Teaching Systems Thinking in a Capstone Mechatronic Design Course

Dr. Mark David Bedillion, Carnegie Mellon University

Dr. Bedillion received the BS degree in 1998, the MS degree in 2001, and the PhD degree in 2005, all from the mechanical engineering department of Carnegie Mellon University. After a seven year career in the hard disk drive industry, Dr. Bedillion was on the faculty of the South Dakota School of Mines and Technology for over 5 years before joining Carnegie Mellon as a Teaching Faculty in 2016. Dr. Bedillion's research interests include distributed manipulation, control applications in data storage, control applications in manufacturing, and STEM education.

Dr. Marsha Lovett, Carnegie Mellon Univeristy

Dr. Marsha Lovett is Associate Vice Provost of Teaching Innovation, Director of the Eberly Center for Teaching Excellence and Educational Innovation, and Teaching Professor of Psychology – all at Carnegie Mellon University. She applies theoretical and empirical principles from learning science research to improve teaching and learning. She has published more than fifty articles in this area, co-authored the book How Learning Works: 7 Research-Based Principles for Smart Teaching, and developed several innovative, educational technologies, including StatTutor and the Learning Dashboard.

Dr. Karim Heinz Muci-Kuchler, South Dakota School of Mines and Technology

Dr. Karim Muci-Küchler is a Professor of Mechanical Engineering and Director of the Experimental and Computational Mechanics Laboratory at the South Dakota School of Mines and Technology (SDSM&T). Before joining SDSM&T, he was an Associate Professor of Mechanical Engineering at the University of Detroit Mercy. He received his Ph.D. in Engineering Mechanics from Iowa State University in 1992. His main interest areas include Computational Mechanics, Solid Mechanics, and Product Design and Development. He has taught several different courses at the undergraduate and graduate level, has over 50 publications, is co-author of one book, and has done consulting for industry in Mexico and the US. He can be reached at Karim.Muci@sdsmt.edu.

Dr. Cassandra M. Degen, South Dakota School of Mines and Technology

Dr. Cassandra Degen received her B.S. degree in Metallurgical Engineering from the South Dakota School of Mines and Technology in 2007. She received her Ph.D. in Materials Science and Engineering in 2012 from the University of Illinois at Urbana-Champaign, studying mechanochemical reactions of a spiropyran mechanophore in polymeric materials under shear loading. She is currently an Assistant Professor in the Mechanical Engineering department at the South Dakota School of Mines and Technology where her research interests include novel manufacturing and characterization techniques of polymer and composite structures and the incorporation of multifunctionality by inducing desired responses to mechanical loading.

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Introduction

Engineers involved in product design and development have been facing a clear trend towards the integration of multiple subsystems into existing and new devices. Sensors, actuators, and processors are now ubiquitous components in design, which has led to the rise of mechatronics engineering and subsequent curriculum changes in conventional disciplines such as mechanical engineering. Moreover, along with the expansion of technical knowledge requirements, the trend towards greater product complexity brings with it an increased need for students to learn and apply holistic, systems-level approaches to design problems [1, 2]. This paper describes the effects of infusing systems thinking concepts into a capstone mechatronic design course for mechanical engineers.

Given the importance of systems thinking skills, there has been much prior work on infusing the undergraduate curriculum in traditional disciplines with basic systems thinking and systems engineering concepts [3-10]. Most closely related are works that focus on identifying skills that can effectively be taught to college students and infusing them into the curriculum [11-15]. This work expands on prior efforts by the authors that introduced systems thinking concepts to sophomore mechanical engineering students [16-19]. While sophomore-level students can gain an understanding about conceptual design, their analytical skills are generally not refined enough to understand the connections between conceptual and detail design activities. For senior students, these connections can be made more explicit, ideally increasing student interest in topics that they may incorrectly perceive as less relevant than technical courses focusing only on analysis.

