Divergent Thinking in Front-End Design

by

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Abstract

The "front end" of the design requires divergent thinking during concept generation and problem definition as engineers both explore the initial problem from multiple perspectives and consider alternative solutions. Divergent thinking encourages engineers to explore a wide variety of options throughout a design process to support the development of innovative products.

Typically, divergent thinking is a focus during concept generation as engineers explore a wide variety of different, potential solutions to a problem. Mechanical engineers in particular find it challenging to consider multiple ideas during concept generation and often become fixated on a particular concept or type of concept, limiting solution exploration. Studies have explored aspects of engineers' practices and struggles in concept generation, but little research has addressed the approaches mechanical engineers use without direction and how to support them in readily adopting best practices.

Less recognized in the divergence occurs during problem definition. One way that problems are defined in design is by developing a novel technology and then identifying potential problems to address with the specific technology, a process I define as "solution mapping." Designers must follow diverging paths in making and testing assumptions about potential problems they can solve with their technology. However, how to perform solution mapping is neither obvious nor addressed in engineering education; consequently, engineers find it challenging to recognize opportunities for their solutions. Resources addressing this process are limited in terms of existing research, empirically-based strategies, and educational tools to support solution mapping.

My collection of empirical studies examined differing approaches to divergence during design and developed empirically-derived design tools to support divergent thinking in concept generation and problem definition. Within concept generation, I studied novice mechanical engineers' approaches to generation, development, and selection, and examined the impact of an asynchronous learning intervention. I also studied engineering practitioners' divergent thinking approaches in concept generation. In problem definition, I studied design strategies for solution

mapping through practitioner interviews and developed an evidence-based design tool to aid in divergent thinking. Then, I tested the solution mapping design tool with novice engineers.

As a result of my studies, I identified specific factors that limit and promote divergent thinking in engineering design. Novice engineers during concept generation came up with assumed requirements that limited their solution exploration by generating early evaluation criteria. Practitioners in solution mapping minimized risk taking and explored possible problems only within their area of expertise, reducing the number of problems they considered. In both concept generation and solution mapping, providing direction and scaffolding through empirically-derived design tools promoted divergent thinking.

My research has direct implications for engineering design and education. Engineers and educators need to promote divergent thinking by considering multiple pathways to successful design outcomes. Designers can follow a problem-first or technology-first process, and the design environment affects how designers approach their task. Engineering design educators can provide explicit direction and guidance in both concept generation and problem definition processes to support engineers in achieving success at these front-end phases of design processes, improving design outcomes.

Chapter 1: Introduction and background

1.1 Introduction

Design is crucial to developing innovative products and services (Ottosson, 2001; Soosay & Hyland, 2004). In developing transformative products that disrupt the current marketplace, divergent thinking, defined as considering as many appropriate alternatives as possible (Guilford, 1967), is valuable because it encourages engineers to come up with many ideas that may be unrelated in an effort to explore a wide variety of options. Divergent thinking exists throughout design; particularly, the front end of design requires divergent thinking to promote flexibility in broadly exploring the initial problem from multiple angles and generating potential concepts (Breuer et al., 2009). My focus is on divergent thinking in problem definition and concept generation. Front-end processes of design have the largest potential for changes and improvements with the least amount of effort because they focus on conceptual rather than implemented ideas (Cooper, 1993; Verganti, 1997). Researchers estimate that while only 8% of development costs are incurred during the early front-end phases, decisions made at these phases determine up to 70% of the total cost (Pahl & Beitz, 1991). The front-end activities serve as the final steps before the engineering design team decides to pursue manufacturing products. Thus, it is crucial to ensure that engineers implement good front-end design practices for product success.

Divergent thinking is a component of creativity because diverging calls for considering original alternatives, making unexpected combinations, and identifying connections among remote associations (Treffinger, Young, Shelby, & Shepardson, 2002). While creativity has been defined in many ways, broadly speaking, creativity is the creation of something that is novel and useful within a field (Runco & Jaeger, 2012). In alignment with divergent thinking, researchers also conceptualize creativity as the production of ideas that are abundant and unique (Wallach & Kogan, 1965). Divergent thinking is often measured by fluency, flexibility, originality, and elaboration (Guilford, 1962). Fluency refers to quantity or the ability to generate a large number of responses to an open-ended problem. Flexibility involves an openness to examine different types of ideas. Originality is the ability to generate new and unusual ideas. Elaboration refers to the ability to expand ideas and add details. Divergent thinkers who are able to generate many, varied, unusual ideas are considered creative thinkers (Treffinger et al., 2002).

In contrast to convergent thinking, which relies on focusing and narrowing ideas leading to conventional ideas (Runco & Acar, 2012), employing divergent thinking can support coming up with ideas that deviate from existing ideas. This dissertation will focus on studying divergent processes in the front-end of design.

1.2 Divergent thinking in problem finding

In design, the initial problem sets the trajectory for the process. Identifying the "right" problem is crucial in developing a successful design solution (Christensen, Cook, & Hall, 2006). Problem finding is the process that engages with the world around to discover needs and insights that might drive the innovation of products, services or systems (Cross, 2008). Engineers can identify a problem before considering potential solutions or start with a technology and search for problems they can solve with the technology.

