

## **Incorporating Basic Systems Thinking and Systems Engineering Concepts in a Mechanical Engineering Sophomore Design Course**

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# **Incorporating Basic Systems Thinking and Systems Engineering Concepts in a Mechanical Engineering Sophomore Design Course**

## **Abstract**

Mechanical engineering undergraduate programs in the US commonly have in their curricula one or more courses and a capstone design project in which students can learn and put into practice some of the methodologies and tools typically used during the design and development of new products. However, in most instances the product design and development process considered is geared towards products of low to moderate complexity. Furthermore, usually little emphasis is placed on exposing students to systems thinking (ST) and systems engineering (SE) concepts. As a result, student teams often struggle when they have to design products involving multiple subsystems and areas of technical expertise. A possible strategy to incorporate ST and SE concepts in the undergraduate curriculum is to introduce the concepts in a gradual fashion, beginning in the freshman or sophomore year and culminating in a capstone design experience in which the students can apply and improve the knowledge, skills, and abilities that they have gained in their previous design related courses. This paper presents the approach that was used to include basic ST and SE concepts in a sophomore-level product design and development course for mechanical engineering undergraduate students. In addition, the results obtained during the first implementation, including data collected using two different assessment instruments, are discussed.

## **Introduction**

Mechanical engineering undergraduate programs in the US commonly have in their curricula one or more courses and a capstone design project in which students can learn and put into practice some of the methodologies and tools typically used during the design and development of new products. However, in most instances the product design and development process considered is geared towards products of low to moderate complexity. Furthermore, usually little emphasis is placed on exposing students to systems thinking (ST) and systems engineering (SE) concepts [1-10]. As a result, student teams often struggle when they have to design products involving multiple subsystems and areas of technical expertise. This deficiency becomes evident when students work on collegiate design competitions such as the Society of Automotive Engineers' Formula or Mini Baja competition or the American Society of Mechanical Engineers' Human Powered Vehicle competition. In those projects, problems with the integration of subsystems can be prevalent, causing major delays and last minute design changes that can lead to poor product performance or even failure [11-16].

A possible strategy to incorporate ST and SE concepts in the undergraduate curriculum is to introduce the concepts in a gradual fashion, beginning in the freshman or sophomore year and culminating in a capstone design experience in which the students can apply and improve the knowledge, skills, and abilities (KSAs) that they have gained in their previous design related courses. This approach requires identifying the ST and SE KSAs that will be introduced each year of the undergraduate program and selecting the courses in which they will be addressed. In

addition, the cognitive level and instructional methods for each added topic must be considered and assessment instruments need to be developed to measure student progress.

The Engineering Competency Model jointly developed by the American Association of Engineering Societies (AAES) and the US Department of Labor (DoL) [17], the Systems Engineering Career Competency Model (SECCM) proposed by the Naval Postgraduate School (NPS) [18, 19], and the second version of the CDIO (Conceiving, Designing, Implementing and Operating) Syllabus available from the CDIO organization [20], among others [21-25], are useful resources to identify potential topics related to ST and SE that can be incorporated in the undergraduate curriculum. In a recent study [26], the SECCM and the CDIO Syllabus were used to identify possible topics to be included in a sophomore design course to start developing basic ST and SE KSAs in the students. Table 1 summarizes the topics proposed in [26], which include new topics to be added as well as topics to be expanded by applying them first at the system level and then to system elements.

Table 1. Suggested topics to incorporate basic ST and SE concepts in an existing sophomore-level product design and development course.

| <b>Suggested Topics [26]</b>   |   |
|--|---|
| <b>Add</b>   | <b>Expand Scope</b>   |
| <ul style="list-style-type: none"> <li>• Systems and system boundaries</li> <li>• System context and systems of systems</li> <li>• System function, behavior, and emergent properties</li> <li>• System element</li> <li>• Definition of systems thinking</li> <li>• Definition of systems engineering</li> <li>• Definition of systems architecting</li> <li>• System life cycle</li> <li>• The systems engineering “V” model</li> <li>• Basic types of system architecture</li> <li>• System decomposition and system structure</li> <li>• Interfaces, interactions, and dependencies between system elements</li> <li>• Cascading requirements</li> <li>• System integration, verification, and validation</li> </ul> | <ul style="list-style-type: none"> <li>• Identification of stakeholders</li> <li>• Identification of customer needs</li> <li>• Setting target specifications</li> <li>• Concept generation</li> <li>• Concept selection</li> <li>• Prototyping</li> </ul> |