This work focuses on training mechanical engineering undergraduate students in the following product development activities: identifying customer needs, setting target specifications, concept generation, and system architecture. Case studies originally developed for sophomore students [19] are adapted for use with senior students by illustrating the impact of each of the selected product development activities in the analysis that takes place during the detail design phase of the product development process. By including a brief analysis example, the aim is to better engage senior students by showing the connection between conceptual design and later analysis activities while increasing students' appreciation of the life-long learning that is required in the engineering profession.

Assessing changes in students' systems thinking skills is notoriously difficult [20-23]. This work leverages the Systems Thinking Skills Survey (STSS) described in [17] to assess students' systems thinking skills. In addition to gauging changes in students' systems thinking skills via a concept inventory, the effects of the learning materials are assessed by studying changes in students' self-efficacy and surveying students on the appeal of the new learning materials. Results are presented for a class of 37 students that features a mix of undergraduate and graduate students. The graduate students form a particularly interesting cohort in that they have presumably previously taken a conventional capstone senior design course as undergraduate students.

This paper is organized as follows. First, a description of the course is provided along with a glimpse into the curriculum structure and student backgrounds. Second, a description of the interventions is provided with a focus on new analysis components. Third, the results of student surveys on the learning materials and their pre and post scores on the STSS are presented to assess the intervention's success.

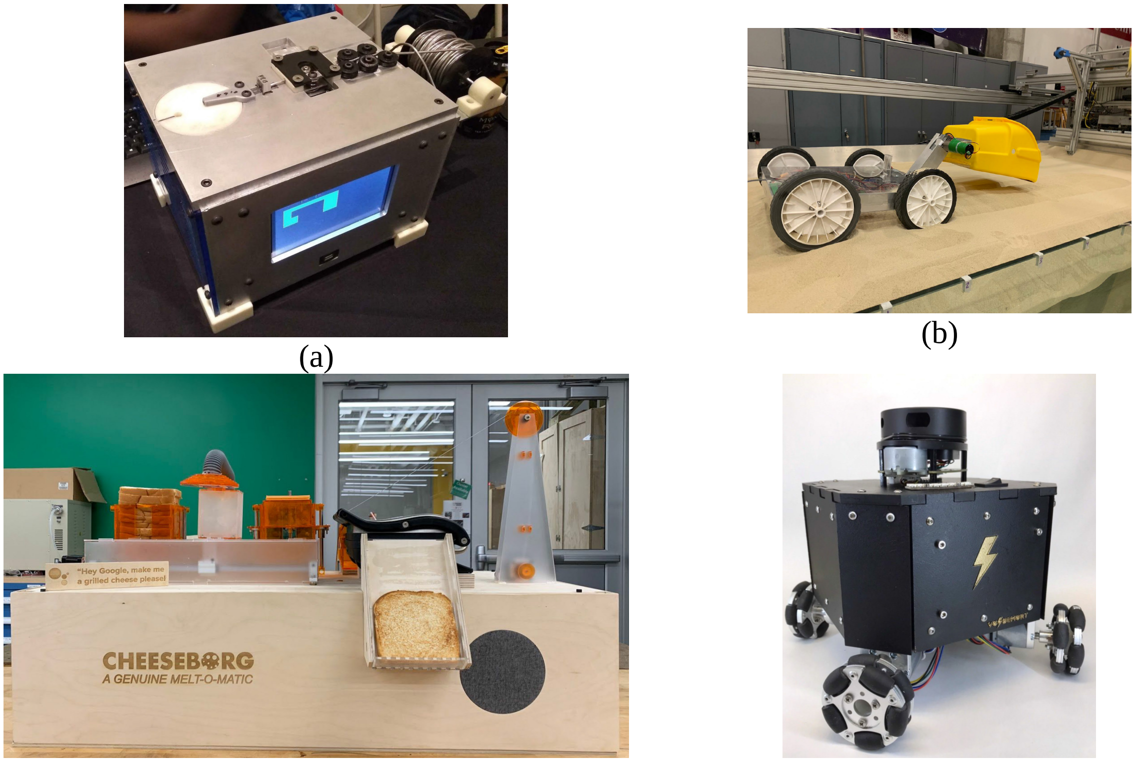
Course description and student backgrounds

