Extending Systems Thinking Skills to an Introductory Mechanical Engineering Course

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Abstract

Despite a widespread acknowledgement of the importance of systems thinking and systems engineering, most undergraduate programs in mechanical engineering do not formally instruct students in those subjects. While producing graduates ready to fill the role of a systems engineer is not realistic, it is feasible to train mechanical engineering graduates that can successfully participate in the development of a complex product or system.

Prior work aimed at developing and implementing educational materials appropriate for teaching selected systems thinking and systems engineering topics to sophomore-level mechanical engineering students showed that teaching systems thinking and systems engineering skills in the context of a single course is difficult. The work presented in this paper is an extension of that previous effort at the sophomore level and focuses on incorporating basic systems thinking and systems engineering concepts in a freshman-level Introduction to Mechanical Engineering course. The selection of topics and their appropriate cognitive level as well as the proposed implementation approach are discussed. Results from a systems thinking skills survey implemented as a pre- and post-test in the unmodified course are used to highlight the potential benefit of the proposed intervention.

Introduction

In most academic institutions the mechanical engineering undergraduate curriculum places a strong emphasis on preparing graduates that can successfully perform the discipline specific analysis required during the detailed design phase of the product development process (PDP). The curriculum includes well-defined course sequences in areas such as solid mechanics, thermofluid sciences, and dynamics and controls, aimed at gradually developing the analysis capabilities of the students in those subjects. In contrast, the number of courses and practical experiences specifically devoted to learning about the process to design and develop products are usually very limited. Furthermore, in general mechanical engineering undergraduate students have little or no exposure to the fundamental systems thinking (ST) and systems engineering (SE) concepts needed to effectively participate in the development of products involving several subsystems.

Turning our attention to the practice of the profession, the level of complexity of the products and systems that engineers develop keeps increasing at a very fast pace. In addition, as time progresses the customers of those products or systems have higher expectations regarding their quality and performance. Moreover, customers want more features without an increase in price and, in some instances, stricter government safety or environmental regulations also need to be met. There are many examples, like cars and home appliances, that reflect this challenging scenario. Consequently, industry needs mechanical engineering graduates that have the necessary knowledge, skills and abilities (KSAs) to successfully participate in the design and development of complex products or systems.

The fact that companies need engineering graduates with a good foundation in the process to design and develop products and systems is reflected in the new ABET accreditation criteria [1] and in references such as the Engineering Competency Model that was jointly developed by American Association of Engineering Societies (AAES) and the United States Department of Labor (DOL) [2], and the CDIO (Conceiving, Designing, Implementing, Operating) syllabus proposed by the CDIO organization [3]. In the case of the new ABET accreditation criteria, it is interesting to note that it includes a comprehensive definition of engineering design and that the student outcomes refer to complex engineering problems.

Based on the preceding discussion, it is evident that most mechanical engineering undergraduate programs need to include more learning activities that allow students to develop the basic KSAs required to effectively participate in the development of a new product or system. In this regard, fundamental ST and SE concepts need to be formally taught so that students are better prepared to deal with products involving several subsystems.

It is relatively easy for academic institutions that are starting a new mechanical engineering undergraduate program to create a curriculum that includes a sequence of courses and learning experiences to teach product design and development as well as fundamental concepts related to ST and SE. Unfortunately, in the case of existing programs it can be difficult to make substantial modifications to the curriculum. Under those circumstances, the only option is to work within the framework of the curriculum that is already in place. In this regard, most mechanical engineering undergraduate programs have a capstone senior design experience, and many programs include a course in which students learn about product design and development. Unfortunately, basic ST and SE concepts are seldom included as part of these existing courses.

Different efforts to teach fundamental ST and SE concepts to undergraduate engineering students in conventional disciplines have been reported in the literature [4-12]. In most cases, the interventions involve a single course. The work presented in this paper is most closely related to [4], which focuses on introducing ST in the civil engineering curriculum; [9], which applies ST in the industrial engineering curriculum; and [12], which provides guidelines for infusing any curriculum with ST and SE concepts. This paper brings the focus to the mechanical engineering curriculum and discusses specific ways in which freshmen may begin to think about systems holistically.

