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Engineering Change: Introducing Systems Thinking as an Engineering Leadership Skill

Dr. Emily Moore, University of Toronto

Emily Moore is the Director of the Troost Institute for Leadership Education in Engineering (Troost ILead) at the University of Toronto. Emily spent 20 years as a professional engineer, first as an R&D engineer in a Fortune 500 company, and then leading

Dr. Lisa Romkey, University of Toronto

Lisa Romkey serves as Associate Professor, Teaching and Associate Director, ISTEP (Institute for Studies in Transdisciplinary Engineering Education and Practice) at the University of Toronto. Her research focuses on the development of sociotechnical thinking and lifelong learning skills in engineering.

Mr. Amin Azad, University of Toronto

Amin is a doctoral student at the University of Toronto's Department of Chemical Engineering, pursuing a collaborative specialization in Engineering Education. Amin focuses on applying Systems Thinking Principles to Engineering Education and assessing its learning outcomes when solving wicked problems, especially in the field of Entrepreneurship. Amin obtained his MASc. and BASc from the University of Toronto, both in Industrial Engineering, and has worked as a consultant and researcher in tech companies.

Engineering Change: Systems Thinking as an Engineering Leadership Skill

Introduction

As engineering leadership educators, we must constantly ask ourselves what skills, attitudes and perspectives students need to gain from our programs. If leadership is “a process whereby an individual influences a group of individuals to achieve a common goal” [1], we have a responsibility to equip students with the skills not only to influence others, but also to identify the goal; in engineering terms, to define the problem to be solved by understanding context, scoping the problem effectively, and consulting with stakeholders.

The problems that we face as a society are becoming more open, complex, dynamic, and networked: they cannot be solved by individual people in siloed disciplines, but rather require an interdisciplinary approach. Originally conceptualized by Rittel & Webber [2], wicked problems are problems with multiple stakeholders and competing demands, which often contain ethical, social, political, or environmental dimensions. They are challenging to frame and scope, given the lack of an obvious “stopping point” when the problem to solution process is complete. Wicked problems reflect pressing societal issues like climate change, transportation and urban development, healthcare and technological unemployment – problems that frequently engage the technical expertise of engineers but require a breadth of disciplinary knowledge outside of engineering as well, requiring strong collaborative skills and an intellectual openness to new ways of thinking and knowing.

Kendall et al. [3] articulate an expansive definition of Engineering Leadership that incorporates many of the dimensions of complexity inherent in wicked problems:

> *“Engineering Leaders (a) employ the full range of engineering skills and knowledge in the design of socio-technical innovations, while (b) seeking to understand, embrace, and address the current and future impact of their work in context by (c) actively fostering engaged and productive relationships with diverse stakeholders, including themselves and their team, the users of their technologies, and those impacted by their engineering work”.*

We argue that systems thinking is an important engineering leadership competency. Scholars have argued for the importance of integrative or systems thinking for leadership in business, politics, education, health and engineering [4-8]. Wicked problems require a new set of tools to both understand a multi-dimensional problem and communicate with practitioners in other disciplines. To prepare our students for engineering leadership, we need pedagogical approaches that give students the space and time to explore the multiple dimensions of the problem and to frame questions and goals to enable and lead meaningful change.

While engineering students are taught to think in terms of systems, these are often limited in scope to the technical realm. Most engineering programs do not give students the chance to examine truly complex, interdisciplinary problems, in part because design courses require students to converge to a solution quickly without opportunity to fully explore the problem space. Schuelke-Leech [9] reviewed the curricula for eight North American undergraduate engineering programs to look at the types of problems presented to students. In her analysis, she used a matrix that categorizes types of problems based on predetermined vs complex solutions, and well-structured vs poorly structured problems. Schuelke-Leech found that over 95% of engineering courses used well-structured problems and no courses in the review engaged students on wicked problems i.e. problems that were both complex and poorly structured.