The mechanical engineering curriculum at Carnegie Mellon University (CMU) includes two design courses: a junior course on solution methods for constrained design problems and a senior capstone course that introduces the design process for open-ended problems. Unlike many universities, CMU provides students with options for the capstone design experience. Currently, students may choose between a conventional design class with a focus on entrepreneurship and a course that focuses on design of mechatronic systems. This paper relates to an intervention that occurred in the mechatronics-based class (Electromechanical Systems Design, or EMSD). The learning objectives in EMSD relate to both the product development process and to selected topics in mechatronics; Table 1 provides a list of key topics in both areas. Product Design and Development [24] and Introduction to Mechatronic Design [25] are used as the course textbooks and the product development process considered is for "market-pull" products of low to moderate complexity.

Table 1: Topics covered in EMSD. The course features a mix of technical content in mechatronics with design theory.

Design	Mechatronics
Stakeholder research / customer needs	Software architecture
Target specifications	Communication protocols
Concept generation and selection	Power
Prototyping	Measurement systems
Design for manufacturing	Noise and grounding

Like the conventional capstone course, the EMSD course revolves around a semester-long project. The projects are student initiated and must contain sensing, actuation, and computation elements. While many students in the conventional design course opt for projects that feature similar components, EMSD students are *required* to include those features and are expected to demonstrate superior performance on the mechatronic aspects of the design. Figure 1 shows four of the eight final prototypes that were generated in the fall 2018 EMSD class.



(a) (b) (c) (d)

Figure 1: Sample student projects. Students explored a wide variety of concepts, including a CNC wire bender (a), a robot for beach cleanup (b), an automated grilled cheese maker (c), and a mobile drawing robot (d).

The EMSD course serves as both a capstone for undergraduate students and an elective for graduate students. As such, there are two distinct populations in the course with varying degrees of familiarity with the design process. As mentioned previously, the undergraduate students are introduced to the full product development process for the first time in EMSD, whereas graduate students have presumably already completed a capstone design experience as undergraduates. Of the 37 students who completed the course in fall 2018, 11 were graduate students (including one PhD student). Unfortunately, the small number of students means that student survey results cannot be discriminated by class standing, but future work will attempt to isolate the results for these two populations.

Learning materials

The authors prior work in [18] identified areas in which systems engineering concepts can be naturally added to a sophomore design class and developed four case studies that can be used to illustrate those concepts. Figure 1 shows the technical topics covered by the case studies along with their corresponding example systems: lower extremity protective armor for ground troops (identification of customer requirements), ballistic missiles (setting target specifications), unmanned ground vehicles (concept generation), and mini-submarines (systems architecture).

Each case study was designed to be 50 minutes in length with a follow-on assignment given as homework or an in-class exercise. Given that the undergraduate students in EMSD were learning the product development process for the first time, the case studies developed at the South Dakota School of Mines and Technology (SDSMT) for sophomore students were relevant for CMU's capstone course. However, given the EMSD students' additional training in analysis, the case studies were modified to better suit their maturity level and interests.

