AC 2011-1499: INTRODUCING SYSTEMS THINKING TO THE ENGINEER OF 2020

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Introducing Systems Thinking to the Engineer of 2020

Abstract

To prepare the engineer of 2020 to address the grand challenges of engineering, the E2020 Scholars Program at Iowa State University seeks to have students become proficient in four pillar areas: leadership, innovation, global awareness, and systems thinking. Each pillar is introduced in three weeks in a freshman-level seminar and reinforced in half of a semester in a year-long sophomore-level seminar. Students applied systems thinking to grand challenge problems by considering factors inside and outside of engineering and using three graphical tools. They identified connections between elements with rich pictures, explained relationships with causal loop diagrams, and sketched the behavior over time of key variables in the system. Qualitative observations and quantitative assessments suggest that the initial offerings were mostly successful: Most students stated that the activities helped them to appreciate the range of issues affecting an engineering problem. Students struggled most with identifying key variables and deriving the behavior over time from causal loop diagrams.

Introduction

The College of Engineering at Iowa State University (ISU) aims to educate engineers who can address the grand challenges identified by the National Academy of Engineering[1]. These challenges include providing abundant clean water, renewable non-polluting energy, safe roads and bridges, access to modern health care, sustainable agriculture and manufacturing, and protection from natural and man-made disasters. The large scale of these challenges and the importance of infrastructure make them especially relevant for civil engineers. Engineers who can tackle such problems need not only solid technical skills but also strengths in leadership, innovation, global awareness, and systems thinking. In particular, in describing the engineer of 2020, the National Academy of Engineering (NAE)[2] aspired to engineers who can "…accommodate new fields of endeavor, including those that require openness to interdisciplinary efforts with nonengineering disciplines such as science, social science, and business." We describe our efforts to introduce systems thinking to engineering students.

These efforts are part of the E2020 Scholars Program in the ISU College of Engineering, which aims to prepare students to fulfill the vision of the NAE[2], create learning outcomes consistent with that vision, and increase student retention. Scholarships are given to engineering students chosen for their academic potential and financial need; among other requirements, students must have grade-point averages and scores on college entrance examinations that exceed minimum levels. Students participate in a learning community, and the four pillar areas of leadership, innovation, global awareness, and systems thinking are introduced in a one-semester freshman-level seminar and reinforced in a two-semester sophomore-level seminar. These seminars supplement the usual program of study for engineering students, and they allowed us to identify ways to include modules on the pillar areas in the rest of the engineering curriculum.

Many definitions of systems thinking have been proposed, but several features appear in most definitions[3-5]: viewing a problem broadly and holistically; identifying interdependence and feedback; synthesizing as well as analyzing individual components; and accounting for dynamic (i.e., time-varying), nonlinear behavior. A survey of practicing engineers showed that understanding synergy, understanding implications of modifying the system, and solving systems failures are also important traits for systems engineers[4]. The definition of Anderson and Johnson[6] adds balancing short-term and long-term views and accounting for both measurable and non-measurable factors, while Dym et al.[7] pointed out the importance of reasoning about uncertainty and making estimates in thinking about and designing systems.

Descriptions of systems thinking sometimes include graphical tools such as rich pictures, causal loop diagrams, and behavior-over-time graphs[3,5]. The rich picture[8] uses pictures, cartoons, text, and sketches to depict various elements of a systems or problem, including structures, processes, and concerns[9]. For example, for the system of managing a theater[10], the rich picture effectively displays possible connections in a cycle of profits, investment, media reviews, ticket sales, and the number of unoccupied seats (Figure 1a). It also shows the total number of seats in the theater as an external factor. The causal loop diagram shows the relationships between the elements in the rich picture; the notation “s” and “o” indicate whether the elements connected with an arrow change in the *same* or *opposite* direction. For the theater example, an increase in profit might cause a manager to invest in better shows, which would increase the number of good reviews and ticket sales. The number of unoccupied seats would decrease, and the profits would continue to increase—at least until all of the seats in the theater are filled. Tracing the loop in the causal loop diagram facilitates sketching the behavior of a key variable (say, profit) over time, as in Figure 1c.

Approaches toward teaching systems thinking have depended on the stage of the students in their education. System thinking skills of sixth graders improved most when a computer simulation of a system was combined with a specific lesson on systems theory[11]. Using the rich picture to introduce systems thinking to engineering undergraduates of all levels, Vanasupa et al.[5] noted the students’ enthusiastic participation, which they attributed to the opportunity for the students to be social and creative. Systems thinking in classes for more senior undergraduates tends to accompany more technical work, such as the multi-university effort to teach design of wireless sensor networks to juniors and seniors[12].

