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A Combined Online Learning / In-Class Activity Approach to Teach Systems Thinking and Systems Engineering Skills to Freshman Engineering Students

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Abstract

Engineering graduates from traditional disciplines (e.g., mechanical engineering) have felt increasing pressure to develop holistic, systems thinking mindsets to tackle today's complex engineering challenges. Some engineering programs have reacted by introducing the fundamentals of systems thinking and systems engineering throughout design courses. However, a stronger approach might be to thread systems thinking / systems engineering skills vertically throughout the curriculum to build students' knowledge gradually. This paper considers infusing such an introduction into a freshman level introduction to mechanical engineering course.

The intervention studied in this paper consisted of two parts: an online learning module developed using the Online Learning Initiative (OLI) platform that introduces both the engineering design process and the fundamentals of systems thinking, and an in-class design exercise in which student groups brainstormed the design of a quadcopter delivery service. When systems thinking was initially introduced in the course, the in-class portion was used to present the material now contained in the OLI. The goal of the new approach was to solidify students' skills by allowing students to directly practice their systems thinking / systems engineering knowledge. The effectiveness of the OLI was determined through the use of the Systems Thinking Skills Survey, which was administered to some students before and some after they completed the OLI. The overall approach was effective in better engaging students in a remote learning environment.

Introduction

Engineers from all disciplines develop products that increasingly feature multiple interacting subsystems. These complex systems force engineers to take a systems engineering perspective that formally analyzes and exploits interactions in the design. For instance, many products that were previously fundamentally mechanical now involve mechatronic components to implement smart features or connect to networks. These mechatronic systems require engineers to understand the system dynamics, the fundamentals of sensing and actuation, the basics of embedded computation and communication networks, and most importantly how all of these subsystems interact in defining overall system performance. Given that the vast majority of engineering graduates come from traditional engineering disciplines rather than systems engineering, there is a need to infuse fundamental systems engineering topics / concepts throughout conventional engineering curricula.

Teaching systems engineering to undergraduate students is difficult for several reasons, among them students' lack of experience in interacting with diverse stakeholders and preference for the well-defined problems common in engineering curricula[1,2]. In the mechanical engineering discipline there have been efforts to incorporate systems thinking activities in courses ranging from the freshman level[3] to the senior capstone course[4], including several by the authors[5,6,7,8]. The work in this paper targets freshman students, and hence is most closely related to[7,8,3]. It differs from prior efforts by taking a flipped classroom approach, with technical content embedded in an online learning module and class time used to perform a group design activity.

An effective means of measuring students' systems thinking / systems engineering skills is needed to assess the effectiveness of the intervention. There have been several approaches in the literature, ranging from comprehensive written / practical exams[9] to computerized tests that measure specific systems engineering skills[10]. This paper uses a survey instrument called the Systems Thinking Skills Survey (STSS)[6] which includes both self-efficacy questions and technical questions to assess students systems engineering skills.

This paper describes results of a flipped-classroom learning experience on systems engineering geared toward freshman mechanical engineering students. First, both online and in-class elements of the intervention are discussed, followed by a description of the assessment approach. Then results are provided that include embedded assessments in the online learning module, designs created in the in-class collaborative exercise, and finally pre- / post-intervention data via the STSS. Finally, the paper concludes by considering implications for curriculum-wide approaches to injecting systems engineering skills into the conventional mechanical engineering curriculum.

Methods

The interventions described in this paper occurred in Carnegie Mellon University's Fundamentals of Mechanical Engineering course. All students at Carnegie Mellon University (CMU) select two introductory engineering courses during their freshman year before formally declaring a major at the beginning of the sophomore year. The introductory mechanical engineering course is the second largest at CMU, with a class size between 120 and 150 students. Like other universities worldwide, the fall 2020 semester was taught in a "hybrid" mode at CMU, with students attending lecture remotely and recitations sections in-person. There were 127 students enrolled in the fall 2020 offering of the course.

The course content focuses on fundamentals in various branches of mechanical engineering along with development of students' practical engineering skills (CAD and fabrication) and professional skills (teamwork and communication). The specific learning outcomes are as follows.

- Describe the role of mechanical engineers in society and identify career opportunities within the field

- Implement a systematic approach to solving problems including accurate use of engineering units
- Apply engineering fundamentals to solve problems in various areas of mechanical engineering
- Use CAD, basic fabrication, and microcontroller tools to develop virtual and physical prototypes for testing
- Effectively launch a team in which members (a) recognize and support each others' styles and strengths and (b) generate and agree to ground rules that they will use to help guide their collaboration
- Build consensus and recognize and address emerging conflicts using active listening and assertion messages
- Apply the engineering design process through the concept development phase and discuss how diverse viewpoints are needed to address engineering challenges

The intervention described here specifically addresses the last item by adding systems engineering content when teaching the design process. The engineering design topic is taught within the first week of the course to try to instill a holistic mindset before moving on to well-defined engineering science problems.

