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The Use of Systems Engineering Principles to Improve Learning Outcomes in a Multidisciplinary Course

Dr. Zachary David Asher, Colorado State University

Zachary D. Asher graduated with a Bachelor of Science degree in Mechanical Engineering from Colorado State University in 2009, a Master of Science degree in Mechanical and Aerospace Engineering from the University of Colorado at Colorado Springs in 2012, and worked full time in engineering industry from 2009 to 2015. He just completed a Doctorate of Philosophy degree in Mechanical Engineering at Colorado State University and is starting a tenure-track faculty position at Western Michigan University in August. His research interests include mathematical modeling for control and optimization of mechanical systems.

Nicole L Ramo, Colorado State University

Nicole Ramo earned a B.Sc. degree in mechanical engineering with a concentration in bioengineering from Kettering University (Flint, MI, USA) in December of 2012. The experiential learning program at Kettering allowed Nicole to work as a research assistant at Henry Ford Hospital's Bone and Joint Center (Detroit, MI, USA), where she developed a love of research. Nicole is currently a doctoral candidate in The School of Biomedical Engineering of Colorado State University (Fort Collins, CO, USA). She has experience working as a graduate teaching assistant for computer aided engineering, biomedical engineering capstone design, and biomedical engineering introductory classes. Nicole's engineering education interests include problem based learning, retention efforts, and incorporation of current research into teaching. Her doctoral research is focused on the material properties of spinal cord tissues to contribute to the understanding and treatment of spinal cord injuries.

Dr. Thomas H. Bradley, Colorado State University

Thomas H. Bradley is an Associate Professor of Mechanical Engineering and Systems Engineering in the College of Engineering at Colorado State University, where he conducts research and teaches a variety of courses in analysis, design and policy for sustainable energy systems.

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Abstract

As individual engineering disciplines and applications mature, there is an increased need for multidisciplinary education and application competencies. As an example, a course on modern automotive vehicles must now incorporate electrical propulsion in addition to mechanical propulsion to reflect the current state of the art. Systems engineering provides a framework for teaching a multidisciplinary approach in the design and analysis of these complex systems. In this study, the hypothesis that exposure to, and retention of, systems engineering principles improves learning outcomes in an multidisciplinary graduate level course is assessed. Students enrolled in a hybrid electric vehicle powertrains course were exposed to systems engineering principles through a dedicated lecture focused on team coordination and management of complex engineering systems in the context of the team-based course capstone project. Students were encouraged to employ systems engineering principles across all aspects of the course (e.g. homework completion and exam preparation) with student collaboration a requirement for the project. Student surveys were completed immediately following the introductory lecture, which quantify students' self-assessed increase in system engineering knowledge and perceived value of system engineering concepts/principles. A follow up survey given at the completion of the course then asked students to re-assess their responses to the initial survey and to report if they implemented systems engineering concepts/principles during work on the capstone project, labs, homeworks, and/or exam preparation for the course. An evaluation of applied systems engineering was conducted by comparing the capstone project scope from the course that included a systems engineering lecture and from the previous time the course was taught that did not include a systems engineering lecture. Results show an increase in students' self-assessed system engineering knowledge and perceived value of system engineering concepts/principles after the introductory lecture and at the end of the course, as well as an increase in applied systems engineering in the capstone projects. The conclusion is that systems engineering principles such as requirements development, applying the V-model, and configuration management may be a key component for multidisciplinary courses to improve learning outcomes. Future work will focus on systems engineering implementation in other multidisciplinary courses as well as improved means of exposing and encouraging students to use systems engineering.

Introduction

Engineered systems are becoming more critical to a broader set of the public who demands an individualized, efficient, and engineered environment in all aspects of life. The modern challenges to engineering include scale, multidisciplinary aspects, hierarchy, and complexity[1]. As the prevalence and relevance of these problems increase, engineering education must be responsive[2,3,4] and many universities are including a special focus of multidisciplinary engineering in basic courses[5], capstone courses[6,7], laboratories[8], clinics[9], and programs[10,11,12]. Overall, as course content is adjusted to the state-of-the-art, there may be a natural shift to multidisciplinary engineering.

One example of this shift is an automotive vehicle design course at our university titled "Hybrid Electric Vehicle Powertrains". This course employs mechanical engineering and electrical engineering skills equally to successfully design and simulate the current automotive state-of-the-art, the hybrid electric vehicle, thus being responsive to industry needs[13]. This type of course is not unique to our university, as many other universities are developing similar hybrid electric vehicle focused labs[14], project focused courses[15,16], and general education[17,18,19,20].