The objectives of our work were to develop instructional modules to teach systems thinking to engineering students and to assess their effectiveness of the modules. In the short time available

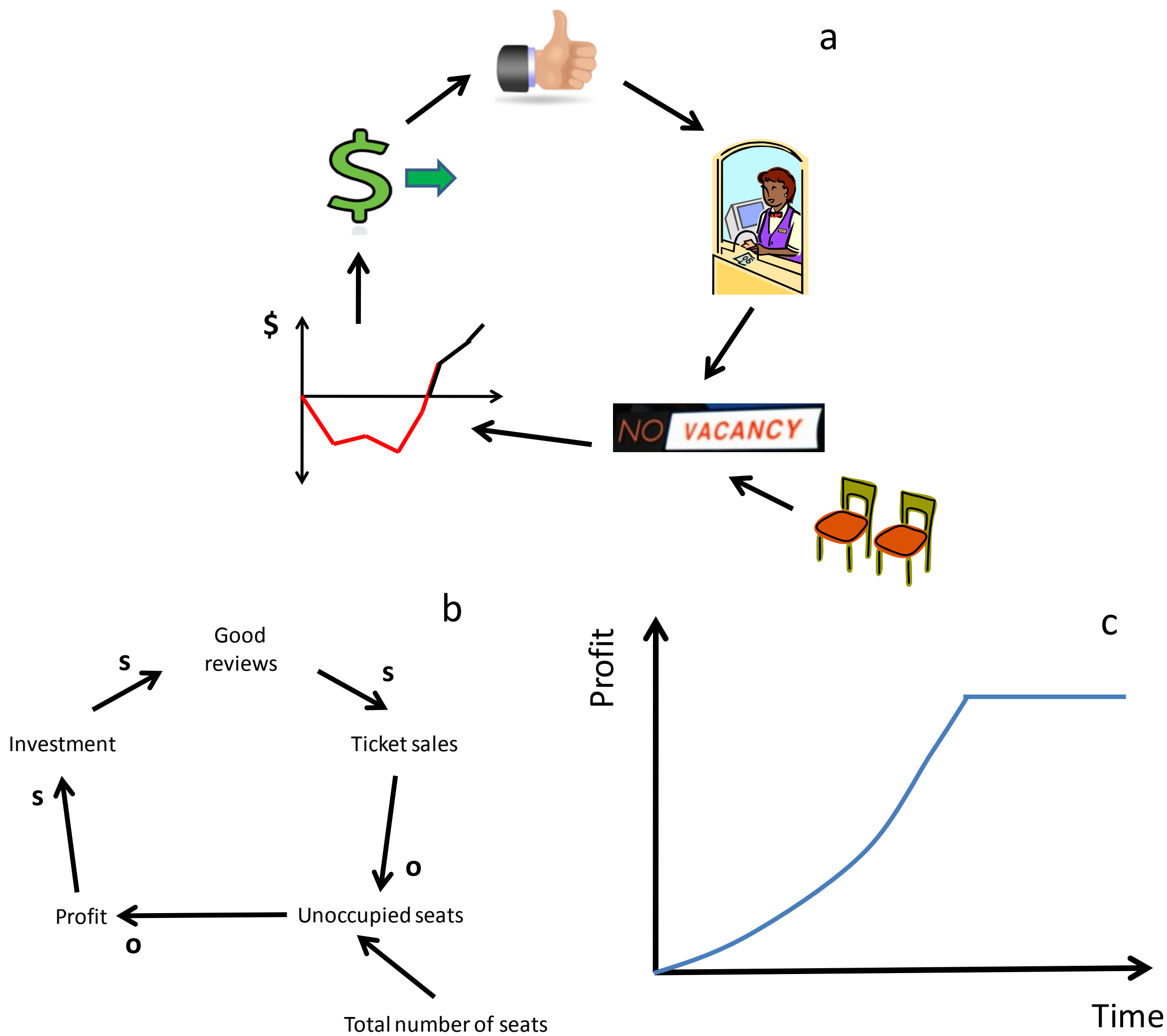

Figure 1. Tools of systems thinking applied to managing a theater: (a) rich picture, (b) causal-loop diagram, and (c) behavior-over-time graph. The example was adapted from MindTools[9].

in the freshman seminar, we focused on getting the students to appreciate the complexity arising from the interaction of factors from inside and outside engineering—that is, we aimed to have students explain the importance of taking a broad view of a problem and considering feedback and dynamic behavior. By the end of the sophomore seminar, the students were expected to achieve the following learning objectives:

> For complex, ill-defined, dynamic problems involving engineering, social, ethical, cultural, environmental, business, and political issues, students will
>
> - Identify connections between subsystems with rich pictures
> - Explain relationships with causal loop diagrams
> - Sketch the behavior over time of key variables in the system.

