Incorporating Systems Thinking and Systems Engineering Concepts in a Freshman-Level Mechanical Engineering Course

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Abstract

The complexity of the products and systems that engineers design, develop, operate, support, and retire from service has increased drastically over time. In order to prepare mechanical engineering graduates who can successfully participate in the different activities that occur over the life cycle of a complex product or system, students need to be exposed to systems thinking (ST) and systems engineering (SE) concepts during their undergraduate education.

Although courses dealing with product design and development are an excellent choice to introduce basic ST and SE concepts, mechanical engineering undergraduate programs seldom offer more than one or two of those courses in their curriculum. Thus, to gradually develop the ST and SE skills of the students during their undergraduate education, it is necessary to identify additional courses throughout the curriculum in which selected ST and SE concepts can be incorporated, starting in the freshman year. To that effect, many universities offer a freshman-level introduction to mechanical engineering course that can be a good a choice to explore how to incorporate basic ST and SE concepts in courses where product design and development is not the primary focus.

This paper presents the approach that was used to add selected ST and SE topics to an existing freshman-level introduction to mechanical engineering course and discusses the results of a pilot implementation.

Introduction

The complexity of the products and systems that engineers design, develop, operate, support, and retire from service has increased drastically over time [1]. In order to prepare mechanical engineering graduates who can successfully participate in the different activities that occur over the life cycle of a complex product or system, students need to be exposed to systems thinking (ST) and systems engineering (SE) concepts during their undergraduate education.

Different efforts aimed at incorporating ST/SE concepts in the undergraduate curriculum of traditional engineering majors have been reported in the literature [2-17]. Several of these efforts focus on specific engineering disciplines (civil, industrial, electrical engineering) [2, 4, 5, 8, 11, 12, 14, 17], while others give suggestions for and highlight the importance of broadly integrating ST/SE into engineering programs [3, 6, 7, 9, 10, 13, 15, 16]. In the case of existing programs, the approach used typically involves including ST/SE-related content in an existing course or adding a new course in which ST/SE is the primary focus. These alternatives may be preferred over more comprehensive ones due to the challenges associated with making major changes to a curriculum that is already in place. Universities that are adding new traditional engineering majors to their undergraduate offerings do not face that difficulty since they have the flexibility to design the curriculum in a way in which ST/SE education is built in rather than added on.

In the case of mechanical engineering undergraduate programs, an existing course that focuses on the process followed to design and develop new products is a logical choice to include fundamental ST/SE concepts. Some of the authors of this paper were involved in a project aimed at incorporating selected ST/SE topics in sophomore-level product design and development course offered at the South Dakota School of Mines and Technology [18-20]. While the overall results of the intervention were positive [18, 21], an important conclusion was that implementing activities in a single course may not be the best or most effective approach. Instead, developing the students' ST/SE knowledge, skills and abilities (KSAs) via a well-planned sequence of interventions that take place in different courses and during different years of the undergraduate program may be a more desirable alternative.

Although courses dealing with product design and development lend themselves to introducing ST and SE concepts, mechanical engineering undergraduate programs seldom offer more than one or two of those courses in their curriculum. Thus, to gradually develop the ST and SE skills of the students during their undergraduate education, it is necessary to identify additional courses throughout the curriculum in which selected ST and SE concepts can be incorporated, starting in the freshman year. To that effect, many universities offer a freshman-level introduction to mechanical engineering course that can be a good a choice to explore how to incorporate basic ST and SE concepts in courses where product design and development is not the primary focus.

Incorporating ST and SE concepts in a freshman-level mechanical engineering course requires careful consideration of which topics to include as well as the approach that will be used to teach those topics. Compared to a product design and development course, there is less flexibility in the amount of class time that can be used and the types of learning activities that can be pursued. Prior work conducted by some of the authors of this paper [22] identified possible ST and SE topics for an intervention in a freshman-level introduction to mechanical engineering course as well as a tentative target cognitive level according to the revised Bloom's taxonomy [23-25] for each one. The list of topics with their corresponding cognitive level is presented in Table 1.

Table 1. ST and SE topics selected for an introduction to mechanical engineering course [22].

