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Systems Thinking Tools In a Graduate Biological Engineering Class - A Work In Progress

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Abstract

When technological challenges involve complex systems that include interactions with other components or agents, the system can exhibit unexpected and counterintuitive behavior. Systems thinking is useful in such cases but is rarely taught in engineering courses that do not explicitly include 'systems' or 'systems dynamics' in the syllabus. This work-in-progress describes an application of systems thinking concepts in an undergraduate and a graduate course in Agricultural Waste Management at North Carolina State University. Two specific systems thinking tools were introduced to help students appreciate the technical, economic, and social challenges related to implementing new animal manure management technologies in a production environment that already includes an established regulatory framework.

The first tool was the concept map. The goal of the project was to explore the complex interactions of various stakeholders and agents of food animal production. Students in the undergraduate class were asked to create a concept map, in the form of a diagram, of the North Carolina swine industry with a focus on manure management and environmental impacts and protections. Each of the six students in the graduate class additionally created their map from the perspective of a different stakeholder group. Students also reviewed and provided feedback on the draft map from a second stakeholder perspective. Each student wrote a description of the system and map from their assigned stakeholder perspective.

The second tool was the analysis canvas. The goal of the project was to identify system components that contribute to sustainable swine manure management in North Carolina and the changes in position, rules, regulations, and relationships among those components needed to facilitate sustainability. Two teams were formed in each class. In the graduate class the teams were formed so that all stakeholder perspectives from the first project were represented by students who had taken that perspective either as a primary or secondary role. Each team investigated a novel swine manure management technology that had previously been studied under the Smithfield Agreement yet had not been widely adopted at the time. Using the Product Archaeology Canvas, each team was tasked with describing what changes were needed to facilitate adoption of an advanced manure management system and the expected improvements in sustainability of the North Carolina swine industry. The teams also identified the critical issues for the stakeholders and the important compromises they would be asked to make for the system to work as described.

Introduction

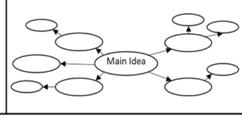
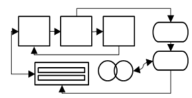
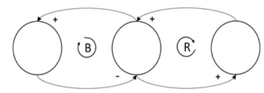
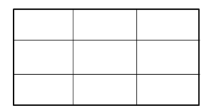
This work in progress describes the introduction of two system visualization tools as a semester project to graduate and undergraduate students in an agricultural waste management course. The student projects and feedback from this introductory offering will help refine a systems thinking approach to engineering education through the use of these types of visualizations. Future trials will include a pre-assessment to determine students' familiarity with systems thinking, an introductory exercise involving a familiar system, and a post-assessment to help students critically evaluate their learning.

Engineering sustainable solutions for complex agricultural systems requires a skillset beyond technical competency. Engineers must have a holistic sense of the system for which they design technologies in order to meet the needs to which those technologies will be applied, how they will be received, and the social, economic and environmental consequences of their use. El-Zein [1] emphasizes this need for engineers to engage in “socially-embedded solutions” when dealing with complex issues such as climate change, which has strong ties to agriculture. This skillset, often described as being able to “think outside the box,” includes systems thinking.

A system can be generalized as a group of elements that interact to perform a function. Arnold and Wade [2] define systems thinking as itself a system for thinking about systems with “a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects.” Thus, the set of analytic skills in this definition are the system’s elements, which include being able to recognize interconnections, identify and understand feedback, understand system structure, and understand systems at different scales, among others. Today’s engineering students need to cultivate these types of skills throughout their coursework to be prepared to address complex challenges such as sustainability and climate change in their future careers.