One approach to assess ST and SE KSAs is to have persons with substantial expertise in those areas perform the evaluation conducting interviews and/or appraising work done during system development. Another option is to rely on assessment instruments in which results can be directly obtained based on the answers provided to conceptual or self-efficacy questions [27, 28]. Recently, a survey was proposed to assess basic systems thinking skills [26]. Since the ST and SE concepts considered in the survey are a sub-set of the ones presented in Table 1, it is an attractive tool to determine the impact of changes made to a traditional sophomore design course in which ST and SE concepts are not covered.

This paper presents the approach that was used to include basic ST and SE concepts in a sophomore-level product design and development course for mechanical engineering undergraduate students. In addition, the results obtained during the first implementation, including data collected using two different assessment instruments, are discussed.

### **Description of the unmodified sophomore design course**

The mechanical engineering curriculum at the South Dakota School of Mines and Technology (SDSM&T) includes a four-credit sophomore-level course that provides an introduction to the product design and development process. The course focuses on the activities corresponding to the concept development phase and a semester-long capstone project allows student teams to apply what they are learning to the conceptual design of a simple product. The book by Ulrich and Eppinger [29] is used as the course textbook and the product development process considered is for “market pull” products of low to moderate complexity. The following list indicates the main topics covered in the course:

- Introduction to the product development process.
- Product planning.
- Identification of customer needs.
- Setting target specifications.
- Concept generation.
- Concept selection.
- Prototyping.

ST and SE concepts are not explicitly addressed in the course or in other courses in the mechanical engineering curriculum.

### **Modifications made to the course**

Three main factors were taken into consideration while making changes to the sophomore design course to incorporate ST and SE concepts. First, the educational materials and learning activities needed to be appropriate for the level of the course. Second, the time required to cover the new content had to be reasonable and the educational materials and learning activities needed to be such that they could be easily intertwined with the topics already covered in the existing course. Finally, the benefits of the modifications made to the course needed to be formally assessed.

The course content was extended to include the topics listed in Table 1. A short teaching module spanning two fifty-minute lectures was used to introduce most of the concepts listed in the left column of Table 1. The International Council on Systems Engineering (INCOSE) Systems Engineering Handbook [30] and the Systems Engineering Body of Knowledge (SEBoK) [31] were used as the main references for the theory portion of the module. The iBOT, a motorized wheelchair, was used throughout the module to illustrate some of the concepts presented. In addition, the module included a hands-on homework assignment in which student teams completely disassembled a two-slice bread toaster for household use, separated its components into subsystems, and identified the interactions between those subsystems.

Product architecture was added as a new course topic and complementary educational materials that could be easily incorporated in the sophomore design course were developed for some of the topics listed on the right column of Table 1. A short motivational example (primer) and a case study were implemented for each of the following topics: identifying customer needs, setting target specifications, concept generation, and product architecture. As can be seen in Table 2, to enrich the learning experience of the students a different product or system was considered for each primer and case study. Since one of the goals of the research team was that the primers and case studies could be easily adopted by instructors teaching similar courses, the following aspects were kept in mind during their development:

- They should be self-contained so that an instructor can adopt any one of them independently of the others.
- They should not require too much class time in order to avoid the need to make major adjustments to the course structure and content or to the instructional materials and activities that the instructor already has in place for a given topic.
- They should focus on selected aspects of the product or system under consideration and should not require an in-depth knowledge of that product or system.

Table 2. Primers and case studies used in the course.

| <b>Topic</b>                  | <b>Primer</b>                 | <b>Case Study</b>                                  |
|-------------------------------|-------------------------------|--|
| Identifying customer needs    | The Tata Nano                 | Lower Extremity Protective Armor for Ground Troops |
| Setting target specifications | Flying Cars                   | Rockets and Missiles                               |
| Concept generation            | Apollo Lunar Module           | Unmanned Ground Vehicles (UGVs)                    |
| Product architecture          | Japanese WWII I-400 Submarine | Navy SEAL Deployable Submarine                     |

For the topics in which primers and case studies were available, the primer was used to introduce the topic and to highlight its importance in the context of the product design and development process. Then, the material related to the topic that was covered in the unmodified course was presented, with minor modifications. Finally, the case study was used to conclude the class sessions devoted to the topic.

