Agency and Capability Development in Engineering Design for Sociotechnical Engagement

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Abstract: *The technological innovations brought on by engineering work has significant impact on a community or nation's social relations as well as the mode of dealing with the natural environment. The role of technology is therefore deeply embedded in social structures and can lead to both capability expansion as well as capability deprivation of individuals. Crises particularly highlight this relation. Ongoing environmental crises often seek technological solutions to change interactions with the environment while in conflict-affected areas, resilient forms of communication are often critical. Such interactions between technology, the environment, and a community are complex and require a critical view of technology's role often opposed to a purely positivist view of technology often embedded within engineering culture. The UN Sustainable Development Goals (UNSDG) offer an important road map to deliver on a commitment to help the world's most vulnerable in the midst of such converging crises. However, developing technology that will positively impact vulnerable communities requires that engineers are adequately prepared to address systemic issues. How then might the capabilities approach help us to prepare engineers to understand and propose solutions for complex, sociotechnical problems?*

Seeking to support broad student capability growth necessary for addressing such challenges, this paper focuses on changes to a 3rd-year engineering design course that has developed over five years. In the course, students collectively choose a UNSDG to explore and use a variety of representational tools to support their understanding of its societal relevance. These tools are informed by interviews and research articles. From a capabilitarian perspective, we seek a balance course between structure and student agency to bring intentional development of a broad set of student capabilities beyond merely producing a working technical product that includes Ability to choose a meaningful project; opportunity to connect engineering with society; and ability to contribute meaningfully to sustainability. Central to this is understanding the role of technology within a specific context. At the end of the course, students present a minimum viable product, or prototype implementation of a technical solution, that demonstrates their understanding of the contextualised problem and technology's role.

In the first two offerings of this course (Autumn 2021, Spring 2022), students struggled to understand the social aspects of design despite asking students to conduct interviews and draw systems maps. Subsequent offerings included more time for structured research of the social system and more class time in developing the systems map with a corresponding reduction in time on producing a product. The deliverables for this course are individual ePortfolio reflection assignments and group final reports. We investigate the results of these changes, comparing ePortfolios & reports from earlier courses with the most recent iterations.

In our analysis, we utilised inductive "In Vivo" coding methods to elicit what students had learned from the assignment in their own words. Assignments were coded by a team of researchers using consensus coding techniques to reduce intercoder bias (Stemler 2019; Harry, Sturges, and Klingner 2005). From these codes, we categorised the first pass codes into Pattern Codes (Saldana 2013) identifying emergent themes. We were able to classify student learning into a few major categories: Social Context Drives Decision-Making, Understands Sociotechnical Context, Experienced Personal Growth, Developed Professional Skills, and Lack of Engagement. In comparing the portfolios between cohorts, we noticed significant improvement in the first two coding categories as a result of the increased time allocation to developing systems maps.

Core to the capabilities approach is freedom to enact functionings that one values. However, at present the narrow focus on engineering science particularly within engineering curricula in North America can act as a structural barrier that impedes capability development of students who have interest in societal problems or non-corporate engineering work. Understanding a larger context and listening to a variety of viewpoints to understand technology's role is essential. This paper suggests that more student agency and sociotechnical exploration within engineering programs helps develop engineers to have the societal impact they may desire. This insight is key to attaining the broad development goals the UNSDG necessitate for significant societal impact.

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Introduction

While technology is deeply embedded in social structures, the social aspect is often minimised in the education of engineers. This is particularly true within the North American educational system where outcomes-focused accreditation processes are heavily influenced from continuous quality improvement metrics that rose to prominence within industry during the 1980s (Cheville et al. 2023; Akera et al. 2019). These processes tend to shift the focus of engineering education to narrow technical development intended to support industry with roots in the engineering sciences instead of a liberal education. This critique is not new and has been voiced for quite some time beginning as the engineering profession within the United States grew in response to industrial shifts from the industrial revolution and first World War with a educational focus on harnessing technology for efficient means of production (Mann 1918). These critiques continue to this day with Nieusma and Riley succinctly noting that '[b]y placing technical functionality at the center of development work, engineering-for-development projects tend to obscure non-technical dimensions of development work that are critical to achieving social justice goals' (Nieusma and Riley 2010).

Central to both engineering work and also development projects is technology. Technology greatly affects human modes of interacting with nature, processes of production, social relations, and even our mental models of the world (Marx 2000). Engineers, as the creators of technology, therefore must operate in a tension between many competing interests. Throughout history engineering work has long been central to nation-state development and imperial expansion (Lucena, Schneider, and Leydens 2010), but is also seen as key to achieving social-justice centered goals such as those encapsulated in the UNSDG. An unstated assumption underlying the beliefs of many engineers and their training is that engineering work and technology development is often value-free and guided by a Smithian 'invisible hand' to guide technology toward benefiting the collective good (Newberry 2015). The effects of this underlying belief have been observed. Cech observed a vector of disengagement in which students enter engineering programs interested in pursuing public welfare concerns and social issues, but over time become disengaged and disinterested with such issues (Cech 2014). This is possibly due to the emphasis on technical skills and problem-solving at the expense of emphasising social responsibility and ethical implications. In their education, engineers are often trained to solve problems using known solution-paths, and can ignore ignore navigating the complex, competing interests that surround difficult problems where technology can support development.

The capabilities approach offers a helpful lens to view this issue of disengagement and technological focus. Students entering engineering programs may intend to develop a capability set that includes supporting the vulnerable and the general public but are not developing these desired capabilities within the current higher education system. This could arise from a lack of agency in which students do not have the opportunity to choose the capabilities they desire to develop (e.g., relevant projects, broad course or study topics, other related functionings) or a structural effect in which engineering programs impose restrictions on the capability development offered to students. The role of education as both a functioning as well as capability—as it is key to opening many other capabilities (Robeyns 2017)—is similar to the role of technology. While access to technology can be a functioning in and of itself, technology often is a desired functioning due to the opportunities it enables. As engineers are educated to be creators of technology in their profession, an increased importance is then necessitated for engineers to think broadly and systemically about their work. Are we meeting this need? A narrow focus on technical skills---at the expense of spending developing developing idea of justice rooted in the social science and humanities for example---can have serious ramifications given the current (and ever increasing) role of technology within society and the world. Compounding this, if education and development of engineers continues to be neoliberalized with engineering work viewed as being 'value-free', the agency of the engineer is easily lost to larger corporate and interests. Or as Carl Mitcham aptly notes, 'What Percy Bysshe Shelley said about poets two centuries ago applies even more to engineers today: They are the unacknowledged legislators of the world. By designing and constructing new structures, processes, and products, they are influencing how we live as much as any laws enacted by politicians' (Mitcham 2014).