We describe the activities in the two seminars used to achieve the objectives, report qualitative and quantitative observations on the students' achievement, and use the lessons learned to suggest improvements to the modules.

Activities

Students

The first cohort in the E2020 Scholars Program consisted of 21 students—fourteen freshmen and seven transfer students. Four were women. Sixteen of the students were white or Caucasian, and three were black or African-American. The remaining two students identified themselves as Hispanic, Latino, or Latina. Twelve of the students came from Iowa, and eight other states, mostly in the Midwest, were represented. Two of the students had not declared a specific major in the College of Engineering. The others came from five departments in the College, including six students from the Department of Civil, Construction, and Environmental Engineering. All but one of the students continued in the program for the sophomore seminar.

Freshman seminar

The fifteen-week freshman seminar consisted of three weeks devoted to each of the four pillars and three weeks for a course introduction, team building, and reflection. The class met for one hour each week, and the first offering was in the spring semester of 2010. The module for each pillar followed a KSA approach: knowledge in week one, skills in week two, and abilities in week three. The systems thinking pillar had a lecture and short class exercises to build knowledge, a small project to develop skills, and presentations to demonstrate abilities.

The first class involved considering and discussing three questions: What is systems thinking? Why is systems thinking useful? What are the tools of systems thinking? The discussion started with an example to contrast the traditional reductionist approach with a systems thinking approach. The students were asked, "Two people take 2 hours to dig a hole 5 feet deep. How deep would the hole be if 4 people dug for 6 hours?" After the first answers were collected, further discussion was seeded with three possibilities: (a) deeper soil layers might be harder to excavate, (b) the job might not have the proper permit, and (c) the people might refuse to work for 6 hours straight. These examples helped to prod students to break away from linear thinking and to consider a wider set of issues from inside engineering and outside engineering.

Tools of systems thinking—rich pictures, causal loop diagrams, and behavior-over-time graphs—were introduced with examples and exercises. Along with a rich picture for the example of the hole, students were shown the rich picture from Vanasupa et al.[5], which depicts an unsuccessful engineering student, and asked to identify the elements. Simple examples of causal loop diagrams and their corresponding behavior-over-time graphs were presented to illustrate several concepts[9]. The most important was feedback—either reinforcing or balancing, but short term vs. long term effects, delays, and external factors were also discussed.

In the second class, students started working on their projects in randomly formed groups of three or four. The groups were asked to choose an aspect of one of the grand challenges listed in the introduction, draw a rich picture for it, and sketch a causal loop diagram and behavior-over-time graph for at least one section of the rich picture. The students spent most of the class working, while the instructors answered questions and provided guidance. In the third class, the groups presented their work to the rest of the class, and all students wrote a short reflection to answer the question "What did you learn about systems thinking?" Students also commented on systems thinking in an email survey conducted by the Research Institute for Studies in Education[13] at the end of their first year in the E2020 Scholars Program (i.e., August 2010). Students were asked to indicate the degree to which they agree with twenty statements; the one statement focused on systems thinking was, "I have an understanding about the systems thinking, including the interdisciplinary engineering design, pillar."

Sophomore seminar

The sophomore seminar spanned two semesters. Each semester consisted of a week of introduction and seven weeks each on two of the program areas. Systems thinking, which was addressed in the first half of the fall semester of 2010, had two weeks of lecture to reinforce the concepts introduced in the freshman seminar, three weeks of work on a project, and two weeks of student presentations. At the end of the module, students wrote reflections that listed strengths of the module, suggestions for improvement, and advice for future students. They also were asked to answer a survey at the end of the semester. The survey was administered through the course website, and the questions are listed in the appendix.

The project involved applying a systems thinking approach to an engineering grand challenge again but in more detail than in the freshman seminar. In particular, the causal loop diagram had to include all elements in the rich picture. Students were assigned groups based on their schedules and interests in the challenge areas. To encourage steady progress and allow regular feedback from the instructors, students were required to submit one part of their project—a problem description, rich picture, causal loop diagram, and behavior-over-time graph—each week. The problem description had to introduce the problem to be addressed, explain how it involves five of the seven areas listed in the learning objectives in the introduction, identify a key variable to be predicted, and list sources of information, including books, journal articles, magazines, newspaper articles, websites, interviews with faculty, etc. Each week students submitted written descriptions of each element and received comments from the instructors.

During the oral presentation, the instructors evaluated the technical content and details of the presentation. The rubric for the technical content is in Figure 2.