Systems engineering (SE) is an effective tool to address multidisciplinary engineering problems. It was first developed in the 1930s and allows for successful design and implementation of machines that would otherwise be too broad, too risky, and too complicated[21,22]. Additionally, SE has also been identified as a key component of sustaining U.S. competitiveness in the sectors of manufacturing, technology, services, and government[23]. Due to the industry needs of SE education, many universities are developing and expanding SE courses and departments[24,25].

This research investigates the potential of an introduction to SE principles to improve learning outcomes for a multidisciplinary, Hybrid Electric Vehicle Powertrains class taught at our university. The class typically consists of two 50 minute lectures and one 50 minute laboratory per week, where students focus on development and applications in the Matlab and Simulink modeling software. There are 12 total laboratories, 2 exams, and 1 capstone project. In the semester for which the survey was administered, there were 18 students enrolled and the previous time the course was taught there were 20 students. Every student enrolled in the class in the two instances it has been offered are graduate level mechanical engineering majors. It is hypothesized that exposure to, and retention of, SE principles improves learning outcomes in this multidisciplinary graduate level course.

Methods

A major component of the Hybrid Electric Vehicle Powertrains class is the capstone project. It is anticipated that the capstone project is also the most beneficial course component to apply SE. Students are encouraged to begin work on the capstone project approximately half way through the semester, when the project requirements are distributed. This timeframe was selected to administer the SE lecture.

Before the SE lecture, a five question survey was distributed that addresses SE knowledge before and after the lecture. All students enrolled in the class are in the Department of Mechanical Engineering and the mechanical engineering curriculum at our university does not include emphasis on SE. Therefore it is anticipated that students will have limited knowledge of SE principles and may not perceive SE to be useful before the lecture. The survey was not for a grade and was voluntary.

The SE lecture administered was a 40-minute lecture covering basic course-relevant SE concepts as well as course-relevant SE applications. Course-relevant SE concepts include:

- Defining the system boundary
- Requirements development
- Concurrent development
- Applying the V-model
- Resource management
- Configuration management
- Risk management
- Tailoring the amount of applied SE

Examples from the lecture of some of these concepts are shown in Figure 1. Each of these concepts was explained from the perspective of completing the capstone project and examples were used to explain how these concepts can be applied to the capstone project.

Also included in the lecture were potential systems-level project scopes that are beyond typical hybrid electric vehicle powertrain design. These project scopes include:

- Well-to-wheel analysis [28]
- Electrical grid power source considerations [29]
- Ride-sharing or non-vehicle ownership scenarios [30]
- Powertrain control optimization [31]

These project scope examples are meant to encourage students to expand their project to a level in which SE concepts will be most useful.

Note that inclusion of 8 major SE concepts and 4 potential systems-level project scopes is a large amount of content to present to students. It is possible that a more in-depth discussion of fewer topics may be more effective but this analysis is out of the scope of the current research.

Post-lecture survey questions are intended to investigate the level of improved SE knowledge and to assess whether students believe that SE can aid their learning. It is anticipated that student's level of SE knowledge will have increased and that students understand how SE can assist them in learning and successful project completion. No other SE lectures or assessments