Topic	**Level**
Systems and system boundaries	Identify
System context	Understand
System function	Identify
System element / sub-system	Identify
Interfaces, interactions, and dependencies between system elements	Identify
Definition of systems thinking	Remember
Definition of systems engineering	Remember
System life cycle	Understand
Identification of stakeholders	Identify
Identification of customer needs	Understand
Prototyping	Understand
System verification and validation	Understand

To gauge the benefits of an intervention aimed at teaching ST and SE concepts in a mechanical engineering undergraduate course, it is desirable to have an assessment instrument that is not tied to the course and that can supplement data collected from evaluations based on course activities such as homework assignments. One instrument that is available for that purpose is the Systems Thinking Skills Survey (STSS) [26]. The STSS has two main sections. In the first section students report their perceived self-efficacy in a number of ST/SE knowledge, skills, and abilities (KSAs). In the second, students demonstrate their proficiency in selected ST/SE concepts by answering a set of technical questions, most of which are presented in the context of actual products or systems. To keep the length of the survey reasonable, the STSS focuses on the ST/SE KSAs listed in Table 2. The cognitive level according to the revised Bloom's taxonomy [24, 25] presented for each KSA in Table 2 is the desired minimum that mechanical engineering undergraduate students should have at the time of graduation. Comparing Table 1 and Table 2, it is evident that several of the KSAs considered in the STSS are in the list of topics suggested for an intervention in a freshman level introduction to mechanical engineering course.

Table 2. STSS focus KSAs and desired cognitive level for each one [26].

KSA	Level
Identify system boundaries and external interfaces.	Apply
Identify major stakeholders.	Apply
Identify possible technical performance measures (metrics) for determining the system's success.	Apply
Explore alternative and innovative ways of satisfying the customer requirements.	Apply
Define selection criteria, weightings of the criteria and assess/evaluate potential solutions against selection criteria.	Apply
Understand the different types of architecture.	Understand

This paper presents the approach that was used to add the topics listed in Table 1 to an existing freshman-level introduction to mechanical engineering course and discusses the results of a pilot implementation. First, background information about the unmodified course is provided. Then, the changes made to the course and the educational materials developed for that purpose are presented, and preliminary results of the pilot implementation are given. Finally, initial conclusions are provided and plans for future efforts are discussed.

Description of the unmodified course

The mechanical engineering undergraduate program at the South Dakota School of Mines and Technology requires a two-credit Introduction to Mechanical Engineering course during the freshman year. Introduction to Mechanical Engineering is a lecture-based class aimed at introducing students to basic mechanical engineering concepts as well as the mechanical engineering profession. Ideally, students are enrolled in the course during their first semester on campus, but they can take the class at later times if necessary (for example, when a student doesn't have the required math prerequisites). Usually two or more course sections are offered in the fall semester and the number of students per section can be large (more than fifty students).

The course content and the textbook were selected by the Mechanical Engineering Department faculty. The book “An Introduction to Mechanical Engineering” by Wickert and Lewis [27] is used as the course textbook and the typical sequence of topics covered in the class is as follows:

- The mechanical engineering profession
- Engineering ethics
- The mechanical design process
- General technical problem-solving approach
- Unit systems and conversions
- Significant digits
- Dimensional consistency
- Estimation in engineering
- Force vectors
- Force resultants
- Moment of a force
- Static equilibrium
- Elementary solid mechanics concepts (such as normal stress and normal strain in uniaxial loading, shear stress in simple connections, and Hooke’s law)
- Types of engineering materials
- Factor of safety
- Elementary fluid mechanics concepts (such as pressure and buoyancy force).

In addition to covering the topics mentioned above, the course is meant to teach students good practices and standards for homework, study habits, student-student interactions, student-faculty interactions, and campus resources.

The structure of the course follows a lecture, activity, homework sequence to allow students significant practice with the topics discussed. Complementary to the traditional lecture topics, the students also complete a team project. Teams are assigned using CATME [28-31], such that each team has a diverse background with CAD software and 3D printing. The project requirements are for students to design a buoyant boat using course topics such as equilibrium and buoyancy. Student teams are limited to a 3-inch by 3-inch by 3-inch space for their boats and, following design, the boats are printed on department 3D printers with PLA. The course ends with team technical presentations on the boat design process and a competition in which the boats are placed in a tank of water and weights are added to each boat until they capsize or sink. Student teams are graded on a written memorandum report and technical presentation of their project, with a small portion of the grade attributed to a buoyancy score (final ballast weight divided by the weight of the boat) and a judges’ score based on criteria such as aesthetics, function, and feasibility.

The project mentioned above evolved over several semesters, but the basic tenants remained the same. One main issue with the project was the lack of exposure of the students to the design process. Aside from one 50-minute lecture near the beginning of the course, freshman students were not introduced to a formal design process. Additionally, due to time constraints and the large class size, students were only able to manufacture one iteration of their design. This left no time for improvement once the students saw their mistakes during the final competition. The lack of time for a "redesign" and second competition were the main complaints from students about the project; otherwise, students stated that they generally enjoyed the project and learned a lot through the hands-on process.