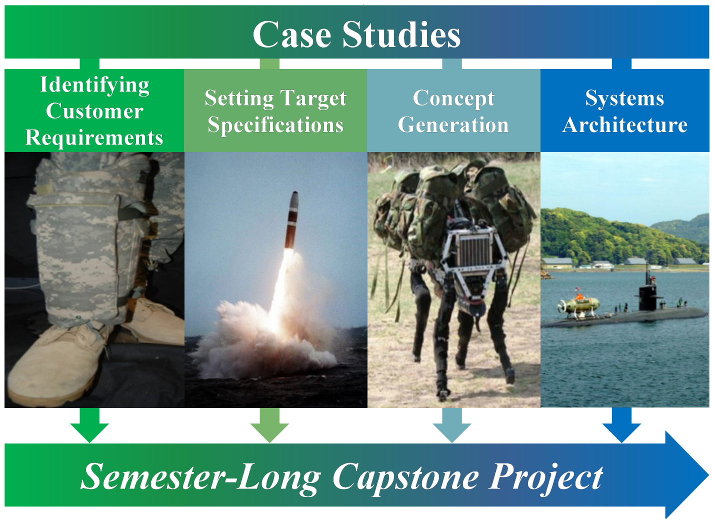


Figure 2: Case study topics and examples. The case studies cover critical elements of the design cycle that are addressed in the students' capstone projects.

Specifically, each case study was modified to include an analysis section demonstrating the breakdown of common engineering assumptions in practical applications. For instance, the case study covering lower extremity armor featured an analysis portion on the mechanics of blast and impact. While three of the topics were amenable to an analysis-based addition, the topic of system architecture defies the use of standard mechanical engineering analysis tools. Instead, the "analysis" section of the system architecture case study focused on the use of heuristics in system design as discussed in [26]. Table 2 shows a full list of analysis topics and associated in-class activities for each case study. The addition of this analysis portion served two purposes, namely helping to connect the engineering fundamentals that they are familiar with to the design process and reinforcing the need for lifelong learning (ABET Outcome 7).

Table 2: Case studies, analyses, and in-class activities for EMSD. Case studies from prior work were augmented with additional analysis content and in-class activities were modified for content and length.

Topic	Case Study	Analysis	Activity
Identifying Customer Needs	Lower Extremity Protective Armor for Ground Troops	Mechanics of blast and impact	Compile customer needs for bird strike resistant aircraft cockpits.
Setting Target Specifications	Rockets and Missiles	Dynamics of variable mass systems	Develop target specifications for a set of customer needs for a rope/line launcher for inland rescue.
Concept Generation	Unmanned Ground Vehicles (UGVs)	Mobile robot kinematics	Generate locomotion subsystem concepts for a duct cleaning robot.
Systems Architecture	Navy SEAL Deployable Submarine	Use of heuristics for complex systems	Draw a functional block diagram of the Navy SEAL deployable submarine as a subsystem and show its interfaces to other subsystems.

Unlike the sophomore class at SDSMT, the class at CMU had a 1 hour and 50 minutes lecture period. The total length of each case study including the newly added analysis material was held at 50 minutes, and the in-class activities shown in Table 2 occurred during the last 15 – 20 minutes of the class period. Thus, just over ½ of the lecture period was used to deliver the case study and give students practice. The beginning of each lecture that contained the case studies was used to introduce or review the design topic in a more conventional lecture format.

The in-class exercises were designed to give students a timely means of testing their understanding of the case study design topics. The exercises did not leverage the analytical materials presented (i.e. students did not need to solve the rocket equation to develop feasible target specifications) but were related to the topic of the case study. In the systems architecture case study, the activity dealt with interfaces rather than heuristics; future iterations will attempt to more closely align the activities with both the topic and the analysis content presented.

Results and analysis

Two primary sources were used to evaluate the effectiveness of the intervention: student satisfaction surveys and the STSS. To gauge student satisfaction, students were asked to fill out a short survey (administered by the courseware Canvas) within a half hour of the completion of each case study. One goal of the case studies was to improve students' appreciation for the importance of systems thinking skills in engineering design, and so students were asked not only to rate the case studies based on how much they learned but also on how their perceptions of the design topic importance were changed. Table 3 shows the student feedback on the case studies based on the following questions:

1. How well did the case study and exercise help you learn the design topic?
2. How much did the case study change your perceptions of the design topic?
3. Rate your satisfaction level with the quality of the learning material used for the case study.
4. Rate your satisfaction level with the relevance of the case to the EMSD's overall goals. (The course goals were listed in the question).
5. Rate your satisfaction level with how the case study engaged you.
6. Rate your satisfaction level with the length of the case study.
7. Did the end-of-case-study exercise support the overall objectives of EMSD? (The course objectives were listed in the question).

