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Fostering and Assessing the Systems Thinking of First-Year Engineering Students Using the System Architecture-Function-Purpose Framework*

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As systems become more complex, demand for teaching systems thinking is increasing. To date, studies in undergraduate engineering education have not presented a pedagogical framework suitable for teaching systems thinking to first-year engineering students. We designed and applied such a framework, the System Architecture-Function-Purpose framework for technological systems, in a semester-long first-year remote course. Forty-four first-year students with undeclared majors studying at an engineering-centric university participated in this study. Participants practiced the framework as applied to multidisciplinary case studies. Participants carried out three in-class individual training assignments during weeks 4, 5, and 6. Each training assignment was followed by an out-of-class team assignment which expanded on the same case study. These assignments comprised the intervention component of the study, intended to improve students' systems thinking. The effectiveness of this intervention was evaluated during weeks 1 and 7 based on self-rated systems thinking (a) knowledge and ability, and (b) systems thinking as expressed in examples provided by participants. While self-rating improved from week 1 to 7, example assignment performance scores remained the same. We discuss future efforts for framework validation and provide suggestions for instructors.

Keywords: assessment; first-year education; remote learning; systems thinking; undergraduate education

1. Introduction

As systems are becoming more interconnected and complex, demand for engineers who possess systems thinking is also increasing [1]. The US National Research Council [2] presented a framework for 21st century skills in science and engineering education – primary, secondary, and higher – which included systems thinking. Additionally, the ABET [3] 2019–2020 criterion 3 (student outcomes) for accrediting engineering programs mentions students must have the ability to produce engineering solutions while considering factors which require a systems perspective, namely global, cultural, social, environmental, and economic factors. Another testament of the need for system thinkers is that *critically important skills for science, technology, engineering, and mathematics (STEM) disciplines*, taken from the US Labor Department database [4], include *systems analysis* and *systems evaluation*.

While the definition of *system* is a subject of rich, ongoing academic debate [5], for the purposes of this study, we define a *technological system*, or *system* for short, as follows: a system is an entity composed of interacting parts. This entity delivers a predetermined function through its architecture, which is a combination of its structure and its behavior. The system's function is realized through interactions of the system parts, both internally and with the system's environment; these interactions can be explained by cause-and-effect relationships. Some whole-system properties vary from those of its individual parts. The purpose of a system is to deliver a predetermined benefit to specific group/s of humans – the system's beneficiaries. The system's purpose is achieved through its function [1, 6–9].

Systems thinking is a higher-order thinking skill or set of skills that enable the identification, understanding, prediction, and improvement of every aspect of a technological system: outcome, function, structure, and behavior, and the way these aspects interrelate within the system. [1, 6, 7]. The authors found four peer-reviewed empirical studies in undergraduate engineering education which explicitly set out to foster and assess students' systems thinking [10–13]. In all these studies, the pedagogical framework used for fostering students' systems thinking was not the same as the one used

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for its assessment, if any framework was mentioned at all. We argue this lack of a joint framework for both fostering and assessing systems thinking precludes its teaching in a valid, reliable, and efficient manner.

The COVID-19 pandemic disrupted teaching in higher education institutions worldwide, with one common response being moving to online (remote) instruction [14]. This study was borne out of the first author being tasked with designing and delivering a fully remote course for the academic year 2020–1, as the Massachusetts Institute of Technology (MIT) pivoted to emergency teaching in mid-spring 2020. To the best of the authors' knowledge, there are no published studies on teaching systems thinking in undergraduate engineering education which are based in a remote teaching setting.

In this study, we describe our preliminary step in applying a newly designed pedagogical framework, titled *System Architecture-Function-Purpose* (SAFP), for fostering and assessing first-year engineering students' systems thinking in a remote setting. To evaluate the effectiveness of the SAFP, we gave students skill-based individual and team assignments based on this framework and asked students to self-rate on the knowledge and abilities they believed they had attained during the course.

1.1 Research Objective and Research Questions

The objective of this study was to investigate the effectiveness of a pedagogical framework in fostering first-year engineering students' systems thinking in a remote setting. To this end, we opted to assess students' systems thinking from multiple perspectives, including individual performance, team-based performance, and self-perception. Accordingly, our research questions were as follows:

1. To what degree, if at all, can an intervention based on such a framework and delivered in a remote setting foster first-year engineering students' systems thinking?
2. To what degree, if at all, can an intervention based on such a framework and delivered in a remote setting foster first-year engineering students' self-perceived knowledge about systems thinking?
3. To what degree, if at all, can an intervention based on such a framework and delivered in a remote setting foster first-year engineering students' self-perceived ability to use systems thinking?

1.2 Teaching Systems Thinking in First-year Engineering Education

The importance of teaching systems thinking in engineering undergraduate education has been vigorously promoted for many years [15, 16]. In the engineering domain, systems thinking can be conceived of as a skill or set of skills that enables the identification, understanding, prediction, and improvement of the parts and interrelations of a technological system [1, 6, 7, 9].

