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Eugene Lesinski
United States Military Academy

Vikram Mittal
United States Military Academy, vikram.mittal@westpoint.edu

Alex MacCalman
United States Special Operations Command

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Bridging Systems Engineering Theory and Application in Undergraduate Curricula

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Mr. Gene Lesinski and Dr. Vikram Mittal
United States Military Academy
West Point, NY 10986

COL Alexander MacCalman
United States Special Operations Command
Tampa, FL 33621

Abstract

Systems engineering undergraduate curricula are typically divided into foundational, methodology, and application courses. The United States Military Academy, Systems Engineering program primary application course, often referred to as a Capstone project, involves teams of students performing client-based work to solve complex real-world problems. Existing foundational and methodology courses tend to emphasize engineering management processes and operations research techniques at the expense of systems engineering technical processes. As such, students often do not have the requisite knowledge base necessary for their Capstone, reducing their self-efficiency, decision-making, overall project interest, and quality of technical artifacts. In an attempt to bridge this gap, the United States Military Academy, Systems Engineering program introduced a cornerstone course to teach system engineering design and system engineering technical processes as practiced in industry and documented in the INCOSE handbook. The course structure follows the system engineering V methodology and uses a realistic, but constrained, design project to teach and apply systems engineering skills. The introduction of this new course was found to increase the overall knowledge-base of the students entering their Capstone project, allowing them to be more self-efficient and capable of making informed engineering design decisions.

Keywords
Academia, industry practices, undergraduate curricula, INCOSE, cornerstone course

1. Introduction

To address the increasing demand for systems engineering (SE) knowledge and skills in industry, universities are adding undergraduate SE programs, though these programs have traditionally been kept at a graduate level. While the graduate programs are fairly application based, the undergraduate programs focus on engineering design principles and management processes, with an emphasis on systems thinking, complex problem solving, and operations research techniques. Similar to other undergraduate engineering disciplines, SE curricula can be divided into foundational, methods, or application courses. The United States Military Academy (USMA), Systems Engineering program primary application course, referred to as the Capstone project, involves teams of students solving complex real-world problems.

An assessment of the ABET-accredited SE program at USMA found that students were not adequately prepared for their Capstone projects. A root cause analysis determined that this issue was caused by the foundational and methodology courses leaving out critical industry practices. In particular, SE industry practices are moving at the "state of technology;" academic programs must adapt to keep pace [1].

This gap in knowledge caused students to not have the necessary knowledge required for their Capstone. This lack of knowledge was found to reduce the students' self-efficiency, decision-making, and overall project interest. As such, a new cornerstone course was introduced into the SE curricula to teach system engineering design and technical processes as practiced in industry and documented in the International Counsel of Systems Engineering (INCOSE) handbook. The objective of the new course is to improve student preparation for their Capstone, increase overall project interest, and improve quality of Capstone technical artifacts.

2. Current Issues

2.1 Current Structure of SE Curricula

Currently many undergraduate SE programs divide their course structure into foundational, methodology, and application courses. Figure 1 shows a summary of these three tiers of courses.

The foundational courses typically focus on critical thinking skills, looking at SE techniques to solve complex problems. An overview of different foundational classes found that these courses tend to teach the following material: critical thinking techniques, problem definition, functional analysis, system decision making, and life-cycle costing [2]. The critical thinking techniques involve a wide variety of different theories. These critical thinking techniques are then used to teach students how to both scope and solve a complex problem. Most foundational classes then lead students through course projects and assignments where they can apply these concepts. Typically, the homework, class examples, and course projects involve solving constrained, pre-solved problems with known solutions, such that the students focus on the process rather than the solution.

Once students learn the processes for complex problem solving, they can learn the analysis tools necessary to design and evaluate solutions. These tools can range from statistics, design of experiments, decision-analysis, linear-modeling, deterministic modeling, probabilistic modeling, and simulation design. These courses are typically designed to build on the foundational classes; however, they are typically taught independent of each other, allowing student to pick which methodologies they wish to learn. Additionally, the methodologies courses, similar to the foundational courses, use constrained problem sets with known solutions, ensuring that the students focus on the analysis processes rather than an engineered solution.

A student's experience in an undergraduate SE curriculum typically culminates in an application-based course, referred to as a Capstone project [3, 4, 5]. It is widely established that these research products are a critical step in providing real-world knowledge to students. These projects involve teams of students solving a complex real-world problem in support of a client. Though these projects have a faculty advisor, the projects are expected to be student-run. The client is typically an industry or government partner that provides a relevant project and appropriate guidance. These projects can vary substantially in domain and technical depth. However, they are typically in-line with what systems engineers are expected to be able to do in industry. Example projects include:

- Developing a component, subsystem, or system test plan for a product under development
- Design a system architecture for future capability needs
- Analyze a capability gap to find novel solutions
- Managing requirements of components, subsystems, or a system

The capstone project concludes with a conference with an associated technical paper. The conference gives the students the opportunity for technical writing and presentations in a professional, yet controlled, environment.

