You have been a participant in an interdisciplinary project that had as one of its goals to apply systems engineering concepts' in senior design.

The following questions are intended to help us evaluate the project, from the perspectives of the individuals involved, in terms of both the disciplinary and systems level aspects.

Please answer all the following:

1. What percentage of your **team's** work over the two semesters would you describe as interdisciplinary as opposed to just involving/applying your discipline?
   0% 25% 50% 75% 100%

2. What percentage of your **individual** work over the two semesters would you describe as interdisciplinary as opposed to just involving/applying your discipline?
   0% 25% 50% 75% 100%

3. Were you a team leader? __________

4. Rate the extent to which your knowledge of systems engineering and its value to interdisciplinary projects has increased by working on this project?
   1 (minimal) 2 3 4 5 (greatly)

5. If you had to do this type of an interdisciplinary senior design project again, how would you organize the students from the participating disciplines and the conduct of the project itself to most effectively achieve a successful system-level outcome to meet stakeholder needs?