Each primer took between 20 and 25 minutes of class-time and the instructional approach used involved a PowerPoint presentation followed by a brief class discussion. The interested reader can find more details about the primers that were used in [32].

Each case study had a lecture portion and a “hands-on” activity. The lecture portion required one 50-minute class session and the instructional approach relied on a PowerPoint presentation and questions to encourage student participation and class discussion. The “hands-on” activity was designed so that student teams could complete it as a homework assignment. To improve student

learning, for some of the case studies a 50-minute class session was devoted to do portions of the “hands-on” activity with support from the person teaching the case study.

As was the case in the original sophomore design course, students enrolled in the modified course were required to work in teams in a semester-long capstone design project focusing on the concept development phase of the product development process and culminating with building a proof-of-concept physical prototype. The design project is very important for student learning because they put into practice the different concepts, methodologies, and tools covered in class. Consequently, careful consideration needs to be given to the project that is selected and how it is implemented in the course. Early on it was decided that all the student teams were going to work on the same project as if they were independent companies competing with each other. By following this approach, at the end of the semester the teams had the opportunity to compare their results and gage the quality of their efforts. In general, those comparisons gave rise to important insights and lessons learned that students could apply in future design projects.

Typically the capstone design projects conducted as part of the unmodified course dealt with simple products. Unfortunately, few ST and SE concepts can be applied in that context. Thus, identifying a suitable project for the modified course was an important task. The following were some of the criteria that the research team took into account while selecting the product for the design project:

- The product has a reasonable number of subsystems.
- The required technical knowledge is consistent with the level of the course.
- Any technical knowledge that the students don't have and is crucial for the project needs to be provided as part of the course.
- The scope of the project takes into account the time constraints imposed by the duration of the course and the amount of time that students are expected to devote to the class.
- The budget required to implement the project needs to be consistent with the available funds.

Since nowadays many mechanical systems include electronic components and software, it was decided that the project should require the use of a simple programmable controller. Taking into consideration the limitations imposed by the level of the course, the time constraints, and the available budget, at the beginning of the semester each team was provided an Arduino Uno based programmable controller that was fully tested and ready to use. The hardware of the control unit (see Figure 1) consisted of an original Arduino Uno board or a compatible RedBoard, an Adafruit motor/stepper/servo shield, an Adafruit 16-Channel 12-bit PWM servo shield, a SparkFun USB host shield, a Grove base shield, a Bluetooth 4.0 USB module, a Sony Dual Shock 3 PS3 controller, and 6V and 12V battery packs. Several class sessions were devoted to give a general overview of the hardware mentioned above, provide the knowledge needed to start using the control unit, and present some programming examples demonstrating how to use the controller for different tasks such as driving multiple motors and servos.

In addition to the control unit mentioned above, a hardware kit with motors, servos, wheels, gears, and other mechanical and structural components, was put together to facilitate the fabrication of prototypes. The kit, which consisted mostly of VEX Robotics EDR parts, was given to the student teams during the first part of the course.

The project selected for the first implementation of the modified course dealt with the design of a small ground robot for Urban Search and Rescue (USAR) operations. For identifying customer needs and setting target specifications, students were asked to adopt the point of view of a company. For the rest of the project, the scope was changed to a small-scale design competition that included aspects resembling some of the tasks that a number of small USAR robots can do, such as delivering items to an injured person or retrieving a sample from an area where injured persons could be present.