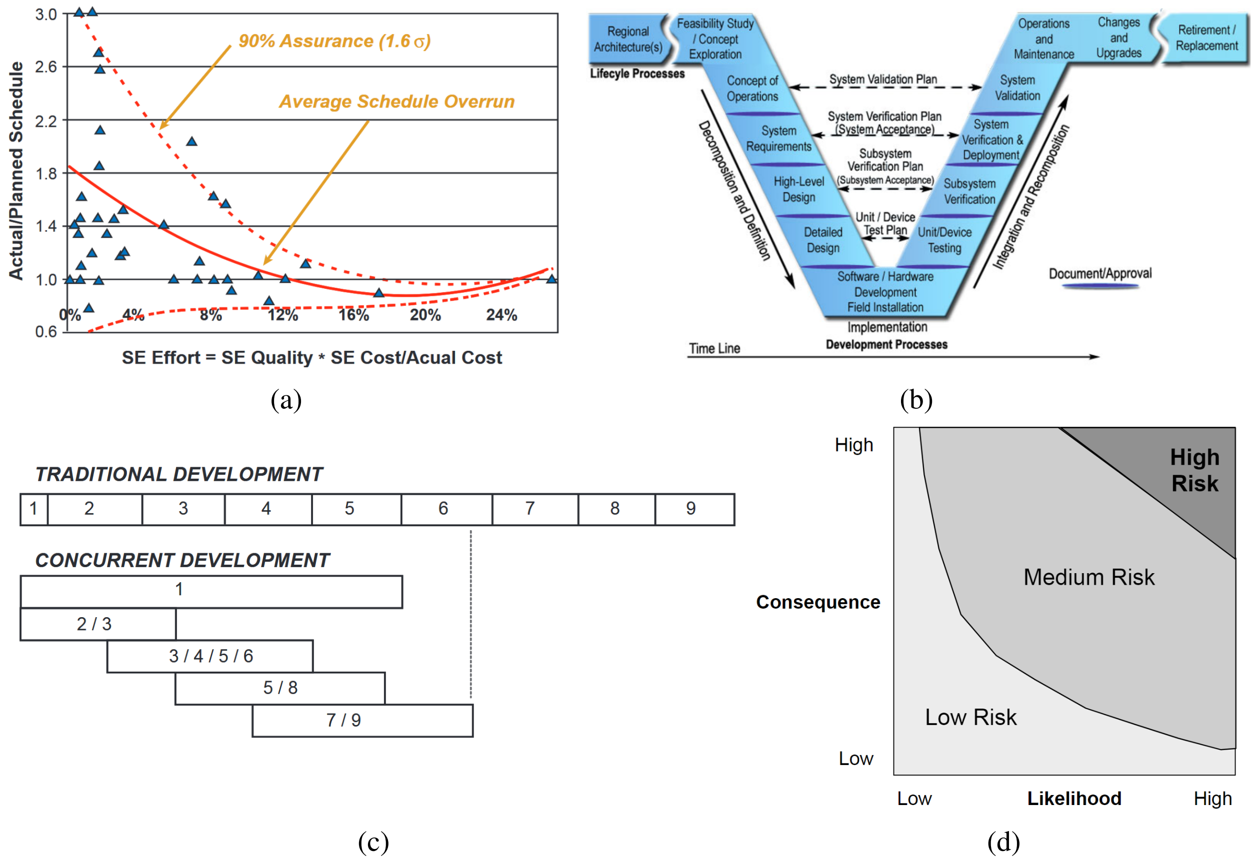

Figure 1: Examples of the SE princples content covered in the SE lecture: SE reduces project cost and time[26] (a), project execution V-model[27] (b), resourse management[21] (c), and risk management[21] (d).

were included in the course. 16 of the 18 students enrolled in the class were present and elected to take this first survey.

At the end of the course, the capstone projects were evaluated to assess the level of SE application. The scope of the projects were objectively determined by the authors to decide if SE principles taught in the lecture were applied to the project. Course projects from the previous time the course was taught, where no SE concepts were presented, were also evaluated.

Lastly, a final survey was given at the end of the course to evaluate SE retention and perceived usefulness at course completion. It is anticipated that student retention will be slightly less than immediately after the SE lecture, and that students will recognize that they have applied SE concepts. Student thoughts and opinions were also requested on the survey to gain insight into their experiences applying SE to this multidisciplinary course. All 18 of the students enrolled in the course were present and elected to take this second survey.

To objectively analyze the survey data, two statistical analysis techniques were used: (1) an independent group t-test to determine if the comparable survey results are independent, and (2) a bootstrapping technique of measuring differences in group means with some confidence interval information. The results for the independent group t-test can be generated using the built-in functions in the Matlab software package or in a statistical software package such as R. One of the comparable survey results are input as one vector and the other comparable survey result is input as another vector. The built-in t-test function can then output whether or not the two vectors represent independent data or, in other words, whether or not there is a change in the answer for comparable questions in the survey. The results comparing group means and confidence interval information are presented as box-and-whisker plots so that inferences can be made directly.

Survey Results and Discussion

Figure 2 shows the survey results of student reported level of SE knowledge using response frequency and horizontal box-and-whisker plots. The independent group t-test results in a confirmation of an independent response from “before the lecture” to “after the lecture”, but does not result in a confirmation of an independent response from “after the lecture” to “end of the course”. The group mean difference information shown in Figure 2b provides strong evidence of an increase in reported knowledge of SE immediately after the lecture, since the mean score increased from 3 to 6.5. This group mean difference information also provides some evidence that students were able to gain additional SE experience after applying SE principles in the course since the mean score increased from 6.5 to 7.