Observations

Freshman seminar

The most effective parts of the lecture—or knowledge portion—of the freshman seminar were the example of digging the hole and the discussion of the rich picture from Vanasupa et al.[5]. Responding to the initial question about the hole, some students provided the answer from traditional linear thinking, while others suspected they were being led into a trap. After being given the three additional examples, the students worked enthusiastically in groups to produce further answers, which included hitting oil (or gold or the water table), not having enough shovels, getting bogged down by bureaucracy, stopping work on a religious holiday, etc. This discussion led to our description of systems thinking as a way to address complex, dynamic, ill-defined problems involving issues in and out of engineering.

The example from Vanasupa et al.[5] depicting an unsuccessful engineering student introduced the concept of rich pictures effectively. It is relevant for the students: They all have had to balance studies, friends, relationships, leisure activities, money problems, etc. Also, because no description or correct answer was provided (or even available), the students enjoyed out-guessing the instructors on the interpretation. The example was a fun way for students to see how connections in a complex system can be described quickly with pictures. Although it does not show feedback between elements, it includes many of the suggested features[10]: facts, structures, subjective information, and conflicts or concerns.

With the assignments, the seven groups mostly focused on the rich pictures. Five groups addressed the problem of safe roads and bridges, and one each dealt with natural disasters and renewable energy. Unlike the project for the sophomore seminar, this assignment had no minimum on the number of types of issues to be included in the rich picture. Nevertheless, all groups had at least four; all included engineering, economic, and environmental issues, and five each included social and political issues. While all rich pictures showed the connections between elements, two did not include feedback. Three groups were able to produce a rich picture and a causal-loop diagram and behavior-over-time graph for a section of it.

(Opposite page) Figure 2. Rubric for the technical content of the projects in the sophomore seminar.

	0 = not addressed	1 = minimally addressed	2 = somewhat addressed	3 = adequately addressed	4 = well addressed
Technical content					
Problem description	Students do not describe the problem at all.	Students give a cursory description of the problem.	Students describe the problem briefly but do not explain how it involves 5 of the 7 areas.	Students describe the problem and motivate the systems approach by explaining how it involves 5 of the 7 areas.	Students explain why the problem is important and integrate their discussion of the 5 of 7 areas well into the rest of the talk.
Key variables	Students identify no key variable.	Students allude to key variables. Key variables are implied.	Students identify several variables involved in the problem but do not identify the key variable.	Students identify a key variable but other possibilities seem more fitting.	Students identify a key variable and explain concisely how it captures the essence of the problem.
Rich pictures to show connections	Students present no rich picture.	The rich picture is carelessly drawn, and the connections show little thought.	The rich picture shows few elements, and connections are merely lines drawn to the key element.	The rich picture is drawn well. It includes several elements from 5 of the 7 areas; connections show considerable thought.	The picture is attractive and interesting; the connections drawn suggest careful thought and contemplation based on research.
Causal-loop diagrams to show relationships	Students present no causal-loop diagrams.	Students present only one or two CLDs and they are not connected in any way. Relationships are based solely on intuition or feeling.	Students present several unconnected CLDs. The relationships are reasonable but not supported convincingly.	Students present a CLD that connects most of the elements in the rich picture and give plausible arguments for the relationships.	Students present a CLD that connects all of the elements in the rich picture and argue convincingly for the relationships using their research.
Graphs to show behavior over time	Students do not show behavior over time.	Students present one BOT graph that was drawn hastily and without much thought.	Students present a BOT graph and explain the behavior briefly.	Students present a BOT graph for one scenario that is carefully contemplated.	Students present BOT graphs for a few interesting scenarios. The graphs illustrate the strength of the systems thinking approach.
Lessons learned	Students do not discuss what they learned. They did not reflect at all.	Students discuss lessons but demonstrate little reflection.	Students explain what they learned about the details of the systems thinking tools.	Students explain what they have learned about the benefits of systems thinking and its tools.	Students explain that the systems thinking approach led to an unexpected lesson or showed an advantage compared to a traditional, linear approach.
Sources	Students used no outside information.	Students used mainly one source but otherwise did not spend time researching the problem.	Students used a few sources but cannot recall where exactly they found their information.	Students performed careful research and demonstrate a thorough knowledge of the sources.	Students synthesized information from many sources to support intriguing or unexpected arguments.