Modifications made to the course

The goal of the modifications made to the Introduction to Mechanical Engineering course was to infuse the ST and SE topics presented in Table 1 without having a significant impact on the coverage of the course's traditional topics. The approach used for the intervention involved:

- A PowerPoint presentation for a fifty-minute class session focused on providing an overview of the product development process (PDP).
- A PowerPoint presentation for two fifty-minute class sessions devoted to present the ST and SE topics selected for the intervention.
- Six homework assignments dealing with one traditional course topic and one ST/SE topic corresponding to the intervention.
- A modified course project in which students could also gain more familiarity with some of the ST and SE topics that they learned in class.

The modified course starts with the same two topics as the original course: the mechanical engineering profession and engineering ethics. Next, the presentation providing an overview of the PDP is used instead of the original course materials about the mechanical design process. Then the ST and SE topics selected for the intervention are covered using the presentation developed for that purpose. Afterwards, the other topics covered in the unmodified course are taught in the same order as in the original course. The only exception is that the buoyancy topic is covered right after static equilibrium since it is needed for the course project. Each homework assignment developed for the intervention is assigned after the corresponding traditional topic is presented in class. At an appropriate point during the semester the modified course project is introduced, and the student teams work outside of the classroom on the project activities until the end of the semester.

Providing an overview of the PDP before presenting the ST/SE concepts selected for the intervention was important since product design and development provides a motivation to learn and a context to apply ST/SE KSAs. While preparing the presentation providing an overview of the PDP, a concerted effort was made to present the information at an adequate level for first semester freshman students and in a way that would attract their attention. The PDP considered in the presentation is shown in Figure 1 and corresponds to the generic PDP proposed by Ulrich and Eppinger [32] for "market-pull" products of low to moderate complexity that are engineered, discrete, and physical.

The presentation to teach the ST/SE topics selected for the intervention was designed for two fifty-minute class sessions keeping in mind the level of the course and the desired cognitive level from the revised Bloom's taxonomy [24, 25] that the students were expected to attain for each topic. An effort was made to present concepts in a simple way and to illustrate each topic using an example that included a figure, picture, or video to maintain student interest. For instance, the human heart and an artificial heart were used to illustrate the concept of system, the parts of a bicycle were used to demonstrate system elements, and a utility task vehicle was used to discuss system context. Also, careful consideration was given to sequence the topics in a logical progression.

The content of the ST/SE presentation was organized as follows:

- Brief motivation of the importance of ST/SE in product design and development
- System, system function, system element, system context, system boundary, and subsystems
- Definition of ST and SE
- Basics of interfaces, interactions, and dependencies
- System life cycle
- Product/system stakeholders
- Importance of identifying stakeholder requirements
- Definition of system verification and validation

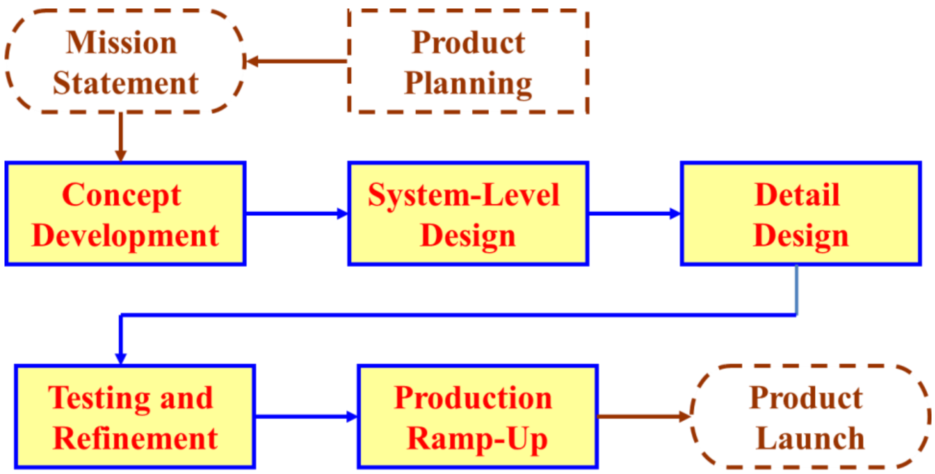

Figure 1. Generic PDP proposed by Ulrich and Eppinger [32].

A junior mechanical engineering student reviewed the first draft of the presentation providing an overview of the PDP and the presentation intended to teach the ST/SE topics selected for the intervention and provided valuable suggestions on how to make the material better suited for the target audience. For example, in the case of the PowerPoint slides about the major phases of the PDP, the feedback provided by the student led to including one or more pictures related to existing products that could serve to illustrate each phase and to help students remember it.