Students were asked to rate each item using a Likert-like scale. The first two questions were rated on a 4-point scale and the others were rated on a 5-point scale. In all cases, the number reported in Table 3 represents the percentage of students that rated the item in the top two levels of the scale.

One number that stands out in the first column of Table 3 is the low number of participants for the System Architecture case study. This case study was delivered in a morning class on the Monday after Thanksgiving break, and the attendance was much less than anticipated.

Table 3: Student case study satisfaction. The table shows the percentage of students that rated each item in the top two categories of a Likert-like scale.

Case Study	**Survey Question**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Customer Needs (*n* = 35)	100	86	83	86	83	71	86
Target Specifications (*n* = 31)	90	71	77	87	84	77	94
Concept Generation (*n* = 26)	92	73	81	81	73	73	77
System Architecture (*n* = 6)	100	83	67	67	83	83	83

The data in Table 3 show that, overall, students rated the case studies quite positively. Based on a weighted average across all four case studies and all seven survey questions, more than 80% of the student ratings were in the top two levels of the corresponding scale. (For a sense of comparison, if students were responding randomly – i.e., uniformly across the rating scales – this proportion would be 43% across all seven questions.) Students responded most positively to Question 1 – that the case studies improved their learning of the topics – with all four case studies showing more than 90% of responses in the top two levels. All but one case study (System Architecture) scored above 80% in terms of relevance to the course (Question 4), and all but one (Concept Generation) scored above 80% in both student engagement (Question 5) and relevance of the in-class exercise (Question 7). The question with the least positive responses from students related to length of the case study (Question 6), but even on that issue, more than 70% of student responses were in the top two levels. Based on these satisfaction data, the case study approach seems generally to be working for students. Nevertheless, future work will target refinements to the case studies based on the feedback provided by the students.

In addition to student satisfaction surveys, the STSS was administered to students as a pre/post-test (with slightly modified forms of the test used for pre vs post-test). The STSS is made up of two major parts. The first part asks students to self-assess their ability to apply various ST/SE concepts and skills to engineering projects. This part represents an indirect measure of students' abilities because students are reporting their *perceptions* of their abilities. By contrast, the second part of the STSS asks students to apply various ST/SE concepts and skills to address technical engineering problems. As such, the second part represents a direct measure of students' ability to apply ST/SE concepts and skills. Results from these two parts of the STSS will be reported in turn below.

The self-assessment portion of the STSS includes 44 items asking students "How well do you think that you can apply the topics mentioned below to an engineering project?" Student responses are collected via a 5-point Likert scale, ranging from 1=Not at all to 5=Excellent. These 44 items are grouped into five categories – Identifying customer needs, Setting target specifications, Concept generation, System architecture, and Other – thus creating a sub-scale for each category. Table 4 provides a sample item and the number of items for each category/sub-scale.

Table 4: STSS Self-assessment categories with sample items and number of items for each.

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

Students' self-assessment ratings at pre- and post-test for each of the five categories are presented in Figure 3. As expected, students' self-assessments significantly improved from pre-to post-test overall (t(36) = 5.75, $p < .01$) and across each of the five categories (by individual t-tests and MANOVA). On average, students' self-assessments increased by approximately 1.3 (on this 5-point scale) from pre-test to post-test.