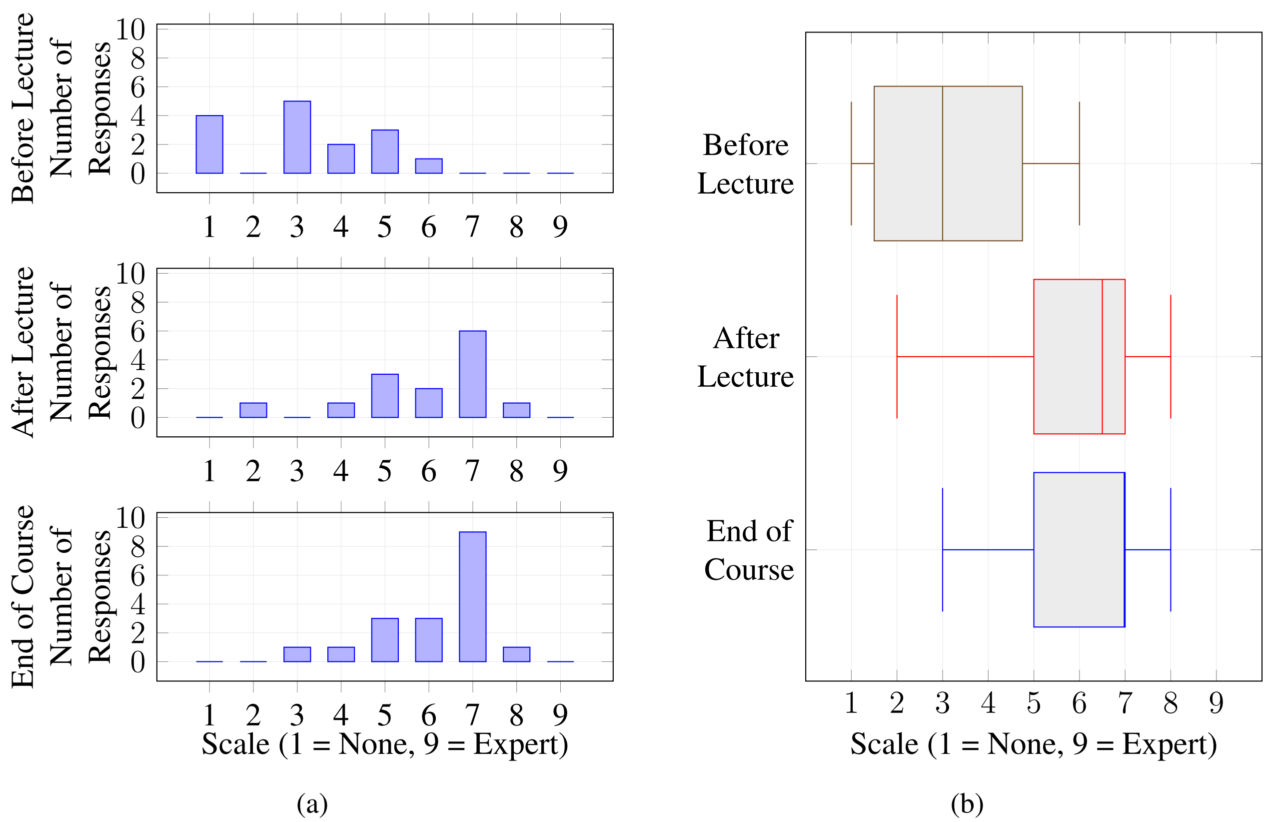

Figure 2: Student reported level of SE knowledge.

Figure 3 shows the survey results of responses to the statement “Development of modern powertrains requires a multidisciplinary approach”. The independent group t-test does not result in a confirmation of an independent response from “after the lecture” to “end of the course”. The group mean difference information shown in Figure 3b also confirms that there is strong agreement with this statement immediately after the SE lecture as well as at the end of the course since there is a mean score of 8 in both cases. Note that there is a slight improvement in the lower whisker from after the lecture to the end of the course, a 3 to a 6.

