Student and Practitioner Approaches to Systems Thinking: Integrating Technical and Contextual Considerations

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Systems thinking is recognized as a critical skill for engineers tasked with addressing complex problems in contemporary society [1] – [3]. Often, engineering definitions of systems thinking foreground the ability to account for relationships between different technical components of a product or process. However, these definitions frequently underemphasize how technical elements of a solution influence and are influenced by contextual and human aspects of a problem, such as the cultural, political, and economic context, required to successfully address a problem [4] – [6]. While there has been national attention [7], [8] to the importance of these contextual skills in engineering, these aspects of engineering work have not often been conceptualized as elements of systems thinking. Thus, few empirical studies of systems thinking have included the ways engineers account for contextual influences in solving complex problems (for one exception, see Grohs [9]). Our team seeks to characterize and eventually develop an assessment for what we refer to as comprehensive systems thinking— a holistic approach to problem-solving in which linkages and interactions of the immediate work with constituent parts, the larger sociocultural context, and potential impacts over time are identified and incorporated into decision making. Promoting comprehensive systems thinking that draws on both technical and contextual competencies can serve to ensure engineering solutions better meet the needs of stakeholders and of communities in which the solutions are implemented. In addition, emphasizing the value of contextual and social aspects of systems thinking as a core engineering skill may help to broaden participation in engineering, as research suggests socially-grounded engineering work attracts a more diverse pool of engineers [10], [11].

Our team's current work details our methods and analysis and presents some preliminary results related to how engineers approach systems thinking in real engineering problems. We present four cases from our data that illustrate what it means for engineers to consider, or not consider, technical and contextual aspects of a system when addressing a systems thinking problem. These illustrative cases are drawn from the 46 interviews we conducted with engineers from a range of engineering fields and levels of educational and professional experience, from undergraduate freshmen to professional engineers with 20+ years in industry. Participants were interviewed about their personal experiences solving a particular complex problem in their field and the ways their educational, professional, and life experiences contribute to their thinking. In this paper, we draw on these four cases to highlight the ways undergraduate students and professional engineers account (or do not account) for technical and social/contextual aspects of engineering problem solving in their work and how they attend to different aspects of comprehensive systems thinking in their processes.

Background

Informed by a synthesis of the literature, we begin with a definition of systems thinking as a holistic approach to problem solving in which linkages and interactions of the immediate work with constituent parts, the larger sociocultural context, and potential impacts over time are identified and incorporated into decision making [1] – [3]. Scholars have cited the growing complexity of technological systems and a number of global, often interdisciplinary, problems that necessitate systems thinking both at the immediate technical and broader social levels [12], [13]. Grotzer [13] described often-disastrous consequences when complex system dynamics were ignored by individuals addressing a problem, including the introduction of disease-spreading invasive species to fight pests or the Chernobyl nuclear plant disaster. In a complex world, she argued, we must do a better job of understanding and preparing students to recognize and understand the complex causality that undergirds such system dynamics.

Though our working definition of systems thinking emphasizes both the proximal problem context and larger social context, these elements have not been emphasized equally in the most prominent definitions of systems thinking in engineering. Perhaps the most prominent definition used in studies of systems thinking in engineering focuses on relationships between the more proximal or internal elements of a solution, as opposed relationships between one's work and broader social and cultural factors. These studies commonly cited Senge's [5] definition of systems thinking as "a discipline for seeing wholes… a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static 'snapshots'" [6], [12], [14]. Focus on the engineering system is, of course, critical, but it is not sufficient. For example, Frank and Elata [4], prominent scholars on engineering systems thinking, defined an engineering system as an integrated collection of components and described systems thinking as the optimal integration of various subcomponents into the whole. Accordingly, Frank and Israel's [12] 30 engineering systems "laws" emphasized relationships between multiple systems components, different means of thinking about and assessing each subcomponent, how changes in one area may affect other areas, the possibility for multiple solutions, considering the future impact of a solution, the importance of expertise from multiple disciplines. In addition, they describe a number of technical logistical considerations, including software needs, shelf life of components, and contract negotiations.