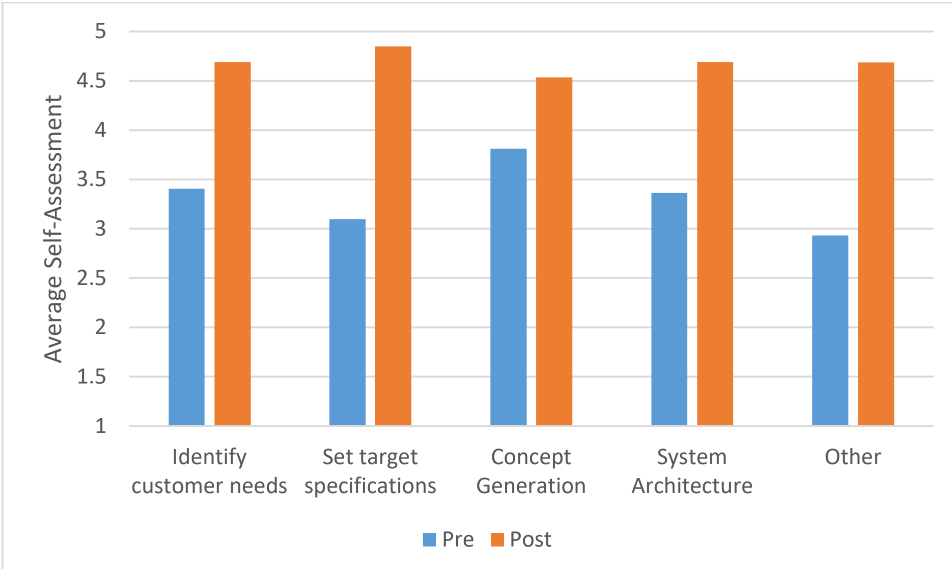


Figure 3: Students' average self-assessment ratings from the STSS, at pre- and post-test, for each of five categories.

For the second part of the STSS, students were asked to apply their ST/SE knowledge and skills in the context of technical problems. The contexts for these problems were chosen to be relatively familiar objects (computer, lawn equipment, jewelry) so students' prior knowledge of the objects would be consistently high, allowing the assessment to focus on ST/SE knowledge and skills. Many of the items involved multiple aspects of ST/SE knowledge and skill (according to domain experts' task analysis), so unlike the self-assessment part, there are no sub-scales reported here. Students' aggregate post-test scores were higher than their aggregate pre-test scores (pre-test average = .59; post-test average = .68), as shown in Figure 4. This difference reached marginal statistical significance (t = 1.52, $p < .07$).

Seeing this increase pre- to post-test was encouraging, even though the difference was not necessarily as robust as hoped. The difference between gains in self-assessed skills and skills as measured by technical questions is not necessarily surprising given the consistent finding that students' self-assessments are not accurate, often reflecting over-confidence (e.g., Kruger & Dunning, 1999 [27]).

One challenge in data analysis was that fewer students completed the post-test (16) than the pre-test (36), likely because the participation in the survey was voluntary and the post-test came at a time when students were finishing high-stakes final projects. So, in addition to enhancing the case study materials and refining the STSS instrument, future work will also include exploring ways to better incentivize students to complete *both* the pre- and post-test.

Finally, it is possible that the STSS results could be somewhat skewed by the fact that, unlike most other universities, students at CMU have two capstone experiences to choose from.

Nonetheless, the authors find these preliminary data sufficiently encouraging to continue development on this case study-based approach to teaching systems thinking and systems engineering skills.