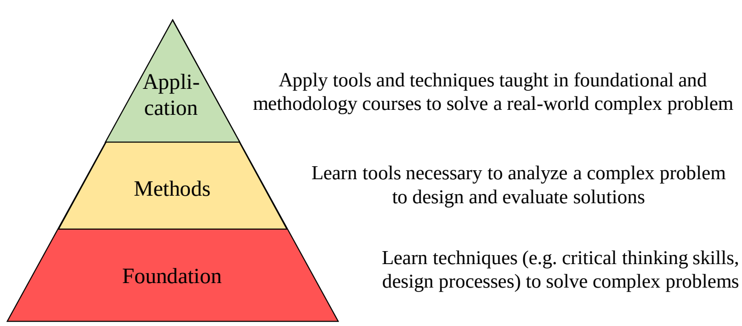

Figure 1: Typical structure for undergraduate system engineering curricula

2.2 Issues with Current Structure

Following a review of the SE program at USMA, it was determined that though the program has "roots in traditional Operations Research and Industrial Engineering" [6], the SE field has significantly matured. As such, the academic program needed to "incorporate changes that better align with the accepted Systems Engineering Body of Knowledge and benchmarked programs with a higher emphasis on interdisciplinary engineering and the integration of hardware, software, and human components" [6].

The 2015 INCOSE handbook lists fourteen fundamental SE technical processes that "…enable systems engineers to coordinate the interactions between engineering specialists, other engineering disciplines, system stakeholders and operators, and manufacturing…These processes lead to the creation of a sufficient set of requirements and resulting system solutions that address the desired capabilities within the bounds of performance, environment, external interfaces, and design constraints" [7]. Close examination of the USMA SE program exposed that several SE technical processes are not adequately addressed in established SE courses or the Capstone project. A mapping of SE design and technical processes against existing SE courses revealed that these critical SE design knowledge and skills were not addressed in any courses within the SE curriculum. The frequency of use of SE technical processes across the portfolio of 35 USMA SE Capstone projects is highlighted in Figure 2. These results highlight gaps in Capstone application of several important SE technical processes including: system requirements definition, sub-system and component specification, architecture definition, detailed design definition with incorporation of 'ilities', testing, integration, verification, and validation.

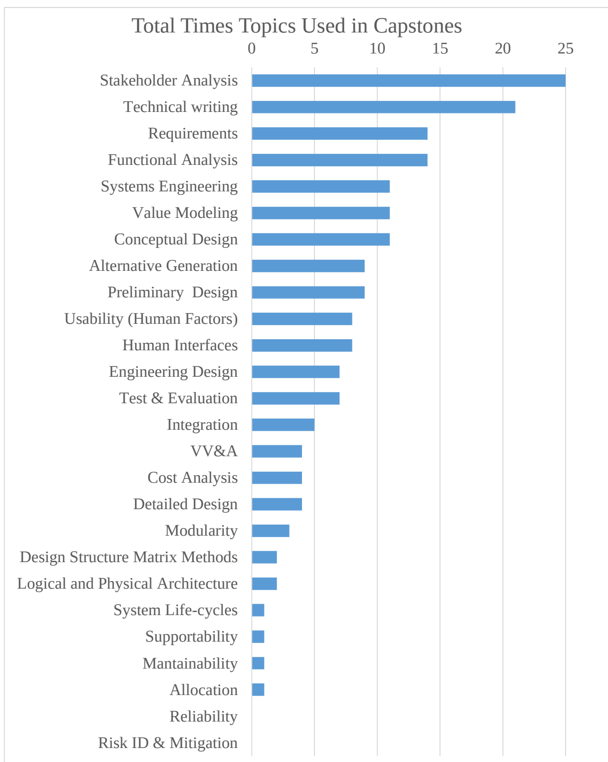

Figure 2: The frequency of different SE topics covered during Capstone course

ABET, the engineering accreditation body, utilizes eleven criteria to assess the effectiveness of engineering programs. One of these criteria (ABET Criterion c) states that students should be able to…."Design a system or process in order to develop innovative alternatives that meet the needs of the client within realistic environmental constraints" [2]. Within the SE program, this criteria has historically been assessed among the lowest by Capstone faculty mentors and Capstone Conference external judges [8].