Education and Capabilities

Individual agency and the role of choice in enacting capabilities into functionings is key to the capabilities approach, yet within educational systems a counteracting force is the inherently confining nature of an educational discipline. While Schiro notes multiple views on the role of a curriculum including more social-oriented reconstructionist views, more prominent within science and engineering faculty is the Social Efficiency model which predominately seeks to prepare students to enter into industrial roles, and the Scholar-Academic which values passing down and retaining the knowledge and practices of the discipline (Schiro 2013). Being trained (or *disciplined* as the name implies) to think and act within the confines of an academic discipline is in tension with an individual selecting from a broad set of academic capabilities they may wish to develop. Imagining a continuum with complete agency in one's own educational development on one hand and on the other a rigid educational program completely defined and constrained by the discipline, institutions of higher education and their constituent departments are found to be at varying points along the axis. Within the United States higher education system, educational programs offering a liberal education trend toward offering student-defined courses of study that emphasize a broad, or liberal selection of topics. At the other end, programs found at many technical institutions and public-funded universities (such as those where large engineering programs are often operating) tend to include a small number of broad elective courses (i.e., those in which students choose the courses they desire to study) and instead prescribe a strict course of study for the degree. Engineering programs in particular have a reputation for being quite rigid with regards to the limited amount of choice students are offered in selecting non-engineering courses, and the strict course pre-requisite structure that further limits student choice.

A capabilities-influenced engineering education however should highlight student agency and development, allowing for individual choice in the capabilities selected to develop and possibly later enact into functionings in parallel with the necessary technical emphasis and training of engineering. This view of an educational program highlights the dual-role of education as both as means to broaden one's capability set, but to also envision new possible functionings that would otherwise remain unimagined. Again we see that education is both a *functioning where* students may be aware of some way of being they desire and see education as a way of enacting this functioning, as well as a capability that may broaden students' own perspective of the world, and new ways of being can be imagined.

What then would an engineering program rooted in the capabilities approach look like? It is difficult to answer this question and fully transition a well-functioning academic program into a capaibities-based program, but as Walker notes, we must commit to radical incrementalism. In this paper, we focus on the developments within an engineering design course that have focused on student agency, and broader development to adequately prepare students with the capability to address the larger, systemic challenges of the modern world. This course is part of a larger design sequence of courses within an undergraduate engineering program in the United States. We study changes to this course seeking to allow for development of students' sociotechnical awareness and contextualising proposed solutions. This paper is organised as follows. The background and context for the course is provided below. The next section discusses the methods used to analyse the changes and how students' developments and experiences changed. The results and a discussion of the findings are presented. Lastly we offer a conclusion.

Overview of Engineering Design and Problem Complexity

As engineering work is centered around the creation and use of technology, it is important for engineers to have some understanding and awareness of the complex systems in which their technological creations will be embedded. While this issue of preparedness of engineers to address complex sociotechnical problems is known, there is not a consensus on how best to modify programs to better prepare students. Technology development has far outpaced our educational systems development and norms of engineering education leading to a potential gap between the problems engineering students are prepared to encounter versus the large, complex problems the world faces. Engineering education has leaned on the understanding of technology and not its role within the larger world. Engineering's focus on specialisation and particular attention to maths and science have created '*curricula [...] so congested with specialised courses that students generally regard literature and sociology as unnecessary chores, to be endured* *rather than enjoyed*' (Mann 1918). This of course is an old argument as evidenced by the quote, yet is just as relevant today as it was over 100 years ago. For engineers, as the creators of technology, to not be able to recognize and effectively enter discussion of the impacts and interplay of technology and society sets dangerous precedents on how technology and sociotechnical relations of the future will be formed. This enables a system where it is easy for economic or corporate interests to control engineering work and technology's applications instead of using engineering for societal good, as the UNSDG seek.

Technological development and engineering science is one central theme of engineering education, though it is often dominant, but it is not the only one. Anotther branch of importance is engineering design. It is in this domain where solutions are proposed to solve or address an issue and been seen as increasingly important over the recent decades (Froyd, Wankat, and Smith 2012). While science seeks to collect observations from specific phenomena and form general laws, engineering design seeks to reverse this abstraction vector and use scientific principles and laws to generate solutions for specific contexts (Krupczak and Bassett 2012) . It is in this domain of engineering design where the importance of understanding a social context and its affect on the technology creation process itself that is important for the development of engineers.

Engineering design itself is often presented as a linear process. Many engineering textbooks describe a linear, circular process such as the example shown below in Fig 1. This process is presented as portraying *the* design process. This linear approach to design is heavily rooted in the principles of engineering science, being separate from the field of engineering design, and aligns with problem-solving methods used within the engineering sciences (Lucena, Schneider, and Leydens 2010). These methods are appropriate for such classes of problems that are termed 'engineering problems' and are approached by categorising a given problem as a member of a particular set of problems, and then applying a known solution method for that set to reach the result. When problems are presented in this manner, a linear process to reach a solution is appropriate. However, presenting engineering design in this way to students can mask the difficulties and intricacies or the more more complicated issues that engineers will face. In approaching design as a linear process, there is an assumption that problem itself will not grow or change and become more complex as one learns more about it. Problems instead are expected to become simpler to solve, or at least more straightforward as the engineer moves through the process.

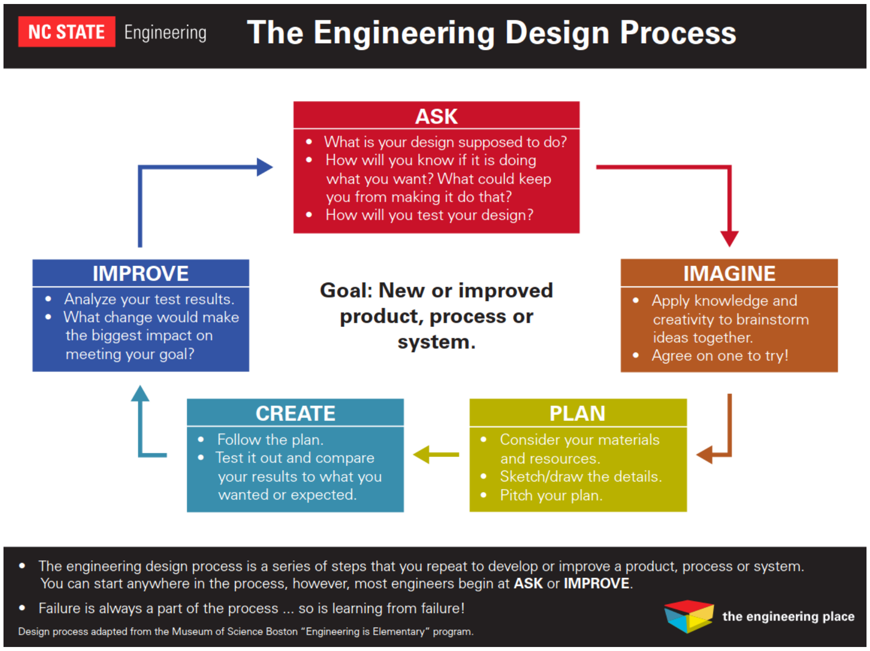

Fig. 1: An example of a linear engineering design process presented commonly presented to engineering students. [Image copyright NC State; available online at https://engr.ncsu.edu/wp-content/uploads/2017/01/design-process-new.pdf]

Most larger applications of engineering design and problem solving are much more complex and do not behave this way. A nonlinear process and approach to engineering design is more appropriate, or at least more accurate as to how engineers work through design in the profession. Larger societal problems are inherently a different class of problems than the toy example problems that students are accustomed to solving in their coursework. Solutions are not known, and may not even exist. The path to addressing problems is not to reduce or divide and conquer, but instead to probe and explore. A framework to discuss such types of problems is needed.