In a design process, engineers often start with a problem and identify possible solutions or follow "problem-first" processes (Cross, 2008; Dubberly, 2004; Eide, Jenison, Northup, & Mickelson, 2011; Ertas & Jones, 1996; French, Gravdahl, & French, 1985). One way to define problems in design is through searching and articulating a clear need. Engineers engage in ethnographic studies with various stakeholders to better understand the actions, words and thoughts of stakeholders to make informed design decisions (Bucciarelli, 1988; Mohedas et al., 2014; Salvador, Bell, & Anderson, 1999). Interviewing and making observations of their stakeholders help engineers to identify their priorities and preferences. These engagements aid engineers in uncovering latent needs and problems.

Divergent thinking is crucial in technology-first processes as engineers develop solutions and diverge to consider potential problems they can solve with those specific solutions (Thomas, Culley, & Dekoninck, 2007). Engineers can develop a novel technology and "match" their new technology with various applications, which I define as "solution mapping." In solution mapping, engineers seek to address various problems using their novel technologies. For example, the development of the 3D printer would be considered a technology-first approach that created a novel technology with multiple applications. Engineers first make assumptions about potential problems they can solve with their new technology and then test their assumptions by engaging with stakeholders. To aid in solution mapping, engineers may leverage the NSF I-Corps program based on Steve Blank's curriculum (Blank & Dorf, 2012), where the participants examine the commercialization potential of their technologies. The curriculum requires the I-Corps participants to form teams, complete over 100 interviews, and work with business mentors who can help them form networks and guide them in business practices. These interviews serve as an opportunity to test the engineers' assumptions about potential problems they can solve with their technologies (Blank & Dorf, 2012). However, in the I-Corps program, limited scaffolding is available to form initial assumptions about solvable potential problems.

Identifying problems to address with a technology is not obvious and literature has documented challenges in recognizing opportunities (Shane, 2000). Few studies have investigated the process of "matching" technologies to problems and few cognitive strategies are available to support the thinking process for solution mapping. Thus, research is needed to understand how engineers identify various different uses of their novel technologies and to develop design strategies in support of divergent thinking within solution mapping.

1.2 Divergent thinking in concept generation

Concept generation is a phase in a design process where the engineer considers several possible solutions to a problem (Cross, 2008a). Concept generation provides opportunities to diverge in order to explore a variety of different, creative ideas (Zenios et al., 2009) that serve as the foundation for synthesizing a final solution. Instead of focusing on one particular approach to the problem, it is recommended to consider a wide range of different ideas before evaluating them (Osborn, 1957). Concept generation is challenging because coming up with non-obvious and creative ideas is difficult, particularly with less expertise.

Engineers have been shown to struggle in considering multiple ideas during concept generation (Cross, 2001). They often become fixated on a particular concept or type of concept and limit the solution exploration process (Jansson & Smith, 1991; Purcell & Gero, 1996). Designers are often not aware of design fixation (Ward, 1994) and can become attached to concepts with major flaws (Rowe, 1987). Some reasons for fixation include having incomplete information and feeling overwhelmed (Niku, 2008). In addition, when engineers become aware of a solution to a problem, it becomes difficult for them to search the solution space for alternatives (Rowe, 1987). Also, even when engineers create multiple ideas, they are often minor variations of the same ideas, limiting the diversity of ideas considered (Rowe, 1987). Fixation has been demonstrated in many disciplines, including engineering design (Linsey et al., 2010), industrial design (Carlos & Petra, 2011), software design (Goddard, 1976), and interaction design (Hassard, Blandford, & Cox, 2009). Also, novice engineers spend too much time working on a single idea, which doesn't leave much time to consider alternatives (Cross, 2008b). Novice engineers approach design as a linear process that can be done once with minimal iterations (Crismond & Adams, 2012).

The current literature on fixation focuses on concept generation and development outcomes with a limited understanding of how engineers approach concept generation during the process. Thus, Part 1 of this dissertation examines how novice engineers approach concept generation and development, and tests interventions to support novices in adopting evidence-based best practices.

1.3 Research objectives

My goal is to identify approaches to divergence and develop explicit strategies to support divergent thinking in problem definition and concept generation. In problem definition, particularly in solution mapping, research has focused on factors that affect the problem definition, such as expertise, prior knowledge, and mentorship (Baron, 2006; Grégoire, Barr, & Shepherd, 2009; Shane, 2000). Much of the literature on technology-first design resides in the entrepreneurship community and emphasizes the importance of finding the right problem instead of studying the process of finding problems. Little research has investigated the process of identifying problems given existing solutions.

In concept generation, studies have investigated the outcomes of generating and developing concepts but limited research exists in examining the process of ideating. Studies have documented the outcomes of a concept generation session and noted challenges in diverging to consider multiple concepts (Crilly, 2015; Linsey et al., 2010). In other studies, researchers focused on the impact of specific design tools in concept generation (Hernandez, Schmidt, & Okudan, 2013; Linsey, Markman, & Wood, 2012; Daly et al., 2016). A gap in knowledge exists in understanding the process of concept generation and development when designers decide on their own methods for approach these front-end phases.