There have been initiatives to try to address this gap, most notably The National Academy of Engineering's (NAE) Grand Challenges program, launched in 2008 [10]. This program has resulted in a number of initiatives for students, institutions and practicing engineers, including the NAE Grand Challenges Scholars Program, which combines curricular, co-curricular and extra-curricular programming to encourage the development of five competencies in the undergraduate engineering population: research and creative skills, multidisciplinary understanding, business and entrepreneurship skills, multicultural understanding, and social consciousness [11]. However, further opportunities are needed to provide students with specific tools to build these competencies.

This practice paper describes a recently developed engineering leadership elective at the University of Toronto: Systems Mapping for Complex Problems. The paper offers observations from the first two offerings of the course based on student assignments and semi-structured interviews conducted with students, augmented by instructor reflections. Our goal is to motivate further exploration in connecting leadership and systems thinking in the context of engineering programs.

Systems Thinking

Donella Meadows, an early leader in the systems thinking movement, defined a system as "a set of things interconnected in such a way that they produce their own pattern of behavior over time" [12]. Her work focused on sustainability; as the lead author on "Limits to Growth," Meadows had a deep appreciation for the complexity of ecosystems, and the resilience and behavior that emerges from this complexity [13]. This early work set the stage for understanding the world and wicked problems as systems, which has more recently been applied across many contexts and problem types.

Systems thinking has been described as a perspective, a language, and a set of tools [14]. Systems thinkers understand how systems fit into the larger context of the world, how they behave, and how to manage them. Systems have purpose, are made up of parts that allow that purpose to be achieved, and the relationship between those parts, as well as the rules that govern them, are key to understanding the system [15]. For a mechanical system, these parts may be cogs and levers and the rules of physics; for a social system, these parts may be human actors and institutions with their own complex relationships and rules.

Authors in the field of engineering education have highlighted the importance of systems thinking in preparing engineers to solve real-world problems. Dym and Brown [16] argue that a systems thinking approach enables engineers to identify and address the root causes of problems rather than just their symptoms, leading to more effective solutions. Byrne and colleagues emphasized the role of systems thinking in promoting sustainability in engineering design [17]. Similarly, researchers at MIT describe the emerging field of Engineering Systems which is "at the intersection of engineering, management, and the social sciences" [18]. MIT now has several credits in engineering systems subjects at the graduate level.

Systems Mapping

Systems mapping is a methodology to help groups collaboratively build shared visualizations of of the systems they are trying to understand and change, gaining insights into the complexities of a given issue [19]. System mapping tools include tools such as actor maps, causal loop diagrams, iceberg models, and journey maps. Systems mapping tools allow individuals and teams to graphically represent their mental model of an issue in in a way that enables collaborative consultation. The mapping tools also guide the team through the issue, thus reinforcing the development of systems thinking and understanding the world as a system.

Although systems mapping is not widely used across engineering education or engineering leadership programs, there are some recent examples of relevant work. In a recent paper, Rodrigues et al. [20] develop a framework to help students broaden their understanding of complex systems, including helping students to understand that technical solutions are not always the way forward. They call for engineers to broaden their perspective, develop more comfort with ambiguity, and embrace the complexity of problems. They introduce systems mapping (more narrowly defined as network visualization), problem framing and system definition using the Cynefin framework into an undergraduate engineering entrepreneurship class. Lavi et al. [21] assessed systems thinking based on the conceptual models generated by 32 undergraduate industrial engineering students as part of an information management. Rehman et al. [22] introduced systems thinking to small Engineering 2020 seminars at Iowa State including causal loop diagrams and behaviour over time graphs.

Many scholars in engineering and related fields have used forms of systems mapping and thinking. Lifecycle assessment, for example, takes a systems approach, albeit with the specific purpose of mapping environmental impacts [23]. Healthcare has utilized systems thinking to support pandemic response (for example: [24]) and have also connected systems thinking to ethical thinking in public health [25]. Scholars have also used systems mapping tools to engage community participants in policy evaluation [26] and connecting transportation systems to health impacts [27].

Previous work by a member of the author team has indicated success in encouraging students to use systems mapping [28]. Although this work was focused on the use of Actor Network Theory (ANT) [29], which includes a layer of complex sociological theory governing socio-technical relations, ANT has a strong link to systems mapping more generally, given the elucidation of human, technical, conceptual and environmental actors and the focus on relationships between them. This previous work noted the benefits of the approach to enhance understanding of complex sociotechnical systems, and to also understand the complexity that exists in even seemingly simple systems. Our assessment of this teaching experience was that it offers students a starting point for a mental practice to consider a broader range of sociotechnical factors in their thinking. More specifically, by mapping out the various actors in a system and refusing to privilege a particular kind of actor, our observation was that ANT encouraged students to identify relations and consider actors that may otherwise not be obvious.

Course Design

A new undergraduate engineering leadership elective course was introduced at the University of Toronto. This course was designed for students across all engineering disciplines, giving them an opportunity to investigate a wicked problem of their choice and to develop their systems thinking skills. The course was based on the Map the System Competition developed by Papi-Thornton and colleagues at Oxford University [19]. The course uses systems mapping as a tool to help engineers better define the environmental and social problems that they are interested in solving, ultimately situating their engineering contribution within the appropriate context. The course emphasizes going beyond the boundaries of a typical engineering system to incorporate other fields of knowledge into the problem definition. Through the course, students gain familiarity with the paradigms and epistemologies of these other fields. Students are introduced to different systems mapping tools, and are encouraged to articulate their purpose, underlying philosophy, methodology and best use cases.

The learning outcomes of the course are organized under three key areas: (1) Using systems mapping to understand wicked problems; (2) Engaging with fields of knowledge outside of engineering; and (3) Articulating and engaging each student's own ways of knowing and leadership style. Within the first area, students are expected, by the end of the course, to be able to describe and create multiple types of system maps and choose appropriate systems mapping techniques for a given problem or task. The course enables the student to construct systems maps which elucidate a complex socio-technical problem, evaluate and provide feedback on maps constructed by others, iterate based on research and reflection, and communicate the map with clarity. The second area signals the need for engagement with and an openness to different knowledge types. Students must describe and work within the socio-technical interfaces of a wicked problem, explain key paradigms and epistemologies representing knowledge fields beyond what's traditionally considered engineering, conduct research and complete knowledge synthesis from a diversity of disciplinary perspectives, and critically assess existing solutions for wicked problems. Finally, the third area focuses specifically on having the individual reflect on their own way of knowing, teamwork and leadership style, with a focus on evaluating disciplinary perspectives, understanding teamwork styles and how they interface, and demonstrating the ability to promote an open and effective exchange of ideas and knowledge. As evidenced by this list, students must demonstrate a variety of skills, competencies, and attitudes to meet course outcomes, enabling a truly multidimensional learning experience.

Learning is supported through lectures, guest speakers, case study discussions and activities, but also through a major project in which student develop a system map of a complex problem. Examples of problems explored include responsible lithium mining in Chile, the transition to automation in manufacturing, or improving transit access to underserved communities. The emphasis is on problem definition rather than solution, giving students the opportunity to explore the problem space in depth. Over the course of a semester, students work in teams to develop systems maps that incorporate both the technical and the social aspects of their challenges; the visualizations enable them to identify leverage points in the system that might yield significant changes [30]. These leverage points can then be used to define the area of intervention, which may or may not require technical interventions at all.

The course is organized into a lecture block and a tutorial block. During the lecture, systems thinking and systems mapping concepts such as iceberg models, causal loop diagrams, and actor maps are introduced, and examples worked through with the whole class. Small group and whole class discussion and activities are used to keep students engaged. Guest lecturers are also invited to join the lecture block to share case studies and insights from other academic domains. During the tutorial blocks, students work in their teams through guided exercises to build out their maps. Peer feedback is incorporated into the tutorials through interim sharing of specific mapping elements. Students then present their projects incorporating at least three system mapping tools to the class at the end of the term. In the final presentation, the students are invited to identify where they might intervene in the system, but they are not required to design the solution. Students are assessed based on the clarity of their final maps, their analysis of the understanding that emerges from looking at the problem as a system, and their ability to communicate their understanding of their systems.

Table 1 summarizes the flow of the course and indicates the timing of individual and team deliverables. Individual assignments include an actor map to illustrate how students interact and make decisions with a given system (e.g. the university or a transit system), four reflections on course content and guest lectures, and a final reflective self-evaluation. The team assignments scaffold the development of the maps through a series of building block deliverables which allows for peer feedback in tutorials and formative feedback from the instructor team.

The Workshop on Disciplinary Perspectives invited students to draw how their discipline represents systems (e.g. process flow diagram, electrical circuit...) and to consider what is and is not included in the representation.

The Workshop on Comfort with Ambiguity aimed to build community and a sense of psychological safety in the course through mindfulness and was conducted by our teaching assistant based on her own work [31].

The Impact Gap Canvas Workshop [19] guides students through a structured exercise that helps students to gather knowledge on the current understanding of the problem, solutions that have been tried, and to work through the current gaps.

The Workshop on Interview Skills introduced best practice for conducting expert interviews as well as ethical considerations.

The 5Rs Workshop helps students to elucidate the Roles, Relationships, Rules, Resources and Results of their system and to create a summative map [19]. This map is used in a Peer Feedback session.

The Team Check-in uses an assessment of Psychological Safety [32] to help teams evaluate how they are progressing and make any course corrections as the enter the final phase of the work.

The Levers of Change workshop is based on definitions of leverage points proposed by Meadows [30] and helps students to explore the potential intervention points in the system.

Table 1: Course Outline (Winter 2023 delivery). Team deliverables are **bolded.**

Week	Lecture (2 hours)	Tutorial (2 hours)	Deliverable
1	Intro to Course	Workshop on disciplinary perspectives	
2	Wicked Problems and Systems Thinking	Workshop on Comfort with Ambiguity	
3	System Mapping 101: Problem Definition	Team Formation and Challenge Selection	Reflection 1
4	Understanding the Challenge Guest Lecture: Research Methods	Impact Gap Canvas Workshop	Individual Map
5	Root Causes Analysis, 5 Whys and Iceberg Model Guest Lecture: Challenges of the Energy Transition	Working Session	
6	Causal Analysis and Feedback Loops	Working Session	**Impact Gap Canvas**
7	Introduction of 5Rs Guest Lecture: World Health Organization	Workshop on Interview Skills 5Rs Workshop (part 1)	Reflection 2
8	Connection Circles and Journey Mapping	5Rs Workshop (part 2)	
9	Visual Story Telling Guest Lecture: Government and Policy	Team Check-in & Peer feedback on 5Rs	**5Rs Map** Reflection 3
10	Stocks and Flows; Levers of change; Intro to power	Levers of Change Workshop	
11	Guest Lecture: Engineering Codes & Equity?	Working Session	**Levers of Change** Reflection 4
12	Discussion/ Guided Reflection	Peer Feedback Session	
13	Closing Session: World Café discussion of key learnings	Final Presentations	**Final Presentation and System Map** Student Self-Evaluation

Evaluation of the Course: Methods

Analysis was conducted on a written final student Self Evaluation assignment for 32 students from the first two cohorts of the course. For this assignment, students were invited to reflect on the course with the following guiding questions:

- How would you describe your key learnings from the course?
- What has been the biggest challenge for you?
- How would you describe the role you have played in your project team?
- What have you learned about yourself through this course?
- What is one commitment you will make to yourself to bring forward your learning into your future work?

Structured interviews were conducted by a graduate student with 5 students from the second cohort. These interviews were conducted after the course had finished and final grades had been awarded, and the graduate student was not a part of the teaching team. The purpose of the interviews was primarily to explore student entrepreneurial intention, but questions also looked at the effectiveness of the course and student understanding of the tools and concepts. The expectation was that the students would be more honest in their assessment of their learning than in the final reflections where there may have been a tendency to tell the instructor what they want to hear.

The student Self Evaluations and interviews were coded using Saldana's [33] structural coding approach, a first cycle coding method with a focus on particular topics relevant to the research questions. In this case, Kendall et al.'s [3] definition of engineering leadership provides a framework to evaluate the evidence of the development of engineering leadership competencies in the course:

> *Engineering Leaders (a) employ the full range of engineering skills and knowledge in the design of socio-technical innovations, while (b) seeking to understand, embrace, and address the current and future impact of their work in context by (c) actively fostering engaged and productive relationships with diverse stakeholders, including themselves and their team, the users of their technologies, and those impacted by their engineering work.*

Instructor reflections were written after the completion of the first two cohorts of the course. Insights from these reflections were incorporated into the discussion of each theme from the coded student self-evaluations and interviews.

Evaluation of the Course: Findings

Theme 1: System Mapping improved student confidence to apply engineering skills and knowledge in the design of socio-technical innovation

Students expressed confidence that they now have a strategy to tackle seemingly overwhelming problems, and many described their approach in their self-evaluations.

> There has been a big shift in the way I approach problems. Whenever I am confronted with a problem, instead of just going with what I think the solution should be, I am also inclined to think of how the approach might affect other aspects.
>
> Looking at [climate change], I wondered how to even begin addressing these issues but as the course progressed, the knowledge of how to begin approaching such problems was provided. The highlight was in the number of tools that I learned that help visualize the problem and help narrow it to a point where it can be understood. My favourite tool is the actor map with a central actor which reminds me of a spider on a web, I find it very informative and a good way to first begin to understand the problem.

Many students commented on the importance and difficulty in scoping the problem to be examined. If the problem was too big, it remained overwhelming. Scoping the problem with a good focus question allowed students to tackle the wicked problem, while recognizing that they may have had to scope out certain aspects that might have been important. Finding the balance between too broad and too narrow a scope was key to a successful project.

> My group had a ... scoping issue during the project because the original focus question that we formed alienated certain aspects of the system that we felt were important to map. We then revised our focus question to allow us to analyze and convey the system in a more comprehensive manner; however, these examples illustrate that forming an inaccurate focus question can lead one to analyze and attempt to solve the wrong system, while at the same time, avoiding the problem and proper solutions entirely.
>
> Defining the end goal was difficult, which made identifying the gaps between the present and the results very ambiguous. We tried our best to define the result through what the ideal scenario would look like over time through data over time... it allowed us to identify critical gaps in the system where we could develop an understanding. Facing these challenges allowed me to learn how to deal with ambiguity and structure in the future. It helped understand how to take undefined problems and create objectives for it such that we can work towards a solution.
>
> Scoping the problem to delays at ports definitely helped us get at the underbelly of visible bottlenecks in a tractable way but it also feels as if, in drawing that dotted line around ports, we ended up black-boxing some other issues too. For instance, we scratched the surface on labor issues, international relations, and differences across company scales. I’m not able to articulate what roles these other issues played at great length; except to say that there’s more to it than we had the chance to unpack over the term.

Several students commented on the idea of systems thinking as a practice that needs to be developed over time and saw utility in using the tools to help them do this.

> It is important to note that system thinking needs to be practised and developed for a long time before someone can be good at it. At this stage in my learning, having the tools readily available and knowing how to use them is beneficial.
>
> Whether it be causal loops, actor maps, iceberg models or journey maps, there were always new understandings from each approach. At first glance, it seemed like system mapping is simple to do with the right instructions. However, I soon realized that thinking about a problem in many different angles requires a lot of practice similar to any math problem.
>
> Also, just like raw mapping skills is something that like I really got better at. In fact, I'm doing like process mapping. Now, at my [internship]the last 2 weeks I definitely feel very comfortable with like just mapping this big process onto the software that we're using, because I feel like I've got experience with that. So that's been really useful.

Instructor Reflections: Theme 1

Students expressed to the teaching team that the system mapping approach was new to them. While a few students had some exposure to tools from other courses (e.g. some students had seen actor network theory in an engineering and society course, others had been introduced to causal loops for control courses, and some students had seen journey maps in their industrial engineering courses) the nature of the projects, the amount of time dedicated to exploration, and the emphasis on thinking holistically was felt to be novel. In class discussions, students offered feedback about the lack of "understanding the problem space" in their previous curriculum and expressed that the tools introduced in the course would have been useful in their design courses.