While definitions of systems thinking in engineering often underemphasize the larger context in which problems are situated, researchers have identified contextual competence as an important skill for engineering work. The program accreditation criteria from the Accreditation Board of Engineering and Technology (ABET) include several student outcomes related to contextual competence: "c) An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability; f) An understanding of professional and ethical responsibility; h) The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context; j) A knowledge of contemporary issues" [15]. Several recent studies explored contextual competence in engineering—"the constraints and impacts of social, cultural, environmental, political, and other contexts on engineering solutions" [7], [8]—but did not explicitly link contextual competence to systems perspectives. These authors argued that engineering solutions need to be technically sound, but also feasible and desirable given a consideration of the contextual constraints of the problem. They thus advocated for a consideration of the local, national, and global environments and how the needs or constraints of each level may relate to one another, proposing two sets of contextual constraints: "1) a potential design solution's scope (local, national, and global), and 2) the potential constraints to which the solution may require attention (historical, social, economic, environmental, political, cultural, and ethical)" (p. 2). Their research resulted in a validated measure of contextual competence to assess student learning at the program level [8] but that is less appropriate for assessing individual growth and is not sufficient for assessing the larger construct of systems thinking ability.

In contrast to how systems thinking is often conceptualized in engineering, Grohs [9] identified it as a metacognitive strategy and also emphasized social and temporal dimensions of systems thinking. Drawing on Jonassen's [16] definition of "wicked problems," he argued systems thinking fluency is characterized by an understanding of a problem, social and temporal dimensions of that problem, as well as the interaction between each of these dimensions. In addition to Grohs' conceptualization of systems thinking, a more comprehensive perspective on systems thinking is espoused in several non-engineering fields. Hogan and Weathers [17] defined systems thinking as comprised by "skills that allow a person to analyze open systems (i.e., those that exchange matter and energy with a surrounding environment) by recognizing how multiple factors interact, and by seeing and predicting patterns of change over time" (p. 234). A stated goal of their research is to help students see whole systems as comprised of component parts that relate to one another and to the larger system. They further argued that systems thinking involves a number of cognitive and interpersonal attributes as well as an awareness of contextual constraints and opportunities. The different dimensions of systems thinking, and the interplay of these dimensions, are represented in their ecological model that includes a cognitive dimension within an interpersonal dimension, within a broader societal/cultural dimension.

Our team's larger study builds upon the work of these researchers who have characterized different elements of systems thinking. We represent our working definition of systems thinking in Figure 1, where the "component" is in the center, which represents a potential solution or solutions to the engineering problem being explored. The expanding circles represent the contexts that can and should be considered in making decisions about the solution(s) and their appropriateness. Many times this component is part of a larger system, thus other pieces or components within the system both must be considered and can have an impact on the success of the solution. This larger system exists within another existing structure, such as infrastructure of the environment or regulations in a particular field of work. Stakeholders include users as well as others that have influenced or will be influenced by the problem and solution developed. These aspects all exist within a larger sociocultural and environmental context as well as within a timeline of what has been done before and the expected future.

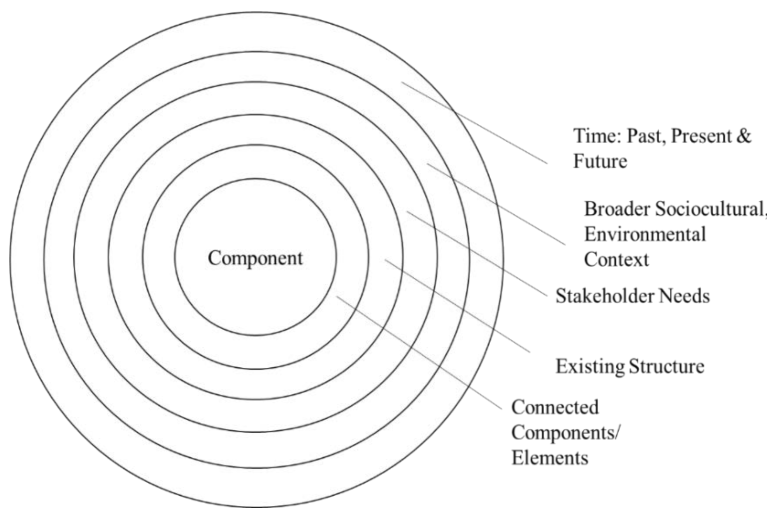

Figure 1: Elements of Systems Thinking

Research Methods

Study Goals. The goal of the present study is to begin to understand how engineering students and practitioners account for various aspects of systems thinking when solving a real-world complex problem. For the purposes of this initial analysis, we simplify our categorization of different aspects of systems thinking into internal, proximal aspects of a system, such as technical considerations and the interrelationships between different components of a product, and contextual aspects, such as the larger, social, political, economic, and temporal context in which an engineering problem is embedded. What does it look like for an engineer to consider both proximal/internal aspects and broader contextual aspects of systems thinking? What does it look like when an engineer does not account for one or both of these broad aspects of systems thinking in a problem? Drawing on four cases from our larger pool of interviews with 46 engineering students and practitioners of different levels, we present an initial exploration into what distinguishes these different foci when solving complex engineering problems.