OLI Module

The online learning module was developing using the Open Learning Initiative (OLI) platform developed at CMU[11]. The OLI platform aids educators in developing online learning modules by clearly linking activities to learning objectives and supporting both formative and summative assessments. The fundamental strategy was to migrate previously developed learning materials[8] to the OLI platform while developing supporting assessments. The OLI module has two "units": unit one covers a conventional introduction to the product development process, whereas unit two focuses on fundamental definitions in systems engineering along with the importance of applying a systems thinking mindset. Figure 1 shows the student view of the unit that deals with the product development process, and Figure 2 shows the unit on systems thinking and systems engineering. As can be seen in the figures, the learning objectives are displayed along with all modules associated with each unit. It is important to note that the learning objectives are hierarchical; as the students click through the modules, learning objectives become more specific to the pages that they are viewing.

The product development process (PDP) for products of low to moderate complexity proposed by Ulrich and Eppinger[12] is used as the general framework for the first unit. The intent is to make students aware of the activities that take place during the main phases of the PDP, placing more emphasis on the concept development phase since it is directly tied to one of the course objectives. Once the students have completed the overview of the PDP, the context is set for presenting basic systems thinking and systems engineering concepts.

The systems thinking and systems engineering topics considered in the second unit were taken from prior work[8]. For reference purposes, Table 1 summarizes the topics considered and the level

Module 1 / Engineering Design

LEARNING OBJECTIVES

Acknowledge the importance of engineering design

Understand how engineering design works

Why Study Product Design? 2
Definition of Engineering Design 3
Successful Design is Hard! 4
Engineering Competency 5

Figure 1: Landing page for the product development process unit of the OLI. Note the prominent placement of the learning objects and clear layout of the modules within the unit.

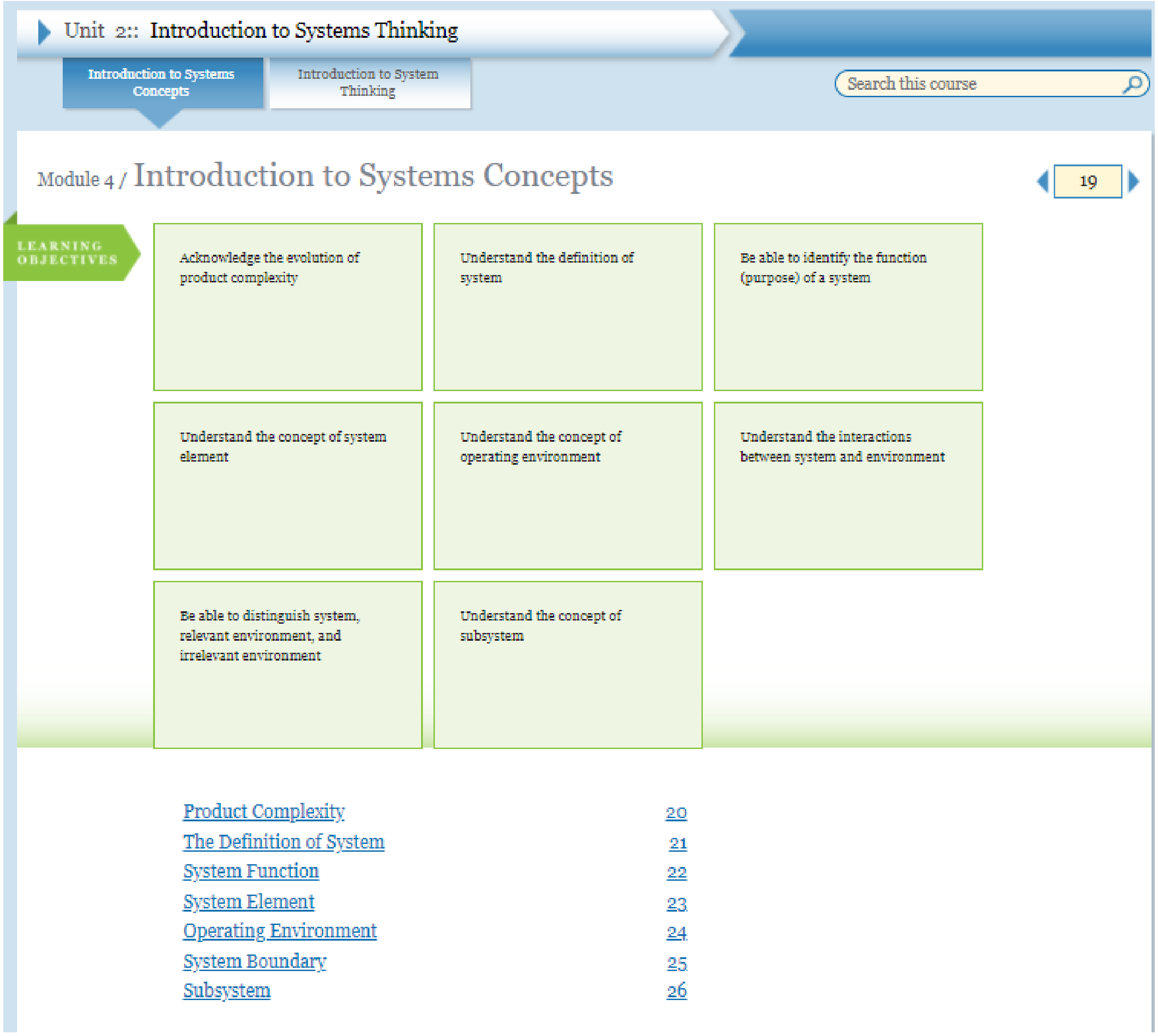
from the revised Bloom's taxonomy at which they are addressed. The topics are presented in the unit in the order in which they are listed in the table.