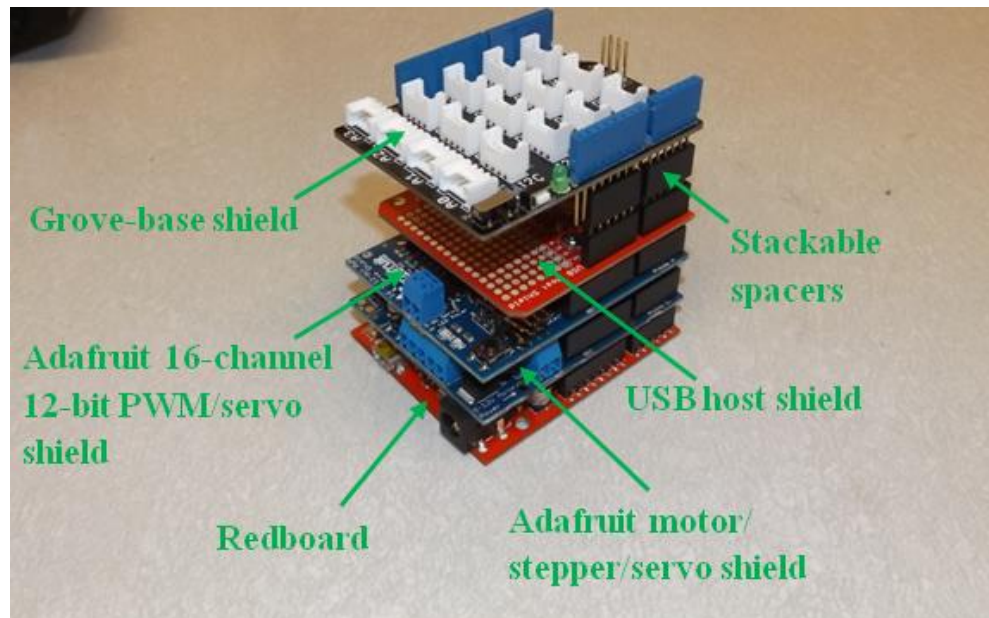


Figure 1. Programmable controller used in the capstone design project.

### Results of the first implementation

To assess how the modifications to the sophomore-level product design and development course impacted students' understanding of basic SE concepts as well as their systems thinking skills (STS), a Systems Thinking Skills Survey (STSS) was developed and the validity and reliability of the instrument were tested using a set of preliminary data. In addition, a Course Evaluation Questionnaire (CEQ) was developed to collect data on student perspectives toward the curriculum design of the modified course. Sample questions from the STSS are given in the Appendix. The plan is to make the STSS available to faculty members interested in implementing it in courses similar to the one considered in this paper.

The STSS was implemented in the modified sophomore design course as pre- and post-tests in fall 2016. In order to have a reference point to gauge the impact of the course modifications, students that took the unmodified course and were enrolled in a second-semester junior-level class in spring 2017 were invited to answer the post-test survey and used as a control group.

The twenty two students that completed the modified sophomore design course in fall 2016 served as the experimental group for this study and answered the pre and post STSS as well as the CEQ. The students formed seven teams at the beginning of the semester: three teams of four



students each, two teams of three students each, and two teams of two students each. Three of the students enrolled in the course were underrepresented minorities and twenty students were males. The two female students in the class selected different teams. Figure 2 shows the distribution of the cumulative GPA of the students; the average cumulative GPA was 3.0 out of 4.0 (SD = 0.56). The majority of the students (72.7%) indicated that they had prior experience in product design activities before taking the modified sophomore design course.

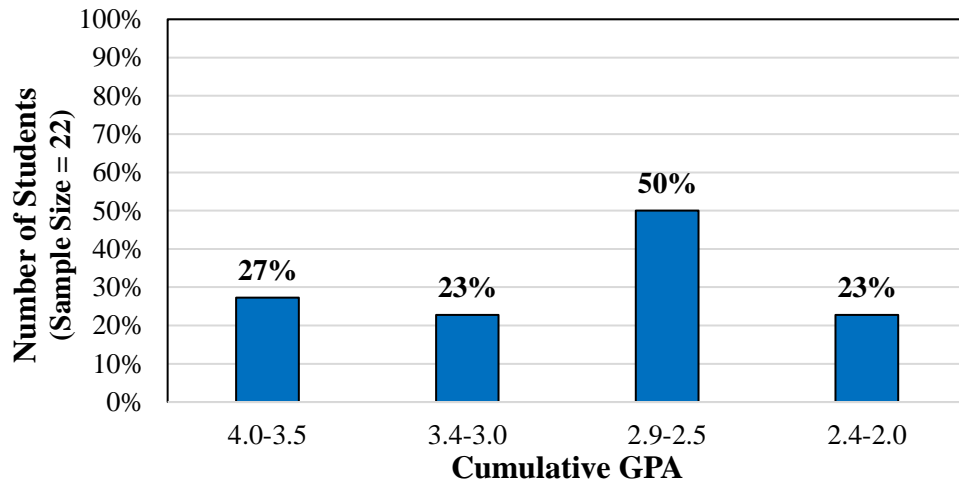


Figure 2. Student cumulative GPA distribution.