Cynefin framework and classifying problems

Many sociotechnical problems are complicated and require adaptation as the problem understanding itself changes. One framework to classify such problems could as wicked problems, as opposed to tame problems (Rittel and Webber 1973). Rittel and Webber describe wicked problems as those known to be complex and ill-defined, often involving multiple stakeholders with competing interests and goals. Tame problems have clear definitions with verifiable solutions achievable through the scientific method. Other characteristics of wicked problems include not being able to know when to 'stop' as the solutions are often better/worse as opposed to true/false; uniqueness making solutions for other problems not directly transferable; difficulty in measuring progress; interventions or attempted solutions often have consequences and can greatly affect understanding of the problem. These descriptions of wicked problems are applicable to many sociotechnical problems and require different approaches that a linear process may not capture.

One way to further break apart wicked problems and their nature is through the Cynefin framework (Kurtz and Snowden 2003). The Cynefin framework was developed by Dave Snowden as a decision-making model to help leaders and managers navigate complexity and uncertainty. Problems can be categorised into four domains: Clear (or Simple), Complicated, Complex, and Chaotic. A different approach to problem-solving is required for problems in each domain. The Clear domain is characterised by stability and clear cause-and-effect relationships. Solutions in this domain are based on best practices and standard operating procedures. Most so-called *engineering problems* rooted in the engineering sciences can be found in this domain. Undergraduate work reinforces the idea of clear solutions and known methods. However, as we move through the domains into more wicked types of problems, different approaches are required.

The Complicated domain, while still being predictable, involves more analysis and expertise. Problems in this domain have multiple correct or right answers, and solutions are found through analytical processes and expert knowledge. When operating in this domain, a major goal is to reduce and simplify components of the larger problem such that they can be solved as a series of smaller problems residing within the Clear domain. Problems are analysed and broken down until they are a set of problems with known methods.

In the Complex domain, cause and effect are only apparent in hindsight, and solutions emerge through experimentation, probing, and sensing patterns. This domain requires adaptive and iterative approaches as understanding of the problem's nature changes, often involving collaboration and innovative thinking. The Chaotic domain is marked by high turbulence and lack of clear patterns. Immediate action is essential to stabilize the situation, and solutions are typically novel and untested. When one finds oneself working in this domain, the goal is simply to get out.

This framework can help to understand the nature of various problems. Engineers are predominately trained to work in the Clear domain where problems have known answers. As we have alluded to, design problems are rooted in other domains—often the Complex and Complicated domains. Training engineers to have the sociotechnical awareness to work in these domains may require a fundamental shift in educational approaches. Problems that have multiple right answers and evolve over time are not compatible with the banking model and traditional classroom approaches of a professor pouring out knowledge to students who store this information to later recall it when asked (Freire 2000). Instead, students must take agency to establish their own understanding of the problem space and navigate uncertain solutions. Or as Verela would say, we need a structure that supports an *enactive approach to cognition* (Varela 1999).

If we expect engineers to be prepared to begin addressing complex sociotechnical problems where technology may offer vital affordances yet are predominately educating engineers to address more simple problems with linear problem solving methods, we begin to see a gap between preparation and expectations. This critique is specifically centered around North American engineering education systems where an underlying assumption is that most engineers will enter into private enterprises and corporations and should be prepared for such endeavors. At the same time, the technology currently being designed in the Global North has tremendous global impacts. Such a system can introduce a form of techno-colonialism in which engineers creating technology may continue to reinforce by leaving these relations unquestioned. Alienation of technology users from technology designers can further exacerbate this relationship. In viewing engineering student development through a capability lens, we can see that the current system seeks to confine the functionings of engineers to pre-selected outcomes decided on by accreditation organisations and faculty committees. Engineers students can develop capabilities with agency, but must demonstrate these outcomes to become a practicing engineer. While are not yet calling for a whole-cloth change to the system, we do see value in pursuing more student agency in engineering education and creating a space for student values and voices to emerge. An overview of curricular changes to an undergraduate engineering program and specifically the changes to a third year engineering design course in support of these larger goals are discussed in the next section.

Curricular Changes and Context

Recognizing the issues outlined above, we have sought to modify an undergraduate electrical and computer engineering curriculum to better support student development through reducing curricular complexity (Heileman et al. 2019) with more electives and working to coordinate curricular 'threads'. This change process has been greatly informed by the Capabilities Approach which offers a helpful lens to view the balance between individual agency and resources and the larger structures that help and hinder student development (Appelhans, Thomas, and Cheville 2023). These changes seek to support increased individual student agency in navigating a curriculum and working toward the known functionings that students desire to enact, as well as opportunities to envision new, potentially unimagined functionings. This requires the broad capabilities that are necessary for a normative justice stance for students as agents in the world (Nussbaum 2011) as well as higher education (Walker 2006) capabilities in addition to capabilities specific to engineering or the local university institution.

These changes have taken place at an elite private four-year private, undergraduate-only liberal arts university within the United States of America. The institution is primarily white-serving. The engineering college is one of three colleges at the university in addition to a business college, and a college of arts and sciences. As a liberal arts institution place high value is placed on students being able to select electives and shape their studies. This stance can be at odds with often strict requirements of an engineering curriculum (Heileman et al. 2019) and how accreditation requirements have been interpreted (Akera et al. 2019). The institution also has a strict four-year graduation requirement. The electrical and computer engineering department has worked to reduce course pre-requisite chains and add options for students to take electives every year and the flexibility to study in another country during their undergraduate career if they so choose. These curricular changes coincided with departmental discussions and negotiations about fundamental engineering principles such as what constitutes engineering design, and what core technical engineering courses should be required.