In both solution mapping and concept generation, designers can benefit from design strategies that scaffold their thinking processes. Research has demonstrated that design strategies can be developed from varied approaches. Strategies may be developed from research on successful design artifacts; for example, TRIZ was developed from studying patterns of patented inventions (Altshuller, 1997) and has been validated to support concept generation (Cascini & Rissone, 2004; Hernandez, Schmidt, & Okudan, 2013). Strategies can also be developed from studying designers' working practices. *Design Heuristics* were developed from the combined studies of a longitudinal case study, examining successful products and identifying designers' approaches in a think-aloud task (Daly, Yilmaz, et al., 2012). In another study, prototyping strategies were developed from extended observations of practitioners as they engaged in design tasks (Lauff et al., 2018). In this research, I studied the impacts of using design strategies in solution mapping and concept generation.

Research is needed to better understand how experienced engineers approach front-end phases of design, particularly in concept generation and solution mapping. Also, design strategies need to be developed and tested to support design practices. The research presented here examines the following research questions (as seen in Figure 1):

- How do engineers with various levels of expertise approach solution mapping and concept generation?
- How do design tools impact divergence in solution mapping and concept generation?

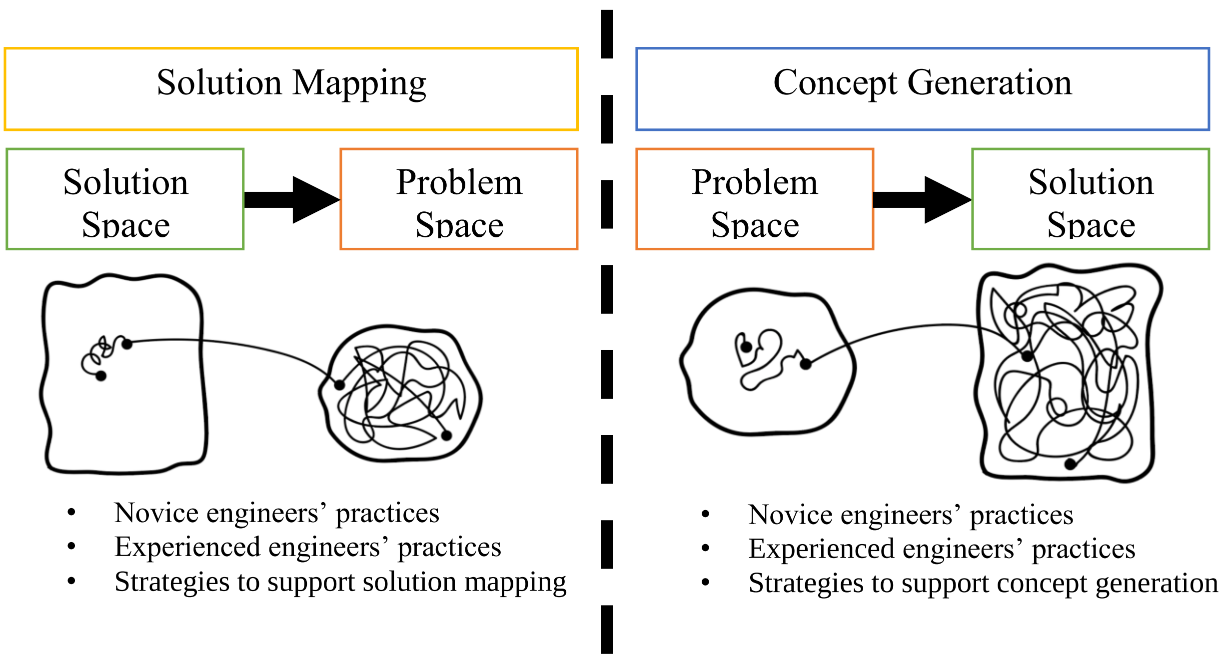

Figure 1. Dissertation overview. I examined divergent thinking in solution mapping and concept generation.

1.4 Chapter overviews

This section provides an overview of the dissertation and a brief description of each chapter.

Chapter 2 discusses a study designed to investigate how novice mechanical engineers approach concept generation and development. Using the think-aloud method, novice mechanical engineers were asked to generate and select concepts based on a design prompt and verbalize their entire thought processes. The study demonstrated that novice engineers focused on existing ideas, assumed requirements that constrained their divergence, limited their development of ideas, and selected their favorite idea. After completing the initial design task, students were instructed to go through a learning intervention. After going through a learning intervention, students generated unconventional ideas while abstaining from requirement assumptions, and generated a larger quantity of ideas, intentionally developed ideas, and used more rigorous idea selection methods. The learning intervention aided students in adopting new techniques and approaches in concept generation and development.

Chapter 3 describes a qualitative study that examined engineers' front-end design practices in academia and industry. This study aimed to investigate how engineers approach problem finding and concept generation in two different design contexts, as design is affected by contextual constraints. Chapter 3 reveals that engineers in large companies followed problem-first design approaches and identified problems before considering alternative solutions. On the other hand, engineers in academia engaged in solution mapping processes and searched for applications of their technologies. This study demonstrated that constraints and goals of the design environment influence design processes.