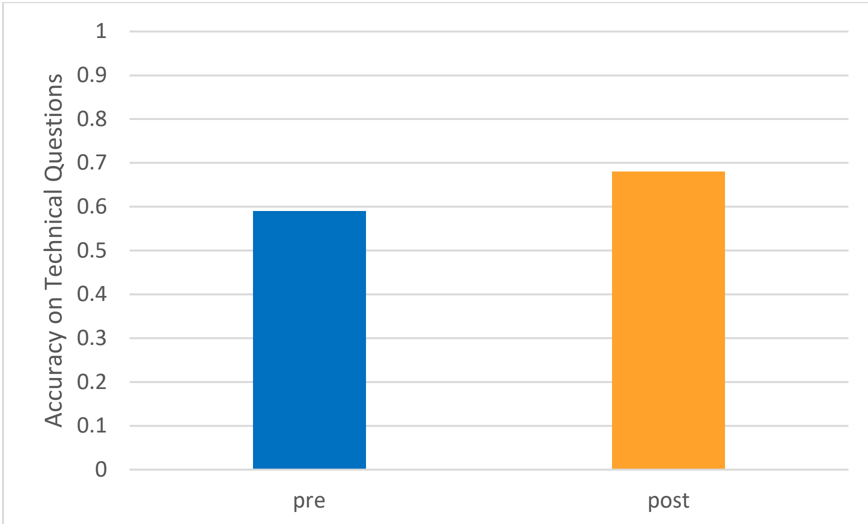


Figure 4: Students' accuracy on technical (direct measures) questions on the STSS at pre- and post-test.

Conclusions and future work

This paper has described a modification to a mechatronics-based capstone design course to include more systems thinking concepts. Case studies that were initially developed to target sophomore students were modified to include higher-level analysis topics that might appeal to seniors and graduate students. Most of the 37 students enrolled in the class in which the implementation took place provided positive feedback about the new learning materials. In addition, the STSS showed that (i) students' self-assessments of their ST/SE knowledge and skills significantly improved (by more than one point on a 5-point scale) and (ii) students' performance applying ST/SE knowledge and skills to engineering problems also improved (9 percentage points).

Future work will improve the learning materials based on student feedback and the STSS results presented here. In addition, the STSS itself is currently being revised to better measure the skills targeted by the intervention. The newly modified learning materials and STSS will be tested in the near future.

From a broader perspective, the limited gains showed in this study point to the need for a more systematic, curriculum-wide approach for introducing systems thinking and systems engineering skills. Effective application of these skills requires a change in student mindset that is not realistic to produce through four case studies in a single course. The authors' future work will measure students' skills development throughout the curriculum and target interventions in earlier courses that maximize impacts on learning.

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Bibliography

[1] Frank, M., Sadeh, A., and Ashkenasi, S., 2011, "The relationship among systems engineers' capacity for engineering systems thinking, project types, and project success," Project Management Journal, 42(5), pp. 31-41.
[2] Monat, J., and Gannon, T., 2018, "Applying Systems Thinking to Engineering and Design," Systems, 6(3), p. 34.
[3] Aurigemma, J., Chandrasekharan, S., Nersessian, N. J., and Newstetter, W., 2013, "Turning experiments into objects: The cognitive processes involved in the design of a lab‐on‐a‐chip device," Journal of Engineering Education, 102(1), pp. 117-140.
[4] Cattano, C., Nikou, T., and Klotz, L., 2010, "Teaching systems thinking and biomimicry to civil engineering students," Journal of Professional Issues in Engineering Education & Practice, 137(4), pp. 176-182.
[5] Chenard, J. S., Zilic, Z., and Prokic, M., 2008, "A laboratory setup and teaching methodology for wireless and mobile embedded systems," IEEE Transactions on Education, 51(3), pp. 378-384.
[6] Dyer, S. A., and Schmalzel, J. L., 1998, "Macroelectronics: A gateway to electronics and instrumentation education," IEEE Transactions on Instrumentation and Measurement, 47(6), pp. 1507-1511.
[7] Guardiola, I. G., Dagli, C., and Corns, S., 2013, "Using university-funded research projects to teach system design processes and tools," IEEE Transactions on Education, 56(4), pp. 377-384.
[8] Jonassen, D., Strobel, J., and Lee, C. B., 2006, "Everyday problem solving in engineering: Lessons for engineering educators," Journal of Engineering Education, 95(2), pp. 139-151.
[9] Murray, R. M., Waydo, S., Cremean, L. B., and Mabuchi, H., 2004, "A new approach to teaching feedback," IEEE Control Systems, 24(5), pp. 38-42.
[10] Hung, W., 2008, "Enhancing systems‐thinking skills with modelling," British Journal of Educational Technology, 39(6), pp. 1099-1120.
[11] Lesh, R., 2006, "Modeling students modeling abilities: The teaching and learning of complex systems in education," The Journal of the Learning Sciences, 15(1), pp. 45-52.
[12] Squires, A. F., Wade, J., Bodner, D. A., Okutsu, M., Ingold, D., Dominick, P. G., Reilly, R. R., Watson, W. R., and Gelosh, D., 2011, "Investigating an innovative approach for developing systems engineering curriculum: The Systems Engineering Experience Accelerator," ASEE Annual Conference, American Society for Engineering Education.
[13] Squires, A., Wade, J., Dominick, P., and Gelosh, D., 2011, "Building a competency taxonomy to guide experience acceleration of lead program systems engineers," DTIC Document.
[14] Gelosh, D. S., Snoderly, J. R., Heisey, M., Anthony, J. F., and Nidiffer, K., 2014, "Developing the Next Generation of the INCOSE Systems Engineering Competency Framework," INCOSE International Symposium, 24(1), pp. 635-642.