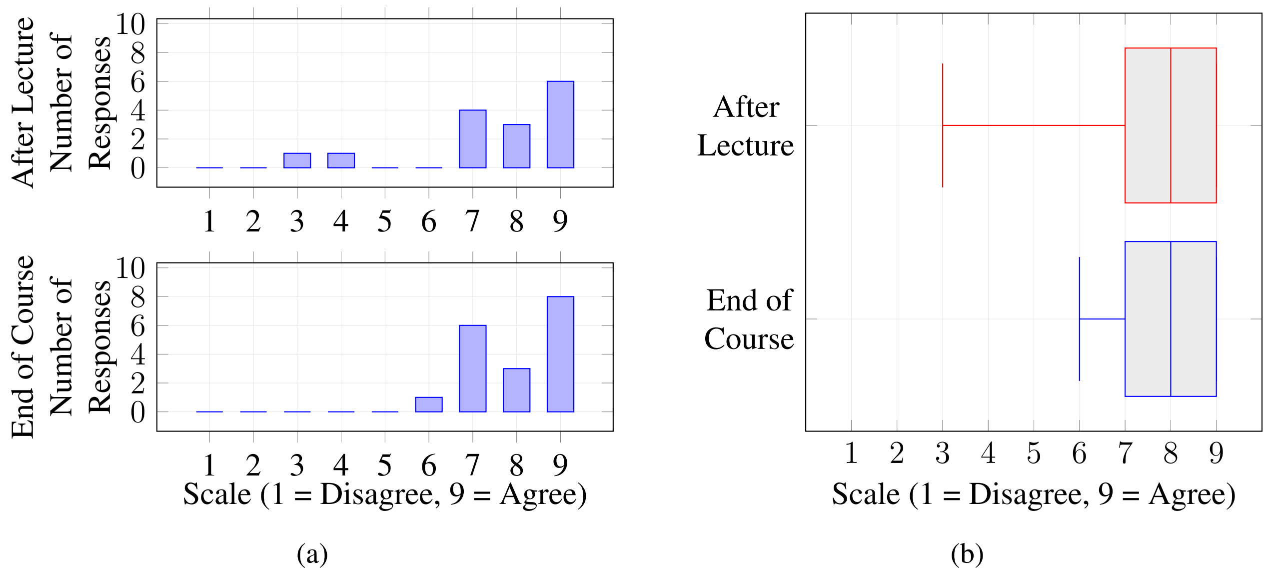

Figure 3: Student responses to the statement “Development of modern powertrains requires a multidisciplinary approach”.

Figure 4 shows the survey results of responses to the statement “Is SE useful?”. The independent group t-test does not result in a confirmation of an independent response from “after the lecture” to “end of the course”. But, the group mean difference information shown in Figure 4b provides some evidence that students agree with this statement more after completion of the course since the lower quartile improved from 7.25 to 8 and the lower whisker improved from 4 to 5 at the end of the semester. In other words, student perceived value of SE may have increased after completion of the course.

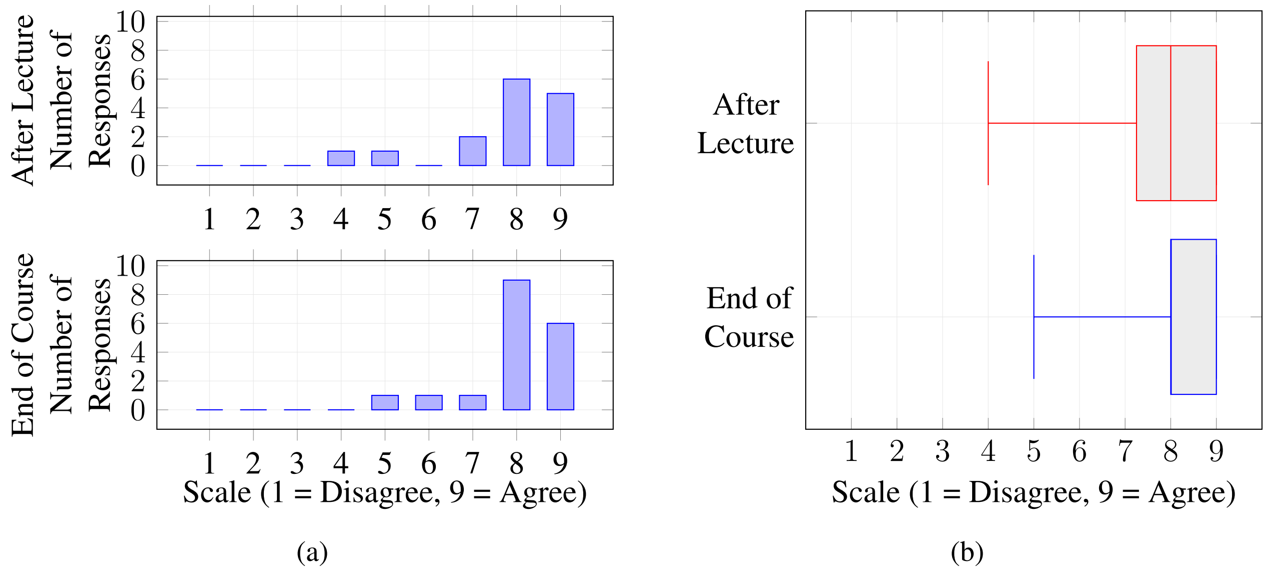

Figure 4: Student responses to the statement “Is SE useful?”.

Figure 5 shows the survey results of responses to the statement “Implementation of SE improves development of multidisciplinary systems”. The independent group t-test results in a confirmation of independent data from “before the lecture” to “after the lecture”, but does not result in a confirmation of independent data from “after the lecture” to “end of the course”. The group mean information shown in Figure 5b indicates that students may not be sure if implementation of SE improves development of multidisciplinary systems at the beginning of the course since the mean response to this question before the SE lecture was a 5. But, after the lecture, the median response was an 8 indicating strong agreement that implementing SE improves development of multidisciplinary systems. There was an increase in the upper quartile from 8.75 to 9 as well as an increase in the lower whisker from 4 to 6 indicating a slightly stronger student agreement after completion of the course. In other words, student engagement with SE may have increased upon completion of the course.