Regarding the six homework assignments developed for the intervention, the objective was to reinforce concepts covered in the ST/SE presentation later in the semester. Each assignment started with a brief background about a product or system. Then, that product or system was used to briefly illustrate one ST/SE concept and, in most of the assignments, one or more questions related to that topic were included. Finally, one or two problems corresponding to a traditional course topic were provided. For example, one homework assignment used mountain bicycles to illustrate the idea of internal and external interfaces and included three problems. In the first problem, students were asked to identify the external interfaces between a mountain bike and the biker. In the remaining two, students needed to solve simple static equilibrium problems involving a mountain bike. Table 3 provides general information about the six homework assignments developed for the intervention.

Table 3. Homework assignments developed for the intervention.

Homework	Traditional Topic	ST/SE Topic	Product or System Considered
A	Unit Systems and Conversions	System Verification	The Mars Climate Orbiter [33, 34]
B	Equilibrium: Concurrent System of Forces	System Elements	Rock Climbing Gear
C	Equilibrium: General Coplanar Forces	Identification of Interfaces	Mountain Bicycle
D	Engineering Materials	Stakeholders, Customer Needs	Prosthetic Arm
E	Axial Stress and Factor of Safety	Subsystems	Off-Road Utility Vehicle (UTV)
F	Buoyancy Force	System Life Cycle	The Ocean Cleanup Project [35]

The modified course project used in the intervention was a variant of the one used in the unmodified course. It involved proposing and building a "seaworthy" and exceptionally buoyant small-scale boat using only materials and tools contained in a kit provided by the course instructor. The length, width, and height of the boat could not exceed 4.5 inches, 3 inches, and 3.5 inches, respectively. The kit provided to the students contained items such as balsa wood sheets of different thicknesses, sticks made of natural bamboo, balsa wood sticks, basic tools to cut wood, two rulers, a hot glue gun, and glue sticks. The boats were tested in a small 20-gallon aquarium tank in which waves were generated using a system of four wave pumps. Steel spheres of two different diameters (0.75 inches and 0.5 inches) were added to the boat one by one until the boat sank or capsized. As was the case in the original project, the performance of the boat was determined using a "buoyancy score" that was computed as the final ballast weight that the boat could hold before sinking or capsizing divided by the weight of the boat.

Students teams were formed during the first part of the course using CATME [28-31] and students were encouraged to get acquainted with their teammates as soon as possible. The course project was introduced at the beginning of the second half of the semester after the topics of static equilibrium and buoyancy force were covered in class. Neither the document with the information about the project provided to the students nor the information about the project that the instructor shared in class when the project was assigned revealed the fact that testing conditions would involve waves. The course instructor only stated that the boats were going to be tested in a small aquarium tank. As expected, after receiving that information, the students assumed that the water was not going to be moving and did not ask questions in that regard. When the students asked about the weights that were going to be added to the boats, the instructor intentionally told them that different alternatives were being considered and that they would know the specific option that was selected at the time of testing.

About three weeks after the project was assigned, the teams were given the opportunity to test their initial boat design. Each team scheduled a separate time in which only members of that team could go to the lab where the aquarium tank was located. The performance of the boat during this first test was recorded for reference purposes and did not have an impact on the project grade. The main goal of the test was to make the students aware of the importance of asking questions and finding information about the operating environment of a product at the beginning of the design process, rather than making assumptions about the operating environment and proceeding to conceive design alternatives based on those assumptions.

After the boat test mentioned above, the teams had about three and a half weeks to use the lessons learned to change or improve their boat designs. The actual competition was held during the final week of classes. Besides testing their boats, the teams gave a brief presentation about process that they followed to design and build their boat and turned in a short project report.

Results of the first implementation

The first implementation of the modified course took place during the fall 2019 in one section of the Introduction to Mechanical Engineering course offered at the South Dakota School of Mines and Technology. The first day of class 60 students were enrolled in that section. Towards the end of the semester, the class size was 41 students, but one of them was not attending the lectures or doing course assignments. In this regard, it is important to mention that the decrease in the number of students was not related to the modifications made to the course. For the course project, the students worked in teams of three to five students and the total number of teams was 10: three teams of three students each, four teams of four students each, and three teams of five students each.