The use of systems thinking in education has already demonstrated a benefit to students by encouraging active learning, fostering collaboration, improving metacognition, developing interdisciplinary skills, and improving complex problem solving [3]–[6]. These benefits appear to be most significant when systems thinking teaching strategies are an intentional and integral part of a syllabus or curriculum [7]–[9]. Yet, the tools for systems thinking are not often explicitly addressed in engineering courses that do not include ‘systems’ or ‘systems dynamics’ in the title. This is despite a typically “hard” systems focus in agricultural engineering on controlled production systems for crops and livestock at the farm level with feed and fertilizer inputs and product and waste outputs. Shiere at al. [10] suggest this hard systems method treats each system in isolation by ignoring or externalizing dynamic behavior, stakeholder perceptions, uncertainty, or the effects that inputs and outputs have on resources, ecosystems, or society. For more sustainable agricultural production, a broader systems approach is required to incorporate these externalities and capture emergent properties of complex systems.

A key component of incorporating complex systems thinking into education is through the use of tools that help students develop, expand, and visualize their mental models. Mental models are the intellectual constructs created by individuals to represent real world systems, elements and relationships [11]. Visualizing mental models often involves diagramming the systems or concepts of interest. This can be done using a variety of tools including the mind map, concept map, cognitive map, causal loop diagram, analysis canvas, and other graphical representation collectively known as conceptual models (Figure 1) [12], [13]. The choice of which type of conceptual model to use may depend on whether its purpose is to organize ideas, communicate information, or simply retain knowledge about a system. Although such visualizations may not capture a system’s more dynamic behaviors, identifying a system’s elements and relationships can help students begin to think more holistically.

	Mind Map	Cognitive Map	Causal Loop Diagram	Analysis Canvas
Purpose	Expansion of a single topic	Capture a process or dynamic ecosystem in free-form	Show causal relationships between interacting elements	Collects and organizes information relevant to an objective
Defining Characteristic	One central idea with hierarchy of nodes; one parent per node	Lack of any consistent structure; mixed forms (list, diagram, graph, flowchart)	Reinforcing and balancing feedback loops	A framework organized into conceptual boxes
Adaptability	Low	High	Low	Medium
Example				

Adapted from Eppler (2006) [12], Tranquillo (2016) [15], and Williams and Hummelbrunner (2010) [19]

Figure 1. Examples of Conceptual Models

Studies support the use of systems thinking visualization tools in education. For example, Budd [14] demonstrated the use of mind mapping as an active learning exercise to facilitate brainstorming in small student groups. Dhindsa et al. [7] used mind mapping techniques to help students use their existing knowledge to organize information and relate to new concepts, improving learning outcomes. Wang and Wang [9] formalized the use of Strategic Options Development and Analysis (SODA) maps – a type of conceptual model developed for operations research – as a tool for teaching systems thinking in a classroom setting. The SODA map allowed students to practice collaborative and higher level problem-solving by deriving and visualizing different strategies for a case study. Eppler [12] discussed applications of concept maps in the classroom and the benefits of complementary visualization by combining different mapping methods to enable a "richer learning experience for students." Tranquillo et al. [15] explored various one-page canvas frameworks as tools to help students model and decompose systems to facilitate decision-making with incomplete information. These techniques have also been demonstrated in real world applications. DeFranco et al. [16] implemented cognitive collaborative modeling to help engineering teams evaluate a situation and develop a unified understanding of a problem. In the authors' scenarios, concept maps were used to help collaborators find convergence in their individual mental models, resulting in improved team performance and project outcomes.

These illustrations suggest that the application of systems thinking in the classroom and the selection of tools for helping students visualize and analyze their mental models should be tailored to the specific education goals and desired learning outcomes. Thus, the purpose of this pilot study is to examine students' output and perceptions of a concept map and an analysis canvas utilized in an agricultural waste management course to evaluate how the students responded to these tools and to identify how to improve the integration of such tools into engineering coursework.

Methodology

Agricultural Waste Management is a biological engineering course that focuses on waste management strategies and technologies for different types of livestock and poultry operations. For the past ten years, this graduate course has been taught as an asynchronous distance education class. An undergraduate version has only been taught once before as a separate synchronous on-campus course using the flipped-classroom model. In this model, readings and / or video materials are made available before class and the synchronous class time is used for discussions, guest lectures, and question sessions.

