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Divergent thinking in engineering: Diverse exploration is key to successful project outcomes

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Abstract

Engineers have the power to drive innovation and rethink the way the world is designed. However, a key practice often absent from engineering education is facilitating innovation and considering diverse perspectives through divergent thinking. We define *divergence* in engineering practices as exploring multiple alternatives in any stage of engineering processes. Currently, engineering education and research focuses on divergence primarily in the generation and development of design solutions, supported by idea generation methods such as Brainstorming and Design Heuristics. But in practice, there are many other opportunities throughout an engineering project where engineers may find it useful to explore multiple alternatives. When does divergent thinking take place during engineering problem solving as it is currently practiced? We conducted 90-minute semi-structured interviews with mechanical engineering practitioners working in varied setting to elicit their experiences with divergent thinking taking place in their engineering projects. The initial results document divergent thinking in six different areas of engineering design processes: 1) problem understanding, 2) problem-solving methods and strategies, 3) research and information gathering, 4) stakeholder identification, 5) considering potential solutions, and 6) anticipating implications of decisions. These findings suggest engineers find divergent thinking useful in multiple areas of engineering practice, and we suggest goals for developing divergent thinking skills in engineering education.

Background

Divergent thinking is an important tool in solving complex challenges to explore multiple options, alternatives, and perspectives. For engineers, practicing divergent thinking is especially important in order to approach complex problems creatively and to develop innovative solutions [1], [2]. Engineers often struggle with divergent thinking, restricting their approach to a single perspective or to methods that already exist [3]–[5]. Inclusive design processes, on the other hand, require learning from diversity and exploring many perspectives [6], [7]. Supporting divergent thinking, therefore, has the potential to support efforts for more inclusive and equitable engineering outcomes.

Research has focused primarily on the divergence in the generation of design ideas (i.e. [8]). Divergent thinking methods used in engineering education and practice are also primarily focused on idea generation, such as Design Heuristics [9], Brainstorming [10], TRIZ [11], and Morphological Analysis [12], and SCAMPER [13]. These idea generation strategies help engineers to push beyond their initial ideas to explore many varied potential solutions. Design Heuristics, for example, are a set of 77 evidence-based strategies that help engineers generate more diverse [14], elaborate [15], and unusual ideas [16]; Morphological Analysis is a method of combining many alternative means of achieving the necessary functions of a product [12]; and SCAMPER (Substitute, Combine, Adapt, Modify, Put to other uses, Eliminate, and Reverse) are general strategies to transform existing ideas [13].

However, divergent thinking can take place across many stages of engineering problem solving; idea generation and solution development in design is not the only potential arena in which engineers could explore multiple options and perspectives. Divergent thinking may be leveraged, for example, when identifying possible design changes. For instance, what are the implications of altering the size of a bolt? If it holds a car seat in place, changing one bolt has implications that impact manufacturing, supply chains, logistics, meeting safety regulations, and the user experience of the final product. Divergent thinking about the implications of changes can help to anticipate unintended consequences. But in comparison to the many idea generation strategies, very few strategies exist to support engineers in the many other places where divergent thinking takes place.

Currently, little is known about divergent thinking during engineering projects beyond idea generation. To investigate, we asked experienced engineers about their experiences with divergent thinking in their professional practice. Through an iterative protocol development process, we identified five areas where exploration by engineering practitioners may occur based on common activities during engineering problem-solving processes (e.g. [8]). Those five areas are: 1) problem understanding, 2) problem-solving methods and strategies, 3) research and stakeholder identification, 4) generating potential solutions, and 5) anticipating implications of decisions. With these five areas as a framework, we interviewed four engineering practitioners to ask about their experiences with divergent thinking.

Methodology

Participants were U.S.-based mechanical engineering practitioners employed as professionals in the automotive, aerospace, and defense industries. Three participants identified as male and one as female; their years of experience as professional engineers ranged from 2-27 years; and three participants identified as white and one as Guyanese. In the interview, participants were asked to recall a specific engineering experience involving "exploration" that they felt was successful or 'went well.' We asked them how they explored multiple options or perspectives during the project, and how the project may have benefitted from further exploration (even if something about the situation limited their ability to do so). Each participant was asked to choose which of the six areas (problem understanding, problem-solving methods, research and stakeholder identification, generating potential solutions, and anticipating implications) felt most relevant for that project. For the selected areas of exploration, the interview schedule directed questions about exploration on their project within a given area:

1. How did you go about [X]?
2. How did you decide to do that?
3. What alternative options did you explore?
4. How did you know you had explored enough alternatives?
5. Thinking more broadly, what alternatives did you *not* explore?
6. Why did you not explore those alternatives?
7. How successful do you think were you at exploring [X]?

For example, when interviewing practitioners about their exploration of problem-solving strategies, the questions were as follow:

1. How did you go about solving the problem?
2. How did you decide this was the strategy you wanted to use?
3. What other ways did you consider solving the problem other than the strategy you used?
4. How did you know that you had considered enough possible problem-solving strategies for you to move forward with the project?
5. Thinking more broadly, are there multiple different ways the problem *could* have been approached to reach solutions that were not considered?
6. Why were those strategies not pursued within this project?
7. How successful do you think you were at exploring problem solving strategies?

Preliminary Findings

We identified instances of divergent thinking across all five areas of exploration. In analysis, we found divergence in research and in identifying stakeholders to be distinct. Thus, the definitions and examples of each area of exploration shown in Table 1 represent six distinct areas of exploration. The examples of divergent thinking below suggest that engineering practitioners practice divergent thinking across many areas of engineering projects, and participants felt that divergence contributed to the ultimate success of their engineering projects.