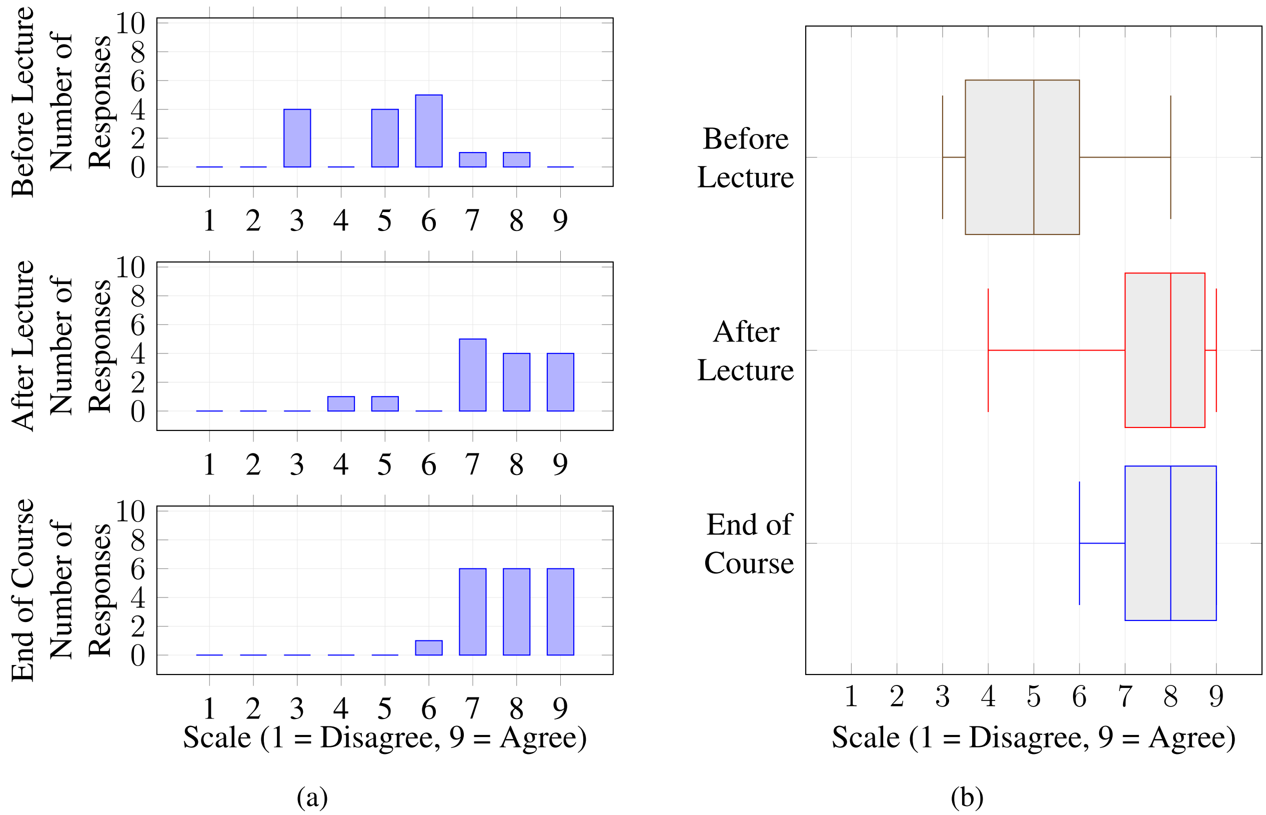

Figure 5: Student responses to the statement "Implementation of SE improves development of multidisciplinary systems".

Figure 6 shows the survey results of responses to the statement "SE could improve performance in": "labs, homework, and/or exam prep" (a), (b) and "the capstone project" (c), (d). The independent group t-test does not result in a confirmation of independent data from either "after the lecture" to "end of the course" survey questions. But, for both cases, the mean score is relatively high, 7 and 6.5 for (b) as well as 8 and 7 for (d), indicating agreement that SE could improve performance in labs, homework, exam prep and the capstone project. But, the mean score decreased in both cases indicating that students saw potential in applying SE to class assignments immediately after the SE lecture but may have lost confidence in applying SE by the end of the course. On the other hand, a student may not have used SE for their project, but recognizes that it would have been better if they had. Either way, this disparity is interesting for educators because this issue might be improved through more effective teaching.