Chapter 4 describes the process of identifying cognitive strategies used in solution mapping. I recruited engineers who have developed novel technologies with multiple applications and used semi-structured interviews to gain in-depth understanding of the process of identifying problems with solutions. My findings articulate a collection of cognitive strategies that practitioners used to identify problems. By understanding and developing explicit cognitive strategies used in solution mapping, we can better scaffold the process of identifying various applications of technologies.

Chapter 5 studies novice engineers' solution mapping practices and the impact of their use of the cognitive strategies developed and explained in Chapter 4. By employing a controlled study to examine the effects of the cognitive strategies, Chapter 5 is the first study to provide evidence-based scaffolding to aid solution mapping.

In Chapter 6, I provide a summary of this dissertation, discussing the contributions and implications of my research.

1.5 References

Altshuller, G. (1997). *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc.

Baron, R. A. (2006). Opportunity Recognition as Pattern Recognition: How Entrepreneurs "Connect the Dots" to Identify New Business Opportunities. *The Academy of Management Perspectives*, *20*(1), 104–119. https://doi.org/10.5465/AMP.2006.19873412

Breuer, H., Hewing, M., & Steinhoff, F. (2009). Divergent innovation: Fostering and managing the fuzzy front end of innovation. In *PICMET '09 - 2009 Portland International Conference on Management of Engineering Technology* (pp. 754–761). https://doi.org/10.1109/PICMET.2009.5262066

Bucciarelli, L. L. (1988). An ethnographic perspective on engineering design. *Design Studies*, *9*, 159–168.

Carlos, C., & Petra, B. (2011). The Influence of Different Pictorial Representations During Idea Generation. *The Journal of Creative Behavior*, *45*(2), 130–146. https://doi.org/10.1002/j.2162-6057.2011.tb01092.x

Cascini, G., & Rissone, P. (2004). Plastics design: integrating TRIZ creativity and semantic knowledge portals. *Journal of Engineering Design*, *15*(4), 405–424. https://doi.org/10.1080/09544820410001697208

Christensen, C., Cook, S., & Hall, T. (2005). Marketing Malpractice. *Harvard Business Review*, *83*(12), 74–83.

Cooper, R. (1993). *Winning At New Products: Accelerating The Process From Idea To Launch* (Second). New York: Basic Books.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies*, *38*, 54–91. https://doi.org/10.1016/j.destud.2015.01.002

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, *101*(4), 738–797. https://doi.org/10.1002/j.2168-9830.2012.tb01127.x

Cross, N. (2008a). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Cross, N. (2008b). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Cross, Nigel. (2001). Design cognition: Results from protocol and other empirical studies of design activity. *Design Knowing and Learning: Cognition in Design Education*, *7*, 9–103.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design heuristics in engineering concept generation. *Journal of Engineering Education*, *101*(4), 601–629. https://doi.org/10.1002/j.2168-9830.2012.tb01121.x

Dubberly, H. (2004). *How do you design*. A compendium of Models.

Eide, A., Jenison, R., Northup, L., & Mickelson, S. (2011). *Engineering Fundamentals and Problem Solving* (6 edition). New York, NY: McGraw-Hill Education.

Ertas, A., & Jones, J. C. (1996). *The Engineering Design Process* (2 edition). New York etc.: Wiley.

French, M., Gravdahl, J., & French, M. J. (1985). *Conceptual design for engineers*. London: Design Council.

Goddard, W. (1976). *Transfer and einstellung effects of examples on devising computer algorithms*. University of British Columbia. https://doi.org/10.14288/1.0093821

Grégoire, D. A., Barr, P. S., & Shepherd, D. A. (2009). Cognitive Processes of Opportunity Recognition: The Role of Structural Alignment. *Organization Science*, *21*(2), 413–431. https://doi.org/10.1287/orsc.1090.0462

Guilford, J. P. (1962). Potentiality for Creativity. *Gifted Child Quarterly*, *6*(3), 87–90. https://doi.org/10.1177/001698626200600307

Guilford, J. P. (1967). *The nature of human intelligence*. New York, NY: McGraw-Hill.

Hassard, S. T., Blandford, A., & Cox, A. L. (2009). Analogies in Design Decision-making. In *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology* (pp. 140–148). Swinton, UK, UK: British Computer Society. Retrieved from http://dl.acm.org/citation.cfm?id=1671011.1671027

Hernandez, N. V., Schmidt, L. C., & Okudan, G. E. (2013). Systematic Ideation Effectiveness Study of TRIZ. *Journal of Mechanical Design*, *135*(10), 101009-101009–101010. https://doi.org/10.1115/1.4024976

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11.