Formative assessments are embedded into the OLI on various pages to test students' understanding and increase engagement. The questions were written at a level of basic understanding and included multiple question types (short answer, multiple choice, and matching). An example question is shown in Figure 3, which reveals the use of two different question types to test student understanding of interfaces and interactions for an artificial limb. Prior to answering this question students watch a short video on artificial limbs to understand the system context.

The OLI was assigned to students the first day of class and was due on the second class session. It took approximately three hours for students to complete both units, which is about the same time that was previously devoted in class to cover the topics. No specific credit was given for completing the OLI outside of participation, and 2/3 of the students enrolled in the course completed the full OLI (nearly all at least started it). A high degree of participation was expected because these were freshman students within their first week of college.

In-Class Activity

In-class time was devoted to an activity in which students worked on the conceptual design for a quadcopter delivery service that could be used to make deliveries in urban environments. There were four breakout sessions within the one hour fifty minute class in which small groups of students worked on the problems of stakeholder identification, customer needs, target specifications, and concept generation. Students were asked to limit the design to retrofits to existing quadcopter platforms (i.e. they assumed that they would retrofit their solution to existing



Unit 2:: Introduction to Systems Thinking

Module 4 / Introduction to Systems Concepts

LEARNING OBJECTIVES

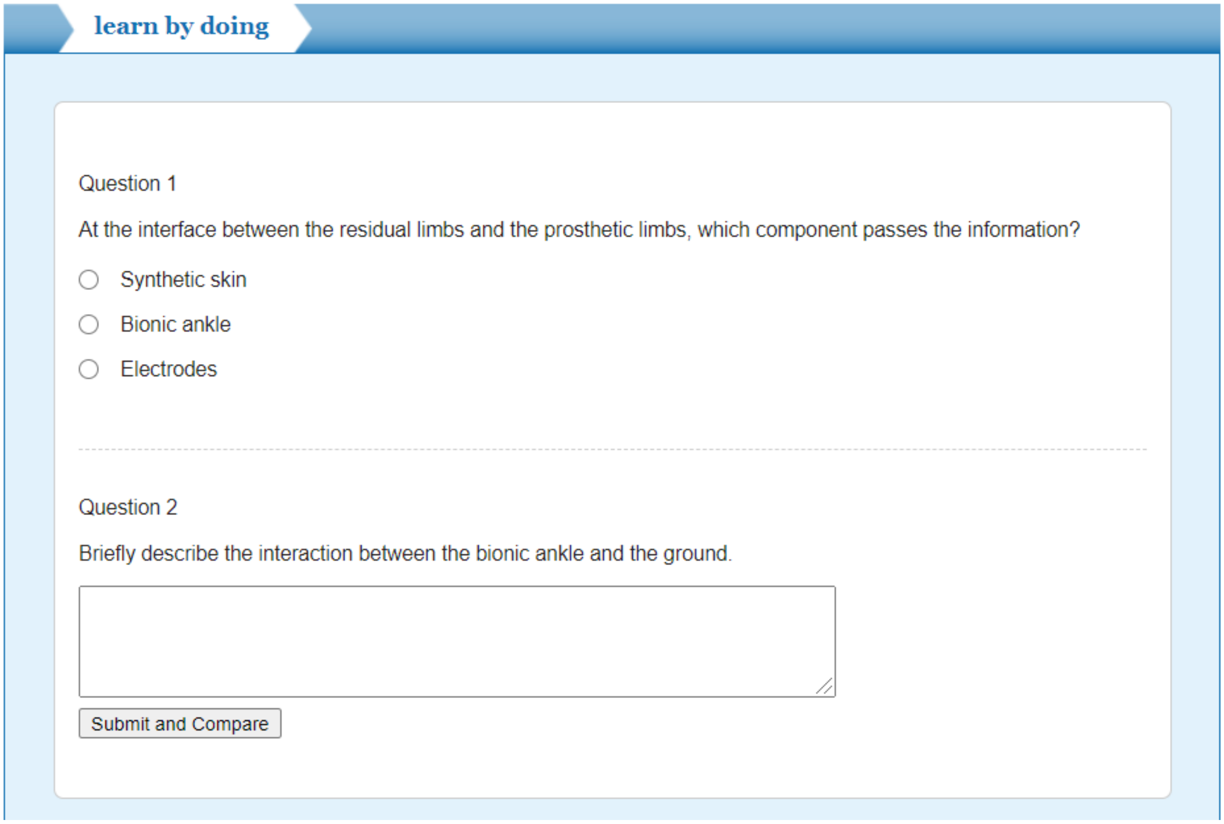
- Acknowledge the evolution of product complexity
- Understand the definition of system
- Be able to identify the function (purpose) of a system
- Understand the concept of system element
- Understand the concept of operating environment
- Understand the interactions between system and environment
- Be able to distinguish system, relevant environment, and irrelevant environment
- Understand the concept of subsystem

Product Complexity	20
The Definition of System	21
System Function	22
System Element	23
Operating Environment	24
System Boundary	25
Subsystem	26

Figure 2: Landing page for the systems engineering unit of the OLI. The systems engineering unit has a more fine-grained set of learning objectives associated with it.