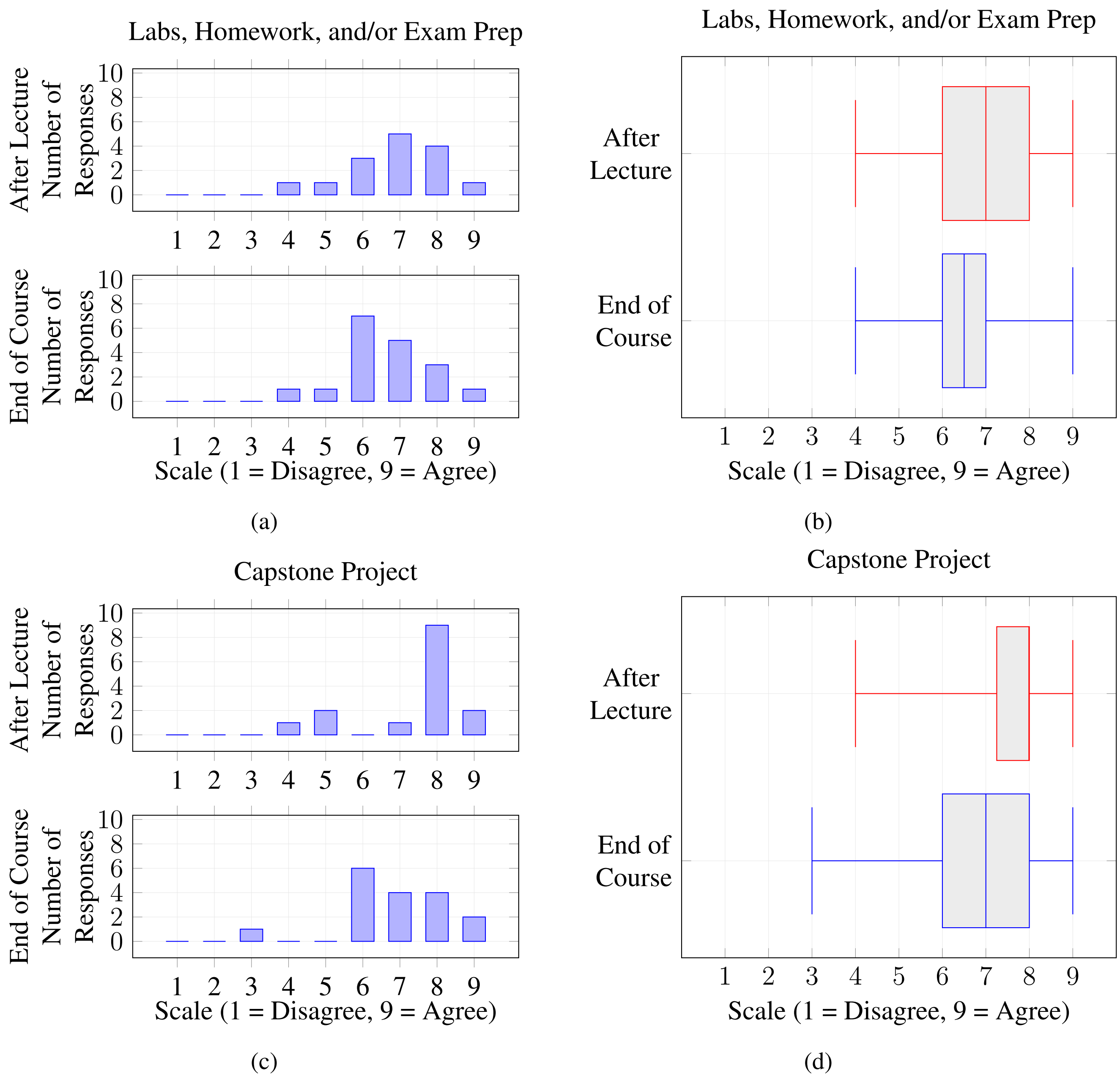

Figure 6: Student responses to the statement “SE could improve performance in”: “labs, homework, and/or exam prep” (a),(b) and “the capstone project” (c),(d).

Also included in the end of the course survey was a comments section where students could share their thoughts about SE and a multidisciplinary course. Applicable written comments include:

- The split between mechanical and electrical engineering is much more prominent in education than in industry. Any course that bridges the gap is A-Okay in my view!
- Two lectures on SE and its application to the class would be beneficial

These comments suggest that students perceive value in teaching SE principles in a multidisciplinary course and might further suggest than additional SE teaching may be necessary.

Evaluation of SE Implementation in the Capstone Project

The scope and impact of the student capstone projects were also evaluated and compared to an alternate semester where a SE lecture was not given. The semester where the SE lecture was given was in Fall 2017 where there were 5 groups who each completed a project and 18 students total. The last time the course was taught was in Fall 2014 in which there were 6 groups who each completed a project and 20 students total. The Fall 2014 class was not given a SE lecture, and no survey addressing SE was given.