If fostering systems thinking is important in undergraduate engineering education, then, we argue, engineering schools should begin teaching it in the first year. However, teaching systems thinking in first-year engineering education is different to teaching it in later years, because first-year students are not yet specialized in any sub-discipline of engineering and have at best rudimentary understanding of technological systems from an engineer's point of view. As a result, any pedagogical framework for teaching systems thinking in first-year engineering education needs to be rooted in the fundamentals of engineering and yet also be agnostic to any sub-discipline of engineering. Another difficulty with teaching systems thinking in first-year engineering education is the lack of frameworks that allow for both fostering and assessing systems thinking, and for the design of multiple types of assignments and assessments.

Merrill's *first principles of instruction* [17] state that learning is promoted when instruction is: (1) problem-centered, (2) activates existing knowledge, (3) includes demonstrations, (4) provides opportunities for application, and (5) supports integration into the real world. As good practice, it would behoove any intervention aimed at improving students' systems thinking to follow these principles.

As Table 1 shows, we found four peer-reviewed empirical studies in undergraduate engineering education that are concerned explicitly with fostering students' systems thinking [10–13]. Interestingly, none of these studies were conducted in remote teaching settings. None of the studies shows consistency in terms of the frameworks used for fostering and for assessing students' systems thinking; either different frameworks were used for fostering and for assessment, or no frameworks were mentioned for one or for both aspects. In addition, none of these studies used systems thinking frameworks that were engineering-specific yet agnostic to specific sub-disciplines of engineering.

Two elements that were common to all four studies in fostering the systems thinking of undergraduate engineering students were the use of a preparatory systems thinking activity, followed by one or more case studies as an intervention for fostering systems thinking. Two of the four studies had an intervention for fostering systems thinking that lasted for a few lessons [10, 12], while the other

Table 1. Studies published in English in peer-reviewed journals and conference proceedings concerned with the fostering of undergraduate engineering students' systems thinking

Title of paper	Systems thinking intervention	Discipline Duration of intervention *N*	Systems thinking assessment	Merrill's *first principles of instruction*[1] [17] being followed
Teaching systems thinking and biomimicry to civil engineering students [10]	1. Systems thinking play activity adapted from *The Systems Thinking Playbook* [24] 2. Case-study challenge adapted from [25] based on the systems thinking concepts of Senge[2] [26]	Civil engineering Two lessons *N* not specified	Conceptual/Skills Open-ended items: • Give an example of systems thinking • Give an example of a lack of systems thinking	1, 2, 4, 5
Measuring the impact of a new mechanical engineering sophomore design course on students' systems thinking skills [11]	1. Introductory talks 2. Presentation of real-world examples 3. Hands-on activity 4. Four primers and case studies, including hands-on assignments, based on the Career Competency Model [27] and the second version of the *Conceiving, Designing, Implementing and Operating* (CDIO) syllabus for systems engineering education[3] [28] 5. Integration of systems thinking concepts with capstone project	Mechanical Engineering One semester *N* = 35	Attitudes/Personality Conceptual/Skills Engineering Systems Thinking Survey: • Systems thinking self-efficacy • Application of systems thinking skill	1, 2, 3, 4, 5
Promoting systems thinking and problem solving skills through active learning [12]	1. Hands-on activity 2. Case-study challenge based on Kepner-Tregoe Root Cause Analysis[4] [29]	Chemical engineering Practical session Duration not specified *N* = 54	Attitudes/Personality Close-ended items in Likert scale	1, 2, 3, 4
Incorporating basic systems thinking and systems engineering concepts in a mechanical engineering sophomore design course [13]	1. Introductory talks 2. Hands-on homework assignment 3. Four primers and case studies, including hands-on assignments, based on the Career Competency Model [27] and the second version of the CDIO syllabus for systems engineering education [28]. 4. Design of capstone design project requiring systems engineering skills	Mechanical Engineering One semester *N* = 22	Attitudes/Personality + Conceptual/Skills Systems Thinking Skills Survey: • Systems thinking self-efficacy • Application of systems thinking skill	1, 2, 4, 5

[1] (1) Problem-centered, (2) Activates existing knowledge, (3) Includes demonstrations, (4) Provides opportunities for application, and (5) Supports integration into the real world.
[2] For an example of instructional materials, see https://ecs.syr.edu/centers/SustainableEngineering/modules/10-18_Nikou.pdf
[3] The general objective of the CDIO Syllabus is to summarize formally a set of knowledge, skills (including systems thinking), and attitudes that alumni, industry, and academia desire in a future generation of young engineers.
[4] Retrieved from http://www.itsmsolutions.com/newsletters/DITYvol6iss19.htm

two studies had an intervention that lasted an entire semester [11, 13]. All four studies we found followed principles 1, 2, and 4 from Merrill [17] in their design, while two studies did not follow principle 3 [10, 13], and another study did not follow principle 5 [12].