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

Table 1: Topics and their associated Bloom's taxonomy levels taken from prior work[8]. As should be expected for a freshman course, the coverage was at a relatively low level for each item.



Question 1

At the interface between the residual limbs and the prosthetic limbs, which component passes the information?

○ Synthetic skin

○ Bionic ankle

○ Electrodes

Question 2

Briefly describe the interaction between the bionic ankle and the ground.

Figure 3: Example formative assessment based on an artificial limb. This question includes both a multiple choice and a short answer portion.

drone designs), with some examples of delivery drones shown in class before the activities. Before each student activity the main highlights of the OLI content were reviewed both to reinforce concepts for students who completed the OLI and to give minimal background to students who did not. Students completed each activity on a shared Google drive document.

After each activity, solutions were discussed as a class. With the large number of student groups there was little need for instructor-generated solutions; the union of student solutions for most activities created a sufficient coverage of the design space for the exercise. Student participation in the class discussion was high over the Zoom chat with each group contributing.

STSS Delivery

Students were instructed to complete the STSS prior to completion of the OLI material and were also given the STSS at the end of the class. In total, 41 of the 127 students in the course completed the STSS for both phases. Many students said that they were unaware of the pre-test; it was only communicated via a Canvas announcement, whereas the OLI was discussed in the first class session. Ten of the students who completed both the pre- and post-tests took the pre-test after completing the OLI and were excluded from the analysis, which means that pre/post data from 31 students was used in analyzing STSS results in the next section.

Results and Discussion

The intervention's effectiveness was evaluated via three methods: performance on formative assessments within the OLI, analysis of student artifacts from the in-class design exercise, and study of the pre- and post- STSS results. Given the relatively low level of the OLI questions, student performance was high throughout the OLI questions with the exception of a question on identifying external stakeholders. Across the twelve OLI assessments the median score was 94% and the mean was 86%, with the mean dropping substantially due to a single question as shown in Figure 4. The question that students struggled with focused on external stakeholders and featured two internal stakeholders in the list of options. The primary reason for the low score was that the question was of "select all that apply" form and credit was given only for completely correct answers. If partial credit were given for each item of the selection list, the score would have been in the 80% range.

Students completed their in-class work on a shared Google slides document, with each student group working on a single slide. An example of student work is presented in Figure 5. There were 41 groups in total who worked on the activity. The student submissions were evaluated by examining the number and quality of student entries in each category (stakeholders, customer needs, target specifications, and concept generation). Each response was evaluated on a three point scale for each category, with three corresponding to the best performance. Note that the "best" performance does not necessarily mean a good design; students had very little time to consider the design of a complex system, and the assessment focused on to what extent students demonstrated basic competence. The score distribution is shown in Figure 6, which shows that students generally performed strongest in generating customer needs and weakest in concept generation. The customer needs activity requires little technical sophistication and relatively little time for the students to come up with long lists. However, the generation of technical concepts