To assess the benefits of the intervention, the Systems Thinking Skills Survey (STSS) [21, 25] was applied as a pre-test at the start of the course and as a post-test during the last week of classes. In addition, data related to the performance of the students in ST/SE related homework problems and exam questions was collected. Finally, the PowerPoint presentation and the report each team prepared as part of the course project were saved for further analysis. Given the short period of time since the end of the first implementation and the time required for a detailed analysis of the collected data and student work, only some general results will be presented here.

In the case of the STSS, students' self-efficacy regarding ST/SE significantly improved from pre- to post-test. In particular, when students were asked to rate their ability to apply particular ST/SE skills to an engineering project involving the development of a product or system, using a scale of 0 (not at all) to 4 (completely), the students rated themselves on average 1.6 at pre-test. At post-test, they rated themselves on average 2.8, for a 1.2 point difference, $t(32) = 7.76$, $p < .01$ (see Figure 2). This significant increase in self-efficacy ratings held for all six KSA categories that were targeted in this part of the survey: Identify Customer Needs, Set Target Specifications, Concept Generation, Concept Selection, System Architecture, Other ST/SE KSAs (see Figure 3). Note that the corresponding six sub-scales (composed from self-efficacy items targeting each KSA category) all showed good internal consistency, with Cronbach's alpha values averaging 0.82 (range: 0.55 to 0.93).

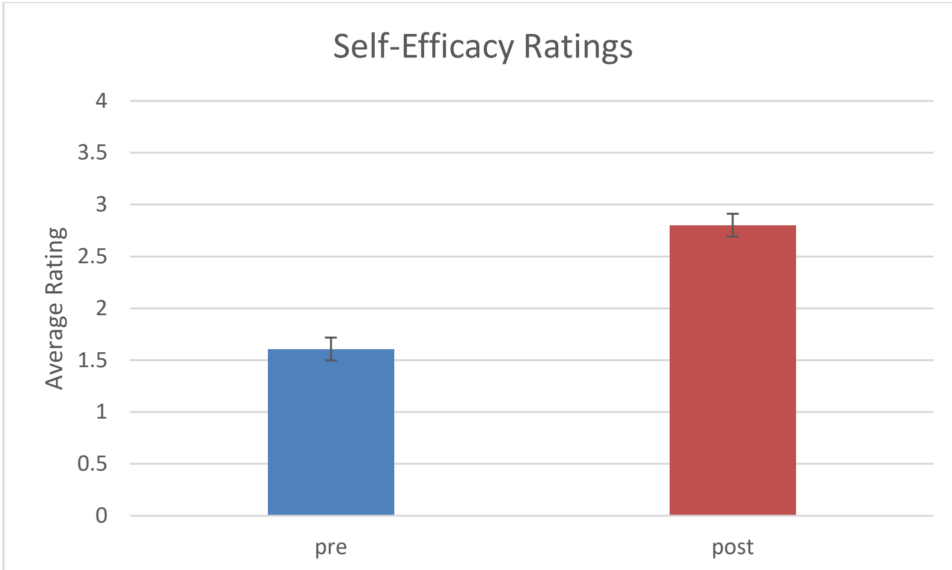

Figure 2. Students' average pre and post ratings of their self-efficacy for various ST/SE skills: 0 = Not at all; 4 = Completely.

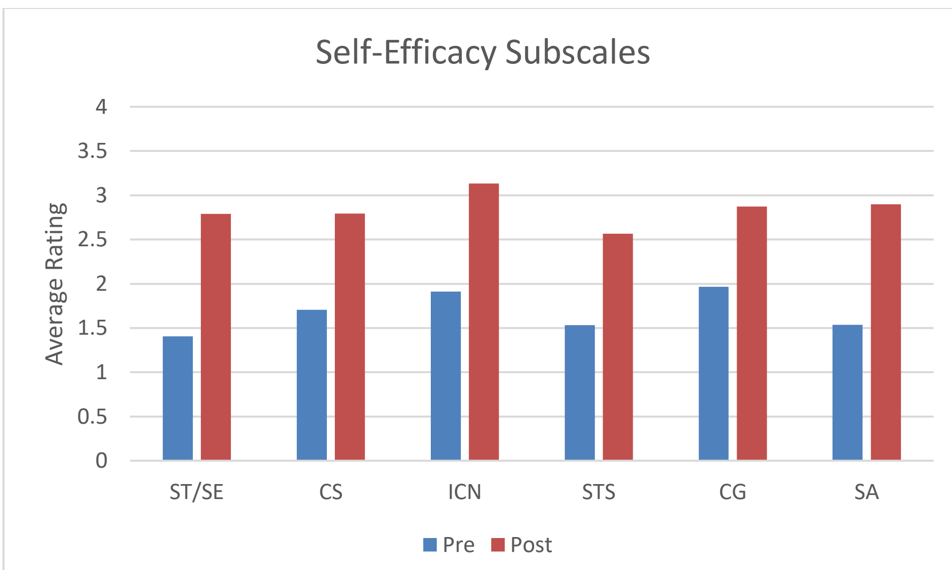

Figure 3. Students' average pre and post self-efficacy ratings, organized by KSA category. ICN = Identify Customer Needs; STS = Set Target Specifications; CG = Concept Generation; CS = Concept Selection; SA = System Architecture; ST/SE = Other ST/SE KSAs.