Along with the fours studies we outlined above, we found six additional peer-reviewed empirical studies in undergraduate engineering education that reported exclusively on the assessment of students' systems thinking [18–23]. Out of the total of ten studies we found concerning the fostering and/or assessing of systems thinking in undergraduate engineering education, five were concerned only with assessing conceptual understanding or skills related to systems thinking [10, 18–21], two were concerned only with assessing attitudes or personality traits related to systems thinking [12, 22], and three were concerned with both categories of assessment [11, 13, 23].

The rest of this paper is structured as follows: first, we describe the SAFP pedagogical framework, including its conception, design, and an illustrative example. We go on to detail the materials and methods of our study, applying the SAFP framework in a section of a first-year engineering course. Next, we outline the findings of our research in applying the SAFP framework to fostering and assessing students' systems thinking. Finally, we discuss our findings, limitations, and contributions of our work, and also provide suggestions for educators.

2. The System Architecture-Function-Purpose Framework

The SAFP framework was designed for introducing first-year engineering students to systems thinking about technological systems in any domain, assuming a complete lack of knowledge in the discipline of engineering. SAFP fully captures the definition of system given under 'Introduction' above.

In prior works in science and engineering higher education [30, 31], the first author co-developed, applied, and evaluated STAR – Systems Thinking Assessment Rubric – for conceptual models of technological systems. STAR was designed based on (a) the constructivist notion of concept maps [32], (b) systems engineering principles [1, 7, 8], and (c) a literature review of systems thinking assessment in science and engineering education [33]. While originating in STAR, the SAFP framework does not require conceptual modeling for its application and it also applies to both fostering and assessing systems thinking. As such, the SAFP framework is a pedagogical framework.

SAFP distinguishes explicitly between a system's *function* and its *purpose*, both emergent aspects of a technological system: while function represents the interaction of the whole system with its immediate environment, purpose represents the outcome/s of the system function on groups of people. The system purpose in SAFP includes the problem being solved by the system's intended function as well as the group/s of people affected by it, thus explicitly including the human element in the description of a technological system.

SAFP also uses distinct terms for the parts of a system (structure) and the relations and interactions between those parts (behavior). *System structure* in FBS is replaced in SAFP with *system architecture*, a system engineering term [1]. This allows for making clear distinctions between static and dynamic parts of a technological system [7].

The SAFP's simplicity, coupled with the fact that it captures the essential aspects of technological systems, allows for the design of multiple types of assignments and assessments that address the description and improvement of systems. As well, SAFP allows for the assessment of conceptual understanding concerning these systems.

Because SAFP is a pedagogical framework, allowing for both the design and assessment of assignments, and it explicitly differentiates between function and purpose, SAFP is distinct from popular methodologies and ontologies in systems engineering such as (a) *function-behavior-structure* (FBS) [34, 35], (b) *systems modeling language* (SysML), (c) *object-process methodology* (OPM) [7], and (d) *integrated definition* (IDEF) [36].

However, it should be noted that as an introductory framework meant for first-year engineering students, the SAFP framework does not address attributes of system complexity [37]. This element remains for future work as a potential extension of the SAFP framework.

Finally, the diagrammatic representation of SAFP (a top-down flow diagram) illustrates the directionality of cause and effect of system operation, from architecture toward function and from function toward purpose. This depiction clearly demonstrates how changes to system architecture may affect function which in turn may affect purpose as well. Table 2 depicts the SAFP framework as applied to a petrol-powered private car.

Table 2. The System Architecture-Function-Purpose framework template with the example systems of a petrol-powered manually driven vehicle (private car)

Systems aspect **Guiding question**	**Component: Description**	**Example**
System architecture *What is the system and how does it operate? Mechanics, hardware, and software.*	Structure (static): parts and their structural relations	• Steering wheel • Gear box • Engine • Wheel axle
	Behavior (dynamic): Interactions – cause-and-effect relations between parts	• Steering wheel *rotates* wheel axle • Gear box *transmits* to engine • Engine *spins* wheel
System function *What does the system do?*	Key interactions with other systems on the target system's boundary	Human driver commands manually driven petrol-powered car that rolls on road network
System purpose *Who and what is the system designed for?*	Key problem: the key detriment which the system function solves or improves	Commuting to work using public transportation can be time-consuming, inconvenient, and unreliable
	Key stakeholders: the group of people most affected by the key problem	Working adults who live far away from their workplace
	Key benefit: the key expected positive outcome of the system function	Commuting to work quickly, conveniently, and reliably

This is the same content which the students participating in this study described were introduced to when first learning SAFP.

3. Materials and Methods

3.1 Research Setting

The study included 44 participants – all first-year students enrolled in MIT. We conducted the study in a fully virtual (remote) three-unit first-year elective course – *SP.248 – NEET Ways of Thinking* – during the fall semester of 2020–1 and the spring semester of 2021. The fall course had 36 students who gave their informed consent to participate, while the spring course had eight students. The format and structure of the course was identical in both semesters.

In this course, students learned about and were trained in higher-order thinking skills – specifically, creative thinking, systems thinking, and analytical thinking – via interdisciplinary case studies. This paper concerns only the systems thinking section of the course, which lasted for three weeks. The course was delivered via Zoom, a video conferencing Web-based platform. The systems thinking section of the course took place during weeks 4–6 of the course. Each class was 50 minutes followed by weekly, two-hour out-of-class assignments. Between the first and second class, students self-selected into teams of three or four, forming 14 teams for the fall course and three teams for the spring course. Students remained in their teams for the duration of the semester and completed most of the out-of-class assignments in their teams. Students were given either a 'pass' or 'no record' evaluation at the end of the semester, depending on their attendance in class and submission rate of assignments. The quality of submissions did not factor into students' completion status.

3.2 Intervention: Instructing Students in Systems Thinking

During the classes of weeks 4–6, the learning progression was most like [10] (see Table 1) and was congruent with Merrill's *first principles of instruction* [17]. As noted above, the intervention included both individual and team components. During each class of weeks 4–6, the following learning activities took place, covering principles 1–3:

1. A presentation of the challenge, centered around a real-world technological system.
2. A five-minute mini lecture on SAFP. Students were free to ask questions for clarification or to expound on the material.
3. A five-minute *training assignment* – an individual assignment based on the SAFP and on an example from a specific domain; these were intended to prepare students for the out-of-class application assignments. The assignment was co-developed with an expert in the relevant domain, who is the third co-author of this paper.

3.3 Data Collection

We received approval from the MIT Committee on the Use of Humans as Experimental Subjects to conduct this study (exempt reviews #E-2532 for Fall 2020 and #E-2912 for Spring 2021). As Table 3 shows, data were also collected from three types of assignments, which covered principles 4 and 5 from Merrill [17]:

1. Three out-of-class *application assignments* over Weeks 4, 5, and 6 – A1, A2, and A3, respectively – which built on the training assignment but were of higher complexity and difficulty. These assignments applied to principle 4 from Merrill [17], and together with the training assignments fulfilled the role of intervention in this study. The assignment was based in a specific domain and was co-developed with an expert in that domain. These assignments were carried out by student teams and were designed to help answer Research Question 1: *To what degree, if at all, can an intervention based on a framework like SAFP and delivered in a remote setting improve students' systems thinking?*
2. Two out-of-class *example assignments* over Weeks 1 and 7 – E1 and E2, respectively – which asked students to "Give an example, preferably from your own experience, of someone exhibiting systems thinking". These assignments applied to principle 5 from Merrill [17]. These assignments were carried out by student teams and were also designed to answer Research Question 1: *To what degree, if at all, can an intervention based on such a framework and delivered in a remote setting improve students' systems thinking?* While E1 was used to set a benchmark (pre-test) score for each student, E2 was used as a measure of improvement in systems thinking ability. Appendix A, Table A includes samples of student responses and their scores.
3. Two out-of-class *self-rating assignments* over Weeks 1 and 7 – SR1 and SR2, respectively – which asked students to score their own knowledge, *self-rated knowledge* (SRK – "I know a lot about systems thinking"), and their ability for systems thinking, *self-rated ability* (SRA – "I am a systems thinker"), from 1–5 by indicating their degree of agreement with the respective statements in parentheses. These assignments

applied to principle 5 from Merrill [17]. These assignments were carried out by individual students and relate to Research Questions 2 and 3: To what degree, if at all, can such an intervention delivered in a remote setting improve students' self-perceived systems thinking knowledge? Can such an intervention delivered in a remote setting improve students' self-perceived systems thinking ability? While SR1 was used to set benchmark (pre-test) scores for each student, SR2 was used as a measure of improvement in students' own perception of their ability to use systems thinking.

All the assignments involved filling out and submitting an electronic form using Google Forms, a Web-based online form editing and distribution program. All 44 participants submitted every assignment from Week 1 through 7. Table 3 shows student assignments in systems thinking from Week 1 to 7.

In each class, following a short talk, individual students filled-out and submitted an online form that asked them to apply the SAFP to the design of an abstracted microfluidic device (bioengineering system). Upon submission of the form, respondents automatically received a copy of their responses to their institutional email address. Immediately following the assignment, possible solutions for the design challenge were revealed and explained. Because this task took a short amount of time (due to the small number of items included), and the fact that it was not supported by the instructor, the data were not analyzed – the instructor simply checked everyone had submitted it within the allotted time.

Then, after class in week 4, student teams filled-out and submitted an online form that also asked them to apply SAFP to the design of an abstracted microfluidic device, but this assignment used a different device that was purposely made more difficult. The students were given an intended function for this device – a specific concentration gradient – and a list of six potential parts which microfluidic devices can consist of. The teams were asked to select the minimum number of parts for fulfilling the intended function of the microfluidic device and justify their selections. They had to respond to three items: (1) which parts they would choose and why, (2) what the benefit of the designed device would be for the researcher, and (3) how this benefit would differ from the benefit to the researcher of the device designed in the training assignment. Note a correct answer for #3 could be qualitative, i.e., a different benefit that of the device designed in the training assignment, or quantitative, i.e., the same benefit, but better in the case of the application assignment.

Week 5's application assignment was the same as week 4's assignment, but with a different intended function for the microfluidic device, which necessitated a different combination of parts. Again, this assignment expanded on that week's training assignment but used a different, more difficult challenge. Respondents received a copy of their responses to their institutional email. In the next week's class, the solution(s) for the assignment was shown and explained by the instructors.

Following Week 6's lesson, student teams were asked to fill-out and submit a form that contained two freely available, public sources for collecting information concerning the operation of two kinds of electrical energy production systems, namely solar farms and nuclear power plants. For this assignment, student teams were asked to provide descriptions of the parts, interactions, function, and benefits of each system, and then compare the two systems via the benefits and costs they had described.

Table 3. Student systems thinking assignments included in data collection

Week #	Assignments, in sequential order of deployment
1	Self-rating1 (pre-test) Example1 (pre-test)
4	Training1 (intervention) Application1 (intervention)
5	Training2 (intervention) Application2 (intervention)
6	Training3 (intervention) Application3 (intervention)
7	Self-rating2 (post-test) Example2 (post-test)

3.4 Hypotheses

Research Question 1: *To what degree, if at all, can an intervention based on a framework like SAFP and delivered in a remote setting improve students' systems thinking?*

Application assignments 1–3:

- H_1: Total scores for A2 will be higher than total scores for A1, and total scores for A3 will be higher than total scores for A2.
- H_0: Any other result.

Example assignments 1 and 2:

- H_1: Total scores for E2 will be higher than total scores for E1.
- H_0: Any other result.

Research Question 2: *To what degree, if at all, can such an intervention delivered in a remote setting improve students' perception of their knowledge of systems thinking?*

Self-rating assignments 1 and 2 – systems thinking knowledge:

- H_1: Total scores for SRK2 will be higher than total scores for SRK1.
- H_0: Any other result.

Research Question 3: *To what degree, if at all, can such an intervention delivered in a remote setting improve students' perception of their ability to utilize systems thinking?*

Self-rating assignments 1 and 2 – systems thinking ability:

- H_1: Total scores for SRA2 will be higher than total scores for SRA1.
- H_0: Any other result.

3.5 Data Analysis

We used SPSS 28 for all the data analyses. Before we tested our hypotheses, we checked for significant differences in performance between participants in the fall and spring courses. Such differences, if significant, would indicate the presence of one or more confounding variables related to cohort, time of year, or other potential factors. To check for significant differences in scores between semesters, we used Shapiro-Wilk tests of normality on Application, Example, and Self-rating assignment scores. We found that scores for all these assignments had an abnormal distribution, except for A2, for which scores were normally distributed. We therefore used Mann-Whitney U tests for independent samples with a 95% confidence level, two-tailed, to compare scores by semester for all assignments except for A2, for which we used a two-tailed t-test for independent samples, also with a 95% confidence level. We found no significant differences in scores between semesters for any of these assignments. We include the results of all these tests in Appendix B, Tables B and C.

Finally, we confirmed interrater reliability for scoring the example assignments with two raters: one of the co-authors of this paper, who is an educational researcher and an expert in systems thinking assessment, and an expert in both educational. Both raters compared their scores for 18 out of all 88 statements (44 statements in E1 and in E2). We found good interrater reliability for scoring the example assignments, $r = 0.830$. We now turn to testing our hypotheses, based on our research questions.

Research Question 1: *To what degree, if at all, can an intervention based on a framework like SAFP and delivered in a remote setting improve students' systems thinking?*

- Example Assignments 1 and 2: we compared total scores between E1 and E2 using Wilcoxon signed-rank tests with a 95% confidence level, one-tailed.

Research Question 2: *To what degree, if at all, can such an intervention delivered in a remote setting improve students' perception of their knowledge of systems thinking?*

- Self-rating Assignments 1 and 2: We compared rankings for SRK1 and SRK2 using Wilcoxon signed-rank tests with a 95% confidence level, one tailed.

Research Question 3: *To what degree, if at all, can such an intervention delivered in a remote setting improve students' perception of their ability to utilize systems thinking?*

- Self-rating Assignments 1 and 2: we compared rankings for SRA1 and SRA2 using Wilcoxon signed-rank tests with a 95% confidence level, one tailed.

4. Results

Table 4 shows descriptive statistics for each scored assignment.

Table 4. Descriptive statistics for assignment scores

Week #	Assignment	*N*	Median	Range of actual scores	Range of potential scores
1	Self-rating knowledge 1	44	2	1–4	1–5
1	Self-rating ability 1	44	3	1–5	1–5
1	Example 1	44	0	0–4	0–4
4	Application 1	17	50[1]	0–83	0–100
5	Application 2	17	67	17–100	0–100
6	Application 3	17	88	63–100	0–100
7	Self-rating knowledge 2	44	4	2–5	1–5
7	Self-rating ability 2	44	4	2–5	1–5
7	Example 2	44	1	0–3	0–4

[1] For purposes of comparing scores of Application assignments, we normalized those scores to 0–100.

4.1 Research Question 1: To what degree, if at all, can an intervention based on a framework like SAFP and delivered in a remote setting improve students' systems thinking?

Wilcoxon signed-rank tests showed no significant difference in total scores between A1 and A2 ($Z = 0.601$, $df = 16$, $p < 0.274$). We therefore retain the null hypothesis.

Wilcoxon signed-rank tests showed total scores for A3 were higher than total scores for A2 ($Z = 3.106$, $df = 16$, $p < 0.05$). We therefore reject the null hypothesis.

Wilcoxon signed-rank tests showed total scores for E2 were not higher than total scores for E1 ($Z = 1.276$, $df = 43$, $p = 0.101$). We therefore retain the null hypothesis.

Fig. 1 shows the breakdown of responses to the assignments E1 and E2. In each of these assignments, students were asked to provide an example of systems thinking from their own experience. We divided responses into five types: (1) inadequate responses without concrete examples or system aspects mentioned, (2) responses with a concrete example and one system aspect mentioned, (3) responses with a concrete example and two system aspects mentioned, (4) responses with a concrete example and three system aspects mentioned, and (5) responses with a concrete example and all four system aspects mentioned. The percentage of adequate responses, i.e., responses which included a concrete example and mentioned at least one system aspect, increased from 48% for E1 (week 1) to 82% for E2 (week 7).

Fig. 2 shows the breakdown of responses for E1 and E2 by how frequently purpose, function, structure, and behavior were mentioned within a concrete example of a technological system.

4.2 Research Question 2: To what degree, if at all, can such an intervention delivered in a remote setting improve students' perception of their knowledge of systems thinking?

Wilcoxon signed-rank tests showed SRK2 scores were higher than SRK1 scores ($Z = 5.101$, $df = 43$, $p < 0.05$), with a large effect size ($r = 0.769$). We therefore reject the null hypothesis.

4.3 Research Question 3: To what degree, if at all, can such an intervention delivered in a remote setting improve students' perception of their ability to utilize systems thinking?

Wilcoxon signed-rank tests showed SRA2 scores were higher than SRA1 scores ($Z = 4.091$, $df = 43$, $p < 0.05$), with a large effect size ($r = 0.617$). We therefore reject the null hypothesis.

5. Discussion

This discussion starts with outlining the limitations of our study. We then provide suggestions to instructors and to researchers based on our findings. We end by describing the contributions of this study to research in first-year engineering education.

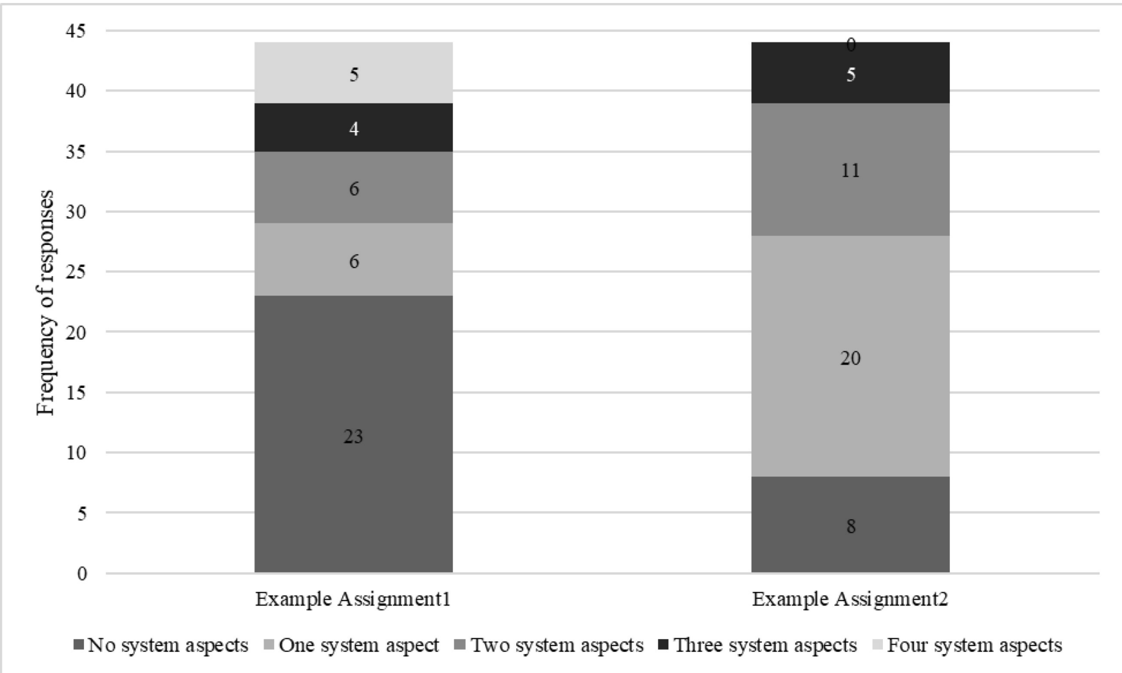

Fig. 1. Example assignments: Frequency of responses by number of aspects included in each participant's response.

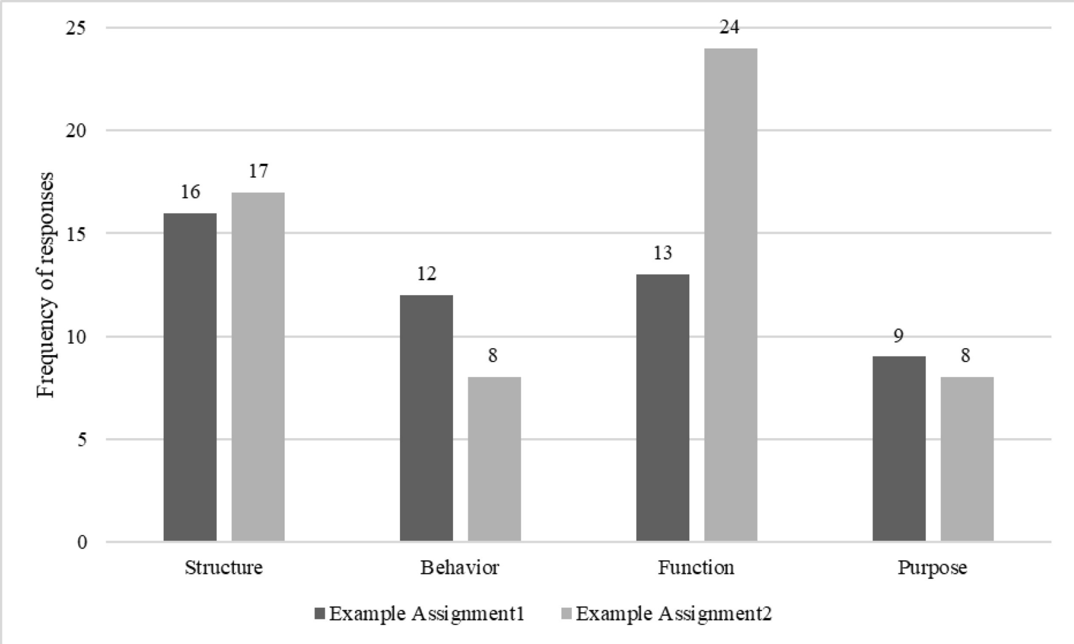

Fig. 2. Example assignments: Frequency of responses by the system aspect included in participants' responses.

5.1 Limitations

The constraint of three weeks and three classes was not under the control of the researchers, and so this presented the instructor, the first co-author of this paper, with the challenge of teaching systems thinking in a short amount of time. In this regard, the intervention presented herein is most like the two-lesson study described in [10] (see Table 1). This time constraint limited the depth and detail of knowledge which students were able to acquire and integrate regarding technological systems, which, in turn, limited the fulfilment of Merrill's [17] principles 2 (activate existing knowledge) and 5 (support integration into the real world). Another limitation of this study is that there were no external incentives for performance on any of the assignments since this class was not required for completing a major and assignments were not graded.

However, self-rating is one of the most popular approaches for identifying differences between individuals in psychological science [38]. Similarly, we found self-rating is the most prevalent method for assessing undergraduate engineering students' systems thinking, with six out of nine papers employing a self-rating method or instrument (see Table 1). However, as [38] asserts, across a series of domains, self-rating and performance (behavioral) measures tend to be weakly correlated (from 0 to 0.20). [38] does mention creativity as an example of this weak correlation. In the case of self-rating on creativity, social factors – specifically, illusory superiority, leniency biases, and social desirability – have been suggested as playing a crucial role in students' self-rating [39]. We argue the same can reasonably be speculated for systems thinking. However, [38] suggests that low-reliability measures can be used to predict short-term changes in individuals, which is what we did in this study as we compared scores obtained by individuals between assignments.

5.2 Suggestions for Researchers

A potential study for fully evaluating the validity and reliability of SAFP would include a larger number of participants. A larger sample would allow for evaluating SAFP's construct validity. Further studies could evaluate the extent to which an intervention of the type described here promotes retention. This could be done by assigning Example Assignments several weeks following the intervention, or by devising an alternative assessment of system design artefacts produced by students in courses either outside of or following an introduction to systems design.

As Fig. 3 shows, we found descriptive differences between function, structure, and behavior scores for the two Example assignments, with scores related to structure and function improving, but those related to behavior decreasing. A future study could investigate whether there are similar significant differences between scores, and look for explanations for these differences, if they exist. It would also be interesting to delve into why students seemed to have had difficulty providing examples for the purpose(s) of a system, seeing it had the lowest overall frequency (7) of all the Example assignment.