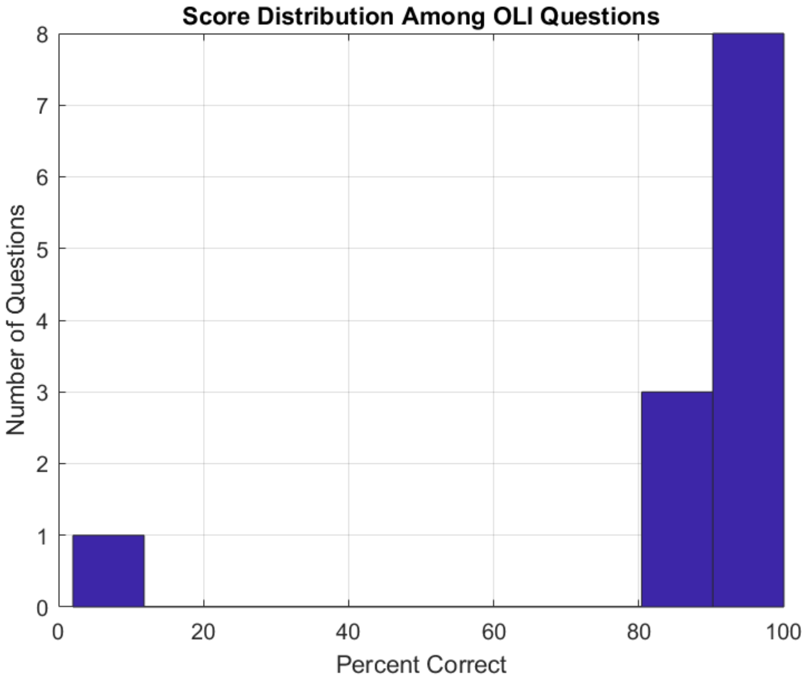
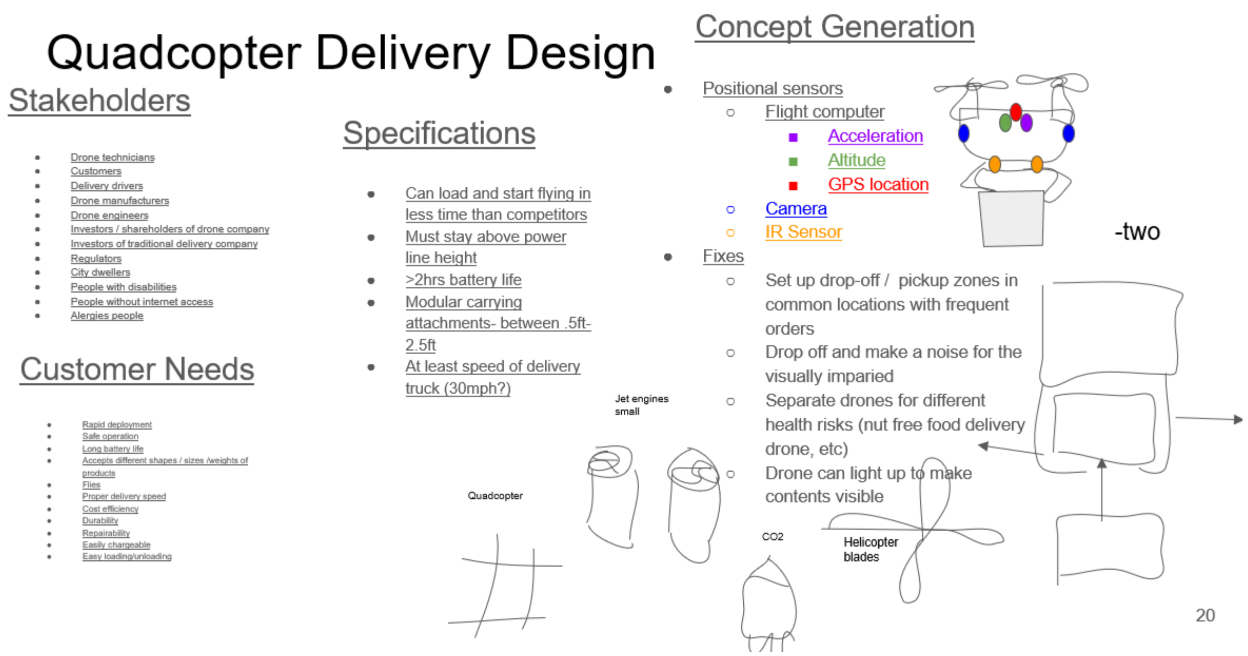


Figure 4: Histogram of OLI assessment performance. Only a single item fell below 80% performance; this question was a "select all that apply" question on external stakeholders with several internal stake holder distractors.



Quadcopter Delivery Design

Stakeholders

- Drone technicians
- Customers
- Delivery drivers
- Drone manufacturers
- Drone engineers
- Investors / shareholders of drone company
- Investors of traditional delivery company
- Regulators
- City dwellers
- People with disabilities
- People without internet access
- Alergies people

Customer Needs

- Rapid deployment
- Safe operation
- Long battery life
- Accepts different shapes / sizes /weights of products
- Flies
- Proper delivery speed
- Cost efficiency
- Durability
- Repairability
- Easily chargeable
- Easy loading/unloading

Specifications

- Can load and start flying in less time than competitors
- Must stay above power line height
- >2hrs battery life
- Modular carrying attachments- between .5ft-2.5ft
- At least speed of delivery truck (30mph?)

Concept Generation

- Positional sensors
  - Flight computer
    - Acceleration
    - Altitude
    - GPS location
  - Camera
  - IR Sensor
- Fixes
  - Set up drop-off / pickup zones in common locations with frequent orders
  - Drop off and make a noise for the visually impared
  - Separate drones for different health risks (nut free food delivery drone, etc)
  - Drone can light up to make contents visible

Figure 5: An example of student in-class work. Students worked through the design process up to the concept development phase. Submission quality can be judged by the quality and quantity of responses in each category. This particular submission was considered to be among the best.