To evaluate the scope and impact of each capstone project, the final report and project presentations were individually evaluated. Identified systems-level scopes include:

- Well-to-wheel analysis
- Vehicle fleet-level impacts
- Electricity pricing to evaluate total fuel costs
- Powertrain control informed by external factors such as urban zones or high traffic

These concepts might be used in addition to the vehicle modeling, simulation, and design requirements. Note that SE principles such as concurrent development and risk management could have been implemented in the project execution but student application of these SE concepts is difficult to evaluate and was not chosen as part of this study.

Figure 7 shows a comparison of the capstone projects that included a SE scope to those that didn't for a class that included a SE lecture and a class that did not include a SE lecture. In the course without a SE lecture, one third of the projects incorporated a systems-level scope. In the course with a SE lecture, all projects included a systems-level scope. The indicates that the SE lecture may have engaged students to the point where they were able to successfully apply SE even though it was not a requirement.

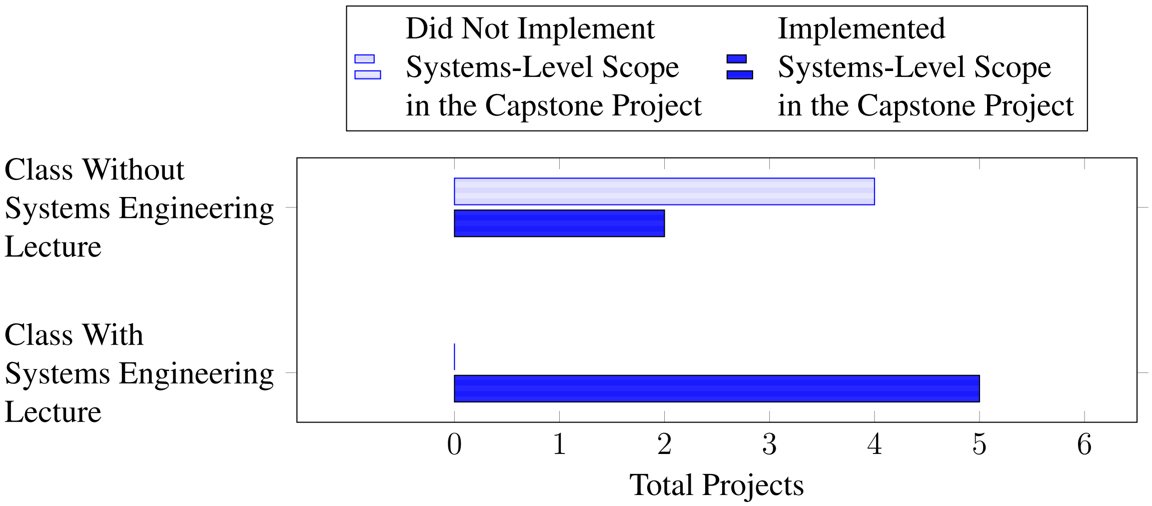

Figure 7: Comparison of the capstone projects that included a systems engineering scope to those that didn't for a class that included a systems engineering lecture and a class that did not include a systems engineering lecture.

Conclusions

In this study, a SE lecture was given in a multidisciplinary engineering course focused on automotive hybrid electric powertrains at our university. A survey was administered before and after the lecture to evaluated student SE knowledge, perceived value, and engagement. An additional survey was given at the end of the course to address any changes in the student reported SE areas. Evaluation of the student capstone projects was performed to address the potential improvements from incorporating a SE lecture in this multidisciplinary course. Since the previous time the course was taught, which did not include a SE lecture, the student project scope increased from a 33% systems-level scope to 100% systems-level scope.

Overall, it was found that student knowledge about SE significantly improved after the lecture and further improved after completion of the course despite no other SE guidance being given. Students report high confidence that development of modern powertrains requires a multidisciplinary approach to which SE concepts are useful and improve development. Students acknowledge that SE can improve performance in all aspects of the course, but may have lost confidence after completion of the course indicating that teaching of SE could be improved. One student directly suggested an additional lecture on SE which could expand student understanding of SE principles by focusing on in-depth examples. These results support the conclusion that exposure to and retention of systems engineering principles improves learning outcomes and team function in an multidisciplinary graduate level course.

A caveat with this research is that it is based on student self-reporting. However, it can be plainly stated that we were able to raise SE awareness/understanding and the students attributed a benefit to this. The quality of the course capstone projects improved significantly and there may be a need to incorporate more SE concepts in future iterations of the course. For other graduate level engineering courses, it may be difficult to apply this methodology due to the large variety of course designs but the results from this study indicate that it is worth the effort. Additional future work will explore using this idea in other course settings to generalize our findings, identifying which SE principles may be most effective, and investigating the role of previous SE education in multidisciplinary course outcomes.

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