Representational Approach to Design

One curricular aspect where we have seen the most change is within a six-course sequence over all four years in the curriculum that focuses on engineering design topics. This thread consists of two courses taken in the first year with one required of all engineering students enrolled in the College of Engineering during their first semester followed by a discipline-specific course in the second semester. This second-semester course guides students through design of an environmental sensor. In the second year, a half-credit course (equivalent to two credit-hours, or four ECTS points) provides skills and tools for device fabrication and testing. In the third year, a half-credit course navigates understanding how to select and understand a design problem, followed by two courses in the fourth year comprising a year-long capstone design experience where students work with external clients to design and prototype a solution.

As this design thread cuts across multiple years for students and many different instructors, it has been important to develop a common language used for discussing engineering design. The current design principle is shown below in Fig. 2. Instead of prescribing a pre-formed linear process (as in Fig. 1) that students must go through to implement a design, we instead introduce students to eight perspectives of design and acknowledge that each perspective must be visited and re-visited multiple times as the understanding of the problem evolves. This highlights both the non-linear nature of design and how an engineer's conception of the entire problem changes as their understanding of the problem and its context changes. Such thinking is a better model of the work that engineers do in their career work. This process is captured through what we refer to as a *representational approach* to engineering design. Students create various artefacts of their design such as block diagrams of systems, user-agent models representing who may use their project, and systems map to look at a larger context, among other representations. While many students focus on the final, built technical 'product', we highlight to students that these representations *are* the product. Often as engineers design technology, the models and artefacts are the final product which are then passed off to other entities who may be responsible manufacture or final product creation. Technology therefore is represented in various models including architecture of the product itself as well as models that represent how the device may be used or interact with the world.

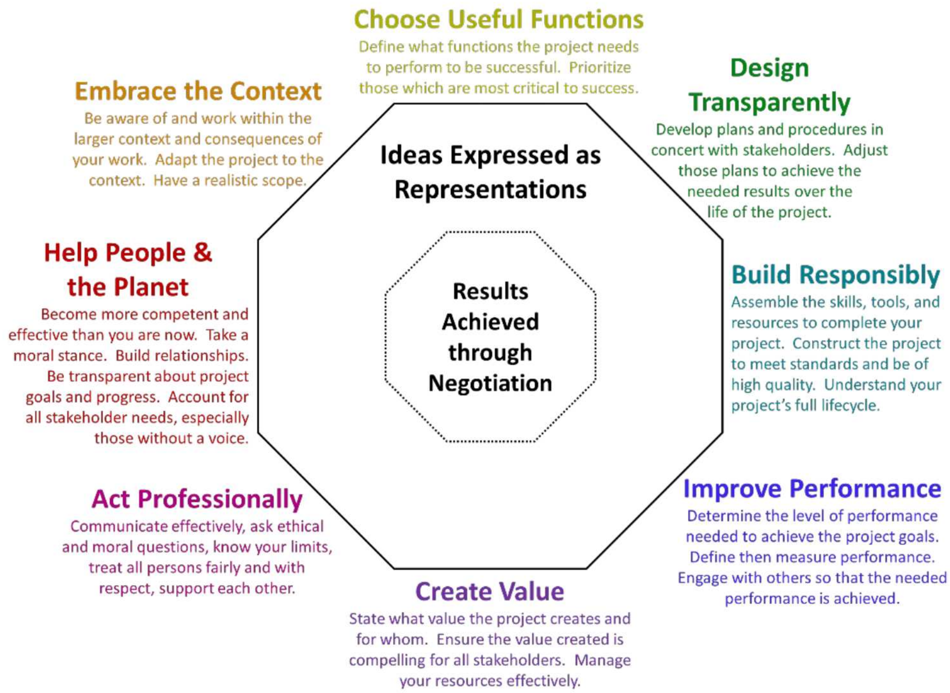

Fig. 2: Eight principles or perspectives for engineering design underlying the six-course design sequence.

Course Description

In the six-course design sequence, the half-credit third year course *ECEG 301: Praxis of Engineering Design* has undergone a series of changes to focus on problem exploration and scoping over several years. The first instance and offering of this course emerged as a simplified and shortened version of the full-year design capstone course. This structure was found to rush students to quickly build or create technology, with a sense that this is what engineers should be doing.. In switching the course to on design exploration, it is in essence working to help students to not answer the question of '*What is a good problem to solve?*' but instead to consider '*What is good to solve?*' While seemingly simple, this represents a fairly important shift within the department as many many faculty are also adopting a more capabilities-focused view of education. These changes have been implemented and evolved over five different offerings of the course. Figure 3 summarises significant changes over this time.

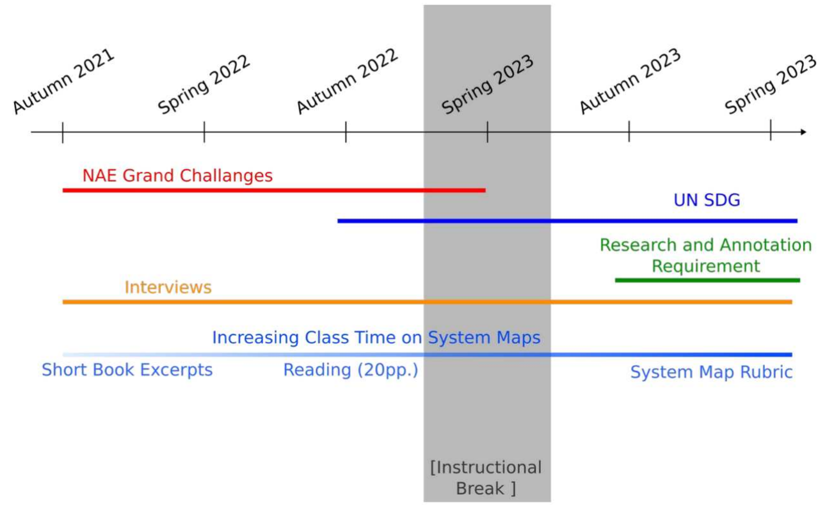

Fig. 3: Timeline representation of changes across offerings to a third-year engineering design course.

Most importantly, the course underwent significant changes to introduce system maps to third-year engineering students, aiming to link their work to broader social and global issues. System maps, which are diagrammatic representations of how complex human-social-technical systems behave, were integrated into the curriculum to help students understand the systemic impacts of engineering solutions. This aspect is easily overlooked in engineering education yet necessary for engineers to understand the significance of their work. This change also allowed students to bring more of their own voices and interests into their engineering work and were invited to question the power structures of the systems students were discovering. The general goal of introducing system maps was to equip students with tools to better comprehend the interconnectedness and complexities of social justice issues. This attitude-shift of the course was achieved through an action-based research approach over five iterations of the course, emphasizing participatory and democratic principles to enhance both understanding and social change.

The initial offerings of the course was a miniaturised version of the year-long fourth-year capstone design course, that focused broadly on eight design perspectives but was overly technology-focused. The revised course redirected its emphasis from the National Academy of Engineering (NAE) Grand Challenges to the UNSDGs, promoting a deeper focus on social issues. The curriculum adjustments included narrowing the scope of topics from broad choice to a single UNSDG which the entire class shares, dedicating more time to problem identification and societal impact, and reducing the number of design iterations and representations. System maps became a central pedagogical tool, with increased classroom time devoted to their understanding and application. This allowed students to move beyond linear solution methods to address complex problems, fostering a more holistic and socially aware engineering mindset.

The course also de-emphasized the technical focus and product development. Possibly because engineers are surrounded by narratives of solving problems or coming to help or even the rational, pragmatic epistemological nature of the engineering discipline, engineers are often quick to act and jump to implementing solutions and ignoring the broader product exploration. To support more time for students to not focus on their technical artefact they build and demonstrate (what is often considered the goal or purpose of a design course by engineering students and faculty), students were allowed only to build a *minimum viable product* that served to demonstrate some basic feature of their larger design and discuss how this fit into their understanding of the larger picture. This shift away from demonstrating technical aptitude was intended to highlight the connectedness of the proposed technical solution to the larger sociotechnical system that the students were seeking to address.

In its current form, the course structures center around three project check-ins as feedback mechansism towards the end semester presentation. At each check-in, students discuss their project status with the course instructors and submit a written report. The check-ins serve to give students formative, developmental feedback which they then bring to the next version of the report at the subsequent check-in. Students work in teams of three, with each team oriented around some aspect of a UNSDG goal which they have chosen explore. At the start of a course the class democratically selects the one UNSDG the class will work on for the entire semester. The students are given full agency to negotiate with each other how they will decide on a goal. The professors only work to make sure that space is heard for all voices to be heard and facilitate vote counts if needed. Once chosen, students then form into teams and begin researching their project idea through research articles, interviews and development of various representations. In this format, projects are not in competition with each other, but each student team explores and works on addressing some aspect of the much larger UNSDG the class has chosen. The course supports collaboration and sharing between all groups. Because the UNSDG issues are extremely broad and open-ended, students are quickly placed into working in the Complex problem domain (of the Cynefin framework) where teams must quickly learn about their problem space and begin making sense of the surrounding issues.

There have three key elements to help support working in the Complex domain where one's own conception of the problem may rapidly change and adapt. We have asked students to read and annotate research articles weekly, which they record in a shared Zotero database. Zotero is a freely-available, open-source reference management software. Importantly for this class, it also supports collaborative work and allows for multiple users to highlight and annotate articles. The design course uses this feature and requires that students not only find and read a relevant article weekly, but also highlight key items within the article and provide a short summary. This is intended to provide a structure where students can develop habits of research and reading while supporting the whole team's understanding through providing annotations and summaries. This research requirement was implemented in the course in Autumn 2023.

While research has been one important piece of the course changes, along with this change has been an increased emphasis on development of systems maps and an interview requirement. As students develop their own understanding of the larger issue they are addressing, this understanding is captured in a systems map representation. A system map is a tool that conveys causal relationships between entities and actions. A simple narrative can be developed in looking through the loops that form within a system map to help others begin to understand the complexity of a larger system. These systems maps change often over the course, and students are encouraged to include citations and other data from their readings.

Because the UNSDG are broad, disciplinary knowledge outside of the discipline and academia is required. Student groups are required to a small number of interviews during the course. Early interviews are key to helping students develop and validate their early system maps. At later interviews, the system map is used to convey to the interviewee the students' understanding of the issue and generate a more targeted conversation. While many students tend to want to talk to other professors and faculty within the university, we encourage students to seek knowledge from a wide range of people, acknowledging the potential issues of only seeking information from a single group. It is in the last few weeks of the course, that students enter the final project phase where a small piece of technology is developed, seeking to have a positive effect on a loop in their system map while being able to effectively convey to importance and relative impact within the larger UNSDG.

As these changes have taken place in the course, it is of interest to see what if any impact this has had on the projects and students understanding of the sociotechnical issues. Faculty have had many opportunities to bring in discussions related to global north/sound divide, economic disparity, who benefits from different technology and other social concerns that are often ignored in engineering contexts.

Study and Results

To study this effect, several course artefacts were gathered. The dataset includes team final project reports from each semester, as well as student self reflections in weekly posts, and a summative self reflection in an ePortofolio. Final reports were written by the student teams with multiple iterations over the whole semester. Weekly self-reflections were recorded in a project management software (Basecamp) where students were asked to discuss their ongoing process over the course, and the final ePortfolio activity was used for students to discuss their progress over the entire course. These items were read and coded using a codebook developed from multiple frameworks. Codes were discussed by the team and then used to to look for emerging themes within the dataset.

The codebook was developed by first creating a set of codes for characteristics of wicked versus tame problems (Rittel and Webber 1973), characteristics of sociotechnical issues, and the Cynefin framework (Kurtz and Snowden 2003). The codebook used for this study is included in the Appendix. Artefacts were coded in nVivo software by the coding team. After coding individually, the team met to discuss codes and work to reach consensus coding. However, due to the breadth of codes and data, strong concensus was not reached. Instead, the emerging themes were discussed by the team as they worked towards consensus coding. Further rounds of coding and meetings are needed to produce tighter consensus between the coders throughout the larger dataset.

Several items can be noted that are indicative of changes in how the students experienced the course. For instance, in the Autumn 2021 semester, one team noted in their final project that: "*Our end goal was to create an immersive environment for students to learn in. In our case, we designed a plant cell to teach students about the various parts of the cell and how they interact with one another. The user can learn about various parts of the cell by walking around to each part of the cell where they are greeted with a description of what that part of the cell is and what it does. The user can then walk over to the next part of the cell to learn more about how the cell works and how that part interacts with the others.*" This team was seeking to enhance a broader goal of transforming education, but we can see indications that the team was desiring to stay in the Clear or Simple domain where problems have known solution paths.

Within this team's reporting, much of the focus is on the engineering design drawings technical aspects. There is little evidence that the team's understanding of the larger problem changed as they worked and researched, but instead noted change in the technical aspects of what they believed they could do such as software or time limitations. In this team's project summary, they state: *"There are a number of constraints that prevent our project from being widely implemented. First and foremost, is the cost and logistics of acquiring and setting up VR* [virtual reality] *headsets. […] This is an enormous cost to many people and can certainly restrain who is able to gain access to this technology as a whole. […] On the other hand, we also had many more immediate constraints. The first being that none of us had any real experience using [the VR development software …] Another constraint is that there is only one computer that we have access to with a VR headset attached to it […]"*

Although the team was working to address a larger issue that affects many people, much of the focus in the reflection was on the team's own difficulties engaging and does not take a critical voice as to the nature of their project itself. Acknowledgment of the cost associated with the VR technology is present, but further ignores the complications of who this technology may benefit and who is left out. Instead, the team focuses on the personal constraints and difficulties they had in creating their demonstration.