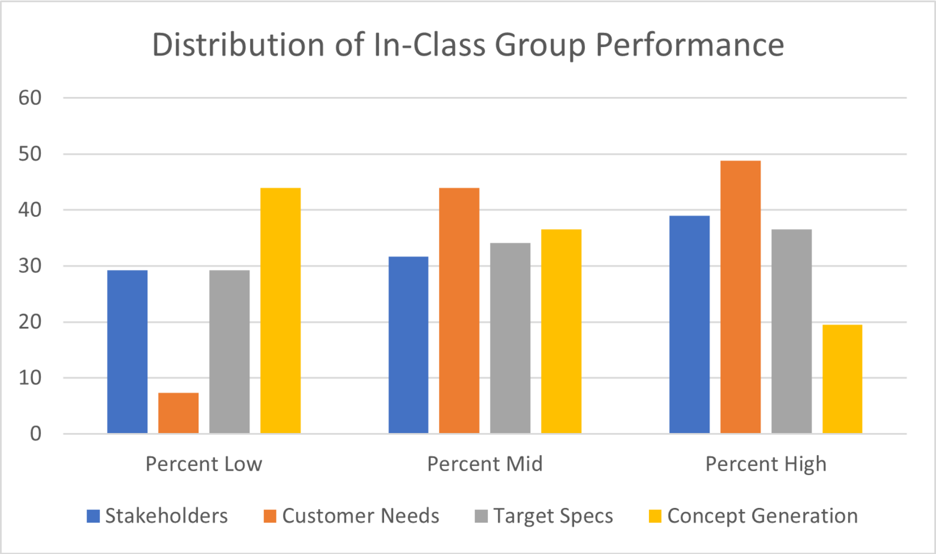


Figure 6: Score distribution for in-class activities. Students performed best in customer needs and worst in concept generation.

Category	**Pre Mean**	**Post Mean**	**Z**	**N**	p
Overall	1.81	2.70	-4.63	31	<0.001*
Systems Engineering	1.73	2.63	-4.63	31	<0.001*
Concept Selection	1.76	2.62	-4.37	31	<0.001*
Customer Needs	2.02	3.05	-4.58	31	<0.001*
Target Specifications	1.67	2.68	-4.20	31	<0.001*
Concept Generation	2.12	2.88	-4.07	31	<0.001*
System Architecture	1.76	2.61	-4.26	31	<0.001*

Table 2: Self-efficacy results by category. Students showed statistically significant improvement in all categories (* indicates $p < 0.05$).

may require technical knowledge that is not available to some freshman engineering students. In addition, student feedback suggested that they felt more rushed during the concept generation phase and more burdened by the Google slides collaboration platform. Overall, most student groups produced reasonable design concepts given the time allotted, which indicates that the highlights of the design process were adequately covered through the OLI and in-class refresher material.

Finally, results from the STSS were used to determine how the course impacted students' self-efficacy and technical proficiency in selected systems engineering concepts. Figure 7 shows the overall change in mean self-efficacy score and Table 2 shows the breakdown of results by skill category. It is clear that taking the course has improved students' self-efficacy significantly across a broad set of skill categories; what is less clear is to what extent this improvement was due to the class overall relative to the impact of the specific intervention.

A separate analysis was conducted on students' performance on technical questions. The STSS

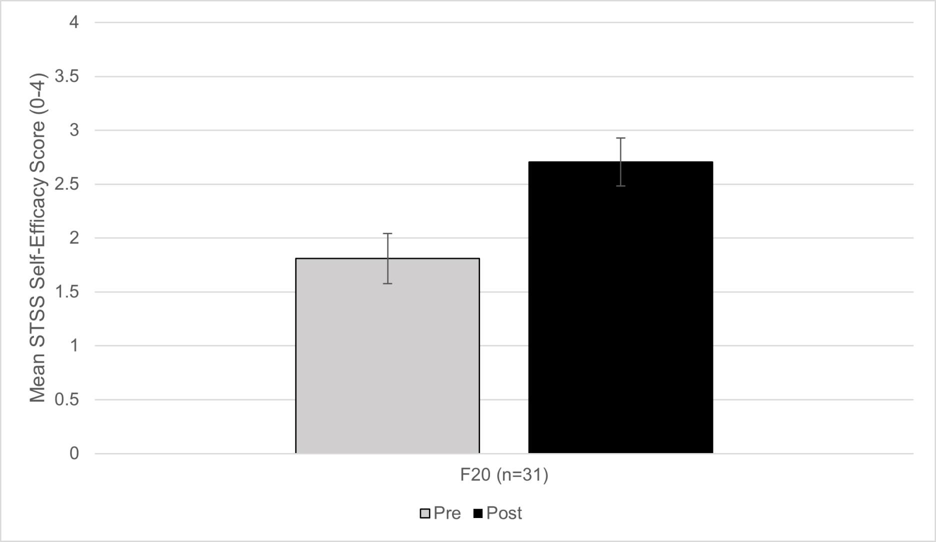


Figure 7: Overall improvement in students' self-efficacy as a result of the course. There was a statistically significant overall improvement in student self-efficacy, but it is unclear to what extent the intervention or the class overall contributed to this impact.

technical questions are written at a level that might be expected of graduating seniors, and hence we would not expect to see dramatic changes from the limited intervention presented in this paper. Table 3 shows the knowledge, skills, and abilities (KSAs) measured by the STSS technical questions along with the number of items in each category. The students overall showed modest improvement in their technical skills as shown in Figure 8 with a breakdown into specific categories provided in Table 4.