Figure 3 illustrates student perceived self-efficacy in STS in the pre- and post-STSS in the experimental group. Results showed improvement in students' self-efficacy in systems thinking by the end of the semester, particularly in the domains of identifying customer needs, setting target specifications, concept generation, and systems architecture. All changes were statistically significant (\*\* $p < 0.01$  and \* $p < 0.05$ ).

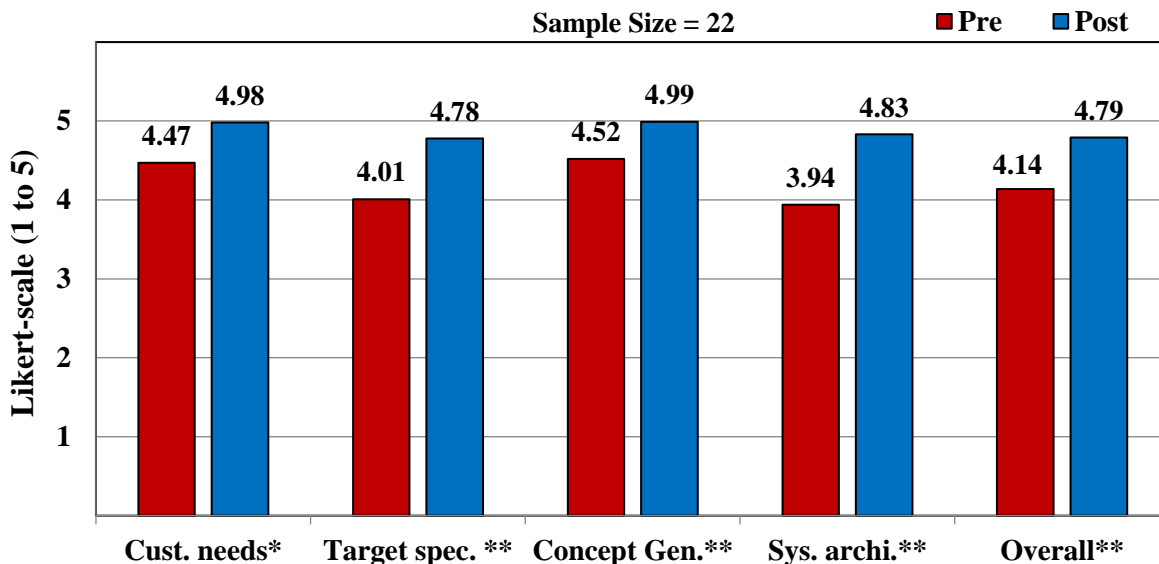


Figure 3. STS self-efficacy comparisons within the experimental group.

Figure 4 compares the student perceived self-efficacy in STS in the STSS between the experimental and the control group. As can be seen in Figure 4, on average students in the experimental group had significantly lower self-efficacy ( $p < 0.05$ ) than those in the control group in the pre-test, especially in setting target specifications and systems architecture ( $p < 0.05$ ). These differences suggest that there are gains in STS self-efficacy as students become more mature with the traditional curriculum. However, students in the experimental group had higher STS self-efficacy than those in the control group in the post-test, although only the difference for systems architecture was statistically significant ( $p < 0.05$ ). The differences for concept generation ( $p < .01$ ), identifying customer needs ( $p < 0.06$ ), setting target specifications ( $p < 0.06$ ), and overall STS self-efficacy ( $p < 0.01$ ) were statistically significant at confidence interval CI = 90%.