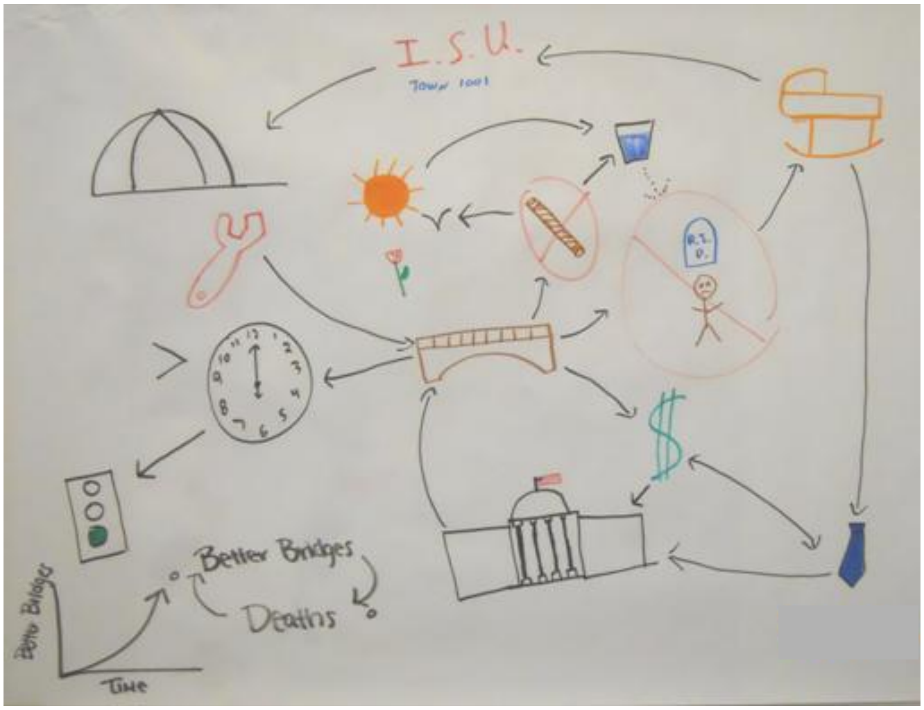

Figure 3. Example of the work of one group from the freshman seminar. The group addressed the problem of safe roads and bridges.

One group's work on safe roads and bridges is shown in Figure 3. This rich picture shows several feedback loops. For example, the loop with the bridge, dollar sign, and capitol building depicts their idea that bridges might generate money (through tolls, say) that goes to the government, which can then spend more money to improve the bridges. Also, the group added—with some humor—that because better bridges would reduce the number of traffic deaths and increase the number of births, some of those children would eventually attend a university, earn an engineering degree, and help to maintain and improve bridges and highways.

Student reflections at the end of the systems thinking module were positive. Most students wrote that before the module, they did not know much about systems thinking. After the module, they knew much more and appreciated the number and diversity of issues that must be considered in a successful engineering project. Most also indicated that the module changed the way they view engineering. Just over half said that systems thinking will help them to plan a project, and a third appreciated having tools to represent the system and its behavior graphically. Two students noted that considering multidisciplinary aspects of a problem will help them collaborate with others. Also, several students stated that they enjoyed the activities, as noted with other groups of students[5].

The results from the email survey[13] at the end of the scholars' first year in the program were consistent with the reflections at the end of the module. By the time of the survey, one of the scholars who took the freshman seminar left the program, and all but one of the remaining students responded. When presented with the statement, “I have an understanding about the systems thinking, including the interdisciplinary engineering design, pillar”, eleven chose “strongly agree”, six chose “somewhat agree”, and one choose “neutral”. Pontius et al.[13] summarized themes from the students’ comments as follows: “Many felt that this pillar gave them a greater appreciation for the complexity of situations. They enjoyed learning about this pillar through talks and projects. One person thought this pillar was challenging to understand fully.”

Sophomore seminar

The topics that students chose for the projects in the sophomore seminar covered a wider range than those for the freshman seminar. Two of the projects dealt with renewable energy, while the others focused on safe roads, sustainable agriculture, protection from disasters, and clean water. One of the challenges was getting the groups to focus on a specific project or problem in their chosen area. While half of the groups either used an example from the introduction to the module or already had an idea in mind, the other half initially had topics that were too general—that is, they allowed mainly broad generalizations about the elements of the problem. Eventually, the groups settled on the following topics:

1. Levees to protect against flooding near Iowa State University
2. Clay pot filtration for clean water in Mali
3. Destruction of habitat for agriculture in Nigeria
4. The 2010 traffic jam on China’s National Highway 110
5. Nuclear power at a proposed plant in Iowa
6. Energy from wind farms in Wisconsin

These projects were broad enough to involve issues outside of engineering but narrow enough to allow students to find specific information on elements of the project.