Lauff, C. A., Kotys-Schwartz, D., & Rentschler, M. E. (2018). What is a Prototype? What are the Roles of Prototypes in Companies? *Journal of Mechanical Design*, *140*(6), 061102-061102–061112. https://doi.org/10.1115/1.4039340

Linsey, J. S., Markman, A. B., & Wood, K. L. (2012). Design by Analogy: A Study of the WordTree Method for Problem Re-Representation. *Journal of Mechanical Design*, *134*(4), 041009-041009–041012. https://doi.org/10.1115/1.4006145

Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., & Schunn, C. (2010). A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty. *Journal of Mechanical Design*, *132*(4), 041003. https://doi.org/10.1115/1.4001110

Mohedas, I., Daly, S., & Sienko, K. (2014). Design Ethnography in Capstone Design: Investigating Student Use and Perceptions. *International Journal of Engineering Education*, *30*(4), 888–900.

Niku, S. B. (2008). *Creative Design of Products and Systems*. Wiley.

Osborn, A. (1957). *Applied Imagination: Principles and Procedures of Creative Problem Solving New York*. Scribner.

Ottosson, S. (2001). Dynamic concept development - A key for future profitable innovations and new product variants. In *International Conference on Engineering Design* (pp. 331–338). Glasgow.

Pahl, G., & Beitz, W. (1991). *Engineering Design: A Systematic Approach*. Berlin: Springer.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies*, *17*(4), 363–383. https://doi.org/10.1016/S0142-694X(96)00023-3

Rowe, P. (1987). *Design thinking*. Cambridge, MA: The MIT Press.

Runco, M. A., & Acar, S. (2012). Divergent Thinking as an Indicator of Creative Potential. *Creativity Research Journal*, *24*(1), 66–75. https://doi.org/10.1080/10400419.2012.652929

Runco, M. A., & Jaeger, G. J. (2012). The Standard Definition of Creativity. *Creativity Research Journal*, *24*(1), 92–96. https://doi.org/10.1080/10400419.2012.650092

Salvador, T., Bell, G., & Anderson, K. (1999). Design Ethnography. *Design Management Journal (Former Series)*, *10*(4), 35–41. https://doi.org/10.1111/j.1948-7169.1999.tb00274.x

Shane, S. (2000). Prior Knowledge and the Discovery of Entrepreneurial Opportunities. *Organization Science*, *11*(4), 448–469. https://doi.org/10.1287/orsc.11.4.448.14602

Soosay, C. A., & Hyland, P. W. (2004). Driving innovation in logistics: Case studies in distribution centres. *Creativity and Innovation Management*, *13*(1), 41–51. https://doi.org/10.1111/j.1467-8691.2004.00292.x

Thomas, T., Culley, S., & Dekoninck. (2007). Creativity in the Engineering Design Process. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Treffinger, D. J., Young, G. C., Shelby, E. C., & Shepardson, C. (2002). *Assessing creativity: a guide for educators.* (Monograph No. RM02170). University of Connecticut, The National Research Center on the Gifted and Talented.

Verganti, R. (1997). Leveraging on systemic learning to manage the early phases of product innovation projects. *R&D Management*, *27*(4), 377–392. https://doi.org/10.1111/1467-9310.00072

Wallach, M. A., & Kogan, N. (1965). *Modes of thinking in young children*. Holt, Rinehart and Winston: New York.

Ward, T. B. (1994). Structured Imagination: the Role of Category Structure in Exemplar Generation. *Cognitive Psychology, 27*(1), 1–40. https://doi.org/10.1006/cogp.1994.1010

Zenios, S., Makower, J., Yock, P., Brinton, T. J., Kumar, U. N., Denend, L., & Krummel, T. M. (2009). *Biodesign: The Process of Innovating Medical Technologies* (1 edition). Cambridge, UK ; New York: Cambridge University Press.

Chapter 2: Idea Generation, Development, and Selection: A Study of Mechanical Engineering Students' Approaches and the Impact of a Learning Intervention

2.1 Abstract

Developing effective design solutions requires successful idea generation, development, and selection. Early ideas serve as the foundation for the final concept, and require development and iteration to improve their potential. Then, the right idea or subset of ideas must be selected for continued pursuit. However, studies have demonstrated that engineering students face challenges in these idea phases and may struggle to implement best practices, hindering the potential for an innovative outcome. While studies have explored some aspects of student practices in these idea phases, research is limited in what approaches students use without direction, and to what extent students can readily adopt approaches more in line with best practices with strategic educational interventions.

Thus, the present study investigated student practices in idea generation, development, and selection through a think-aloud experimental session and post-session interview both before and after engagement with three "Learning Blocks," a hybrid (online and face-to-face) intervention that leverages research-based educational best practices. Data analysis from 10 mechanical engineering students' two sessions, including 203 ideas and over 30 hours of think-aloud and interview data, revealed that before engagement with the learning blocks, students focused on existing ideas, assumed requirements that constrained their divergence, limited their development of ideas, and selected their favorite idea. After engaging with the learning blocks, students generated unconventional ideas, abstained from requirement assumptions early in idea generation, generated a larger quantity of ideas, intentionally developed ideas, and used more rigorous idea selection methods.