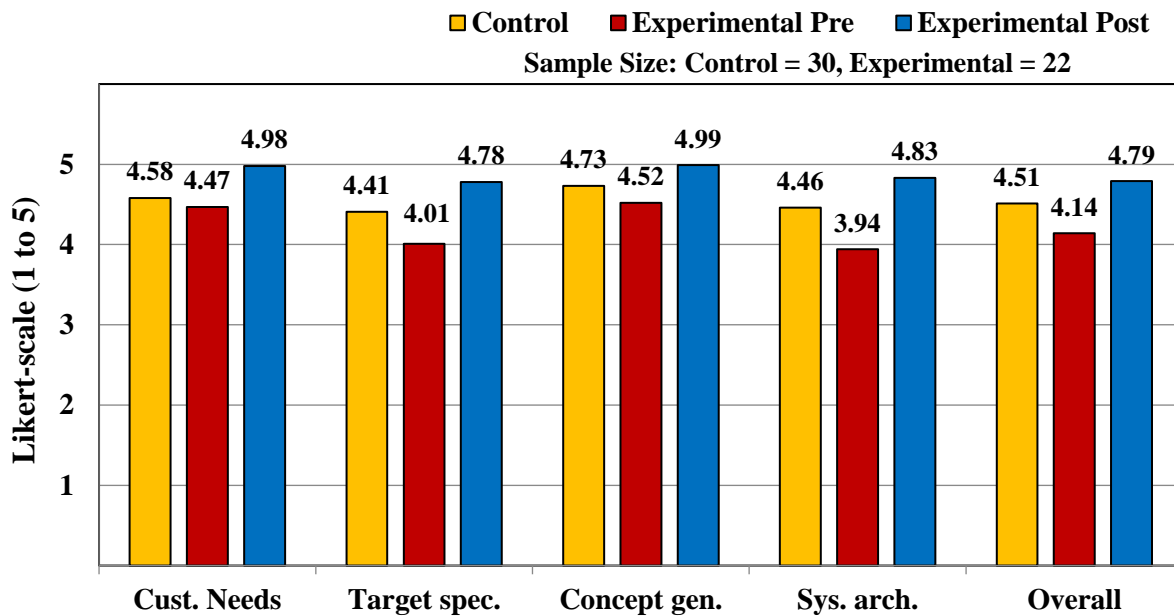


Figure 4. Between-group comparison in STS self-efficacy.

A set of questions was designed in the STSS to test students' application of systems thinking skills. At the beginning of the semester the experimental group had the same skills as the control group in identifying customer needs, concept generation, and systems architecture ( $p > 0.1$ ). The only exception was in setting target specifications ( $p < .001$ ). By the end of the semester the experimental group had the same skill levels as the control group in identifying customer needs, setting target specifications, and systems architecture ( $p > 0.1$ ), and a higher skill level in concept generation ( $p < 0.05$ ).

The changes mentioned above suggest that the students gain experience in setting target specifications through the traditional curriculum and/or extra-curricular activities. However, they have little opportunity to practice in the domains of identifying customer needs, concept generation, and systems architecture. Although the students in the experimental group did not perform better than those in the control group in those three domains, the significant differences in STS self-efficacy suggest promising changes in students' skills if the interventions are implemented for more than one semester.

The CEQ focused on the students' perceptions about the primers and case studies as well as the educational materials used in class. On average, the students thought the lengths of the primers and case studies were acceptable. However, the students indicated they were less interested in primers and case studies about global perspectives such as the primer about the Tata Nano. This is evident in Figure 5 which presents students' attitudes and perceived engagement during the four primers implemented in the modified course. It is interesting to note that students' engagement in the case study on identifying customer needs improved to 4.3 out of 5 because it did not use an example from a foreign country. This phenomenon may conflict with findings in studies conducted at different geographic locations and may be due to the general background and experiences of the students at SDSM&T.

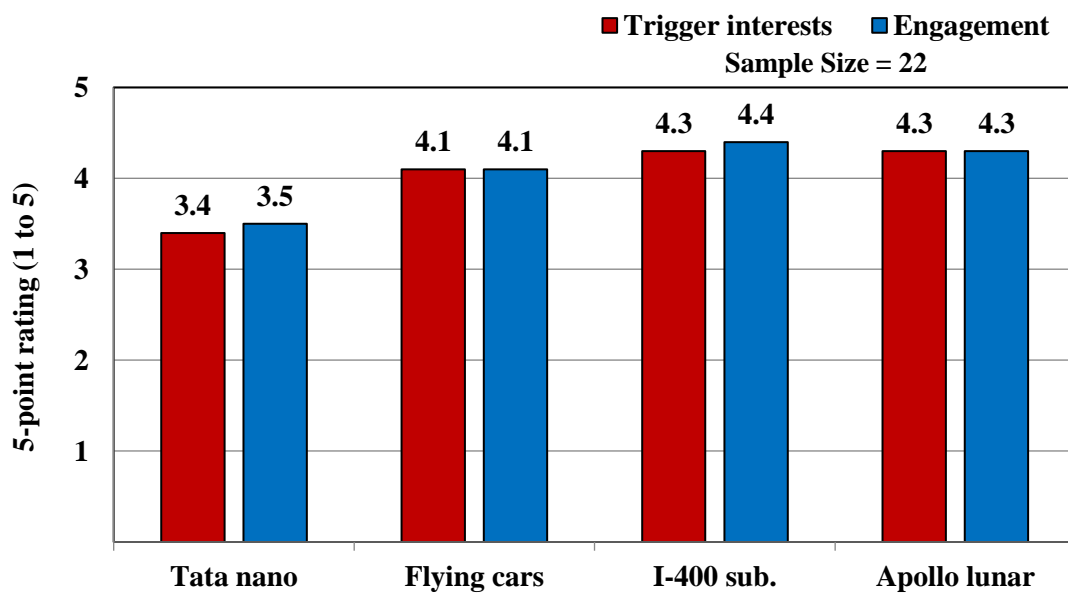


Figure 5. Student feedback on the primers.