On average, the students addressed the technical content adequately (Figure 4). The strongest points were the descriptions of the problem and the lessons learned. All of the projects involved at least five of the seven types of issues (engineering, economic, environmental, political, social, cultural, and ethical). Some interesting points emerged. The group studying the China traffic jam learned that 90% of the traffic consisted of trucks transporting coal; therefore, what they initially viewed as a transportation problem could also be cast as an energy problem. Because they presented their work on the same day as the groups studying nuclear energy and wind energy, the questions and discussion were quite lively. The three projects involved energy from different sources, but the broad view fostered by the systems thinking approach allowed the students to assess and critique the work of their classmates in detail. Also, while all groups noted an appreciation for the importance of factors outside engineering in engineering problems, the

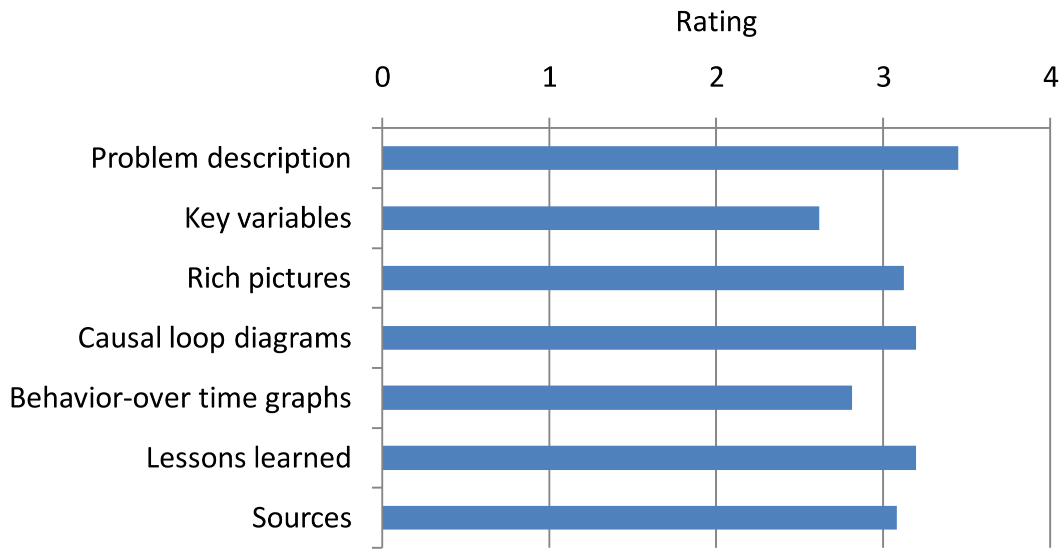

Figure 4. Average ratings for the technical content of the projects in the sophomore seminar. The ratings follow the rubric in Figure 2.

group studying sustainable agriculture in Nigeria showed that non-engineering factors can dominate: In fact their five areas did not include engineering at all!

The students used the tools of systems thinking fairly well. The rich pictures included all of the types of issues identified in the problem description, and they showed the connections and feedback between elements. The causal loop diagrams included all of the elements of the rich pictures and identified the relationships between the elements. Some groups demonstrated an ability to consider short-term and long-term perspectives by indicating relationships that change more slowly than others. An example is the relationship between "completion of levees" and "perceived safety of public" in Figure 5. The students' work with these tools demonstrated an improvement from the freshman seminar.

Students were less proficient with the behavior-over-time graphs for a few possible reasons. Groups had trouble identifying the key variable of the problem, or the quantity that captures the health or success of the projects. For example, the group studying flooding chose "completion of levees" as a key variable rather than damage from flooding, say. Also, instead of deducing the behavior over time by methodically tracing changes through the causal loop diagram, students relied on their intuition or an incomplete and imprecise—and sometimes incorrect—mental model (Figure 6); although they explained their rationale in the written report, it did not necessarily correspond to the causal loop diagram. In particular, their causal loop diagram included no clear way for "completion of levees to decrease. Flawed predictions from intuition are common; examples range from a filling a bathtub[14] to revising an engineering curriculum[15] to reducing greenhouse gas emissions[16] and cocaine use[14].