The technical questions in the STSS are at a level that is above the scope of the intervention that took place in the Introduction to Mechanical Engineering course (see Table 1 and Table 2 in the Introduction section). In general, those questions are geared towards what would be expected of mechanical engineering students at the time of graduation. Thus, data obtained from homework assignments, exam questions, and/or the course project is needed to assess the benefits of the intervention. Nevertheless, the STSS technical questions were analyzed for any changes.

As expected, students' performance on the technical questions did not change from pre-test to post-test. At pre-test, students completed the technical questions with accuracy of 0.59 (on a scale of 0 to 1); after the post-test, students completed the technical questions with accuracy of 0.55; $t(33) = 0.89$, n.s. (see Figure 4). This lack of change in performance could be attributed to several factors. First, as was mentioned before, the assessment items where at a higher level than the scope of the intervention. The questions targeted rather advanced levels of ST/SE skills for a first-year course (e.g., around Bloom's taxonomy level "apply"). Also, it is possible that the students were less motivated to answer questions carefully at the post-test relative to the pre-test, given busyness and fatigue at the end of the semester. There are also other possible factors including the validity, reliability, and difficulty of the instrument. It is worth noting that, in parallel with the instructional intervention described in this paper, we are evaluating the psychometric properties of the STSS and working to improve its quality as an assessment instrument.

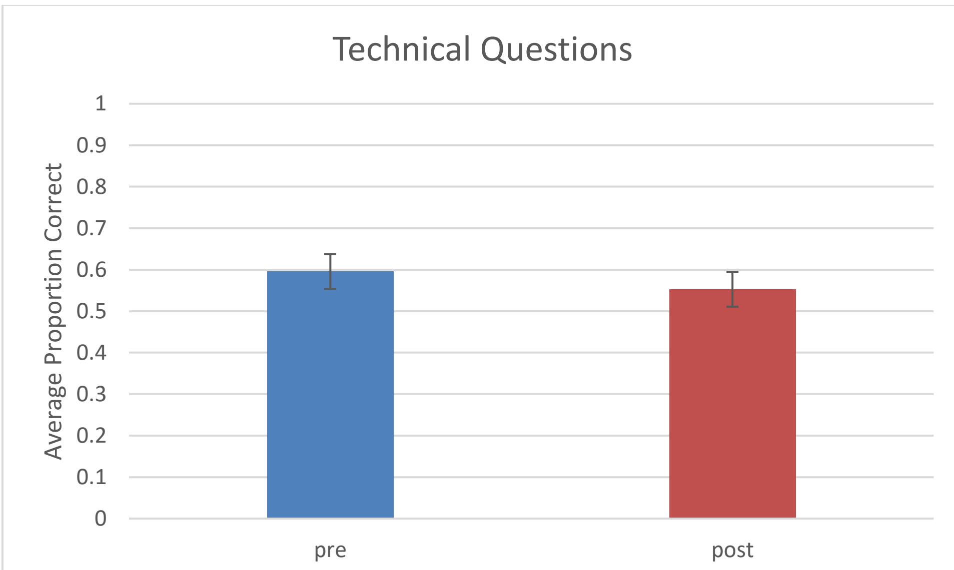

Figure 4. Students' pre- and post-test accuracy on the technical questions of the STSS.

Unlike the technical questions in the STSS, the ST/SE-related questions included in homework assignments and exams were consistent with the scope of the intervention. For example, an exam question asked students to list three elements of the operating environment or context of an all-terrain vehicle (ATV). The answer was graded based on how many of the three elements listed could reasonably be considered part of the operating environment of an ATV. Of the 58 students that took the exam, 25 (43.1%) received all the points corresponding to the problem, 6 (10.3%) received two-thirds of the points, 4 (6.9%) received one-third of the points, and 23 (39.7%) received zero points. Students that provided incorrect answers typically listed elements of the ATV rather than elements of its operating environment.