Overall, the students in the experimental group perceived a good amount of skill gains in the modified course in terms of understanding the product development process (4.3 out of 5.0), identifying customer needs (4.4), setting target specifications (4.2), establishing the architecture of a product (3.8), and generating product concepts (3.8). However, some students suggested changing the class into a two-semester course. For example, one student gave the following feedback: "I think that the class should be spread over 2 semesters. It was set up well that it split up the learning and applying, but it should really be two separate entities." It is possible that this was due in part to the capstone project that required using and programming an Arduino Uno based controller.

Finally, Figure 6 presents as an example the physical prototypes built by two different teams for the design competition corresponding to the semester-long capstone project. Five out of the seven teams in the class were able to complete the mission corresponding to the competition. Although a mandatory freshman programming class that is part of the mechanical engineering curriculum at SDSM&T was a pre-requisite for the course and several class sessions of the

modified course were devoted to learning how to program the Arduino Uno based controller, most of the students struggled with the programming aspects of the project.

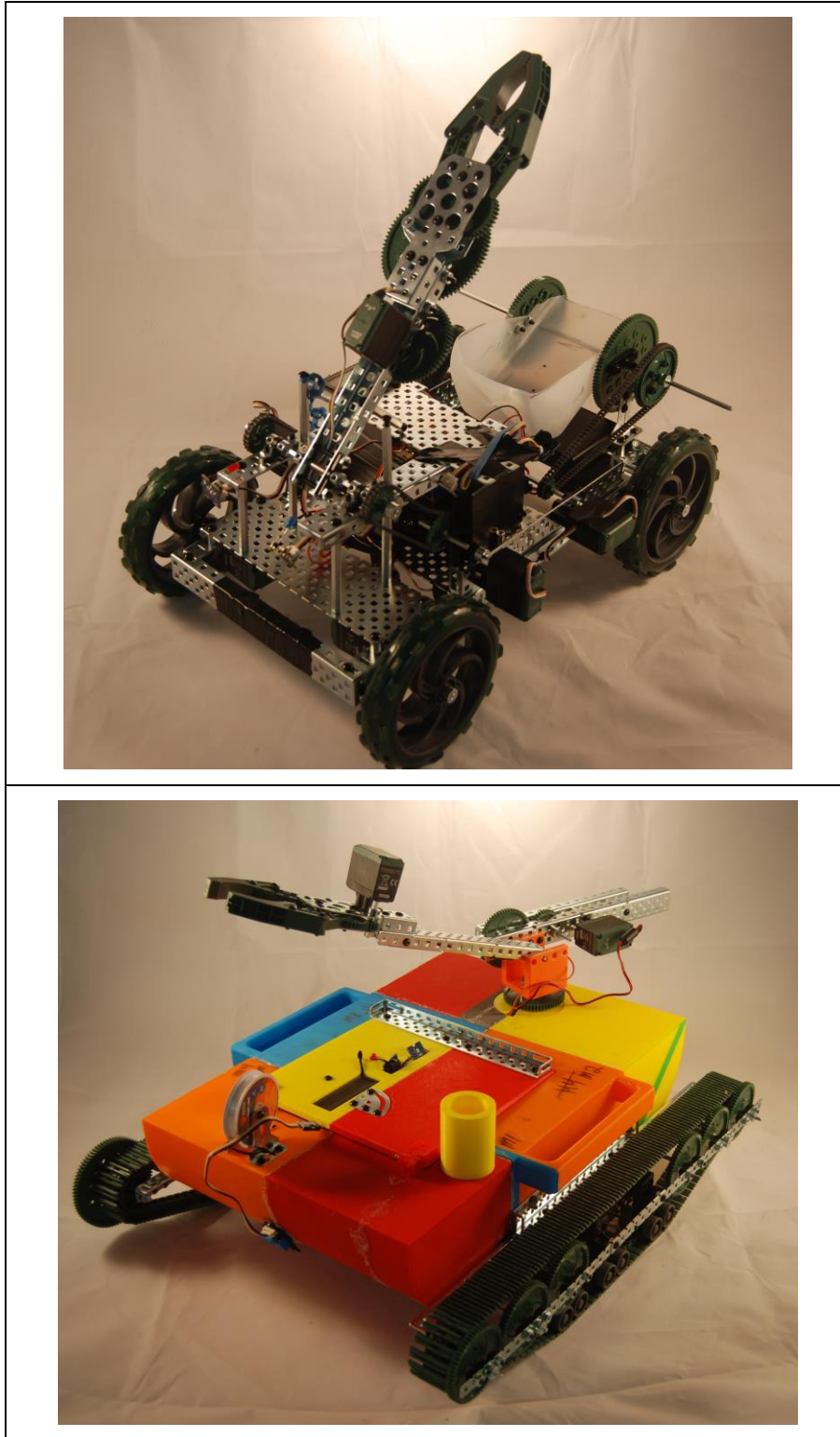


Figure 6. Examples of the physical prototypes built by the student teams.

## **Conclusions and future work**

As the complexity of engineered systems continues to grow with increasing integration of electronics, computation, and networking capabilities into formerly “mechanical” components, there is a corresponding growth in the need for engineers who understand the fundamentals of systems engineering. This paper has presented an effort to improve mechanical engineering students’ systems engineering skills through the redesign of a sophomore design course. Students were exposed to primers and case studies that covered essential steps in the systems engineering process and completed a semester-long project that required integration of various subsystems.

The effectiveness of the intervention was assessed through a newly designed systems thinking skills survey and through a course satisfaction survey. Students showed a statistically significant improvement in self-efficacy for all measured skills, but showed a statistically significant gain over the control group only for the skill of systems architecting. One difficulty in assessing results is the small sample size, a problem that future work will address, both by expanding the number of students at SDSM&T and by exporting the program to other academic institutions.

The ultimate goal of this work is a gradual introduction of systems engineering fundamentals throughout the standard mechanical engineering curriculum. Future work will expand the sophomore intervention described in this paper to both lower-level and upper-level courses, with pedagogically appropriate targets for each year. It will also refine and further validate the assessment instruments for broad distribution.