[15] Simoni, M., Andrijcic, E., Kline, B., and Bernal, A., 2016, "Helping Undergraduate Students of any Engineering Discipline Develop a Systems Perspective," INCOSE International Symposium, 26(1), pp. 495-511.
[16] Ziadat, J., Ellingsen, M., Muci-Kuchler, K. H., Huang, S., and Degen, C., 2016, "Using practical examples to motivate the study of product development and systems engineering topics," ASME International Mechanical Engineering Congress and Exposition, Phoenix, AZ.
[17] Muci-Kuchler, K. H., Bedillion, M. D., Degen, C., Ellingsen, M., and Huang, S., 2016, "Incorporating basic systems thinking and systems engineering concepts in a sophomore-level product design and development course," ASME International Mechanical Engineering Congress and Exposition, Phoenix, AZ.
[18] Muci-Kuchler, K. H., Bedillion, M. D., Huang, S., Degen, C. M., Ellingsen, M. D., Nikshi, W. M., and Ziadat, J., 2017, "Incorporating basic systems thinking and systems engineering concepts in a mechanical engineering sophomore design course," ASEE Annual Conference, Columbus, Ohio.
[19] Degen, C. M., Muci-Kuchler, K. H., Bedillion, M. D., Huang, S., and Ellingsen, M. D., 2018, "Measuring the Impact of a New Mechanical Engineering Sophomore Design Course on Students' Systems Thinking Skills," ASME International Mechanical Engineering Congress and Exposition, Pittsburgh, PA.
[20] Shuman, L. J., Besterfield-Sacre, M., and McGourty, J., 2005, "The ABET "professional skills"—Can they be taught? Can they be assessed?," Journal of engineering education, 94(1), pp. 41-55.
[21] Huang, S., Muci-Kuchler, K. H., Bedillion, M. D., Ellingsen, M. D., and Degen, C. M., 2015, "Systems thinking skills of undergraduate engineering students," 2015 IEEE Frontiers in Education Conference (FIE), pp. 1-5.
[22] Squires, A., and Larson, W., 2009, "Improving systems engineering curriculum using a competency-based assessment approach," International Journal of Intelligent Defence Support Systems, 2(3), pp. 184-201.
[23] Frank, M., and Kasser, J., 2012, "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, pp. 217-230.
[24] Ulrich, K. T., and Eppinger, S. D., 2016, Product design and development, McGraw-Hill Education, New York, NY.
[25] Carryer, J. E., Ohline, R. M., and Kenny, T. W., 2011, Introduction to mechatronic design, Prentice Hall Boston.
[26] Maier, M. W., 2009, The art of systems architecting, CRC press.
[27] Kruger, J., and Dunning, D., 1999, "Unskilled and unaware of it: how difficulties in recognizing one's own incompetence lead to inflated self-assessments," Journal of personality and social psychology, 77(6), p. 1121.