In the case of the ST/SE-related questions included in the homework assignments, some of the questions were such that evaluating the student responses was straightforward. For example, in one problem students were asked to identify the external interfaces between a mountain bicycle and its rider. Taking into consideration the level of the course and that the students were learning the concept of interfaces for the first time, an answer was considered to be satisfactory if the student identified the seat, the handlebar, and the pedals. Of the 54 students that completed the assignment, 53 provided a satisfactory answer.

There were other ST/SE-related homework questions for which the authors felt that a more detailed analysis of the answers provided by the students was required and the authors are currently working through this analysis. For example, one problem asked the students to watch a video about a prosthetic device [36] and to identify the device stakeholders as well as their needs. In the context of the first implementation, full credit was given for the successful identification of at least three stakeholders and listing a minimum of three reasonable needs for each one. The average score of the 38 students that completed the assignment was 82.5% (the minimum score was 50% and the maximum score was 100%). However, for the purpose of this research, a more detailed evaluation and comparison of individual student responses will be performed and reported in a later publication.

Regarding the course project, Figure 5 shows examples of the boats that the teams built for the competition and Figure 6 illustrates how the boats were tested in the 20-gallon aquarium tank in which waves were generated using four wave pumps. Both the test of the initial boat design and the test corresponding to the actual competition were conducted in a small laboratory and took place outside of the regular class time. Each team had a separate twenty-minute time slot to test their boat and members of other teams were not allowed in the laboratory during that time. This particular format allowed the course instructor to talk about the project with one team at a time. The following observations are based on those conversations:

- During the first test, the students realized the importance of gaining a good understanding of the operating environment of a product/system before generating possible solution concepts. All the teams assumed that the water in the aquarium tank was going to be still and didn't ask questions in that regard when the project was assigned.
- Since the result of the first test didn't have an impact on the project grade, the teams focused on the lessons learned and didn't develop a negative attitude towards the project.
- After seeing that the testing conditions involved waves, the majority of the teams welcomed the challenge and became more interested in the project.
- The teams felt that the project was a good opportunity to put into practice some of the ideas presented in class about product design, ST and SE, static equilibrium, and buoyancy.

The results of the first boat test are consistent with a problem commonly observed in design projects that are conducted in academic settings: many students don't devote enough time and effort to gain a thorough understanding of all the requirements that need to be met (i.e., to fully understand the design problem). Thus, the students end up proposing, and sometimes even building, a design that does what the they think it should do but that fails to meet one or more important requirements. In this regard, design experiences like the short project discussed in this paper can serve as an eye-opener for the students early in their undergraduate education.

Although a specific project was presented here, other short projects emphasizing the same or other important ST/SE concepts could be conceived and implemented. In this regard, it is important to make sure that a proposed project meets the following requirements:

- Attracts the attention of the students.
- Is adequate for the level of the course.
- Requires knowledge consistent with the traditional and the ST/SE topics covered in the class.
- Can be completed by a small team of students in a reasonable amount of time.
- Has a cost within the limits of the available course budget.
- Features parts that can be made with commonly available tools and materials and/or using equipment and materials readily available on campus laboratories.

Regarding the last point mentioned above, the use of 3D printing to make parts could be an attractive alternative if the facilities available on campus can support the number of teams that will be working on the project and the parts the teams may need to make.

Figure 5. Examples of the boats that the teams built for the competition.