A major challenge for students was coming to grips with the ambiguity of the course – the idea that there was not one right answer as well as struggling with the idea that their final maps would still be incomplete representations of their problems. The instructors observed that the students became increasingly comfortable with this ambiguity as the course progressed and students were able to present their final maps with pride and confidence. In fact, the quality of the final deliverables surpassed the initial expectations of the instructors. Students were able to demonstrate significant engagement with wicked problems and achieve new insights, with students reporting that their engagement with systems thinking methodologies gave them new perspectives on the selected problems, augmented their decision making and enabled effective expression.

Theme 2: System Mapping helped students to understand, embrace, and address the current and future impact of their work in context

Student self-evaluations included a lot of commentary on the identification of non-technical drivers of problems and the fact that systems are multilayered and interconnected, recognizing that ignoring root causes can lead to misspecification of the problem. Further, students saw that integrating these aspects into design was key to achieving the desired impact.

> The Challenger Space Shuttle case study is when I really started seeing the merits of systems thinking. If I was just looking at the Challenger without a systems thinking lens, I would have just chalked up the failure to faulty construction. But using the iceberg model to analyze, there was an underlying reason to why the construction was faulty. All the reasons why something went wrong could be traced back to another part of the system that went wrong. The Challenger exploded because of faulty O-rings, but the reason why they were faulty was because of the short timeline, and the reason for that short timeline was the pressure to produce results. It really made me realize that everything is connected to each other, whether it is the physical event or the mental models of the actors.

> My team considered what factors affect automation adoptions, and while many factors were technical (more on the traditional "engineering" side), most were non-technical (social, cultural, environmental). As an engineering working in that field, I'd think you'd have to consider all of those factors if you wanted to start a business in the field, or even if you're trying to implement an automation solution…

> This connects to the responsibilities of an engineer and their duty to perform their due diligence in determining who will be affected by their designs. What I thought was just a checkmark to quality an engineer of having good ethic or not turned into a detailed and meticulous process that required lots of critical thinking and reflection.

> [The course] has taught me that finding a solution is not as easy as solving a mathematical equation but requires awareness of all the factors that surround the problem… The nuance of wicked problems makes a solution for one area a problem for the other finding it difficult to find solutions that minimize impacts.

Students demonstrated an appreciation for the contributions of other academic disciplines and a more nuanced understanding of engineering's role in addressing societal issues.

> The idea of different disciplines approaching situations from different paradigms… became apparent when conducting research and collecting information for my project… and found that different stakeholders have very different perspectives surrounding what is happening in the system.

> Engineering is much needed for progress that makes our lives better. However, a change in how I view this role is that engineering is one half of the solution; the other half of the solution is the social aspect that is often very difficult to convert into numbers to be optimized. Realizing this gave me a realistic expectation of what engineering can and cannot solve.

Instructor Reflections: Theme 2

Students expressed surprise at the different disciplinary perspectives and approaches to problem solving even within engineering, noting that the course gave them a new appreciation for the tools of other disciplines. Introduction of the different epistemologies of other academic disciplines was an area of great interest and novel to the students. There were rich class discussions on the distinctions between paradigms in science/engineering and social sciences, and several students wrote about these in their reflections during the course.

The inclusion of the guest speakers as well as the use of case studies from other disciplines (for example, a case study on ending homelessness) helped students to see the non-technical interfaces of engineering problems. It was surprising to the instructors how new many of these concepts seemed to be new to students. For example, one instructor expected industrial or civil engineering students to be very aware of the social-technical interface; however, in class discussions it became clear that students while some students had been introduced to user needs (for example in concepts like transit rider experience), students had not seen the interface of policy or government decision making with their engineering decisions (for example, how urban planning policy might impact the equity of access to transit).

Theme 3: Systems mapping enabled students to actively foster engaged and productive relationships with diverse stakeholders.

Students noted the importance of visualization for their own learning and effective communication. Many students discussed the importance of simplifying their maps to get the main message across. This speaks to not only the importance of visual communication, but also to a concept in systems thinking about using a "mental helicopter" [18] to zoom in and out when considering a problem.