An initial attempt was made to address this identified program shortcoming by inserting these missing topics into the sole existing foundational course: SE301 – Fundamentals of System Design and Management. SE301 is a required course for all three majors offered within the Department: Systems Engineering, Engineering Management, and System Decision Science. The addition of these SE specific technical topics appeared disjointed and diluted the previously existing content of the course. However, as more information was added to the foundational courses, the depth of the course material decreased to the point that students were only familiarized with the course objectives. As such, students ended up less able to handle a Capstone project [8].

2.3 Impact on Capstone Experience

These gaps and shortcomings manifest themselves within the Capstone program. Since Capstone projects are client-based efforts with industry and Department of Defense (DoD) customers, for a student to realize the full benefits of the Capstone course, they should have a knowledge base that is in-line with current industry and government practices. Since current foundational and methods courses do not appropriately align (as described by INCOSE) with current industry practices, students are not adequately prepared for their Capstone projects, creating a number of issues [10, 11].

First, the purpose of a Capstone class is for students to apply the knowledge gained in their foundational and methodology classes. Though the foundational courses exposed students to the topics relevant to their Capstone, much of the knowledge was superficial or tangential from the material that was actually required. As a consequence, many Capstone advisors reported that students spent the first 30 to 50 percent of the course learning the underlying processes and material necessary for their research. To gain the requisite knowledge, the students could either attempt to learn the material on their own, learn from their Capstone advisor, or learn from their industry partners. Scheduling time with the industry partners is typically difficult, and often they are not trained or equipped to teach. Similarly, the Capstone advisors only have limited time and do not necessarily have the ability to prepare a full course to re-teach the necessary material to their team. In some situations, the Capstone advisor did not have the technical depth and expertise necessary to instruct their Capstone team. As a consequence, students would struggle with learning the material through books and online resources. Not only was this learning process not efficient, but it also led to students being frustrated and disillusioned.

Second, a critical component of the Capstone is that the students must own the research process, while advisors serve to simply advise, not lead. However, when students did not have the requisite industry-based knowledge, they lacked confidence in their ability to understand and solve the problem, even after devoting significant time to learning the processes. Their lack of confidence manifested in not taking ownership of their project and forcing the faculty advisor to play the role of a leader. The reduced ownership can in turn reduce the student's motivation to learn the requisite knowledge, creating a reinforcing causal loop.

3. Introduction of New Foundational or Cornerstone Course

After the ineffective attempt in adapting SE301, a new cornerstone course, Systems Engineering 302: Fundamentals of Systems Engineering, was introduced to the USMA curriculum in September 2015. A cornerstone course builds on the foundational courses and supports the methodology and application courses. The goal of the course was to address the gaps in SE design and SE technical processes mentioned in the previous section with an expectation of better prepared Capstone students and higher quality design artifacts. The course employs a project-based learning pedagogical approach, aligned with the system engineering V methodology, with primary content drawn from Blanchard and Fabrycky's *Systems Engineering and Analysis* [9]. Course graded events are divided into individual and group events all focused on an assigned group-specific effective need. The course is organized into three major segments: conceptual design, preliminary design, and detailed design.

The conceptual design block is focused on stakeholder analysis, identification of effective need, requirements and functional analysis, concept generation, concept feasibility analysis, concept selection, and preliminary cost and risk analysis. The block includes one individual homework and a Conceptual Design briefing for the group project. The preliminary design block is focused on incorporation of "ilities" (reliability, usability, maintainability, supportability) to improve system design, basic architecture of a system, preliminary design synthesis and analysis, and refined cost and risk analysis. The block includes two individual homework assignments and a Preliminary Design Report for the group project. The final block, detailed design, focuses on a finalized architecture, component specification, detailed risk and cost analysis, testing, integration, and validation of a system design. The detailed design block includes one individual homework, a Detailed Design briefing and final report for the group project.

Concurrent to the classroom lectures, students work in project groups on a group-specific course project. The course project is focused on solving a constrained Department of Defense problem progressing from customer need to system design and validation. For example, one iteration of the course required students to design unmanned aerial vehicle variants that addressed capability gaps specific to different branches of the Army. In another iteration, students designed soldier biomedical monitoring systems. Students are provided an opportunity to elicit stakeholder needs and operational requirements from the instructors and subject matter experts. Each group must design a system concept, a preliminary design, and a detailed design. Multiple design reviews are conducted, and the students are required to either give a presentation or write a technical report for each milestone.