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## **Appendix: Systems Thinking Skills Survey (STSS)**

The STSS was developed to assess how the modifications to the sophomore-level product design and development course for mechanical engineering undergraduate students impacted students' understanding of basic SE concepts as well as their systems thinking skills. The survey starts with a set of questions aimed at collecting background information about the student. Then, it has exam like questions and self-efficacy questions. Most of those questions focus on the four topics for which case studies were implemented in the modified course: identifying customer needs, setting target specifications, concept generation, and systems architecture. Sample questions from the STSS are provided below. The plan is to make the STSS available to faculty members interested in implementing the assessment instrument in a course similar to the one considered in this paper.

### Sample question 1: Background information.

1. Describe your first-hand engineering experience (such as participating in the first robotics competition in high school).

Sample question 2: Basic systems thinking and systems engineering concepts.

2. A computer is an example of a product that can have modular or integral architecture. Below are two examples of different personal computer designs (Figure 7). Answer the questions below about the computers and their architecture.



Figure 7. Figure corresponding to the sample question dealing with a basic concept.

- 2.1. Which computer has a modular architecture?

- a. Computer A
- b. Computer B
- c. All of the above
- d. None of the above

- 2.2. Which computer has an integral architecture?

- a. Computer A
- b. Computer B
- c. All of the above
- d. None of the above

Sample question 3: Systems thinking and systems engineering self-efficacy.

Table 3 provides examples of the self-efficacy questions used in the survey.



Table 3. Sample self-efficacy questions.

| 3. How well do you think that you can apply the topics mentioned below to an engineering project dealing with the development of products or systems? | N/A                   | Not at all            | Not very well         | Moderate              | Good                  | Excellent             |
|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 3.1. Assigning a relative importance to customer needs.   | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 3.2. Creating a thorough list of system performance metrics.  | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 3.3. Generating multiple alternatives for the design of a product or system.  | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 3.4. Differentiating the main types of architecture that can be used for a product or system.   | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |