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Assessing Student Growth in Systems Thinking and Systems Engineering Skills in an Online Learning Environment

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The role of systems engineering in conventional engineering disciplines

While graduating engineers' first jobs often revolve around design problems at the component level, as they progress in their careers they typically need to understand the problems they work on at the systems level[1,2]. For instance, a recent mechanical engineering graduate working in the hard disk drive industry might be tasked with designing a head suspension system to meet specific stiffness and resonance frequency goals. However, he or she likely has little insight into *why* these particular goals must be met, or the ability to push back effectively if the goals prove difficult to meet. Generating these specifications requires a systems-level understanding of the recording system, including how the recording physics interacts with the fly height (the distance of the head above the recording medium), how the channel error rates are affected by head positioning errors relative to data track centers, and how the servo control performance is affected by the resonance modes of the suspension. While some of the engineers who determine these specifications will have formal training in systems engineering, the majority will be trained in traditional disciplines and learning systems engineering principles on the job.

There have been several efforts to better train engineering graduates from traditional disciplines to apply systems thinking and systems engineering (ST / SE) principles early in their careers[1,3–26]. These include various course interventions in the undergraduate curriculum, with some efforts even targeting pre-engineering programs in high schools[27] and technology programs[28]. Alongside these content interventions have been various approaches to measuring students' skill[29] and self-efficacy[30] in systems thinking and systems engineering principles[31–36].

Applying these interventions in the conventional engineering curricula is challenging for several reasons. One challenge is that many engineering faculty, while certainly subject matter experts in their fields, often do not have a background in ST / SE principles. Another challenge is that the undergraduate curriculum is already full, and with pressure to add ever more emerging topics (e.g., AI / ML) it is difficult to find space for ST / SE topics. Prior work by the authors has attempted to alleviate these issues by developing self-contained online learning modules that can be assigned as homework in various classes through the mechanical engineering curriculum[23,25]. However, while earlier work showed that students' overall ST / SE self-efficacy grew as a result of taking a fundamentals of mechanical engineering course with an intervention applied, they did not directly measure the learning that occurred as a result of taking the online learning modules[25].

This work extends prior results in[25] by using pre-post measurement of students' ST and SE skills taken within the online learning environment[37]. It also correlates students' post-test results with their self-efficacy in various ST / SE skills. This helps to separate the effects of the online learning modules from the overall first-year class, and also helps to gauge students' incoming knowledge of ST / SE concepts. This paper provides assessment data from three institutions' first-year mechanical engineering courses, and looks at overall trends along with differences between institutions. After briefly describing the classes and the online learning modules, the paper focuses on the specific assessment approaches and their results.

Intervention Design and Assessment Approach

While a detailed accounting of the online learning module design is presented in[25], a brief summary is presented here for completeness. All three institutions feature a first-year course that covers fundamentals of mechanical engineering with a brief coverage of engineering design. At Carnegie Mellon University (CMU) and Texas State University (TXST) the interventions were applied to this first-year course, whereas at South Dakota School of Mines and Technology (SDM) they were applied in a sophomore design course that covers the product development process in depth. In the Fall 2025 semester 72 students at SDM, 275 students at TXST, and 134 students at CMU completed the online modules, for a total of 481 students. While 481 students participated in the modules, only students who completed both the pre- and post-assessments are included in the analysis (N=412).

The online learning modules were developed in the Open Learning Initiative (OLI) framework[38] and were assigned as homework prior to discussions of design in the classroom. The OLI is broken into two large units, the first of which covers the conventional product development process (PDP) as presented in Ulrich and Eppinger[39], and the second of which covers basic ST / SE concepts. Given students' exposure to the OLI contents prior to class, the approach in the classroom focused on active learning activities rather than lecturing[26]. An image showing part of an OLI module introducing ST / SE is shown in Fig. 1. Although these learning modules are tailored to mechanical engineering students through discipline-specific examples and course references, the core content is discipline-agnostic and easily portable to other contexts.

Students complete unscored formative assessment questions in each module (a "module" is a subset of a "unit" in OLI terminology), along with a summative assessment that is given as a pre-post assessment at the unit level. They are unable to see their scores or any feedback on their pre-test responses. A unit-level survey delivered *after* the post-test asks students to rate their confidence in applying various ST / SE concepts. It is important to note that the summative assessment questions cover only a subset of the topics covered by the self-efficacy questions; however, all self-efficacy questions are correlated at a minimum with one formative assessment question throughout the modules. The summative assessments focus on practical applications of the material to electrified transportation devices. The setup prompt for the Unit 2 summative assessment is shown in Fig. 2 and an example summative assessment question is shown in Fig. 3.

Table 1 shows the self-efficacy questions that students answer at the end of Unit 1, which covers the conventional product development process. Each of these questions measures a specific learning objective that is covered in the formative assessment questions. The filled boxes in Table


While not universally true, today’s engineers generally design systems that are much more complex than those that were designed a generation ago. Much of this complexity comes from the infusion of computation, actuation, and sensing into devices that were previously purely mechanical. For example, the image below shows a fingerprint-enabled bike lock that comes with apps for phones and smart watches. Of course not all devices are increasing in complexity; it seems unlikely that we will see “smart” scissors or hammers anytime soon. However, even for these simple mechanical devices the production system has become more complex over time through automation.

Figure 1. Smart bicycle lock. Locks were previously the epitome of a purely mechanical system.
Source: https://www.amazon.com/eLinkSmart-Fingerprint-Waterproof-Refrigerator-Furniture/dp/B0BQHKMXJV

Figure 1: Snapshot of OLI content. OLI content can include a mixture of text, images, audio, and video.

1 indicate learning objectives that are covered in the pre-post assessments that are analyzed in this paper. Table 2 provides similar information for Unit 2 (fundamentals of ST / SE).

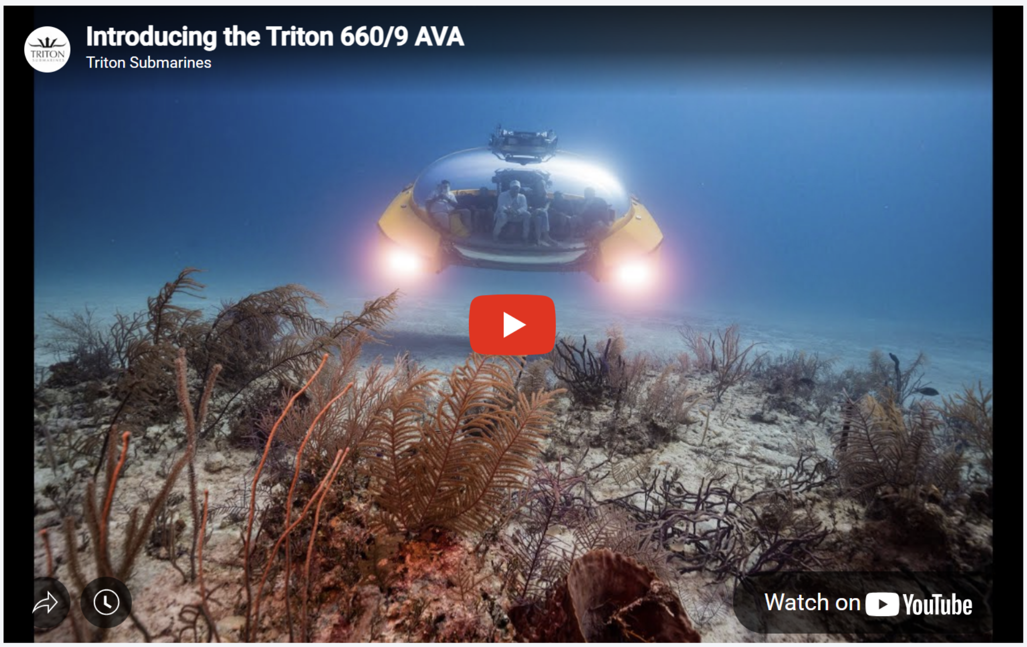
Results and Discussion

In the aggregate, the pre-post test results indicate that students show substantial performance benefits as a result of taking the OLI modules. For both the Unit 1 and Unit 2 knowledge assessments, on average students demonstrated an increase in performance following the online learning modules (Table 3). A paired-samples t-test indicated that this difference was statistically significant for both the Unit 1 assessment ($t(411) = -13.69$, $p < .001$, $d = -0.68$) and the Unit 2 assessment ($t(397) = -9.65$, $p < .001$, $d = -0.48$).

Question-level analysis of the pre-post outcomes shows that students improved performance on all topics, but also indicates that for some topics students’ pre-existing knowledge was sufficient to answer the questions. Tables 4 and 5 show students’ pre-post growth on each measured learning objective (see Tables 1 and 2 for question to topic mapping).

Table 4 shows that students’ pre-existing knowledge on Unit 1 contents varied widely between topics, ranging from excellent (explaining the need for multiple conceptual solutions) to poor (understanding contents of a product/system mission statement). Students’ post-test scores improved on every topic, but even after taking the OLI modules students struggled to identify the components of product/system mission statements and to identify quality metrics for customer needs. This lag suggests that while students grasp the *concept* of design, they struggle with the

This module will test your knowledge on several main concepts presented in Unit 2. All questions below will revolve around the development of a tourist submarine like the Triton 660 AVA described below. The video below highlights the main features of the Triton 660.



If interested you can learn more about the Triton Submarines at https://tritonsubs.com/.

As you consider the following questions, which are based on hypothetical scenarios, imagine that you are an engineer in a small start-up company working as part of the product development team for a new tourist submarine.

Figure 2: Example of OLI summative assessment scenario. Students are given a problem setup that ties the summative assessment questions together.

Table 1: Self efficacy questions covering Unit 1 learning outcomes. Only a subset of the learning outcomes were assessed in the pre-post assessment. Numbers are used to identify questions for subsequent analysis.

Unit 1 Self Efficacy Questions

Question	Assessed
I can explain the importance of following a structured product development process	1
I can provide examples of products with different levels of complexity	-
I can list key considerations in product planning	-
I can provide a solution-neutral description of a product	-
I can identify a well-written product mission statement	2
I can explain the advantages and disadvantages of electrification of personal transportation devices	-
I can list the major phases of the product development process	3
I can organize the phases of the product development into a flow chart	-
I can describe the use of iteration and rapid learning cycles within a product development process	-
I can explain how prototypes are used in the product development process	4
I can define design for X and explain its purpose	-
I can list the main steps of the concept development phase	-
I can identify well-written customer needs	5
I can identify appropriate metrics for a customer need	6
I can explain the importance of considering many conceptual solutions	7
I can list the key activities of the system-level design phase	-
I can explain the difference between modular and integral system architectures	8
I can describe the use of analysis in the detail design phase	9
I can list required courses in the major needed for detail design	-
I can explain the role of CAD and CAE in detail design	-
I can explain the difference between product validation and product verification	10
I can explain the purpose of the testing and refinement phase	-
I can indicate the purpose of the production ramp-up phase	-

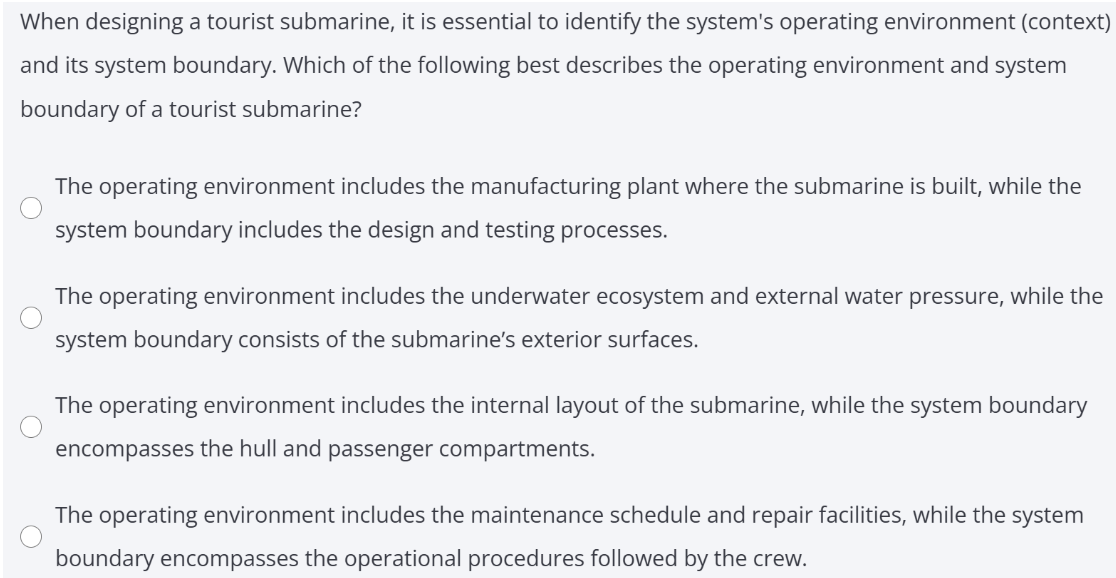
Table 2: Self efficacy questions covering Unit 2, which focuses on fundamental ST / SE concepts

Unit 2 Self Efficacy Questions	
Question	**Assessed**
I can recognize the evolution of product complexity over time and its challenges	-
I can recognize the need for systems thinking and systems engineering in the development of complex products	1
I can recognize the concept of subsystems and their role in managing complexity	-
I can define "system" and explain how the concept of system is used in problem-solving	-
I can identify the purpose, elements, and subsystems of a system	-
I can divide a simple or moderately complex system into subsystems and recognize that the division is not unique	2
I can identify a system's environment and its system boundary	3
I can identify fundamental and incidental interactions	-
I can define systems thinking	-
I can define systems engineering and list the relationship between systems engineering and systems thinking	4
I can list key characteristics of a systems thinker	-
I can describe the phases in a system's life cycle, from conception to retirement, and how the characteristics of the system affect its life cycle	5
I can identify the stakeholders of a product / system	-
I can explain the importance of identifying the needs of all the stakeholders of a product / system	6
I can recognize that systems thinking involves more than the basic concepts presented in the course	-

Table 3: Mean Pre and Post Knowledge Assessment Scores (All Institutions)

		Mean Score 0-1 (SD)			
Unit	**N**	**Pre**	**Post**	**t**	**p**
Unit 1	412	.79 (.19)	.92 (.11)	-13.69	$< .001$*
Unit 2	398	.86 (.25)	.98 (.09)	-9.65	$< .001$*

* Statistically significant


When designing a tourist submarine, it is essential to identify the system's operating environment (context) and its system boundary. Which of the following best describes the operating environment and system boundary of a tourist submarine?

- The operating environment includes the manufacturing plant where the submarine is built, while the system boundary includes the design and testing processes.
- The operating environment includes the underwater ecosystem and external water pressure, while the system boundary consists of the submarine’s exterior surfaces.
- The operating environment includes the internal layout of the submarine, while the system boundary encompasses the hull and passenger compartments.
- The operating environment includes the maintenance schedule and repair facilities, while the system boundary encompasses the operational procedures followed by the crew.

Figure 3: A summative assessment question for Unit 2. 82% of students answered this question correctly on the pre-test, whereas 98% answered it correctly on the post-test.

specific *terminology* and *syntax* required for formal requirements definition. This finding identifies a specific area where the online module content may need to be bolstered with additional examples or scaffolded practice to bridge the gap between intuition and formal specification definition for products/systems. It is important to note that Questions 2 and 3 were “check all that apply” items rather than multiple choice, which may have impacted student performance.

Unlike the spread shown in pre-test results for Unit 1, the Unit 2 pre-test results showed more uniformity in pre-existing student knowledge. All questions again showed growth from pre to post, with students performing exceptionally well on the post-test questions. The post-test results for Unit 2 reveal a potential ”ceiling effect,” with students achieving near-perfect scores across almost all learning objectives. For example, the ability to “divide a system into subsystems” rose from 85% to 97%.

While these high scores confirm the efficacy of the modules in teaching foundational vocabulary and identification skills, the lack of variance in post-test data suggests that the assessment questions may primarily target the lower levels of Bloom’s Taxonomy[40] (remembering and understanding). As these modules are intended for first-year and sophomore students, this level of mastery is appropriate; however, future assessments may require more complex scenario-based questions to better differentiate between “competence” and “mastery” as students progress to upper-division design courses.

A two-way mixed ANOVA was used to determine the impacts of time and year in school (First Year vs. Sophomore) as well as their interaction on student performance. When examining student performance on the Unit 1 assessment by year, there was no significant interaction between time and year, which suggests that the rate of change in scores did not vary between the two groups (see Table 6). Additionally, there was a significant main effect of time with improvement on students’ scores from pre to post-assessment ($F(1, 410) = 54.06$, $p < .001$,

Table 4: Unit 1 Pre and Post Knowledge Assessment Scores by Item

	Mean Score 0-1 (SD)		
Question	**Pre**	**Post**	**Mean Diff (Post-Pre)**
1	.92 (.27)	.99 (.10)	0.07
2	.38 (.49)	.67 (.47)	0.29
3	.86 (.34)	.97 (.18)	0.11
4	.95 (.22)	.98 (.15)	0.03
5	.87 (.34)	.96 (.19)	0.09
6	.67 (.47)	.82 (.38)	0.15
7	.96 (.19)	.99 (.09)	0.03
8	.77 (.42)	.89 (.31)	0.12
9	.74 (.44)	.94 (.24)	0.20
10	.75 (.43)	.97 (.18)	0.22

Table 5: Unit 2 Pre and Post Knowledge Assessment Scores by Item

	Mean Score 0-1 (SD)		
Question	**Pre**	**Post**	**Mean Diff (Post-Pre)**
1	.89 (.31)	.98 (.12)	0.09
2	.85 (.36)	.97 (.18)	0.12
3	.82 (.39)	.98 (.15)	0.16
4	.85 (.36)	.98 (.14)	0.13
5	.86 (.35)	.98 (.13)	0.12
6	.90 (.30)	.98 (.12)	0.08

Table 6: Mean Pre and Post Knowledge Assessment Scores by Year

Assessment	Year	N	Mean Score 0-1 (SD)	
			Pre	**Post**
Unit 1	First Year	381	.79 (.18)	.92 (.11)
	Sophomore	31	.81 (.23)	.95 (.09)
Unit 2	First Year	374	.86 (.25)	.98 (.09)
	Sophomore	24	.83 (.27)	.96 (.11)

partial $\eta^2 = .12$). However, there was no significant main effect of year on student scores for the Unit 1 assessment.

The same pattern appeared for the Unit 2 assessment with no significant interaction between time and year and no significant main effect of year on students' scores. Similar to Unit 1, Unit 2 assessment also had a significant main effect of time with improvement on students' scores from pre- to post-assessment ($F(1, 396) = 22.15$, $p < .001$, partial $\eta^2 = .05$).

Taken together, results from Unit 1 and 2 assessments indicate that student performance improved following the modules with no significant differences appearing based on a students' year in school. The unbalanced nature of the sample size when comparing across years should be noted.

A one-way ANOVA was performed to determine if students' average self-efficacy (see Table 7) at the end of each unit varied across institutions. While sample sizes were unbalanced and Levene's test for homogeneity of variances was violated for the Unit 1 analysis results suggest that there are no statistically significant differences between institutions for either of the surveys.

Table 7: Mean self-efficacy scores by institution

End of Survey	Institution	N	Mean Score 1-5 (SD)
Unit 1	SDM	21	3.86 (.46)
	TXST	220	3.86 (.83)
	CMU	127	4.04 (.73)
	Total	**368**	**3.92 (.79)**
Unit 2	SDM	17	3.97 (.42)
	TXST	216	4.02 (.77)
	CMU	128	4.04 (.74)
	Total	**361**	**4.03 (.74)**

When examining the relationship between students post-assessment performance and their end of survey self-efficacy scores, there was a small positive correlation for Unit 1 ($r(368) = .13, p = .014$). There was no significant correlation between the Unit 2 post-assessment performance and students' self-efficacy scores ($r(361) = .03, p = .52$).

Conclusions and Future Work

This paper has extended prior work on the use of online learning modules to teach fundamental ST/SE skills in undergraduate mechanical engineering courses. Pre-post measures of student learning embedded within the learning environment show significant growth in student performance as a result of taking the online learning modules. Beyond the aggregate growth, three key insights emerged from the assessment data.

- **Intuition vs. formalism in design:** In the product development unit (Unit 1), students demonstrated strong pre-existing intuition for iterative concepts like prototyping and solution generation. However, they struggled with the formal syntax of requirements engineering (e.g., mission statements and metrics) even after the intervention. This suggests that while students intuitively "get" design, they require more targeted scaffolding to master the formal language of systems engineering.
- **High mastery of fundamentals:** In the systems thinking unit (Unit 2), post-test scores neared 100% across almost all learning objectives. While these strong scores validate the modules' ability to teach core vocabulary and identification skills, this ceiling effect suggests that the current assessment may not sufficiently discriminate between basic competence and deeper mastery.
- **Distinction between confidence and competence:** The weak to non-existent correlation between students' self-efficacy ratings and their objective test performance highlights the importance of using direct measures of learning. Self-efficacy surveys alone may not accurately capture the nuance of student learning gains, particularly in introductory courses where students may overestimate their mastery of new concepts.

Furthermore, the consistency of these results across three different institutions and two different academic levels (first-year and sophomore) supports the scalability of these online modules as a "plug-and-play" curriculum enhancement.

Based on these findings, future iterations of this work will focus on increasing assessment rigor, scaffolding formal specifications, and tracking longitudinal impact. To address the ceiling effect in Unit 2, we plan to introduce more complex, scenario-based assessment questions that target higher levels of Bloom's Taxonomy. These will require students to not just identify systems concepts, but apply them to low-complexity scenarios. The Unit 1 content will be revised to include additional interactive exercises specifically focused on writing and critiquing mission statements and customer needs. By providing immediate feedback on the syntax of these specifications, we aim to bridge the gap between students' design intuition and formal engineering practice. Finally, while this study measured immediate learning gains centered around systems "literacy", the ultimate goal is to produce engineers who apply these skills in practice. Future work will attempt to track these students into their upper-division design courses to determine if the ST/SE terminology and concepts are retained and applied during capstone projects.

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References

[1] C. Rehmann, D. Rover, M. Laingen, S. Mickelson, and T. Brumm, "Introducing systems thinking to the engineer of 2020," in *ASEE Annual Conference and Exposition*, 2011.

[2] J. E. Kasser, P. John, K. Tipping, and L. W. Yeoh, "Systems engineering a 21st century introductory course on systems engineering: the seraswati project," in *Asia Pacific Conference on Systems Engineering*, 2008.

[3] J. Monat, T. Gannon, and M. Amissah, "The case for systems thinking in undergraduate engineering education," *International Journal of Engineering Pedagogy (iJEP)*, vol. 12, no. 3, pp. 50–88, 2022.

[4] R. Khan, C. Whitcomb, and C. White, "Self-efficacy analysis of student learning in systems engineering," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 50571. American Society of Mechanical Engineers, 2016, p. V005T06A043.

[5] R. E. Thomassie, "Systems engineering competencies essential for mechanical engineering graduates," Ph.D. dissertation, Texas A&M University, 2019.

[6] A. Azemi, "Benefits of teaching systems thinking as part of an engineering curriculum," in *2019 IEEE Frontiers in Education Conference (FIE)*. IEEE, 2019, pp. 1–6.

[7] C. Cattano, T. Nikou, and L. Klotz, "Teaching systems thinking and biomimicry to civil engineering students," *Journal of Professional Issues in Engineering Education & Practice*, vol. 137, no. 4, pp. 176–182, 2011.

[8] I. G. Guardiola, C. Dagli, and S. Corns, "Using university-funded research projects to teach system design processes and tools," *IEEE Transactions on Education*, vol. 56, no. 4, pp. 377–384, 2013.

[9] R. Jain, K. Sheppard, E. McGrath, and B. Gallois, "Promoting systems thinking in engineering and preengineering students," in *2009 Annual Conference & Exposition*, 2009, pp. 14–994.

[10] R. Lesh, "Modeling students modeling abilities: The teaching and learning of complex systems in education," *The Journal of the Learning Sciences*, vol. 15, no. 1, pp. 45–52, 2006.

[11] J. P. Monat and T. F. Gannon, "Applying systems thinking to engineering and design," *Systems*, vol. 6, no. 3, p. 34, 2018.

[12] M. Simoni, E. Andrijcic, B. Kline, and A. Bernal, "Helping undergraduate students of any engineering discipline develop a systems perspective," in *INCOSE International Symposium*, vol. 26, no. 1. Wiley Online Library, 2016, pp. 495–511.

[13] M. Valenti, "Teaching tomorrow's engineers," *Mechanical Engineering*, vol. 118, no. 7, p. 64, 1996.

[14] M. K. Yurtseven, "Teaching systems thinking to industrial engineering students." in *ICSTM*, 2000.

[15] C. M. Birrenkott, K. H. Muci-Kuchler, M. D. Bedillion, M. Lovett, and L. O. Pottmeyer, "Evaluation of targeted systems thinking and systems engineering assessments in a freshmen-level mechanical engineering course," in *2021 ASEE Virtual Annual Conference Content Access*, 2021.

[16] K. H. Muci-Kuchler, C. M. Birrenkott, M. D. Bedillion, M. Lovett, and C. Whitcomb, "Incorporating systems thinking and systems engineering concepts in a freshman-level mechanical engineering course," in *2020 ASEE Virtual Annual Conference Content Access*, 2020.

[17] K. H. Muci-Kuchler, C. M. Degen, M. D. Bedillion, and M. Lovett, "Extending systems thinking skills to an introductory mechanical engineering course," in *2019 ASEE Annual Conference & Exposition*, 2019.

[18] C. M. Degen, K. H. Muci-Küchler, M. D. Bedillion, S. Huang, and M. Ellingsen, "Measuring the impact of a new mechanical engineering sophomore design course on students' systems thinking skills," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 52064. American Society of Mechanical Engineers, 2018, p. V005T07A050.

[19] K. H. Muci-Kuchler, M. D. Bedillion, S. Huang, C. M. Birrenkott, M. D. Ellingsen, W. M. Nikshi, and J. Ziadat, "Incorporating basic systems thinking and systems engineering concepts in a mechanical engineering sophomore design course," in *2017 ASEE Annual Conference & Exposition*, 2017.

[20] K. H. Muci-Küchler, M. D. Bedillion, C. M. Degen, M. D. Ellingsen, and S. Huang, "Incorporating basic systems thinking and systems engineering concepts in a sophomore-level product design and development course," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 50571. American Society of Mechanical Engineers, 2016, p. V005T06A040.

[21] J. Ziadat, M. D. Ellingsen, K. H. Muci-Küchler, S. Huang, and C. M. Degen, "Using practical examples to motivate the study of product development and systems engineering topics," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 50571. American Society of Mechanical Engineers, 2016, p. V005T06A042.

[22] M. D. Bedillion, M. Lovett, K. H. Muci-Kuchler, and C. M. Degen, "Teaching systems thinking in a capstone mechatronic design course," in *2019 ASEE Annual Conference & Exposition*, 2019.

[23] M. Bedillion, K. H. Muci-Küchler, A. Emami, L. Kojtek, L. Pottmeyer, and C. M. Birrenkott, "Developing online learning modules on systems concepts for first year mechanical engineering students," in *ASME International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, 2024.