2.2 Introduction

Numerous reports have called for engineering students to develop the ability to design innovative solutions to complex problems of our world (Duderstadt, 2008; Sheppard, Macatangay, Colby, & Sullivan, 2009). Successful solutions to these problems require designers to successfully implement idea generation, development, and selection practices. At any of these phases, best practices support ideas to be created, developed, and selected. If best practices are not followed in these idea phases, designers may pursue conventional ideas that may be small modifications of existing ideas (Cross, Nigel, 2001) and potentially great ideas are not considered. Ideally, designers need to generate a diversity of novel concepts in the initial stages of design to create innovative solutions (Brophy, 2001; Zenios et al., 2009). These initial ideas need to be developed to have the potential to succeed; thus designers need to combine, build on, and iterate on these early ideas by adding new features and transforming aspects of the design ideas (J. Kim & Wilemon, 2002). After rounds of development, ideas can be evaluated according to important criteria given the problem and context, and subsets of ideas are selected to further refinement until designers arrive at a final solution (Rietzschel, Nijstad, & Stroebe, 2006).

While these phases of idea generation, development, and selection are crucial to successful innovation, studies indicate numerous challenges faced by students and practitioners in their idea generation (Ahmed, Wallace, & Blessing, 2003; Ball, Evans, & Dennis, 1994; Cross, Nigel, 2001; Jansson & Smith, 1991; Purcell & Gero, 1996; Ullman, Dietterich, & Stauffer, 1988; Youmans & Arciszewski, 2014), idea development (Crismond & Adams, 2012), and idea selection practices (Toh & Miller, 2015). While some challenges within these idea phases are known, much of the idea generation literature is focused on specific elements or tools, rather than the implementation of a collection of best practices, and limited research has focused on student idea development and selection approaches. Additionally, research has not focused on the extent to which instruction can support students to adopt best practice strategies.

To fill this gap, this study used a think-aloud approach during idea phases paired with pre-and post-instruction interviews to investigate how engineering students generated, developed, and selected designs. In addition to capturing students' natural idea generation, development, and selection practices, we studied the impact of the "Learning Block" intervention, which combines online learning with one-on-one coaching sessions focused on the topic of interest, on engineering students' approaches to idea generation, development, and selection.

2.3 Related Work

2.3.1 Idea generation approaches

Best practices in idea generation recommend that multiple, diverse concepts are generated and considered (Brophy, 2001; Liu, Chakrabarti, & Bligh, 2003; Zenios et al., 2009). By creating a large quantity of diverse ideas, designers are more likely to generate non-obvious solutions (Zenios et al., 2009). Additionally, diverse ideas support broader perspectives on solution options, support deeper consideration of the real problem (Dorst & Cross, 2001), prompting iteration of the problem, and provide more variety in functions and features that can be synthesized into new ideas (Zenios et al., 2009). Diverse ideas can include unconventional ideas, and these ideas can stimulate novel approaches that have not been previously considered (Kelley & Littman, 2001). Idea generation best practices also encourage limiting evaluation early on and documenting any new idea even if it seems impractical. That "crazy" idea could be transformed into a successful solution and could also inspire other ideas that had not been explored (Kelley & Littman, 2001).

While these best practices set up a designer to be successful, both novice and experienced designers have been shown at times to struggle to implement them. Novice engineers have difficulty generating and considering multiple ideas (Cross, Nigel, 2001). Novices often limit the diversity of ideas by focusing on a particular concept or variations of the same types of ideas early in the idea generation phase, a term called fixation (Jansson & Smith, 1991; Purcell & Gero, 1996). In addition to fixating on particular idea type novices can fixate on early ideas even when they realize that these ideas have major flaws (Ball et al., 1994; Rowe, 1987; Ullman et al., 1988). Across design expertise, designers have been shown to struggle to break away from existing, well-known solutions (Linsey et al., 2010) and evaluate ideas too early (Kelley & Littman, 2001). To support designers in achieving best practices in idea generation, the use of ideation structures and tools is recommended. For example, brainstorming "rules" provide a structure for how groups should collect ideas, by building off of other suggestions and not limiting the types of ideas collected (Osborn, 1963).

Ideation tools have been shown to promote quantity, creativity, diversity, and elaboration of ideas generated (Daly, Seifert, Yilmaz, & Gonzalez, 2016; Hernandez, Schmidt, & Okudan, 2013; Lee, Daly, Huang-Saad, Seifert, & Lutz, 2018; Linsey, Green, Murphy, Wood, & Markman, 2005; Linsey, Wood, & Markman, 2008). Examples of tools include Brainwriting (Heslin, 2009), Design Heuristics (Daly et al., 2012), IDEO cards (IDEO, 2002), Morphological analysis (Allen, 1962), SCAMPER (Eberle, 1995), Synectics (Gordon, 1961), TRIZ (Altshuller, 1997), and Wordtree Design-by-Analogy (Linsey et al., 2008). Some tools may be better suited for achieving particular goals, i.e., some tools may best limit fixation while others improve quantity of ideas generated. Structures and tools are sometimes specifically meant for group ideation (i.e. Brainwriting) while others support individual ideation. Group idea generation can benefit ideation, but individual ideation is recommended prior to group ideation (Diehl & Stroebe, 1987).

While prior studies have focused on the impacts of structures and tools, studies have not addressed the extent to which students aim to employ best practices in their approaches and the associated structures and tools they use when given free rein on how to approach idea generation.

2.3.2 Idea development approaches

Designers employing best practices in idea development iterate on early ideas to improve their potential. This includes elaborating on existing ideas, building new ideas inspired by existing ones, generating new types of ideas based on gaps identified within existing ideas [40, 41]. Designers often iterate to modify ideas to address inconsistencies or errors, improve solutions to optimize certain characteristics, and integrate multiple ideas to develop new ideas (Adams & Atman, 1999). Furthermore, designers may ask for feedback from their stakeholders to inform where ideas need further iteration (Sanders & Stappers, 2008).

In practice, novice designers have been shown to limit idea development and focus on evaluating and selecting an idea for pursuit (Atman, Chimka, Bursic, & Nachtmann, 1999; Crismond & Adams, 2012). If they do engage in some development, they focus on developing a single idea by refining the same solution and adjusting the details of that solution, and thus do not consider other options (Cross, 2008). Novices engage in minimal iteration on ideas as compared to experts (Atman et al., 1999) and solve design problems as a linear process that can be done only once (Crismond & Adams, 2012), leaving very little room to explore beyond their initial ideas based on information gathered in later design stages.

There are few support tools for idea development discussed in design texts or literature, as design methods emphasize idea generation and selection (Cross, 2008; Dubberly, 2004). Existing support strategies that have been demonstrated to support idea development include Brainstorming in small groups (McMahon et al., 2016), which encourages building on initial ideas without early evaluation. Other group members can use the initial ideas to develop more complete ideas and combine features of multiple ideas. Additionally, some idea generation tools have been explored as idea development tools. For example, Design Heuristics were shown to do support students in elaborating, or further specifying, their design ideas (Christian et al., 2012; Kramer et al., 2015). Also, Design Heuristics helped students to consider additional features and transform their previous ideas to further develop their ideas. C-Sketch in a group setting supports idea development by adding modifications to previous ideas produced by other group members (Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001).

2.3.3 Idea selection approaches

During idea selection, designers evaluate numerous ideas and select promising ideas to move forward (Kudrowitz & Wallace, 2013). Best practices recommend designers to appropriately evaluate and select ideas by balancing systems of benefits and trade-offs to articulate both the positive features as well as drawbacks (Crismond & Adams, 2012). Best practices also encourage ideas to be selected after employing back-of-the-envelope estimated calculations and practice-based guidelines to ensure that their concepts meet functional requirements [47, 48].

While various idea generation and development tools can help in exploring the solution space, innovative ideas are often filtered out during the idea selection process (Rietzschel et al., 2006). Both novice and expert designers who select poor concepts have large costs associated with redesign while designers who select high quality concepts increase their likelihood of product success (Huang, Liu, Li, Xue, & Wang, 2013). Expert designers often select concepts that are conventional or have shown success in the past instead of novel ones (Ford & Gioia, 2000). Also, Toh and Miller found that novice designers focused on technical feasibility and effectiveness (Toh & Miller, 2015) at the cost of originality (Rietzschel et al., 2006). Inherent bias against unconventional ideas exist due to the risk and uncertainties of unconventional ideas (Rubenson & Runco, n.d.). Innovations may be considered risky when the likelihood of failure is assessed but these innovations can often lead to success after commercialization (Baucus, Norton, Baucus, & Human, 2008). Although innovation is emphasized in idea generation, both novice and expert designers often filter out ideas in concept selection to minimize risk.

To support designers in concept selection, various formalized methods have been developed including Analytical Hierarchy Process (Marsh, 1993), Pugh's evaluation method (Pugh, 1991), and Utility Theory (Pahl & Beitz, 1991). These methods assign attribute values to compare characteristics of design options to find an optimal solution. Studies have shown that student designers emphasize technical feasibility (Toh & Miller, 2015). However, limited studies have conducted studying students' concept selection practices and their thought processes during the task.

2.4 Research Design

2.4.1 Research Questions

This study investigated students' idea generation, development, and selection practices. We were interested in students' initial ideation processes, how they refined their concepts, and how they chose a final solution. Additionally, we hypothesized explicit instruction on best practices in idea generation, development, and selection would change their approaches in these idea phases. Thus, we implemented an asynchronous online learning opportunity (umich.catalog.instructure.com/browse/csed/) to study the impact of providing a learning opportunity for students. This project was conducted to gather information about the following research questions:

- How do mechanical engineering students approach idea generation, development, and selection?
- How do the asynchronous Learning Blocks impact students' idea generation, development, and selection practices?

2.4.2 Participants

Participants included ten undergraduate mechanical engineering students who generated 203 ideas and over 30 hours of think-aloud and interview data during the study. This number of participants is appropriate for an in-depth qualitative study (Creswell, 2013; Daly, McGowan, & Papalambros, 2013; Daly, Adams, & Bodner, 2012; Patton, 2015) and similar to other qualitative design studies (Cardoso, Badke-Schaub, & Eris, 2016; Goldschmidt, 1995; E. Kim, Chung, Beckman, & Agogino, 2016; Lauff, Kotys-Schwartz, & Rentschler, 2018).