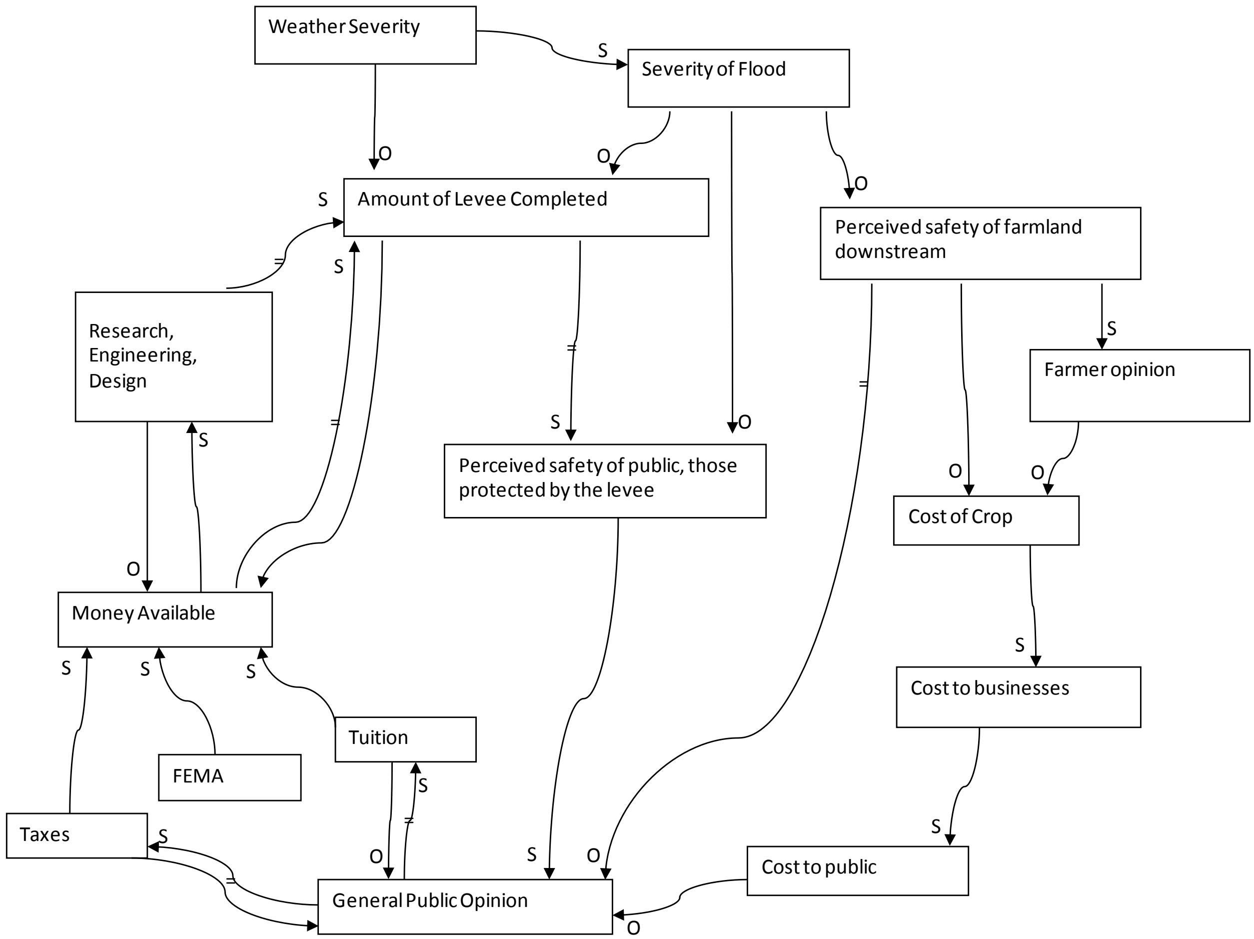

Figure 5. Example of a causal loop diagram from a project in the sophomore seminar. This group worked on levees as protection against flooding near Iowa State University. The double lines on some arrows indicate delays in the relationships.

Students provided constructive feedback in the reflection at the end of the module and survey at the end of the semester. Fourteen students responded. On a scale of 1 to 5 with 5 high, students rated the statements regarding the clarity of the outcomes (#1 in the appendix), teaching methods (#3), relation of assignments to outcomes (#6), and achievement of the outcomes (#14) with scores of 4.5, 4.7, 4.6, and 4.6, respectively. As in the freshman seminar, students thought the strength of the module was that it shows the importance of broadening the view of a project and considering many factors that affect an engineering problem. Suggestions for improvement included changing the project topics because of the repetition between the two seminars, providing more specific guidance on the expectations for the project, and showing in more detail how to sketch behavior over time using a causal loop diagram. One student noted a desire to demonstrate engineering (presumably, technical) skills in the class.