Prior efforts on incorporating basic ST and SE concepts in an existing sophomore-level product design and development course for mechanical engineering students at the South Dakota School of Mines and Technology (SDSM&T) [13-17] showed the potential benefit of the proposed approach and revealed that introducing those concepts in a more gradual fashion starting in the freshman year was desirable to improve understanding and long-term retention.

The work presented in this paper focuses on incorporating ST and SE concepts in an existing freshman-level Introduction to Mechanical Engineering course. First, background information about the course is provided and results from a systems thinking skills survey implemented as a pre- and post-test in the unmodified course are used to highlight the potential benefit of such an intervention. Then, the ST and SE topics selected as well as the cognitive level at which they will be taught are presented. Finally, the proposed approach to add the ST and SE topics selected to the course is explained.

Course description

The mechanical engineering undergraduate program at SDSM&T has a required two-credit Introduction to Mechanical Engineering course during the first semester of the freshman year. The primary purpose of the course is to introduce students to the mechanical engineering profession and to present fundamental concepts in major areas of mechanical engineering such as solid mechanics and fluid mechanics. Because it is a first-year course, the backgrounds of the students are widely varied in both areas of interest and academic preparation. The course utilizes and follows the textbook "An Introduction to Mechanical Engineering" by Wickert and Lewis [18]. A list of topics typically covered in the course is shown in Table 1.

Table 1. Major topics typically covered in the Introduction to Mechanical Engineering course.

Topic List
Introduction to mechanical engineering
The design process
Manufacturing processes
Introduction to engineering drawing
Problem solving
Units
Significant figures
Estimation in engineering
Engineering ethics
Force vectors
Force resultants
Moment of a force
Equilibrium
Tension, compression, and shear of materials
Engineering materials
Factors of safety
Stress and strain
Buoyancy
Overview of fluids engineering
Properties of fluids
Fluid flow
Drag and lift force

The course culminates with a short final project in which students work in teams. Students are assigned teams using CATME [19], and are asked to create an exceptionally buoyant boat. Teams must model their boat design in SolidWorks and 3D print the boat using MakerGear printers available on campus. The constraints on the project are that the boat must be contained within a given volume and must all be printed of the same material. The goal of the project is to create the most buoyant boat with a minimal overall boat weight. At the end of the semester, a competition is held to see which boat has the highest ratio of final ballast weight before sinking to overall weight of the boat. A panel of judges is also asked to rate boats on the overall design (aesthetics, function, feasibility, etc.). Students are graded based on the results of the competition, their team's technical presentation and final project memorandum, and an internal team evaluation. The purpose of the project is to give students a hands-on experience where they can display their knowledge of topics discussed during the course.

Upon completion of the course, students are expected to be able to identify career opportunities for mechanical engineers, understand and use engineering units, follow a systematic approach to solving problems, and demonstrate competence in engineering fundamentals in various mechanical engineering areas such as solid mechanics, engineering materials, fluids engineering, and thermal and energy systems. It should be noted that due to the large list of topics covered in the course, there is typically no time to cover thermal and energy systems, and these topics are addressed in a future course in the curriculum.

Baseline survey results

During the fall 2018 semester a previously developed systems thinking skills survey (STSS) [16, 17] was implemented as a pre- and post-test in the unmodified course in order to collect baseline data. Participation in the survey was voluntary. The STSS was implemented using SurveyMonkey® and the students that decided to participate completed the survey out of the classroom. The pre-test was applied the first week of classes and 56 out of 58 students answered the survey. The post-test was applied the last week of classes and only 34 students completed the survey.

The STSS [16, 17] has two sections. In the first section students use a Likert-scale to report their perceived level of self-efficacy in different topics related to ST and SE. This section represents an indirect measure of students' abilities because students are reporting their *perceptions* of their abilities. By contrast, in the second section, students need to apply knowledge in ST and SE to answer several questions (i.e., direct measure of students' ability to apply ST and SE concepts and skills). Each question provides a product or system familiar to most engineering students for context.