The low p-value (0.101) between E1 and E2 scores, with E2 median scores being descriptively higher than those of E1 (1 and 0, respectively), suggests a significant improvement may be possible with slight improvements to the intervention. For example, students could be prompted to include all four system aspects in their responses. Even though most students responding to E1 would likely not know what all these aspects mean, since they will have not been taught them at the time of this assignment, including this prompt would nevertheless be in accordance with assessing their understanding of systems thinking. Another option for improvement would be to add an item requesting students to provide an example of a *lack* of systems thinking, in the same vein as study [10] (see Table 1).

Finally, we can consider adding another measurement of individual students' performance to test their knowledge of fundamental concepts in systems thinking pre- and post-intervention (weeks 1 and 7, respectively), such as the 'systems thinking technical questions' in [11] (see Table 1). This kind of measurement would allow us to compare students' individual performance to their self-rating of their systems thinking.

5.3 Suggestions for Instructors

We advise first-year engineering instructors who aim to foster their students' systems thinking to follow the *first principles of instruction* as outlined by Merrill [17]. These principles can be fulfilled through collaboration between educators and domain experts in developing or adapting case studies based on real-world technological systems.

We also suggest using multiple tools for assessing students' systems thinking, including but not limited to self-rating. The use of multiple methods ensures a comprehensive and more accurate picture of students' ability. Finally, we can suggest using the same framework, whether the one presented herein or another one, for both fostering and assessing students' systems thinking in the same class.

5.4 Contributions

Our study makes a methodological contribution to undergraduate engineering education research by demonstrating that the use of one pedagogical framework – the System Architecture-Function-Purpose Framework both fosters and assesses first-year engineering students' systems thinking. We also provide a practical contribution to instructors as we demonstrated an instructional methodology for fostering and assessing the systems thinking of first-year engineering students in a remote setting.

6. Conclusion

The intervention improved individual students' self-perception of their ability to use and apply systems thinking knowledge improvements which were still present seven weeks following our intervention. We also found an improvement in scores between Applications2 and Application3, which demonstrated student teams' ability to apply SAFP to real-world technological systems. Since these were team assignments, we cannot affirm this result demonstrates individual improvement; nevertheless, it does at least suggest there was no degradation in the systems thinking of students between weeks 5 and 6. Lastly, we found no significant improvement between the individual Example Assignments (weeks 1 and 7). Therefore, the overall outcome of our intervention ranged from neutral to positive in terms of fostering the systems thinking of students. We conclude that the System Architecture-Function-Purpose framework shows initial promise for fostering and assessing the systems thinking of first-year engineering students.

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Appendix A: Sample Responses to Example Assignment

Table A. Samples of student responses to Example Assignment and how they were scored

	Is the system aspect presented within a concrete example of a technological system? (1: yes; 0: no)			
Student response (verbatim)	**Structure**	**Behavior**	**Function**	**Purpose**
[21.E2] In Economics, thinking about what impact on the nation would happen if the government were to follow a certain economic policy.	1	1	0	0
[26.E1] Systems thinking involves utilizing various disciplines to solve a problem within a specific system. An example of systems thinking is ensuring that a drug targeted towards lowering blood sugar is tested in terms of its response with other organ systems (i.e. making sure the drug is not toxic to the liver or kidneys).	1	1	1	1
[28.E2] Thinking about an overall structure before solving individual problems.	0	0	0	0
[42.E2] Designed a small steam engine that would use a lens to collect the solar heat. The heat would then be used to turn water into the steam and the steam would turn the turbine.	0	0	1	1

Note. Item instructions were as follows: "Give an example, preferably from your own experience, of someone exhibiting systems thinking".

Appendix B: Differences in Assignment Scores between Semesters

Table B. Results of normalcy tests for assignment scores

Variable	*N*	Median	*W*	*p*
Self-rating knowledge 1	44	2	0.867	< 0.05
Self-rating ability 1	44	3	0.861	< 0.05
Example 1	44	0	0.761	< 0.05
Self-rating knowledge 2	17	88	0.861	< 0.05
Self-rating ability 2	44	4	0.807	< 0.05
Example 2	44	4	0.868	< 0.05
Self-rating knowledge 1	44	1	0.868	< 0.05

Table C. Results of Mann-Whitney U tests comparing assignment scores between semesters

	Fall 2020–1 class		Spring 2021 class			
Variable	***N***	**Median**	***N***	**Median**	***U***	***p***
Self-rating knowledge 1	36	2	8	2	122.0	0.520
Self-rating ability 1	36	3	8	3	148.0	0.917
Example 1	36	0.5	8	1	182.0	0.259
Self-rating knowledge 2	36	4	8	4	167.0	0.501
Self-rating ability 2	36	4	8	4	131.5	0.709
Example 2	36	1	8	1	151.0	0.846

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