This course has traditionally focused on mitigating environmental issues related to animal waste management and included a manure storage and land application design project. Projects required teams of students to consider the entire manure management system but limited the scope to the farm operation. However, recent social and economic challenges with manure management in regions of concentrated food animal production have increased the need for engineering sustainable solutions that consider the influences and impacts of solutions beyond the farm gate. In order to foster a broader systems thinking approach to sustainable manure management, projects were devised for both undergraduate and graduate students using two system visualization tools – the cognitive map and an analysis canvas.

Cognitive maps are generally considered freeform visualizations of mental models that can contain various structures including diagrams, graphs, and flowchart elements and identify relationships among those elements. Cognitive maps were introduced to the undergraduates with a class discussion about their college careers. Students volunteered several engineering courses they took. The instructor then asked them to identify which of these courses provided information or skills that were needed or useful in other courses and these relationships were illustrated in a concept map. Students were then assigned to create a more comprehensive concept map of their entire curriculum and write a reflection on the experience. Several students expressed a fresh awareness of the curriculum design and an appreciation of the attention of the faculty to their education. This exercise was especially beneficial to students within one or two semesters of graduation. Because graduate students have moved to a different level of their education and are focused on research projects with timelines not bound by the semester, no similar exercise was used.

The first undergraduate project was an individual assignment titled the North Carolina Swine Industry Summary, and was designed to build on earlier lessons and prior knowledge of animal production, to create a visualization of the North Carolina swine industry as discussed in class, and to write a description the various elements included and the relationships among them. Students largely focused on manure management but were encouraged to include environmental, social and economic aspects beyond the farm boundary. The assignment was left open to interpretation with only simple instructions to consider “inputs, elements, stakeholders and outputs" of the system and the relationships among these various components. Each student created their own map and a written description of the system in a separate document. The maps were shared among all students and discussed at the next class meeting. After a few general comments by the instructor, the students were asked to work together as a group and create a single map that represented their consensus of the system. Each student was then assigned to create their own final version of their individual map and revise their description to include any new information they had learned from their consensus discussion.

The graduate version of the NC Swine Industry Summary project took a more advanced approach, asking students to adopt specific perspectives of the system through assigned stakeholder roles. Six roles were selected (Table 1) with each student given one as a major role and one as a minor role. Additional roles could be identified for larger classes. Each student created their individual map from the perspective of the stakeholder assigned as their major role, with instructions to consider what would be important to that stakeholder. The student then consulted with the student who had that same stakeholder assigned as a minor role. Students were allowed to adjust their map based on their discussion.

Table 1. Perspectives in creating concept maps of the North Carolina swine industry

Role Identity	Description
Engineering Firm Project Manager	Individual employed to design a manure management technology for a farm. Responsible for scheduling construction, conducting meetings, etc.
Farm Manager	The end-user with plans to expand a swine farm in NC. For the assignment, the farm should be modeled on an existing NC operation
NC Cooperative Extension Agent	A county extension agent or specialist, a trusted liaison for innovations and research; familiar with permits and regulations and assists farm manager to maintain compliance
Technical Specialist	Individual (consultant or integrator employee) trained to create certified animal waste nutrient management plans in compliance with state laws and regulations.
Regulator	Employee of the state Division of Water Resources, responsible for issuing permits and enforcing compliance with requirements
Activist	Representative of a local community or coalition that is considering legal action against the farm for nuisance or environmental issues

A second project, referred to as Technology Adoption, was a team project for both undergraduate and graduate students and focused on swine manure management technologies that had been investigated under a five-year agreement between a major pork integrator and the North Carolina Attorney General, starting in 2000 [17]. All students were given access to the technology descriptions and both the technical and economic reports on these technologies that were issued during that five-year period. Despite being the agreement goal, none of the technologies investigated were broadly implemented in the swine industry in North Carolina. The undergraduate teams were each assigned a specific technology and, using an analysis canvas called the Product Archaeology Canvas [18], asked to determine why the technology was not adopted and what could be changed to make it easier for a producer to choose the new technology.