The first section of the STSS includes 44 items asking students "How well do you think that you can apply the topics mentioned below to an engineering project?" Student responses are collected via a 5-point Likert scale, ranging from 1=Not at all to 5=Excellent. These 44 items are grouped into five categories – Identifying customer needs, Setting target specifications, Concept generation, System architecture, and Other – thus creating a sub-scale for each category. Table 2 provides a sample item and the number of items for each category/sub-scale.

Students' self-assessment ratings at pre- and post-test for each of the five categories are presented in Figure 1. Students' ratings significantly improved from pre- to post-test overall even though ST and SE concepts were not addressed in the course ($mean_{pre} = 2.41$; $mean_{post} = 3.49$; $t(63) = 4.9$, $p < .01$). On average, students' self-assessments increased by approximately 1.08 (on the 5-point scale used) from pre-test to post-test. This is not necessarily surprising considering that students may have felt greater self-efficacy in general at the end of the course and given the consistent finding that students' self-assessments are not accurate, often reflecting over-confidence (e.g., Kruger & Dunning, 1999 [20]). This finding of a significant pre/post improvement in student perceptions when the course was unmodified points to the fact that the second section of the STSS – i.e., direct assessment of students' ability to apply ST and SE knowledge and skills – is essential for an accurate assessment of student learning.

Table 2. STSS self-efficacy categories with sample items and number of items for each.

Category	Sample Item	# Items
Identifying customer needs	Assigning relative importance to customer needs	4
Setting target specifications	Creating a thorough list of system performance metrics	9
Concept generation	Generating multiple alternatives for the design of a product or system	13
System architecture	Identifying the boundaries and external interfaces of a product or system	12
Other	Defining the life cycle for a product or system	6

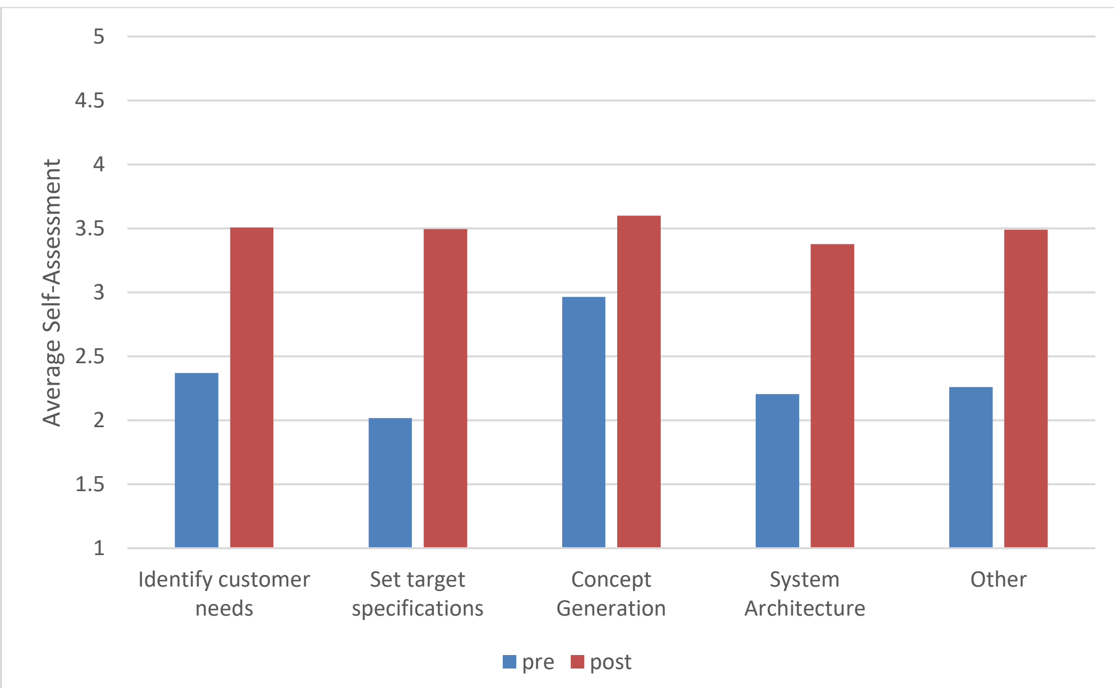

Figure 1. Students' average self-efficacy ratings from the STSS, at pre- and post-test, for each of the five categories.