Table 4 shows that students showed statistically significant improvement in only the skill related to setting target specifications. Results of the non-parametric Wilcoxon signed-rank test indicated that the overall increase from pre-scores ($M = .518$, $SD = .17$) to post-scores ($M = .594$, $SD = .16$) was statistically significant $Z(31) = -2.36$, $p = .018$. Additionally, the increase from pre-scores ($M = .432$, $SD = .22$) to post-scores ($M = .565$, $SD = .18$) was also statistically significant $Z(31) = -2.97$, $p = .003$ for KSA 3. The improvement on this KSA was significant enough to show an overall improvement in technical skills. Note that the mean score for KSA 2 (stakeholder analysis) actually decreased slightly between pre and post tests, but not enough to show statistical significance.

Taken in the aggregate, the results show that students significantly improved both their self-efficacy and systems engineering technical skills as a result of the course. Given that the intervention was the only specific instruction given in the systems engineering technical contents, it is reasonable to believe that the increased performance on technical items comes directly from the intervention. We would expect self-efficacy to improve in general as a result of taking a freshman engineering course, however it is unclear how much of this change to attribute to the intervention. Students' in-class artifacts demonstrate a basic understanding of the engineering design process and show basic competency in the KSAs measured by the STSS.

KSA #	KSA Category	Number of Items
1	Identify and define system boundaries and external interfaces	1
2	Identify major stakeholders and understand that stakeholders must be involved early in the project lifecycle	1
3	Identify possible technical performance measures [specifications] for determining the system's success	2
4	Understand the different types of architecture	2
5	Understand the need to explore alternative and innovative ways of satisfying the need	4
6	Define selection criteria, weightings of the criteria and assess / evaluate potential solutions against selection criteria	1
7	Concept selection	2

Table 3: STSS skills categories and number of elements in each category. The STSS measures skills across seven different systems engineering dimensions.

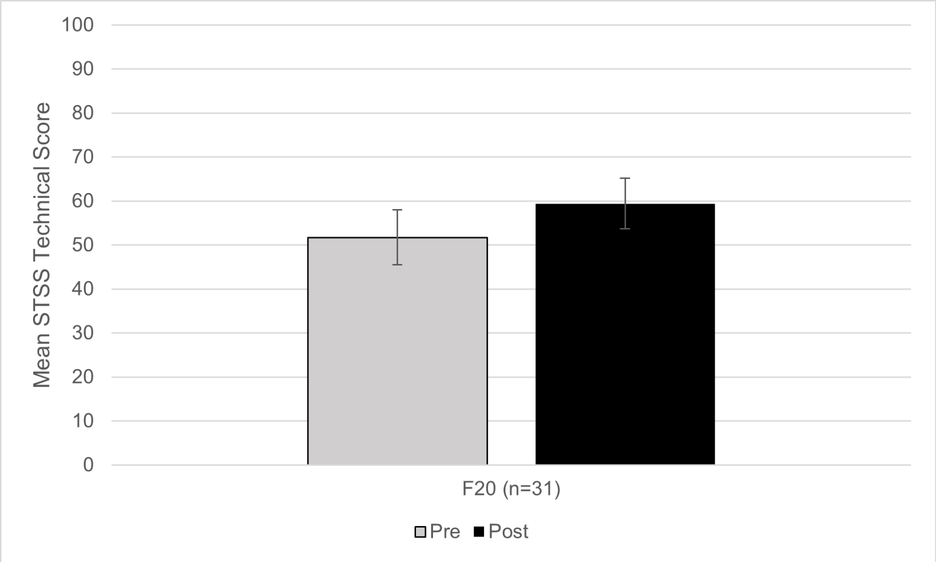


Figure 8: Overall improvement in students' systems engineering technical skills as a result of the course. There was a statistically significant overall improvement in student technical skills, but the effect is much smaller than that seen in self-efficacy

Category	Pre Mean	Post Mean	Z	N	p
Overall	.518 (.17)	.594 (.16)	-2.36	31	<0.018*
KSA 1	.612 (.28)	.672 (.25)	-1.91	31	<0.056
KSA 2	.480 (.51)	.390 (.50)	.823	31	<0.405
KSA 3	.432 (.22)	.565 (.18)	-2.97	31	<0.003*
KSA 4	.790 (.28)	.839 (.30)	-.83	31	<0.405
KSA 5	.557 (.25)	.589 (.22)	-.78	31	<0.438
KSA 6	.450 (.51)	.680 (.48)	-1.94	31	<0.052
KSA 7	.452 (.39)	.548 (.39)	-1.18	31	<0.237

Table 4: Technical performance results by category. Students showed statistically significant improvement in only one category, but that was sufficient to make the overall performance show statistically significant improvement.

Conclusions and Future Work

Engineers from traditional engineering disciplines are increasingly called on to develop complex engineering systems featuring multiple interacting subsystems. This emerging industry need suggests a corresponding requirement for traditional disciplines such as mechanical engineering to adopt more systems engineering content within the undergraduate curriculum. To that end, the flipped classroom intervention in a freshman mechanical engineering course that was presented in this paper proved useful in increasing both students' self-efficacy and technical competence in employing basic systems engineering concepts. Placing the systems engineering content in an OLI rather than teaching in class provides class time to directly practice the concepts in a guided environment, which seems to be a valuable experience.