The graduate teams were given more flexibility in the Technology Adoption project. They were asked to select one or more technologies from the agreement that could function together, identify shortcomings of the technologies, propose improvements, and suggest changes to rules, practices, and attitudes that would improve sustainability of the industry. Building on the relationships identified in the NC Swine Industry Summary project, the teams were also asked to identify critical issues for their different stakeholder roles and any important compromises they would have to make to accommodate the suggested changes.

For the Technology Adoption project, a particular analysis canvas was introduced to students as a technique to assess the past shortcomings of technologies and to relate proposed technology changes to the various elements and relationships of the swine industry they developed in their cognitive maps. The Product Archaeology Canvas was selected as the framework for this project for its demonstrated usefulness in taking a backward-looking approach to decision-making in a technology design (Figure 2). This tool was introduced to students in both classes using an example presented during a face to face session of the undergraduate class which was recorded for the graduate class.

Product Archaeology Canvas		
Broader Impacts: Identify the impacts that accrued beyond the primary customer. Did the product / process impact the community, environment, or nearby ecosystems? Were there benefits to local jobs and education?		
Marketing • What product, service and/or byproducts did the technology create? • How were these outputs marketed? • What was the competition?	**Customers / Stakeholders** • Which customers/clients did the technology target? • What other stakeholders would the technology impact and how?	**Sales & Distribution** • Where would this technology have been used? • How would products or services have been sold and distributed?
Legal and Regulatory • Were permits needed and from which agency? • What other regulator issues needed to be considered with this technology?	**Value Proposition** • What value did this technology create? • Why did customers or stakeholders chose (or not chose) this technology or its products?	**Technical Design** • Why did decision-makers choose to design the technology the way they did? • What made this technology unique?
Finance • Was the technology economically feasible for providers or users? • What non-economic benefits did it provide (e.g., social, environmental)?	**Operating** • What was the user experience like with this technology? • How was it connected to other processes and/or services?	**Resources** • What types of physical and human resources did this technology require to use? (e.g., skills, labor, land, buildings, ancillary equipment, consumables)

Figure 2. Elements of the Product Archaeology Canvas explained for the Technology Adoption Project

In teams of 3-4, students were asked to consider why a particular technology introduced in the past as an alternative waste management system failed to achieve widespread adoption and what types of changes should be considered to the technology, the system in which it would be implemented, the system boundary, or the rules governing implementation of new technologies to facilitate future adoption. The graduate students were also asked to identify the most important issues for each stakeholder and major compromises they would be expected to make.

After all projects were completed and graded, students from both classes were asked to respond to an anonymous survey (Qualtrics, Provo, UT) to share their perceptions of systems and the tools they had used during their assignments. The survey consisted of two parts. The first part contained 12 statements and asked students to respond using a Likert scale from strongly disagree to strongly agree to express their comfort with systems thinking and the two visualization tools. The second part consisted of six open-ended questions that allowed students to express whether they found the tools useful and what they would change.

Results

Although most undergraduate students submitted an individual cognitive map, they were clearly influenced by the consensus map (Figure 3). Some included more detail at the farm level while others explored the broader scope of the overarching industry system. These differences were reflected in the system descriptions each student submitted. Because the Swine Industry Summary project was completed early in the semester, some descriptions did not capture some of the challenges that are specific to North Carolina swine production, especially the fact that most swine farms are relatively small and cannot grow sufficient feed crops to use the nutrients from manure produced on those farms.