For the second part of the STSS, students were asked to apply their ST/SE knowledge and skills in the context of technical problems. The contexts for these problems were chosen to be relatively familiar objects (computer, lawn equipment, jewelry) so students' prior knowledge of the objects would be consistently high, allowing the assessment to focus on ST/SE knowledge and skills. Many of the items involved multiple aspects of ST/SE knowledge and skill (according to domain experts' task analysis), so unlike the self-assessment section, there are no sub-scales reported here. Students' aggregate post-test scores were not significantly different from their pre-test scores (pre-test average = .52; post-test average = .53; $t(68) = 0.40$, n.s.), as shown in Figure 2. This finding of virtually no change in students' directly assessed abilities was expected. It provides a useful control measure of the change in student ST and SE knowledge and skills to be expected over the course of a semester in an unmodified course.

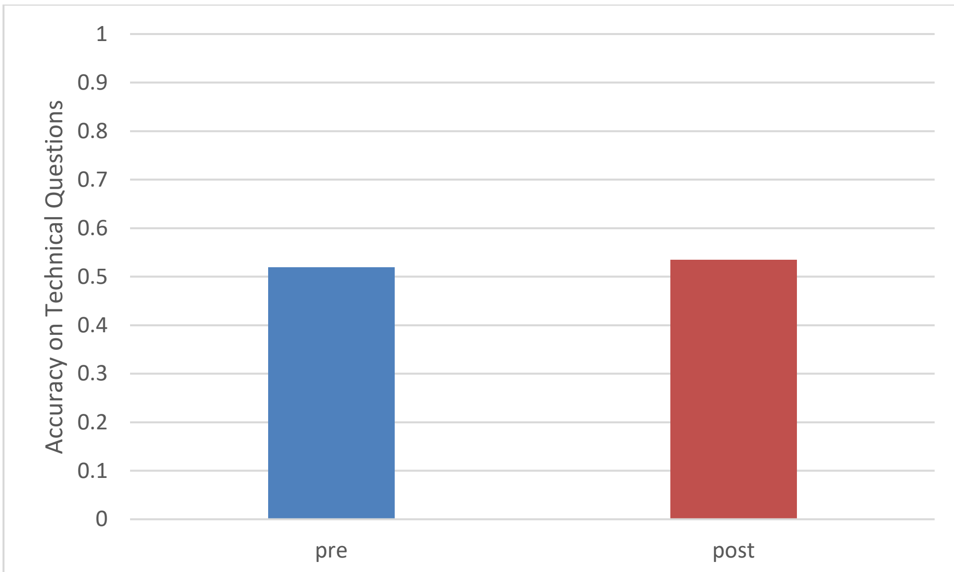

Figure 2. Students' accuracy on the second section (technical questions) of the STSS at pre- and post-test.

Selection of systems thinking and systems engineering topics for the course

The list of ST and SE topics selected for an intervention in a sophomore-level product design and development course at SDSM&T [15] was used as the starting point for the process of identifying the topics that would be added to the Introduction to Mechanical Engineering course as well as an appropriate level for each one based on the revised Bloom's taxonomy [21]. The following factors were taken into consideration during that process:

- The level of the course.
- The number of credit hours of the course and the topics currently covered in the class.
- A long-term vision of gradually developing the ST and SE skills of the students via interventions in different courses throughout the mechanical engineering undergraduate curriculum.