Participants and Data Collection. Data presented in the current paper are drawn from our team's larger study, which includes interviews with 46 engineering students and practitioners about their lived experiences solving complex systems thinking. Participants for these interviews were recruited on the basis of several selection criteria, which we collected in a brief screening questionnaire. All participants were asked to identify an experience they had working on a complex project, defined broadly as any project that had multiple potential solutions and for which there were multiple people with different forms of expertise working on multiple facets or components of the project. To ensure a diverse sample in terms of personal and academic/professional background, we were also mindful of a number of diversity criteria in our recruitment and selection of participants, including in participants' level and type of engineering experience, field of engineering, and sociodemographic traits such as race, ethnicity, and gender. Students were recruited from two universities – one a selective public research university and another regional public university. Professional engineers were recruited locally from a variety of industries. Interviews were conducted in person and lasted approximately 60 to 90 minutes by one member of our research team. Interviews were audio recorded and transcribed for analysis.

Interview Content. Our semi-structured interview protocol included questions about participants' academic and professional history and reasons for pursuing engineering study and/or work. The primary focus of the interview related to participants' lived experiences solving a complex engineering problem in their educational or professional experiences. Participants were asked to describe the problem in detail, how work on the project was organized, steps taken to solve the problem, the major factors (i.e., requirements, constraints, inputs) considered, and any conflicts or tradeoffs that were a part of the process. The protocol also included questions about the skills and knowledge participants felt were important in solving a complex problem, as well as their understanding of what it means to have a systems perspective, both personally and how they perceived it to be defined in their field, company, and/or educational context. Focusing on participants' lived experiences likely facilitated deep reflection, rich detail, and greater accuracy, in contrast to general questions about systems thinking which may only yield vague or superficial responses that may not reflect participants' experiences in practice [18], [19].

Data Analysis. Two trained coders initially coded interviews based on a codebook developed inductively by the study team. This coding scheme was primarily descriptive, flagging participants' responses to different study questions, aspects of participants' professional and academic experiences, and the problem elements or factors that they discussed in relation to solving a complex problem. For the present paper, our analysis focused mainly on questions relating to participants' experiences solving a problem, paying particular attention to the various internal/technical and contextual aspects of the problem that they described attending to in their work. We also examined participants' responses about their personal conceptualization of systems thinking. One research team member conducted a holistic review of participants' responses to these questions and the factors discussed in each participants' description of their problem solving experience. Based on this analysis, we identified four cases that highlight instances in which participants do and do not foreground internal and/or contextual aspects of systems thinking. It is important to note that the aspects of systems thinking discussed by participants are tied to a particular engineering problem context and may or may not reflect their personal predisposition to consider these aspects. Additionally, at this time, we are not presenting an assessment of participants' demonstrated skill or expertise in these areas of systems thinking, though it is a later goal of our team's study to develop such an assessment.

Findings

This section presents four cases of how students and practitioners account for internal and contextual factors in the solution of a complex problem. In the initial analysis presented in this paper, participants' attention to the various aspects of systems thinking outlined in our working definition were categorized into internal, proximal aspects of a system, such as technical considerations and the interrelationships between different components of a product, and contextual aspects, such as stakeholder needs and the larger, social, political, economic, and temporal context in which an engineering problem is embedded. We present four cases that highlight what it looks like when engineers do or do not foreground internal and/or contextual aspects of systems thinking. Sabrina's case highlights an instance of an engineering student who does not emphasize either aspect, Preston's an emphasis on internal but not contextual aspects of systems thinking, Gail's case an emphasis on contextual but not internal aspects, and Jaquelyn's an instance of an engineering professional who considered both internal and contextual aspects in the problem she was working on. The table below presents an overview of these four cases. All names listed are pseudonyms.