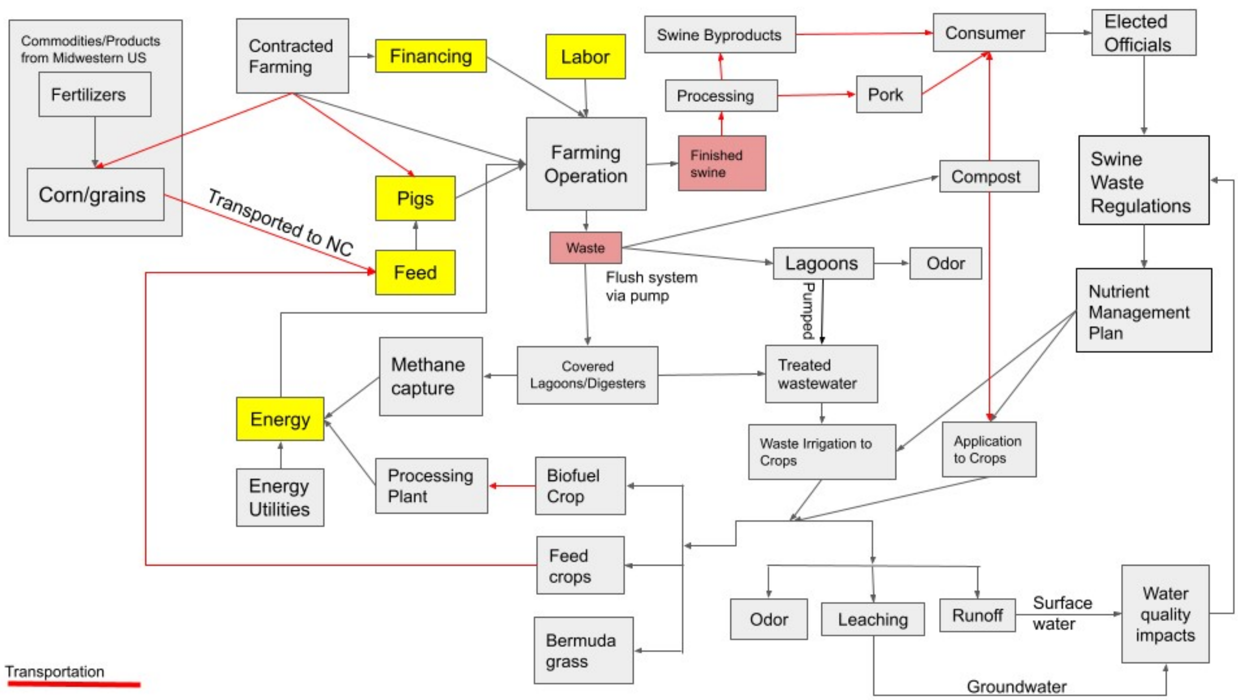


Figure 3. Consensus Concept Map of the North Carolina Swine Industry.

Each graduate student's concept map was distinct because of the different perspective from which each was created. The Farmers' perspective (Figure 4) and the Project Manager's perspective (Figure 5) are shown as examples. The system descriptions also reflected the assigned perspective.