Other teams in the early semesters did acknowledge potentials for wider consequences of their designs, but the overall focus of the project remained on the engineering work and presentation of technical designs. The sociotechnical situatedness seems to be acknowledged, but there is little evidence that these teams spent effort understanding the complex nature of the problem space beyond what was most immediately necessary for their technology to be built or deployed.

In comparison, in later semesters teams began considering broader impacts of their proposed technology. The research team saw an increase seen in codes for recognizing widesperead, interconnected effects in later reports. As an example of a report from the 2024 Spring offering, one group looking at issues relating to clean water access not that: "*... increased contaminated water used in houses causes more health challenges due to waterborne diseases and microbial contamination [citation]. Waterborne illnesses affect people of all ages but are more harmful to children and the elderly [citation]. The degradation of community and public health would lead to more social unrest and demands for the public to access clean, safe drinking water. In response, the government (assuming developed countries, such as the US) acts to provide more funding for these water treatment facilities to provide more clean water to more people [citation], resulting in less contaminated water. This is a balancing loop because the government's funding action treats the problems as they arise to regulate the system. This fix classifies the system as a "Fix That Backfire" because the solution only addresses the symptoms of the problem, namely, societal unrest. Funding water treatment facilities do not necessarily address the cause of contaminated water."*

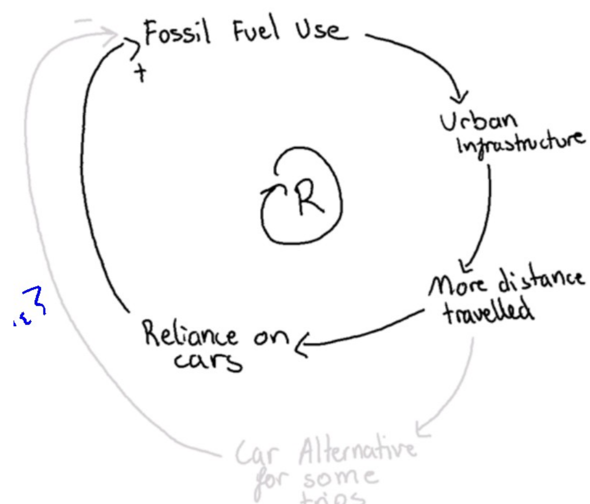

Fig. 4: An example of a system map from Autumn 2021. The map represents an understanding of the problem---options for urban transportation---but is very simple and missing a larger problem context.

In this, we can note several items of interest. Just in this excerpt, we see the team using multiple citations in their work to better back up claims. The team also shows evidence of looking more systemically at the problem of how water access, individual thriving, and government funding may interact to affect this broader issue. They have further classified this example of government funding for water access as having an unintended consequence as the symptoms are addressed, but not the underlying problem.

This change can also be seen in the system maps included in the final report documents. An example of a system map from the Autumn 2021 semester is shown in Fig. 4, and can be compared to an example from the Spring 2024 semester in Fig. 5. In earlier offerings, reports presented system maps more as a way to explain the technology's intended use. In later reports, system maps were used as a motivation for the students to explore particular domains (within their larger UNSDG context) and convey what their technology was trying to achieve. In Fig. 5, the team initially explores a broad, complex interconnected system and later on the left graph, in for the project's final iteration, present a reduced sub-map (shown on the right of Fig. 5) that focuses on the relevant information specific to the technology's sociotechnical context. This combination further supports a non-linear design process in which students probed to understand a complex problem space and then are able to effectively move what they find into the Complicated domain where a solution path is achievable.

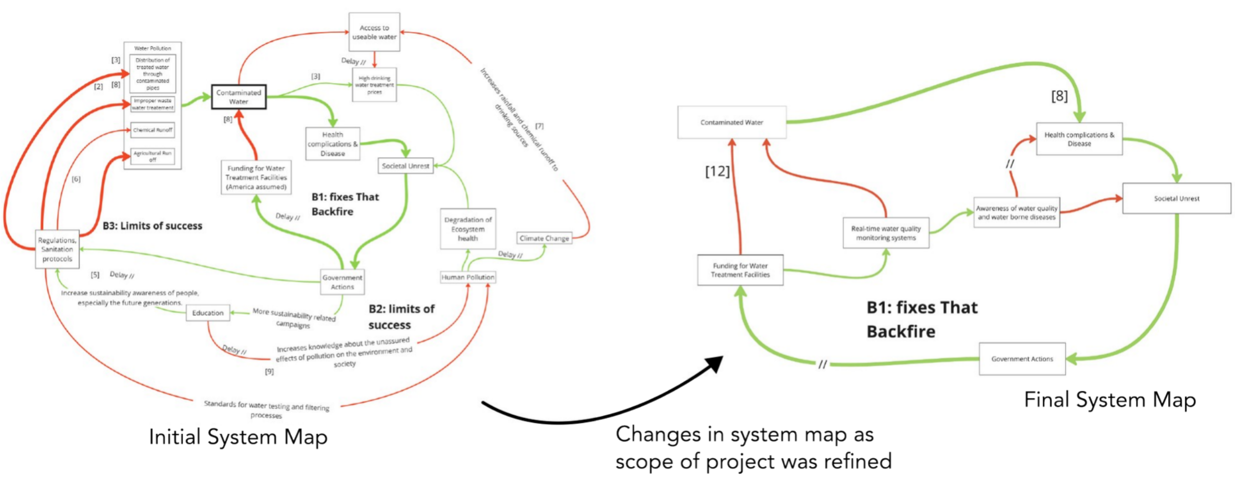

Fig. 5: An example of a system map from Spring 2024. The left map represents the team's initial understanding of the larger problem, and was refined over the course to the focus on a specific technological intervention, as shown on the right system map.

In addition to the ways in which system maps were used, the research team noted that citations both within the report and within the system maps increased over time. As mentioned earlier, a reference management software system was introduced to the class and students were required to read and annotate articles within the software. The effect of this can not only be seen in the system maps with more interconnectedness and included citations for these hypothesis, but also in the reference sections of the final reports. Reports from early offerings used very few references, whereas many reports in the last two offerings of the course used upwards of 20 references. This effect is seen in Fig. 6. Students were not required to meet a certain number of references, but instead were asked to cite their work and backup any claims they made.