Injecting systems engineering concepts into courses that teach the engineering design process is relatively easy compared to infusing it into highly technical courses such as dynamics. Future work will consider strategies to more holistically embed systems thinking and systems engineering within the mechanical engineering curriculum. Like the teaching of professional or coding skills, teaching systems engineering skills can be woven strategically into existing classes so that students progressively develop their capabilities. One preferred method for performing a curriculum-wide transformation is the creation of OLI modules that can be adopted by instructors that do not have specific systems engineering expertise. By developing stand-alone modules and examples for common engineering classes the hope is to maximize ease of delivery and ultimately aid dissemination.

A second avenue for future work is a broad study of how and where ST skills are currently developed in the conventional curriculum. Students likely develop some systems thinking and systems engineering skills in a variety of ways with experiences in engineering courses, humanities courses, and co-curricular activities each contributing differently. By measuring students' systems thinking and systems engineering skills at each year in the mechanical engineering curriculum, this effort would investigate the degree to which these skills are correlated with taking particular kinds of courses or engaging in co-curricular experiences. Furthermore, it will identify gaps in skills improvements (e.g. in years without a dedicated design course) which can be used to develop targeted interventions.

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References

[1] Gerrit Muller and G. Maarten Bonnema. Teaching systems engineering to undergraduates; experiences and considerations. *INCOSE International Symposium*, 23(1):98–111, 2013. doi: https://doi.org/10.1002/j.2334-5837.2013.tb03006.x. URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2334-5837.2013.tb03006.x`.

[2] Federica Robinson-Bryant. Developing a systems thinking integration approach for robust learning in undergraduate engineering courses. In *2018 ASEE Annual Conference & Exposition*, number 10.18260/1-2–30294, Salt Lake City, Utah, June 2018. ASEE Conferences. https://peer.asee.org/30294.

[3] Moti Frank and David Elata. Developing the capacity for engineering systems thinking (cest) of freshman engineering students. *Systems Engineering*, 8(2):187–195, 2005. doi: https://doi.org/10.1002/sys.20025. URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/sys.20025`.

[4] George Youssef and Vladimir Arutyunov. An approach to integrating systems engineering into senior design. In *2016 ASEE Annual Conference & Exposition*, number 10.18260/p.26569, New Orleans, Louisiana, June 2016. ASEE Conferences. https://peer.asee.org/26569.

[5] Mark David Bedillion, Marsha Lovett, Karim Heinz Muci-Kuchler, and Cassandra M. Degen. Teaching systems thinking in a capstone mechatronic design course. In *2019 ASEE Annual Conference & Exposition*, number 10.18260/1-2–33355, Tampa, Florida, June 2019. ASEE Conferences. https://peer.asee.org/33355.

[6] Karim Heinz Muci-Kuchler, Mark David Bedillion, Shaobo Huang, Cassandra M Degen, Marius D Ellingsen, Walelign Messele Nikshi, and John Ziadat. Incorporating basic systems thinking and systems engineering concepts in a mechanical engineering sophomore design course. In *2017 ASEE Annual Conference & Exposition*, number 10.18260/1-2–28504, Columbus, Ohio, June 2017. ASEE Conferences. https://jee.org/28504.

[7] Karim Heinz Muci-Kuchler, Cassandra M. Degen, Mark David Bedillion, and Marsha Lovett. Extending systems thinking skills to an introductory mechanical engineering course. In *2019 ASEE Annual Conference & Exposition*, number 10.18260/1-2–32826, Tampa, Florida, June 2019. ASEE Conferences. https://peer.asee.org/32826.

[8] Karim Heinz Muci-Kuchler, Cassandra M. Birrenkott, Mark David Bedillion, Marsha Lovett, and Clifford Whitcomb. Incorporating systems thinking and systems engineering concepts in a freshman-level mechanical

engineering course. In *2020 ASEE Virtual Annual Conference Content Access*, number 10.18260/1-2–34813, Virtual On line, June 2020. ASEE Conferences. https://peer.asee.org/34813.

[9] Moti Frank and Joseph Kasser. Assessing the capacity for engineering systems thinking (cest) and other competencies of systems engineers. *Systems Engineering-Practice and Theory, B. Cogan, ed., INTECH Open Access Publisher*, pages 217–230, 2012.

[10] John Krupczak Jr. and A. Mehran Shahhosseini. Application of a computerized method for evaluating systems-level thinking. In *2019 ASEE Annual Conference & Exposition*, number 10.18260/1-2–32097, Tampa, Florida, June 2019. ASEE Conferences. https://peer.asee.org/32097.

[11] Marsha Lovett, Oded Meyer, and Candace Thille. The open learning initiative: Measuring the effectiveness of the oli statistics course in accelerating student learning. *Journal of Interactive Media in Education*, 2008.

[12] S. Eppinger and K. Ulrich. *Product Design and Development*. McGraw-Hill Higher Education, 2015. ISBN 9781259297137. URL `https://books.google.com/books?id=S7FZCgAAQBAJ`.