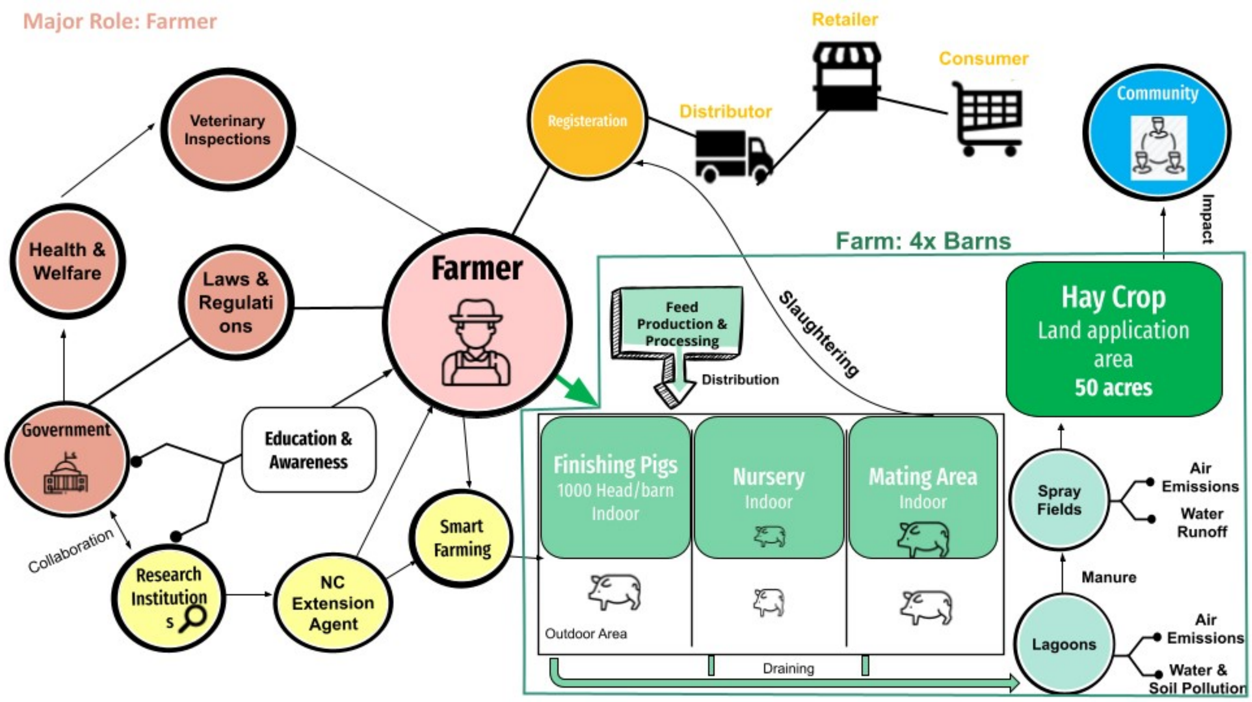


Figure 4. Concept Map of the North Carolina Swine Industry, Farmer's Perspective.