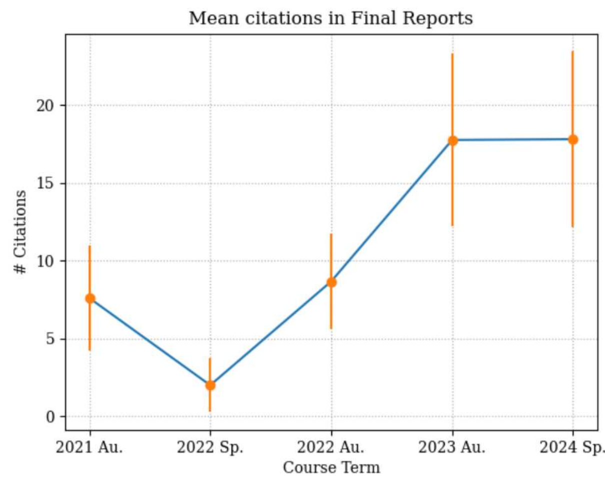

Fig. 6: Average number of citations included in the final report by course offering. Reference management software and a weekly reading requirement was introduced beginning in the 2023 Autumn semester offering.

In research team discussions of the coding, the team found that the largest changes across reports were seen in two areas. Firstly, the team found a decrease in the occurrences of codes related to both *best practices and routine solutions (i.e., working in the Clear domain)* and also e*xpert analysis and good practices (i.e., working in the Complicated domain)*. This was somewhat unexpected as it was originally hypothesized to see a decrease in discussions related to working in the Clear/Simple domain yet with a corresponding increase in the Complicated domain. However, we did observe an increase over time in codes related to *emergent solutions and probe-sense-respond (i.e., working in the Complex domain)* where students were noting how their own perception of the problem changed as they continued to learn. One clear item is that students were moving away from working solely in a domain with simple problems and solutions, to a more nuanced view where difficult problems required research acquiring knowledge from others.

The second major change was found in relation to wicked versus tame problems. An increase in occurrence of codes for noting a context specificity of the problem and/or solution, diverse perspectives related to multiple stakeholders and their goals, and systemic and unintended consequences where there are interconnected effects and solutions may generate new problems. For example, in reports from earlier offerings, problem statements centered on a somewhat general user who may fit a majority-citizen in the global north. In other words, there was very little critical analysis of who specifically was the user or beneficiary of the project. Whereas later semesters included more detail of who the system was being designed for. For example, one team in Spring 2024 describes their project as "*Beginning with a broad perspective, we gradually narrowed our focus to wastewater generated by industrial companies, with a specific emphasis on paper manufacturers discharging their wastewater into rivers.",* and then lists several reasons for choosing such a project with citations of specific examples. The students were looking for ways to address well-being of citizens living near urban areas in developed countries by helping private corporations to clean their effluent runoff, influenced by government incentives and "green tax" benefits. In these later offerings, students were including more contextualization of the project and the specific reasons for the design choices.

As an example, in a design report from the 2021 semester, one team noted that: "*[W]e have decided that students and teachers would be our target audience. [...] we have shifted our project slightly towards raising public awareness by educational means [... and] thus we decided to primarily focus on using technology to educate students who will become policymakers, advocates, and even engineers. By spreading awareness to the youth, we have a higher chance of influencing change rather than creating a technology that will make the change itself."* Although this report included some specific items about the educational context, it served more as a motivation to make something with the report's focus on the technological implementation. The team was not clear on the education range, location, or ages their project was targeting beyond the teacher and student description.

Similarly, a difference in discussions of interconnectedness was seen. A team in 2022 discussed their analysis from interviews as "*Thinking about what we learned from the interviews, we realized that our hypothesis was basically correct. However, there are lots of intricacies and dimensions to the problem that we did not understand. There are certainly measures in place that are basically trying to accomplish our goal but they are not working as intended."* In contrast, a team in 2024 said "*Collaborative efforts among policymakers, urban planners, and community stakeholders are extremely crucial for developing resilient water and sanitation systems that cater to the needs of jumping urban populations. Recognizing the critical connection between infrastructure development, population dynamics, and water clarity is essential for being able to find effective solutions that ensure equitable access to clean water and sanitation services for all urban residents, as technology is just an extension of the necessities of the communities. Because of the complexity of the issue and the dependencies on various parties, we have concluded that by engaging with community stakeholders, local companies, and experts, we can work towards sustainable solutions specifically drafted for local contexts, addressing the challenges of water availability, water quality, and water delivery in urban environments.*" Team reports moved to a discussion of the broader issues surrounding problem students were researching.

Discussion and Limitations

As we have noted, the team noted increased sociotechnical awareness. Teams moved from finding a context that met their desired technological application as was the case in the first two course offerings, to more evidence of the sociotechnical context driving the decision making. For example, one student from Fall 2023 noted in a reflection that early in the project "[w]*e focused* *on small interactions like transporting water in pipes and how that can lead to pollution, rather than telling a story of how people are being affected by this issue. We were missing the bigger picture. To get around this issue I suggested that for the second iteration of our system map that we start with a basic loop of how humans take water, consume it, and then re-enters the water supply and then from there we would be able to add loops to this to about how people are affected.*" This represents a shift many students seemed to encounter. A shift from beginning with a technology and finding reasons to pursue it, to working to understand a problem and then seeking a technological intervention that can affect the system. Although subtle, this change is often difficult for engineers. The structures of an undergraduate education with a focus problems from the engineering sciences, students typically do not get to practice working in such ambiguity and developing an engineering agency.

This struggle was evident in some students. We originally expected to see more struggle and lack of engagement as the course changed, thinking students would push back more against problem exploration. However no significant change was found in coding the artefacts. Most students were eager to explore and learn more about the selected problem, and mostly expressing a lack of engagement as non-course activities such as exams became busier, or technical issues near the end of the semester made it seem like teams would have difficulty completing their demonstration.

However some students did express a disinterest in the course structures. After system maps and a weekly research article requirement were added to the course in 2023, in the early weeks of a semester one student stated: "*for this assignment I was having trouble seeing the direct applicability. Even when it was explained to me.* ***I feel like in a real job we're most likely to be given a problem and the requirements for solving it****. I feel like framing the problem as a story only obscures the real details I would want to work with by adding a layer of unnecessary abstraction.* ***For a lot of my engineering education, I was taught how to read details in as least abstract a form as possible so as to effectively use them.*** *However, when something gets framed as a story I feel like there's so much potential to miss details. [emphasis added]*" For some students, the agency of discovering and choosing which problem to solve was a de-motivator as they saw their role as an engineer to do the job presented to them with little question. Exploring a large problem and understanding the interconnectedness was seen as having little value and a waste of time.

However, at the end of the semester after reflecting on the overall course, this same student said: "*It's hard to qualify what I have learned in this course. Ultimately the general concepts are far more theoretical than in other courses I have taken for my major. For instance, in [earlier course] our first real design course, the topics were very grounded. This is how you test your device. This is how you read a datasheet. This is how you use a laser cutter. However, I can't really say that I learned how to do any one thing thing from this course. Rather, I gained a larger appreciation for the entire process and philosophy of design. […]* ***Before this, I saw the***

engineer as someone who simply takes in problems, creates a solution and spits it out. *But there is so much more to the process.* ***An engineer might have to consider far more factors that go well beyond their current knowledge. They might even have to reconsider the problem as a whole. Whether the identified problem is really the cause or perhaps a solution to this problem is only fixing a minor symptom of something far greater.*** *[emphasis added]*"

While this example is more on the extreme end, it illustrates the general engagement of students and general attitudes of many engineering students. Engineers are prone to see themselves a "problem-solvers" or as coming to help. If engineers are always provided a problem to solve and specifications to meet, it would follow that their work must always be value-neutral---simply providing a helpful solution. As Lucena notes, this attitude can be dangerous when approaching development projects and is important to keep in check (Lucena, Schneider, and Leydens 2010). It is important to remain critical, and work to ensure that all voices are heard.