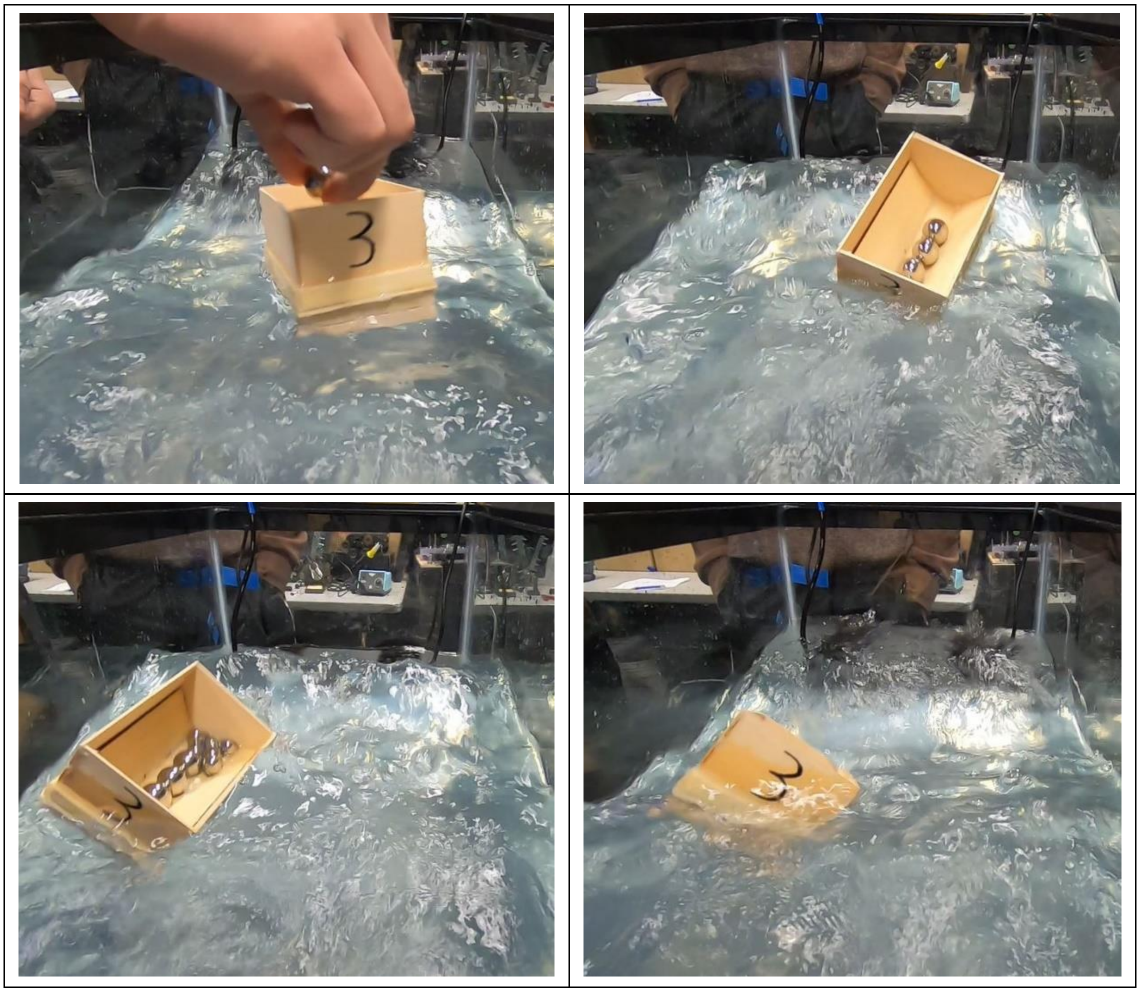

Figure 6. Testing of one of the boats in the aquarium tank fitted with wave pumps.

Conclusions and future work

With the increasing complexity of modern engineering systems comes a corresponding need for engineering graduates with the ST and SE skills to design and analyze them. Developing a ST/SE "spine" throughout the undergraduate curriculum would allow students to gradually develop these skills; however, short of a fundamental curriculum redesign, this would also require infusing ST/SE content in traditionally analysis-heavy classes. This paper has presented one such infusion occurring in a freshman-level mechanical engineering course. The authors believe that interventions of the type described in this paper can be threaded throughout select sophomore and junior courses to substantially improve our graduates' ST/SE skills.

The results of this intervention show substantial improvements in students' self-efficacy in various ST/SE skills. However, the same improvements were not seen on students' performance on ST/SE technical questions of the STSS. This is most likely due to the instrument's calibration to skill levels expected of graduating seniors. Qualitatively, the project performance has shown that students are better at engaging with open-ended design problems by the course's end. Most importantly, they appear to appreciate the need for developing ST/SE skills throughout their undergraduate education. This bodes well for their acquisition of these skills in future courses.

The lessons learned from the first implementation will be used in the future to improve the educational materials proposed for the intervention. Once the final versions of are ready, the authors plan to make them available via an existing website (http://seed.sdsmt.edu/). At the curriculum level, the authors plan to continue their effort of integrating ST/SE topics in other mechanical engineering undergraduate courses. In this regard, the goal is to have at least one course during each college year in which students are exposed to ST/SE concepts. Finally, the idea of transitioning the ST/SE educational materials to an online platform such as Carnegie Mellon University's Open Learning Initiative (https://oli.cmu.edu/) is being considered.

Acknowledgements

This work was supported by the Office of Naval Research under Award No. N00014-18-1-2733. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Office of Naval Research or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation hereon.

The authors want to acknowledge the help of Mr. Ranjun Singh, an undergraduate student at the South Dakota School of Mines and Technology (SDSM&T), in the development of the homework assignments and the modified course project used for the intervention.

Finally, the authors would like to thank the students that took the Introduction to Mechanical Engineering course at SDSM&T in the fall 2019 semester.

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