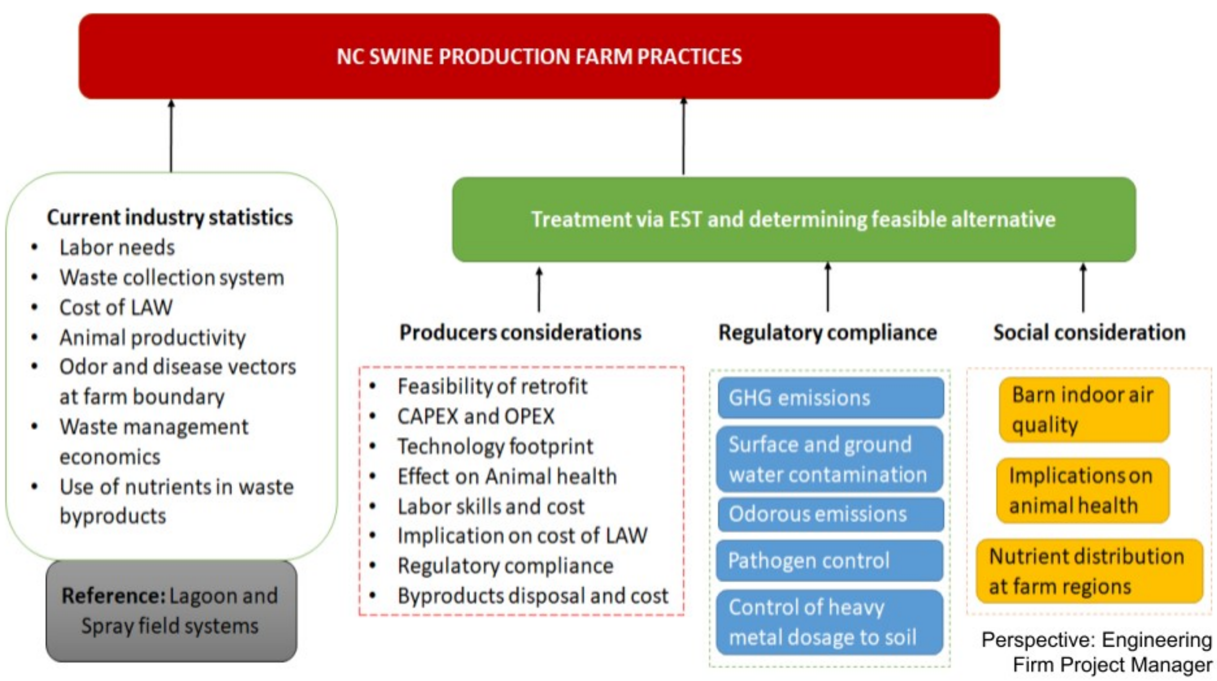


Figure 5. Concept Map of the North Carolina Swine Industry, Project Manager's Perspective.

Even though the Technology Adoption Project was a new concept for students and the Product Archaeology Canvas was not a familiar tool, the teams produced adequate reports that met the primary objectives of the project.

The survey was sent to all students from both sections of the class. Because of the small number of students in each class, surveys did not distinguish between graduate and undergraduate sections of the course to support student anonymity. Six students (43%) completed the first part of the survey and five students (36%) completed the second free response portion. Responses to part 1 are presented in Table 2.

Table 2. Survey responses (Part 1)

# Question Disagree Neutral Agree Total Agree			Somewhat Agree		Somewhat		
1	I can explain to a colleague what it means to use systems thinking to solve problems.	0%	0%	17%	33%	50%	6
2	Using systems thinking tools in class helped me understand the system better.	0%	0%	17%	50%	33%	6
3	Systems thinking tools are useful when collaborating with others.	0%	0%	17%	50%	33%	6
4	I can explain to a colleague what a mental model is.	0%	0%	0%	33%	67%	6
5	I feel confident in my ability to create mental models.	0%	0%	17%	17%	67%	6
6	The mental model we created in class was useful to me.	17%	0%	0%	50%	33%	6
7	I plan to use mental models in the future.	17%	0%	50%	17%	17%	6
8	I can explain to a colleague what an analysis canvas is.	0%	17%	0%	33%	50%	6
9	I am confident in my ability to create an analysis canvas.	0%	0%	33%	33%	33%	6
10	The analysis canvas we created for the project was useful to me.	17%	17%	0%	33%	33%	6
11	I plan to use analysis canvases in the future.	17%	17%	33%	17%	17%	6
12	I am interested in learning about other systems thinking tools.	17%	17%	33%	0%	33%	6

Free response questions focused on the mental modeling using the conceptual map and the analysis canvas visualization tools separately. All five respondents found the conceptual mapping exercise useful for several stated reasons, including being able to "understand the big picture," working in a group, visualizing the system, collaboration and consensus building, and seeing various system elements simultaneously. They particularly enjoyed the group work aspect of the collective model, tracking inputs, using online tools and the visualization facet. Although some students felt the exercise made sense, others felt it was difficult to distinguish between the farm level and industry level when creating their conceptual model. One student felt the individual report was unnecessary, although this comment did not seem to apply to the individual concept model.

Students' responses to the analysis canvas tool were more varied with regard to its usefulness. Some felt it was useful to "understand different facets of the industry," to organize a lot of information about one topic, and to "break down the system's components to access the value and business plan parts." However, other students struggled to see the point of the canvas. One student said it was "too broad and didn't focus on the individual systems" while another was unclear about whether "the point was to fill out each section as our particular constituent or if we were supposed to be general in the way we filled it out." Those that liked the analysis canvas liked the visual aspect of it and using it to learn about a new waste management system. They also mentioned the interdisciplinary nature of the canvas tool and how it helped them "think more big picture." For those who did not like the canvas tool, they felt it was hard to follow and unclear how it was intended to be helpful to the project. With regard to how the analysis canvas project could be improved, students felt that more examples would have been useful to better understand the concept and how it should be used. Other comments included changing the written report portion of the project which felt redundant to them or to focus on "more informative" graphics like the mental model exercise that showed the actual links between relationships.