> During my [internship year] I was often struggling to communicate my thought process and justifying why I chose the final solution to my seniors. However, with an effective system map, I can easily convey my thoughts and walk through the decisions that I made throughout the process.
>
> Choosing the level of abstraction became critical for communicating the main points of a map… I found I had to ignore details (punctualize) in order to make maps that would be digestible for the reader…I also learned the importance of finding the balance of simplicity and complexity that retains key findings while also not being overwhelming or irrelevant.

Finally, many students commented on the importance of a collaborative process that allowed people to contribute and the importance of asking thoughtful questions to get to new insights.

> I was particularly vocal in the direction of the project, and I think this is not something I typically do… Because collaboration is such a significant aspect of this course, I appreciated the level of communication that we had, and I think a big reason we could achieve this is because of the class norms established at the beginning of the course that encouraged discussion.
>
> I believe my most important role in the team was to be a team player… I felt that it is important to create discussion around pivotal topics ensuring that we have a solid reasoning as to why we do it… I believed I was able to fit into this role well and it

> brought value to the team as we were able to engage in deep discussion about certain topics solidifying our understanding of the problem.

However, some students noted difficulties in contributing when healthy collaborative facilitation was not in place. It should be noted that these comments were primarily made by female students.

> Often, I would find myself just barely keeping up with how fast our discussions volleyed and shifted directions when we worked in person. This felt uncomfortable, and it made it difficult for me to contribute as much as I typically do in real time. I also felt that whatever I did contribute, slowed us down. Now, I'm not saying that necessarily detracts from our work: taking time to digest information is valuable because it helps us catch ideas or assumptions that we may have made mistakenly in our rush to get things done. More often than not though, my contributions were peripheral to the subject at hand. I started to take more of a backseat, rather than actively contributing to discussions too.
>
> During the 5R's assignment, I brought up a role, but I did not have any reasoning as to why I thought it was a role, so the team dismissed it. I also had multiple concerns during the 5R's assignment, such as the level of detail in the Results and Resources or the lack of contribution from a team member, but the rest of the team did not see the issue so I felt like I had to let it go for the sake of the team dynamic. After the 5R's assignment, I found that I fell back into the habit of not speaking unless I was absolutely certain of what I wanted to say. It was challenging for me to give input on what direction we wanted to take, and it was harder for me to contribute my ideas towards the project.

Instructor Reflections: Theme 3

Even simple systems exercises demonstrated the value of collaborative thinking and multiple perspectives, and the relevance of both "specialization" and integrative thinking within systems mapping. Students worked well together in discussion and negotiating the ways to represent their understanding, though some issues were observed with less assertive students and students with more limited English language confidence. Students seemed very open to giving and receiving feedback from other teams on their work; the visual nature of the representations and the general familiarity of the topics made it easy for their peers to question, challenge and provide constructive feedback which resulted in changes to the maps from week to week.

A disappointment of the course was the difficulty in getting students to speak to experts or stakeholders from outside engineering. While students did include research literature from other fields, students were reluctant or unable to find stakeholders without instructor introductions. In a few cases, the guest speakers were close enough to the selected topic for a team that they could integrate what they had learned from the speaker.

In the first year of the course, there were issues in teams both in terms of people feeling heard and in members being reliable. In the second year of the course, more deliberate and explicit content on teaming was included and collaboration seemed to improve, though there were still some students who struggled to contribute. This led to better project organization and team function, as well as better demonstrations of systems thinking in the final products.

Discussion

Based on our first few instances of the course, it is feasible and useful to teach systems thinking to undergraduate engineers. Students demonstrated a proficiency with using the tools and connected the use of the tools with the utility of the various tools to approach complex problems, with some expressing that they would use it in the future. Students also successfully demonstrated an ability to incorporate social, economic, and environmental concepts into their problem descriptions in their final maps.