The topics selected and the level at which they are presented need to be appropriate for freshman students. In addition, the intervention cannot have a substantial impact on the amount of time available in and out of the classroom for the other topics that need to be covered in the course. Finally, the ST and SE topics covered in the Introduction to Mechanical Engineering course need to serve as a stepping stone for those that are considered in the sophomore design course.

Table 3 presents the ST and SE topics that were selected for the intervention in the Introduction to Mechanical Engineering course as well as the target cognitive level for each topic according to the revised Bloom's taxonomy. An important aspect that is not addressed in Table 3 is the level of complexity of the products that will be used in examples and learning activities related to the topics listed. Taking into consideration the factors mentioned at the beginning of this section, it was decided that the educational materials and activities that will be developed must be based on simple products that are easy for freshman students to grasp.

Table 3. ST and SE topics selected for the Introduction to Mechanical Engineering course.

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

Before proceeding to discuss the proposed implementation approach, there are a couple of points that are worth mentioning. For most of the discipline specific mechanical engineering courses that focus on analysis, the modified Bloom's taxonomy is sufficient to express the expected outcome for each topic covered in the class. In the case of topics related to ST and SE, the authors feel that it is necessary to consider a second dimension when establishing the desired outcomes: the level of complexity of the product or system. For example, after covering the topic of interfaces in a junior-level course, a student may be ready to define the interfaces of a simple product. However, he/she may only be able to identify interfaces in a complex system, not to define them. Thus, a classification that is easy to understand and convenient to use is needed to characterize the level of complexity of products and system.

Identifying all the relevant stakeholders for a product or system and gathering their requirements is crucial for the success of a product development effort. Unfortunately, most engineering students think that they don't need to be involved in those initial activities of the PDP and that their work begins when someone else provides them a list of target specifications. In part, this attitude could be the result of the type of problems that engineering students are usually asked to solve in most of their technical courses: well-posed problems where they are given some information and data in the problem statement, and then are asked to perform calculations in order to find some desired results. Introducing freshman students to the topics of identifying stakeholders, identifying customer needs, and product/system validation, may help to alleviate this situation.

Finally, the authors hope that introducing ST and SE concepts in a freshman-level course will help students understand the importance of adopting a holistic point of view during the design of products or systems before they are constantly exposed to a reductionist approach in the large number of analysis intensive courses that are part of the curriculum.

Proposed implementation approach

After reviewing the topics covered in the existing freshman-level Introduction to Mechanical Engineering course, it was determined that:

- Modifications could be made to the original course content in order to have three 50-minute class sessions entirely devoted to the intervention.
- Examples currently used to illustrate some of the original topics could be replaced with examples that also illustrate one or more of the topics listed in Table 3.
- The short project that the students complete towards the end of the semester could be changed so that it allows them to utilize some of the ST and SE concepts that they learned during the semester.

Regarding the three class sessions devoted to the intervention, one will be used to give a general overview of the product design and development process, and the remaining two will be used to teach the topics listed in Table 3. The overview of the product design and development process will be based on the generic PDP proposed by Ulrich and Eppinger [22] for “market-pull” products of low to moderate complexity. The instructional approach that will be used in the three class sessions involves a combination of lectures that include several relevant examples, short in-class activities, and homework assignments that don’t require too much time to complete. For the lecture portion, a concerted effort will be made to present concepts in a concise manner and to select examples that capture the attention of the students. Based on feedback collected from the students enrolled in a section of the unmodified Introduction to Mechanical Engineering course taught during the fall of 2018, areas of interest to freshman students include: NASA/space, hands-on building, farm equipment, prosthetics/medical devices, sustainability, entrepreneurship, cars, and sports equipment. As can be expected, some of the areas mentioned by the students are a consequence of the geographic location of SDSM&T and the demographics of the students enrolled in its undergraduate mechanical engineering program.

An important aspect regarding the development of the instructional materials is sequencing the topics in logic progression. For example, before providing a definition of systems thinking or system engineering, students need to be exposed to the ideas of systems and system boundaries, system elements, etc. In this regard, an undergraduate mechanical engineering student will be involved during the development of educational materials and learning activities to make sure that they are at an adequate level and that the examples used remain relevant and of interest to students taking the course.