Discussion

Due to the significant time commitment of these team projects, they were initiated early in the semester. However, an unexpected change for the undergraduate course was instituted two weeks after classes started, when the university closed campus due to an increase in COVID-19 cases and converted all on-campus undergraduate courses to remote learning. The remote format for this synchronous class time created a substantial challenge to student engagement with each other and with the instructor that may have impacted the outcomes of the pilot study.

The concept map that emerged from the curriculum discussion showed the relationships among the courses and was a useful visualization that generated lively discussion. In the same way, the undergraduates' consensus concept map (Figure 3) demonstrated an understanding of the complexity and interconnectedness of pork production, the environment, and society. Although direct comparisons to previous versions of the course are not possible, it was clear to the instructor that these students were thinking differently about food animal production, especially at this early point in the semester. For example, simply asking the students what or who influences food animal production and manure management, generated questions about regulations, impacts, and related issues that are not typically asked until much later in the semester.

The graduate students' cognitive maps were not directly comparable to each other or to the undergraduate class because each was created from the perspective of a different role (Table 1). While all adequately represented the given perspective, some included more details (Farmer's perspective, Figure 4) while others took a much broader view (Project Manager perspective, Figure 5). It is clear from the maps and the respective descriptions that these students successfully captured the industry from the given perspectives.

The Technology Adoption Project seemed to be more of a challenge for undergraduate student teams than the concept map. Although both teams demonstrated an understanding of the different aspects represented in the canvas tool, they did not venture into potential changes in the regulatory, financial, contractual, or operational aspects that might make adoption of the proposed technologies more likely. Both of the graduate student teams, on the other hand, included an adequate analysis of possible changes in rules, practices, and stakeholder attitudes that would assist technology adoption in addition to fairly detailed descriptions of each of the aspects represented in the canvas tool.

While students expressed relatively little enthusiasm for the analysis canvas project, all demonstrated an understanding of the complexity of the system and the importance of interactions with non-technical aspects of system changes. It should be noted that, in spite of challenges encountered in this initial use of these tools, the students' work on these projects represents a significant increase in the complexity of their tasks compared to past years as well as a more comprehensive understanding of the food animal systems than demonstrated in previous classes.

The survey results suggest that while participants were generally able to grasp the concepts involved in using the systems thinking tools, there was not overwhelming agreement on the usefulness of these tools for either classwork or future applications. However, individual responses indicate this may have been due to perceived ambiguity in the project details or in how the tools were explained to students, particularly with regard to the analysis canvas. More intentional scaffolding and discussion would help students identify both the value of using a systems thinking approach to problem solving and how systems thinking tools can benefit them in doing so.

One suggestion is to introduce the tools using a system that students are familiar with, such as the initial concept maps the undergraduate students created to describe relationships in their program coursework. This exercise allowed students to gain experience with how to apply the visualization tool prior to adding the challenge of applying it to an unfamiliar or more complex system. Another improvement could be to focus more on the collaborative nature of the system analysis process. While individual maps were required in both classes for evaluation purposes, a stronger focus on the collaborative aspect of using these visualization tools could reinforce to students their usefulness, particularly in a team setting. Finally, having students critically evaluate their understanding of systems thinking through a pre- and post-assessment would help reinforce the value of both systems thinking concepts and tools.

The concepts of systems thinking, of course, can be integrated in many engineering classes. Especially in core engineering science courses, this approach can answer students' favorite questions, "Why do we need to know this?" or "When will we ever use this?" by connecting their work to other disciplines. While an engineer's role in designing a bridge might be limited to structural integrity or traffic flow, systems thinking can help the engineer appreciate the need to include others with skills in finance, regulations, permits, community relations, or aesthetics in the design process. Does integrating systems thinking concepts take time away from essential content? The question is best addressed by reflecting on course learning objectives and refocusing those objectives on what students need to prepare them to solve society's complex problems. Introducing systems thinking in the context of reality-based projects can equip students with critical tools and expose students to working across disciplines which will greatly benefit them in their careers.

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