As a leadership competency, we argue that systems mapping offers a few key potential outcomes to improve engineering leadership performance. First, engineering leaders need to be able to think on multiple scales – analyzing more constrained technical systems but also understand the role of a technology in a broader social and ecological system and understanding local and global contexts and the relationship between technology and policy at multiple levels. Systems mapping enables that through a constant reflection between “parts” and “the whole.” Systems mapping, because it is inherently multidisciplinary and best when done collaboratively, fosters communication skills with different disciplines and stakeholders, a key competency for engineering leaders [3]. This collaboration can lead to the nurturing of affective traits such as curiosity, humility, and compassion, which are important when leading change in the challenges of our times. Systems mapping attunes us to the complexity of systems, preparing engineering students for the inevitable unpredictable consequences of technology and technological change. Finally, systems mapping, by bringing into focus the diverse relationships between technology, social and environmental factors, can aid in breaking the perceived “sociotechnical dualism” [34,35]. Engineering education has a tradition of separating the technical, sometimes referred to as the “decontextualized” components, from the “social.” What is considered “social” or “political” is not always considered engineering knowledge, but systems thinking and mapping offers a reconciliation of different knowledge traditions to reflect the real nature of engineering work more accurately [35].

It was interesting to note that while many students commented on having gained a more nuanced understanding of engineering's role in society and the need to broaden perspectives and considerations of non-technical factors, there were few expressions of true professional humility. Students continued to express an understanding of engineers as the problem solvers, with only a few students acknowledging that engineers may be only a fraction of the solution in some cases. Further integration of expertise from other disciplines might improve this.

The importance of creating effective, psychologically safe teams to be successful in any endeavour has been a common theme in leadership literature and a common focus of engineering leadership research [36]. As students tackle increasingly complex problems, the ambiguity of the challenges makes framing and scoping critical, and team members must work hard to collaborate in the face of uncertainty. Further, splitting the work up as a team is not an option, as the systems themselves - and the tools used to illustrate them - are interconnected. Instruction in systems mapping processes and tools can help students to facilitate that collaboration, however processes for effective team management are also critical. As other disciplines are brought into the conversation, this importance of consultative communication – listening and incorporating various perspectives to build a shared mental model – will be even more challenging. Creating a safe and engaging classroom environment, where students can ask questions, float ideas, make mistakes, and give and accept feedback, is important, given the iterative and collaborative nature of systems mapping

Future Work

Many students expressed a desire to see the introduction of systems thinking/mapping tools earlier in their undergraduate careers, particularly in design courses where students are quick to converge on a given understanding of the problem. Given the ability of the students to grasp many of the visualization tools, introducing concepts into design courses is feasible. The authors have experimented with introducing systems mapping into a club leader program and a student design competition. Future work will look at developing resources and "drop in modules" for other classes.

Systems thinking pedagogy - the art of teaching systems thinking - should be a focus going forward for further study. There are very few established courses in systems mapping, and so the development of learning activities and assessment required deep reflection and pedagogical development on the part of the course instructors. Finding the best examples to demonstrate systems mapping tools is very important and requires trial and error. Although the tools are designed to provide insight on a diversity of systems and problems, the teaching examples needs to be purposefully selected to showcase the power of the tools. For example, we used the relationship between transportation and health to work on connection circles, but this scope was too broad to make sense of the tool as a learner.

Further pedagogical development is also needed to improve the assessment of systems thinking skills for evaluation of the final deliverables. The significant use of reflections in the course allowed both instructors and students and process learning and refine experiences and approaches to teaching and learning throughout the course. However, this pedagogy requires significant effort in marking, which makes scaling of the course difficult.

Since the course spends so much time with students working to understand the problems, students do not get the chance to further learn by testing solutions. A full year course could allow students to extend their insights as they move into the next phase of design, with the expected iterations to their mental models as they get feedback from the system. The course could also be improved by making it truly multidisciplinary, i.e. bringing in students from other faculties, and by involving experts and stakeholders from the community as both interview subjects and participants in the mapping exercises.

Limitations

This course is a small elective course. Given that students are self-selected, there is likely an existing aptitude and interest in systems thinking and an openness to the topics of the course; teaching this content in a core design course may be more difficult if the broader student population has more difficulty digesting the concepts or being open to consideration of other epistemological paradigms.

The system mapping deliverables were all team based, which meant it was difficult to assess skill development in individuals. The evidence for the development of systems thinking skills, professional humility and consultative communication skills in this study is primarily based on individual self-assessments by the students. More objective assessments are needed to strengthen the conclusions, by interrogative exploration of student experience and learning.

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