Table 1: Quotes from mechanical engineering practitioners identifying instances of divergent thinking across six areas of exploration.

Area of Exploration	Definition	Practitioner Examples
Problem Understanding	Consider the project context and the goals of the project	“And where I said the problem was revealed slowly is you start peeling back the onion. So specifically, as we would create geometry, you would identify a new problem that may not have existed in an existing technology or may not have existed on the existing design specifically because of the added function….So, yeah, in very simple terms**, the boundaries and the constraints increased as you begin studying and noodling**.” (P2)
Problem-solving Methods and Strategies	Identify activities or methodologies to support work towards a solution	“And I think that was key to success of this was we had a check process, right? The designer designed, engineer did the engineering and the checker checked and then it got released and then it went and got built. **And I didn't follow that process. I said – Well, I did because that's how it gets released – but nowhere in the process says go talk to the operator.** By that, that's just not something…you typically design in a vacuum. Here’s the…you know, I had my one sheet of requirements. Design something that meets those requirements and send it out. That's your job. So getting stakeholders involved really early from the concept was what made that a success.” (P1)

Research	Gather information about existing solutions and user contexts	"'Go design something that will do this.' So obviously, first thing, first is, well, 'what materials can I use?' And again, **that was the research. I went and I talked with the actual chemists** and said, 'okay, we had the study that was done. It didn't really give me a bunch of information or design that would go on, that it was a workable, interesting concept, but not feasible, not functional. So tell me what I could work with.' That's again when they said, 'you can use these three materials.' Fantastic. So that limited that down to one design decision done." (P1)
Identifying Stakeholders	Identify anyone who would impact or be impacted by the project	"I don't know the product, so to speak. So I don't even know how to explore the options, you know? **And so literally the first thing I do is find out as many stakeholders as possible in the process. And I just pull them all together in a meeting and force them to talk**. It's less about me exploring the diverse options in this case. And this is what I mean by I moved to kind of a different phase of my career. I'm not exploring the diverse options. I'm sort of pulling diverse people together to explore the options. And that's the best that I can do in helping them problem-solve." (P4)
Identifying Potential Solutions	Consider possible solutions throughout the project	"So we started anywhere from just like modelling with a piece of paper. Some people didn't have like sheets of plastic, so we started with sheets of paper, a whole like plastic dome around your head with like a tube coming out. We thought about, I think somebody modeled what happens if you wear a baseball cap and drape this plastic sheet over your face. There were some that like just cover your face and then kind of…pretty much like the mask we're accustomed to now, but imagine a hard-ish plastic sheet that can bend and it comes over. **There were a whole bunch. And then there was a lot of experimentation**." (P3)
Implications of Decisions	Identify impacts of solutions and decisions on people or environments	**"So obviously there's cost implications. There's material implications, there's recyclability impacts too. Impacts primarily though to the end product owner and the end product repair process**. First and foremost though is the cost and the assembly and the function. So assuring the lifecycle and performance for the 15 years…. [The implications are] given to you by the layer above you. You have to perform this function for this amount of time and you have to have a signal of this fidelity and it needs to tell us when this happens or when this doesn't happen. And then the subsequent component down in line. So in that case, that's again another stakeholder who quantifies and enumerates their needs." (P2)

Discussion

These four interviews suggest the importance of investigating divergent thinking in engineering over a broad range of engineering practice activities. As is typically seen in engineering practices, we saw exploration during solution generation and development. But in addition, we saw practitioners exploring through expanded research, unveiling new understandings of their problem context over time, challenging problem-solving methods and discovering new ways of approaching problems, considering wider ranges of people who might impact or be impacted by their work, and digging into the lasting implications of their engineering decisions. Identifying these six areas where divergence can take place during engineering problem solving is a huge step forward in scaffolding consideration of diverse perspectives throughout all engineering work.

All four participants reported that divergence across these areas of engineering projects was integral for the ultimate success of their projects. Further, practitioners seemed to relate success in divergent thinking to "diversity," meaning both the demographic and experiential differences among team members that promote diversity of thought. Consistently across these interviews, practitioners said that *diversity is key* to both exploring a wide range of options and achieving a successful engineering project outcome:

- "These different backgrounds…They change the way we think and they change the way that we approach problems."
- "It's essentially diversity of thoughts, right? Having multiple points of view and having people [who] have solved other problems."
- "That team was successful. I think we had a wide range of experiences coming in…. People with whom you collaborate are not always widely varied in their position or in their background or in their education. Most of the time we're in solving problems with people that think a lot like us."
- "I'm sort of pulling diverse people together to explore the options. And that's the best that I can do in helping them problem-solve."

Many studies demonstrate the value of diversity in engineering team compositions (e.g. [17]–[19]), while other research builds understanding of the challenges facing under-represented engineering students and practitioners (e.g. [20]–[22]). Our work begins to identify diversity more broadly as a key part of divergent thinking and engineering project success, further underlining the importance of centering diversity and inclusion in engineering practice and culture. Divergent thinking, as a process of exploring many diverse perspectives and options, may be a central tool in advancing the aims of diversity and inclusion within engineering practice.

As currently most divergent thinking strategies focus on exploration of potential solutions (i.e. [8]), naming these six areas highlights the major gaps in divergent thinking literature. Future work should focus on developing strategies to support divergent thinking across all engineering work, not just solution generation and development. Our future work will extend our investigation across a greater number of practitioners to capture greater gender and racial diversity. We will also extend interview collection across more industries and levels of professional experience. Future interviews will examine both experiences where practitioners succeed at divergent thinking and also where they fail to explore multiple options and perspectives. Our research aim is to identify potential opportunities for intervention during engineering education to better support divergent thinking skills across engineering practice.

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