4. Results

4.1 Assessment Technique

The course was first offered in Academic Year 2016. At the end of Academic Year 2017, Capstone students were given surveys to complete, focusing on their capacity for "lifelong learning." Although the goal of these surveys were to determine how well the course encourages students to take initiative and learn new material on their own, these surveys offered insight into the effectiveness of SE302. The survey had students rate their capstone experience in regards to the following 6 dimensions, assigning each one a value between one and four, with four being the maximum:

- Level of independent learning: 4 = I learned a great deal on my own. 1 = faculty taught me what I needed.
- Love of project: 4 = I loved this project. 1 = I disliked working on this.
- Self-efficacy: 4 = I could handle major tasks on my own. 1 = I needed substantial help to complete any task
- Decision making opportunities: 4 = we had complete control on the project. 1 = we had no control on the project.
- Individual responsibility: 4 = we really owned this project. 1 = this was just another requirement.
- Collaboration: 4 = everyone contributed to my learning. 1 = project was collection of individual projects.

4.2 Analysis of Results

The survey was completed by 72 students, of whom 31 had taken SE302. The average and standard deviation of the responses are shown in Figure 3. The surveys found that students that had taken SE302 were significantly more likely to enjoy the project, take control of their project, make their own decisions, and accept responsibility for their project success. To a lesser degree, the students that took SE302 were also more likely to take the initiative to learn the requisite material on their own and form cohesive teams.

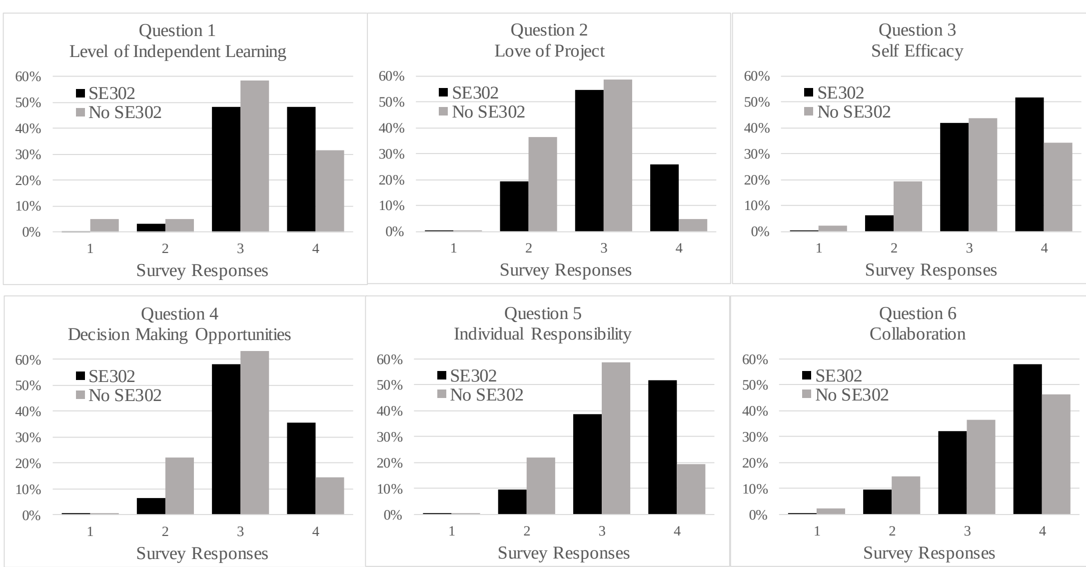

Figure 3: Responses from students to surveys given to gauge their lifelong learning abilities based on their Capstone

Anecdotally, many students that did not take SE302 complained that they did not have the requisite SE technical skills, forcing them to spend a large portion of their capstone time trying to learn that material. In turn, the students got disengaged from the project, reducing the quality of their learning experience. Several capstone advisors also found that the students without an appropriate SE technical skills were less likely to make a meaningful contribution for the project. Group dynamics would typically require the students that had completed SE302 to take a larger role, "sidelining" the students that had not, reducing their role through the project duration. These anecdotes are consistent with the survey results.

At a higher level, since the course is application-based, the course objectives are tied to students applying their knowledge, skills, and abilities to a real-world project. If students do not have the requisite knowledge to apply to the project, they will likely struggle to meet the course objectives.

5. Conclusions

A new cornerstone class was introduced into the systems engineering undergraduate curriculum at the United States Military Academy. This course attempted to fill a gap between academic theory and industry practices, with the intent of helping students be better prepared for their Capstone projects. The course followed the system engineering V methodology and uses a realistic, but constrained, design project to teach and apply systems engineering skills. The course included topics such as engineering design phases, requirements management, 'ilities analysis (reliability, usability, maintainability, supportability), testing, and integration. The introduction of this new course was found to increase the overall knowledge-base of the students entering their Capstone project. Surveys found that that students that had taken this course were significantly more likely to enjoy the project, take control of their project, make their own decisions, and accept responsibility for their project success. Future work would quantify the effectiveness of the course as it translates to design detail and quality.

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