Table 1: Summary of Systems Thinking Emphases in Example Cases

	Internal Systems thinking	Contextual Systems Thinking
Sabrina	✖	✖
Preston	✔	✖
Gail	✖	✔
Jacquelyn	✔	✔

Little attention to Internal or Contextual Aspects of Systems Thinking. Some participants in our study showed little or no awareness of how the internal elements of their project related to each other nor how to consider contextual factors into their solutions. The responses of Sabrina highlight an instance in which an engineering student did not describe taking a systems thinking approach in the particular project she discussed in our interview. Sabrina explained the way she and her group approached their first-year engineering project in which they were tasked with developing a video game for an individual with a visual impairment. Sabrina's answers illustrate someone who focused on the project constraints given by the professor and did not show systems awareness when asked how she would have done things differently.

When asked about the factors she and her group considered for the solution of their project and why those were important, she answered:

> The first one I listed was, that we had to make the game audio based. And that was kind of because the client that we were catering in our project towards. That was the main thing that we had to keep in mind while designing it.
>
> The second one was that we had to use [specific program], and that was just a constraint. That was like part of the class, because that's what they had asked us to do.
>
> Third, I mentioned client feedback. Because since it was for her, we had to ... We even took into consideration her likes and dislikes, and what she wanted to see in the game.

In her response Sabrina explained that the essential factors she considered were those constraints provided by her professor. Additionally, she mentioned other factors that influenced the final solutions such as time constraints and additional technical elements. She did not go deeper into explaining how she and her group built the final project or her thinking about factors beyond the constraints given by the professor of the class. When prompted about other factors she may have considered in her solving-problem process, such as economic aspects, cultural political aspects, stakeholder needs, previous work in the area, environmental input, or future uses of design, Sabrina explained:

> I think for a lot of the ones you mentioned, it didn't particularly apply to this project because it was a very contained project, in a sense like we were mainly just worried about the technical aspect.

This answer may reflect both the nature of the course project as well as Sabrina's thinking. While she had previously named accounting for client needs as a criterion given by her instructor, she did not elaborate on this as an aspect of stakeholder needs or how their client's experiences might be situated in a larger context. When asked if she would have done things differently to solve the problem, Sabrina answered, "I don't think so. I think we all met the goals that we had."

Sabrina's responses may reflect a lack of exposure to systems thinking at this early stage in her engineering training. When asked about if she knew what systems thinking is and whether she had a system thinking approach to problem-solving, she explained that she had never heard the term.

Attention to Internal Factors and Little Attention to Contextual Factors. Other participants in our study described attending to interrelationships between technical elements of a complex problem but did not highlighted how these might influence or be influenced by contextual factors. In other words, some participants showed an internal approach to systems thinking during the interview but did not account for contextual factors that could influence their problem-solving process. Preston's response highlights such an instance.

Preston described how he and his team worked on a first-year engineering project related to the design of a miniature aircraft. Similar to Sabrina, the main factors Preston highlighted were the given constraints of the assignment. However, Preston showed more awareness in how these technical factors were related to each other or were influencing the design of their solutions.

When asked about the factors his team considered, Preston listed all the constraints given by the professor, primarily related to technical specifications. For example, he explained:

> Weight was we had to be under 1kg. […] but that was quite easy to be under given under constraints at least. Number of thrusters. I think we're only allowed three thrusters and they had to be specific motor types that were supplied. Propeller length. I think different propeller lengths would give different thrusts. Possibly even on different power, I'm not sure.
>
> The number of batteries, I think we're allowed to have one or two battery packs. Certainly, we're limited to only what we were given. The envelope material and we had to use helium and the balsa or basswood and other materials we needed to use.
>
> The presence of a microcontroller. It's like a transmitter, a receiver that send signals. It could either have sent signals directly to the servos and thrusters or sent signals to the microcontroller that would process it and send that out to the thrusters and servos. The good part about the microcontroller is without it, you're limited on your controls and it could be a little hard to figure out.
>
> Whereas the microcontroller, you could configure whatever controls you wanted, but it required extra work. Envelope shape would help with aerodynamics, both speed and also turning, because there's one that was super long and super fast, but super slow to turn around in like previous year.

As seen in the second and third excerpts, Preston explained how the presence of a microcontroller was related to different ways of sending signals. Additionally, he emphasized that "you could configure whatever controls you wanted," showing awareness of how technical elements of a problem influenced the final solution of the problem. Preston gave additional details of his team's final solution and how different technical factors related to each other in their problem-solving process.