As this student's excerpts demonstrate, many engineering attitudes and mindsets ignore such voices. Engineering agency and sociotechnical awareness are skills that must be enacted, but require structural support to open up this opportunity. In thinking about student development in these terms, the capabilities approach provides a useful lens to view these course changes. As Cech notes, though students may enter into engineering program with a variety of goals, public welfare considerations are often defined out of engineering mindsets (Cech 2014). The structural influence of existing engineering education practice is barrier for students to develop they capabilities they may desire. The power dynamics of the professor-student relationship are such that the teacher may, within their course or curriculum, restrict broad capability development of students by denying or limiting the opportunities for action. Institutions or accreditation agencies may also require demonstration of meeting certain educational outcomes, but these outcomes may not align with a students individual functionings they desire. There is a tension then between a student exercising their agency in developing capabilities and choosing which to enact into functionings, and the requirements and outcomes required of a degree program. In this course, students are still required to participate in order to finish the program and obtain their degree. They are free to engage in the manner they wish, but are not free from choosing to ignore the course.

The changes to the design course in this paper, do offer some changes to this model. Students are provided some agency in choosing the UNSDG the class desires to study, and are able to work within this issue to learn and discover an area of interest. This creates a path where students are offered opportunities for action by the overall course structure, directed attention through specific assignments and feedback from the course instructors that allows for student capability development. Most topics in the engineering sciences are taught in a way that restricts agency and choice of problems to study, but offering this agency may be one reason that we did not see an increase in student lack of engagement as this course progressed. As students developed their own understanding of the problem space as represented by their systems maps, they may have become increasingly aware of the many opportunities for technology to have a positive impact on the world. This may, in turn, open new opportunities for future development, but is out of the scope of this study.

In terms of limitations, this study is only a small step in understanding the larger changes. As the team could not reach a strong coding consensus, the conclusions should be taken lightly. The dataset is rich, and future work will need to further refine the codebook over more iterations. Much like the students described in this paper, the problem itself of understanding the changes taking place is still ongoing. This work is part of ongoing departmental efforts seeking to actualize the capabilities approach for an engineering program and the ramifications are only beginning to be studied. Nevertheless, many differences in student's discussing engineering work were noted. The systemic nature of problems and a need for the contextual understanding to drive the technical choices were noted. The need for engineers to continually question their motivation was brought up within the course as more time was allowed for system maps. Often students would presume a need or desire for a change, leading to discussions of potential techno-colonialism in which technology may be created or deployed without actually considering or listening to the voices of those it may affect. Although in the course students were often striving to address global issues, the course structures made it difficult to gain community engagement beyond a local context. Research articles were used where available with professors asking students to consider potential issues with the selected sources.

Conclusion

This paper has provided an initial study of changes to an engineering design course that have taken place over several years. These course changes were intended to allow students opportunities to develop their sociotechnical awareness, and use this understanding of a larger problem to develop a technology that may address a part of this issue. As the creators of technology, the engineering profession is powerfully situated to affect the lives and modes of interaction of society. Yet it is often the case of many engineers to ignore the social aspects, and instead focus on the purely technical aspects ceding the engineers' agency in problem choice to corporate or state interests. It is necessary for engineers to recognize their agency and enacted values in choosing what to design. While developing this capability is difficult and requires structural change within a program, the study in this paper has shown examples of this being enacted. While it is not complete and requires both further study to better understand the impact of the changes changes, as well as continued change and partnerships, students are beginning to develop a broader capability set.

In seeking to provide students opportunities to develop along paths they desire and better connect their engineering work their ideals or other efforts, it perhaps is best to close with this quote. In looking at whether the course changes had an impact, at least for the student quoted below the answer is an emphatic: yes. In an end of year reflection portfolio, one student said: "*Moreover, I've thoroughly enjoyed the steps in the engineering design process, and I feel that I lean more towards the creative and iterative process of ideating, brainstorming, and researching the needs and problems of others to solve a problem, as opposed to the the more technical practices of engineering sciences. Being able to create a product that addresses issues has resulted in feelings of accomplishment and altruism. I have also enjoyed the human connection that engineering design process provides as I was working in groups, getting feedback from peers and professors, interviewing experts, and reading stories of people in need. So, I would be interested in pursuing careers and projects that have a more social aspect*."

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Appendix

Codebook

Themes related to wicked problems

W-a1; Ambiguity and Evolution: The problem's nature is ambiguous (alack of agreement on what problem is) and evolves over time.

W-a2; Context-Specificity: Each problem's definition and solution are context-specific.

W-b1; Diverse Perspectives and Conflict: Multiple stakeholders with differing perspectives and potential conflicts and goals.

W-c1; Relative and Iterative Assessment: Solutions are evaluated as "better" or "worse" (as opposed to right/wrong) and require iterative improvement.

W-c2; Resource and Political Constraints: Solutions are constrained by resources and political influences.

W-d1; Systemic and Unintended Effects: Recognition that solutions have widespread, interconnected effects and may generate new problems

W-e1; Adaptive Management and Learning: Solutions require adaptive management and continuous learning.

Themes related to Cynefin framework

Cy-1; Best Practices and Routine Solutions (Clear): Use of established, standardized solutions.

Cy-2; Expert Analysis and Good Practices (Complicated): Reliance on expert analysis and multiple valid solutions.

Cy-3; Emergent Solutions and Probe-Sense-Respond (Complex): Solutions emerge through probing, sensing, and responding, emphasizing learning and adaptation.

Cy-4; Immediate Action and Stabilization (Chaotic): Urgent actions to stabilize and control the situation, often requiring novel approaches.

Domain Transition and Contextual Sensitivity:

Dt-1; Identifying Domain Shifts: Recognizing when a problem transitions between Cynefin domains.

Dt-2; Contextual Adaptation: Adapting strategies based on the problem's current domain.

Dt-3; Hybrid Approaches: Combining methods from different domains for comprehensive problem-solving

Student attitude and engagement

Eg-1; Refusal to Engage with the Problem: Instances where students avoid tackling the problem due to its complexity or ambiguity.

Eg-2; Refusal to Engage with the Process: Instances where students avoid the problem-solving process, preferring simpler or clearer tasks.