[24] C. M. Birrenkott, M. Lande, H. Benes, K. H. Muci-Küchler, and M. Bedillion, "Developing hands-on class activities to enhance systems-thinking and systems-engineering course material," in *ASME International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, 2024.

[25] M. D. Bedillion, L. O. Pottmeyer, K. H. Muci-Kuchler, L. Kojtek, A. Emami, and C. M. Birrenkott, "Assessing learning and self-efficacy in online modules on systems thinking and systems engineering," in *2025 ASEE Annual Conference & Exposition*, 2025.

[26] M. Lande, C. M. Birrenkott, H. Benes, A. Larson, M. D. Bedillion, and K. H. Muci-Kuchler, "Tinkering towards systems thinking: Integrating hands-on design activities in first-year engineering education," in *2025 ASEE Annual Conference & Exposition*, 2025.

[27] A. Shekh-Abed, O. Hazzan, and A. Gero, "Promoting systems thinking and abstract thinking in high-school electronics students: integration of dedicated tasks into project-based learning," *Int. J. Eng. Educ*, vol. 37, no. 4, pp. 1080–1089, 2021.

[28] A. Gero and I. Shlomo, "Promoting systems thinking in two-year technology students: An interdisciplinary course on medical ultrasound systems," *International Journal of Engineering Education*, vol. 37, no. 2, pp. 564–572, 2021.

[29] M. Frank, “Knowledge, abilities, cognitive characteristics and behavioral competences of engineers with high capacity for engineering systems thinking (cest),” *Systems engineering*, vol. 9, no. 2, pp. 91–103, 2006.

[30] A. Bandura, *Self-efficacy: The exercise of control*. Freeman, 1997, vol. 11.

[31] K. E. Dugan, E. A. Mosyjowski, S. R. Daly, and L. R. Lattuca, “Systems thinking assessments: Approaches that examine engagement in systems thinking,” in *2021 ASEE Virtual Annual Conference Content Access*, 2021.

[32] R. Lavi, Y. J. Dori, N. Wengrowicz, and D. Dori, “Model-based systems thinking: Assessing engineering student teams,” *IEEE Transactions on Education*, vol. 63, no. 1, pp. 39–47, 2019.

[33] J. T. Nelson, J. S. Linsey, R. L. Nagel, and M. R. Bohm, “The impact of functional modeling on engineering students’ mental models,” in *2018 ASEE Annual Conference & Exposition*, 2018.

[34] K. E. Dugan, E. A. Mosyjowski, S. R. Daly, and L. R. Lattuca, “Systems thinking assessments in engineering: A systematic literature review,” *Systems research and behavioral science*, vol. 39, no. 4, pp. 840–866, 2022.

[35] M. Lovett, M. D. Bedillion, C. M. Birrenkott, K. H. Muci-Kuchler, and L. O. Pottmeyer, “Building and revising an assessment to measure students’ self-efficacy in systems thinking,” in *2021 ASEE Virtual Annual Conference Content Access*, 2021.

[36] S. Huang, K. H. Muci-Kuchler, M. D. Bedillion, M. D. Ellingsen, and C. M. Degen, “Systems thinking skills of undergraduate engineering students,” in *2015 IEEE Frontiers in education conference (FIE)*. IEEE, 2015, pp. 1–5.

[37] K. R. Koedinger, J. Kim, J. Z. Jia, E. A. McLaughlin, and N. L. Bier, “Learning is not a spectator sport: Doing is better than watching for learning from a mooc,” in *Proceedings of the second (2015) ACM conference on learning@ scale*, 2015, pp. 111–120.

[38] Open learning initiative. [Online]. Available: https://oli.cmu.edu/.

[39] S. Eppinger and K. Ulrich, *Product Design and Development*. McGraw-Hill Higher Education, 2015. [Online]. Available: https://books.google.com/books?id=S7FZCgAAQBAJ

[40] B. S. Bloom, M. D. Engelhart, E. Furst, W. H. Hill, and D. R. Krathwohl, “Handbook i: cognitive domain,” *New York: David McKay*, 1956.