Although Preston was attentive to these internal interrelationships, Preston showed little awareness of contextual systems thinking or how contextual factors related to their problem. When prompted about contextual factors, Preston struggled to answer the question and kept focusing on the technical factors and constraints he already had explained. Additionally, he mentioned that some of the contextual factors prompted by the researcher were not relevant to his team's project, which again could in part reflect the course-based nature of his assignment.

However, when asked about the conditions under which his solution might have looked different, Preston kept focusing on technical specifications of the problem and did not mention any contextual factors that influenced or could have influenced his team's design. Finally, when asked about his perception about systems thinking, Preston answered:

> I guess I think to be able to know how each of the different components fit together and how the different factors affect each other. To be able to... I guess in my mind, how organization is different, like indistinct individual groups. Then how to connect those groups into what needs to be done, because not everything needs to go out, so it's more efficient to have smaller groups, but there needs to be some figuring out how that communication and stuff has to happen.

Based on this answer, we could infer that Preston has an awareness of internal systems thinking. Preston's response highlights an awareness of how a problem has different components and that these components fit together to define a solution. However, Preston did not mention how the problem is embedded in an immediate or larger context, which could also influence an engineer's decision-making towards a solution.

Little Attention to Internal Factors and Attention to Contextual Factors. As mentioned previously, some participants in the study expressed awareness of the context in which their complex problem was embedded, and that such a consideration can be key in developing successful engineering solutions. However, in Gail's case, she did not highlight the ways these contextual factors related to or could be translated into the technical elements of the problem nor any interrelationships between these proximal factors.

In her interview, Gail expressed a particular interest in social issues, explaining that she sees engineering as a platform to contribute to social good. Gail declared that, although she had the technical knowledge of being an engineer, her work within her engineering project team tended to more social than technical. Furthermore, she explained that the importance of her role in the project had to do with thinking about the context, and claimed that when the context is not involved, solutions for a complex problem would not work. The following is an example of the degree of importance Gail put on the social or contextual elements of her project, which involved designing products to improve the domestic lives of women in a developing country:

> And so that is something I'm honestly very proud about our project is that we spend so much time thinking about the cultural ramifications and for these women, so much of their identity in their entire life they've been cooking one way. So how do you come up with a way to tell them, no, that's not the right way and do it this way? Because a lot of the time what happens with technology is it

> just never gets used. […] I don't think anything would ever function or work if you don't think about the context of where it's going, and you have to think from different perspectives.

When asked about the factors that she and her team considered when working on the project, Gail mentioned available resources, the impact on the environment, interpersonal team dynamics, and the cultural and social context in which the solutions were being deployed. However, she did not mention any technical specifications or how her team developed or constructed the technical solutions for the project. Even though Gail demonstrated insight into the importance of considering contextual aspects of engineering problems, she did not highlight how, in her project, those contextual factors influenced the technical decisions her team made to solve the problem. When the interviewer asked about how she would have approached the project differently, she talked again about team dynamics and how they functioned for this particular project.

When asked her definition of a systems perspective, Gail answered:

> I think I said, well that's funny because that's what I study, but the systems perspective to me is seeing. It's like a macro vision. It's zooming out and being able to see all of the inputs and outputs of a system and all the ways that they flow and all the different processes and how especially how everything comes together because a system is the connection of all these different isolated things, and so being able to understand how individual aspects of the system are connected and some are going to be disconnected and then the different ways that connect them all and yeah, that's to me systems.

In her answer, is possible to see how Gail foregrounds contextual aspects of systems thinking more so than internal/proximal relationships. Furthermore, she expressed a preference for engaging with macro-level considerations, rather than technical details, explaining:

> I could never just build a robot. I don't ever get zoomed in enough on something where I'm extremely technically trained in one thing. I'm really good with steel. I'm not like that. And so I think I'm very much a systems person. I like to know a little bit about everything and I've always felt that way about the world in general

Comprehensive Systems Thinking. Finally, some engineers' cases highlighted an inclination for comprehensive systems thinking, as we define it, within the context of the engineering problem they described in our interview. In other words, participants in this category explained how the technical elements of their problem related to each other and how these in turn related to immediate and broader context in considering solutions to their problem. Jacquelyn was an experienced engineer coming from a military background who described her work on an assignment related to identifying an appropriate contractor for a particular IT project. Jacquelyn provided detailed answers and demonstrated systems perspective awareness not only when the researcher prompted for factors that influenced the design of the solution, but also when providing an initial overview of the project. Specifically, Jacquelyn explained how the problem was constrained by the immediate context. The following is an example of her systems approach when Jacquelyn was describing the project:

> I would probably go back to the time that I did the IT source selection for my unit that I was in. It was a $[large dollar among] contract; we were trying to award over 10 years. I think of it in terms of an engineering project because, it was obviously, it's an IT context, but that not alone doesn't make it engineering, but we had to engineer a solution, which was really complex, and had a lot of moving parts, and a lot of different people involved.
>
> We did the source selection at a classified level, but we were also, working with our internal partners to figure out what our requirements were. We basically assembled a team .... Oh, I should back up by saying, so, because it's a government contract, there's, you can imagine like a ton of oversight and a lot of rules. In this sort of engineering of a solution, we also have all these constraints, and boundaries, and rules that we have to apply, that we were lucky enough to have a really good contracting officer, that marched us through that process. Just had a really good experience that could guide us through. And then he also had great relationships with the people that were approving our process.

When asked about the major factors Jacquelyn and her team considered in the problem-solving process, she described factors related to technical elements, stakeholder needs, the immediate context in which the solution would be deployed, the timeline of the project, and the available workforce. Additionally, when prompted about various factors that engineers often consider when solving a problem, Jacquelyn also cited tensions related to cultural norms about how decisions must be communicated with existing contractors, security considerations, and competing stakeholder interests that shaped the selection process. She described the latter, explaining:

> In addition to the cultural component, I think we had a lot of stakeholder needs, lots and lots of stakeholder needs that ... Everyone had somebody, that was their favorite person. They wanted to make sure that they couldn't leave on that contract

When asked about what her definition of a systems perspective is, Jacquelyn expressed an awareness of the ways problem elements related with one another, consistent with her project description, stating:

> It's basically this idea of problem definition and development, and you roll into the course of action, sort of analysis, value modeling, and then choosing those models and implementing them. It's a regular problem solving process, and there's different components, to each part of it. I'm not going to bore you with the details. But I think the systems component that was integrated into this problem, was this idea of value modeling. So what is our primary objective? What are we trying to get to? What are those three or four things under that hierarchy we imagine like a wire diagram? And what are the metrics that support all of those? And so

> deconstructing and critically analyzing it that way, I think that is certainly how I approach a system's problem.

Jacquelyn's case highlights how an engineer may approach comprehensive systems thinking, considering interrelationships between more proximal technical aspects of a problem as well as the ways these relate to the context in which the project is situated.

Discussion and Next Steps

Often, discussions of systems thinking within engineering foreground engineers' ability to account for complex relationships between technical components of a given problem. Integrating systems thinking literature from engineering and other disciplines, we seek to define and better characterize a more comprehensive systems thinking that includes both these technical interrelationships as well as relationships with relevant contextual considerations, including stakeholder perspectives, economic constraints, temporal considerations, and the immediate and broader social context in which an engineering solution may be deployed. Drawing on a small subset of cases from our team's larger study in which we interviewed engineering students and professionals about their experiences solving problems that may require systems thinking, we provide real-world examples of engineers who did and did not consider both of these broad dimensions of comprehensive systems thinking in a given problem. As the examples we highlighted were grounded in both educational and professional engineering contexts in which a consideration of both dimensions of systems thinking may or may not always be relevant or feasible, we provide these cases for illustrative, not evaluative purposes. However, we suggest that broadly, as calls for the development of systems thinking skills grow within engineering, it is important that engineers be trained to account for interrelationships between both technical and contextual aspects of an engineering problem. This is essential for two reasons: 1) because neglecting a consideration of either technical and/or contextual aspects of a solution risks being it being of little use or even potentially harmful to their intended beneficiaries [13], and 2) highlighting the value of contextual and social aspects of systems thinking as a core engineering skill may help to broaden participation in engineering, as research suggests socially-grounded engineering work attracts a more diverse pool of engineers [10], [11]. The present work represents a first step toward developing and testing an inductively-derived assessment of comprehensive systems thinking, which will also draw on literature and data from a common scenario-based problem solving interview. In addition, our team is exploring the types of educational and professional experiences that might facilitate engineers' consideration of both technical and contextual aspects of systems thinking in their work.

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