In the unmodified course, the structure of the class is such that a topic from Table 1 is briefly introduced and then examples are given for students to work through in class with or without the instructor’s guidance. These in-class examples provide a convenient opportunity for illustrating selected SE and ST topics from Table 3. The initially identified places where the traditional topic can be easily used to exemplify ST and SE topics are: problem solving, units, engineering ethics, and factors of safety. For example, the case of the NASA Mars Climate Orbiter [23] could be discussed while covering the topic of units. Besides serving to illustrate the use of different systems of units to represent physical quantities, students could see how a transfer of purely numerical data between two separate teams using different systems of units led to the loss of the spacecraft. Expanding further, the instructor could discuss numerical data transfer at interfaces between subsystems.

The existing final project for the course described in a previous section of this paper will also be slightly modified to highlight ST and SE topics in Table 3. The project will be driven by the product design and development process that students will learn early in the course. The project will also span a longer time period, allowing students to create an initial prototype and to test it in a "pre-competition". During this testing phase, an outside factor will be introduced that students may not have considered during the first iteration, such as waves within the testing tank. Teams will then have an opportunity to redesign based on what they may have not considered about the overall system of the boat and testing parameters.

Modifications to the Introduction to Mechanical Engineering course from the general overview of the product design and development process, the updated examples for existing topics, and the changes to the final project will strive for an overarching goal to highlight each ST and SE topic chosen for the course (see Table 3). In this manner, the authors envision that freshman students will have a solid foundation in ST and SE and be more capable to handle more complex problems in future courses.

Conclusions and future work

To make a significant impact in the systems thinking and systems engineering education of undergraduate mechanical engineering students, carefully selected ST and SE topics should be integrated through the entire undergraduate curriculum. In addition, it is necessary to gradually increase the complexity of the products and systems considered so that the topics and activities can build upon each other and students can be better prepared to participate in the design of more complex products and systems when entering the workforce. Building upon the authors' prior work on integrating selected ST and SE topics in a sophomore-level design course [14-17], this paper outlined a possible approach to translate that effort to other stages within an undergraduate mechanical engineering program, specifically at the freshman-level.

The baseline STSS results reported here highlight the potential of the proposed intervention to significantly improve students' abilities in ST and SE. For example, average post-test performance on technical questions was only 53%, indicating plenty of room for learning and improvement. In addition, the difference in results between the two sections of the STSS – namely, significant change in students' self-efficacy (perception) vs. no significant change in students' performance (direct measure) – emphasizes the importance of including direct performance measures in assessments of ST and SE.

The educational materials for the first implementation in the freshman course will be ready by August of 2019 and the first offering of the modified Introduction to Mechanical Engineering course will occur in the fall 2019 semester. The effectiveness of the intervention will be assessed using an improved STSS that is currently under development as well as analyzing the performance of the students on in-class and homework assignments related to the ST and SE topics presented in the course. In addition, a brief satisfaction survey will be used to collect student feedback regarding the ST and SE educational materials and learning activities.

In the long term, it is expected that the results from the interventions in the freshman-level Introduction to Mechanical Engineering course considered here, the sophomore-level product design and development course at SDSM&T [14-17], and a senior capstone design course at Carnegie Mellon University (CMU), will provide the foundation for incorporating fundamental ST and SE concepts throughout the entire mechanical engineering curriculum.

Finally, once a successful approach to incorporate fundamental ST and SE concepts in the mechanical engineering undergraduate curriculum is established, it could be adapted to other traditional engineering majors. The latter would require identifying appropriate courses for interventions, developing educational materials that take into consideration the interests of the students in the major, and adjusting the assessment instrument so that the students are familiar with the products or systems considered in the technical questions. Also, the group leading the effort should include faculty members that are very familiar with the curriculum of the major in which ST and SE concepts will be incorporated.

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