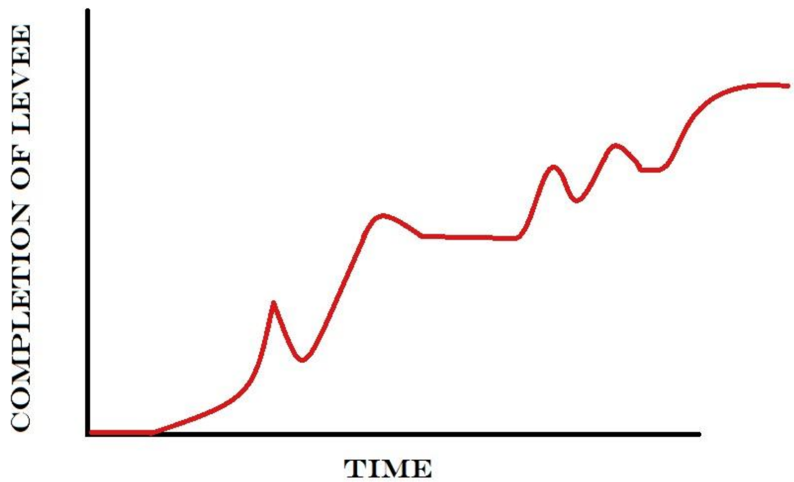

Figure 6. Behavior-over-time graph from the project on levees as protection against flooding near Iowa State University.

Improvements

The observation that students struggled with identifying a key variable and deriving behavior over time from the causal loop diagram suggests several ways to improve the two seminars. For the next offering of the freshman seminar, a different topic will be used for the assignment. For example, students may be asked to apply systems thinking to the system of a team in an engineering class, student group, sports league, civic organization, etc. Such a choice would offer several advantages: It avoids the repetition that some of the students identified in the survey of the sophomore seminar. Because working on a team of some sort should be familiar to all students, the students should be more engaged in the activity, as they were in the discussion of the example from Vanasupa et al.[5] Also, the familiarity of the topic and the smaller scope relative to the engineering grand challenges should make identifying a key variable simpler. Finally, the assignment should help the students reflect on teamwork, which is vital for the engineer of 2020. This assignment should also connect well with the leadership module in the freshman seminar.

The main improvement for the sophomore seminar is to use the lecture portion to work an example more fully. In particular, exercises will be devised to help students identify a key variable, and more guidance will be given on sketching the behavior over time from a causal loop diagram. Previous examples of the failure of mental models or intuition[14-16] will be used to highlight the importance of deriving temporal behavior from the causal loop diagram. One approach might be to devise differential equations that correspond to the relationships between the elements; the system of equations could be solved with analytical calculations, numerical methods in a spreadsheet or Matlab, or a commercially-available solver for differential equations. Nehdi and Rehan[15] employed the last of these in applying systems thinking to study the reform of civil engineering education. Furthermore, constructing behavior-over-time graphs in this way might help sophomores apply and reinforce concepts they learn in a course on differential equations, typically taken in the first semester of sophomore year.

Conclusion

The qualitative observations and quantitative assessments suggest that the initial attempt at introducing systems thinking to the engineer of 2020 was mostly successful. Most students can now better appreciate the range of issues affecting an engineering problem. Although the instructional activities can be adjusted to help students achieve the learning objectives more fully, most students demonstrated proficiency with the tools of systems thinking after the sophomore seminar. Along with improving the modules for the two seminars, we will also develop modules that can be used in other classes in the College of Engineering so that more students in the College can gain the skills needed to be an engineer of 2020.

Acknowledgments

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Appendix

The survey after the sophomore seminar included fifteen sets of statements. For each set, the student could choose 1 (least positive) to 5 (most positive), and statements were provided for scores of 1, 3, and 5. The statements corresponding to 5 in each set were the following:

1. The expected student learning outcomes and other expectations for my performance in this class were very clear.
2. Consistently, the instructor could explain concepts or clarify areas of confusion.
3. The instructor used teaching methods and classroom activities that enhanced my achievement of the expected student learning outcomes.
4. The instructor used an appropriate number and quality of case studies, stories, humor, personal experiences, and/or other fitting methods to allow me to determine how the course material was related to practical engineering or technology situations.
5. The instructor encouraged class participation by asking questions and/or holding students accountable.
6. All of the assignments were related to the expected student learning outcomes of the course.
7. All of the assignments helped me meet the expected student learning outcomes of the course.
8. Assignments were returned quickly enough to benefit my performance on future assignments.
9. Instructor’s oral or written feedback was very helpful in enhancing my learning.
10. My grades to date are an accurate reflection of how much I have learned and/or my achievement of expected student learning outcomes.
11. The text and/or supplementary resources used in this course were very effective in helping me to meet the expected student learning outcomes.

12. If I needed to communicate with the instructor outside of class, s/he was readily available and made an effort to meet with me.
13. Overall, the instructor was very effective in helping me meet the expected student learning outcomes.
14. Overall, I achieved all of the expected student learning outcomes for this course.
15. I always came to class fully prepared and actively contributed to class discussions and projects.

In addition to ranking these statements, students were asked two more questions:

a. What suggestions for changes do you have that would have improved your learning in this portion of the class?
b. What suggestion do you have for improving this design project experience?