The student participants were recruited through targeted emails to undergraduate mechanical engineering students at a large Midwestern university and compensated 200 USD for approximately 18 hours of their time. All participants had taken at least one design-related college course where they gained experience in idea generation, development, and selection. Also, all students had participated in design related internships or co-curricular design activities. Thus, they had multiple exposures to design, and had the opportunity to develop strategies to employ in idea generation, development, and selection. Participant background information is included in Table 1.

Table 1. Participant demographics

Pseudonym	**Gender**	**Grade**	**Ethnicity**	**Design Background**
Andrea	F	Senior	Asian	3 design courses, 1 design internship
Brian	M	Sophomore	White	1 design course, 1 extracurricular design team
Cathy	F	Junior	White	2 design courses, 1 extracurricular design activity
Daniel	M	Junior	White	3 design courses, 2 extracurricular design activities
Ethan	M	Senior	Asian	3 design courses, 1 extracurricular design activity, 2 design internships
Fredrick	M	Senior	Asian	3 design courses
Grace	F	Junior	African American & White	1 design course, 1 extracurricular design activities
Henry	M	Senior	Asian	2 design courses, 3 extracurricular design activities
Isaac	M	Junior	Asian	3 design courses, 1 design internship
Jeffrey	M	Sophomore	White	1 design course, 1 extracurricular design activity

2.4.3 Data Collection

The participants engaged in a three-step procedure during the study: 1) a design task with natural approaches and interview, 2) completion of 3 Learning Blocks, and 3) a post-block task and interview (Figure 2).

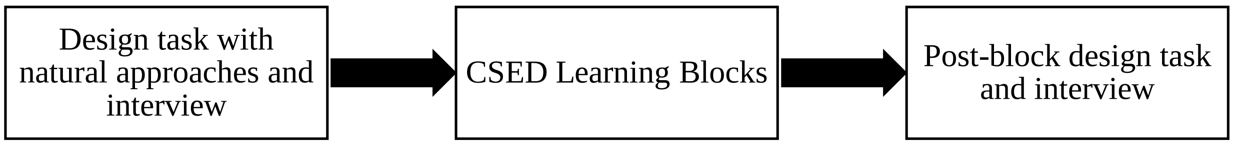

Figure 2. Study procedure

The design task with natural approaches asked students to develop solutions to a given problem statement and select a final solution at the end. Students completed this task using whatever approaches they wanted. This was to capture their natural tendencies in a non-guided setting. They were asked to spend a minimum of an hour working on the design task using any resources they needed.

Participants were asked to think-aloud throughout the session as they wrote and completed the design task. The think-aloud data were recorded using a Livescribe Echo pen. The think-aloud method asks participants to verbalize their thought process during a problem solving task (van Someren, Barnard, & Sandberg, 1994). Think-aloud approaches capture processes and ideas in a person’s working memory rather than their long-term memory (Ericsson & Simon, 1980, 1993). Working memory provides accurate representation of the current processes compared to recalling information after completing a problem-solving event.

The problems for the design task were developed based on a number of criteria. Solutions to these problems should be product oriented since we planned experiment with mechanical engineering students. The problems were developed to minimize the expertise needed in a particular context to ensure that students did not need extensive knowledge to generate ideas. We modified three existing tasks used in other studies that had similar criteria (Rechkemmer et al., 2017; Sevier et al., 2017) and them conducted two rounds of pilot tests to refine language and select two design contexts for the study. After the pilot tests, two tasks we selected included the low-skill snow transporter problem asks students to design a personal tool for people with that lack ski and snowboard experience, and the one-handed opener for lidded food containers problem asks students to develop a way for people with limited use of one upper extremity to open a lidded food container. The full problem descriptions are included in Appendix 1.

After the design task, the students were interviewed using a semi-structured interview protocol. Interviews allow for exploration of perceptions and opinions, and enable probing for more information, which helps ensure validity of the data because it allows for clarification of responses (Hutchinson & Wilson, 1992; Louise Barriball & While, 1994) and more complete information (Bailey, 1994; R. Gordon, 1975). The interview questions were developed through multiple iterations. Open-ended questions were constructed to understand students' idea generation, development, and selection practices (Jacob & Furgerson, 2012), and questions were framed neutrally to avoid expressing personal opinions and leading interviewees (Patton, 2015). Examples of questions included: How did you generate ideas to address the problem? Can you tell me about how you selected your final idea?

Prior to using the protocol for data collection, one pilot interview was conducted to ensure clarity of the protocol. To guarantee protocol consistency for all participants, one person interviewed every participant. The sole interviewer for this study was a graduate student who has received interview training and previously completed studies using qualitative research methods. Each interview was audio-recorded for analysis. Although the same protocol was used for all participants, the interviews varied in length from 20- 60 minutes depending on how elaborate students were as they answered the open-ended interview questions.

Students were then instructed to complete three Learning Blocks created by the Center for Socially Engaged Design in the following sequence: "Idea Generation", "Concept Development" and "Concept Selection" within a 3-4 week time frame ("Center for Socially Engaged Design," n.d.). Each learning block took approximately 5-8 hours to complete. each block had specific learning objectives aligned with best practices in the particular idea phase. These objectives are listed in Figure 3. Additional information on the learning block structure is described in the next section.

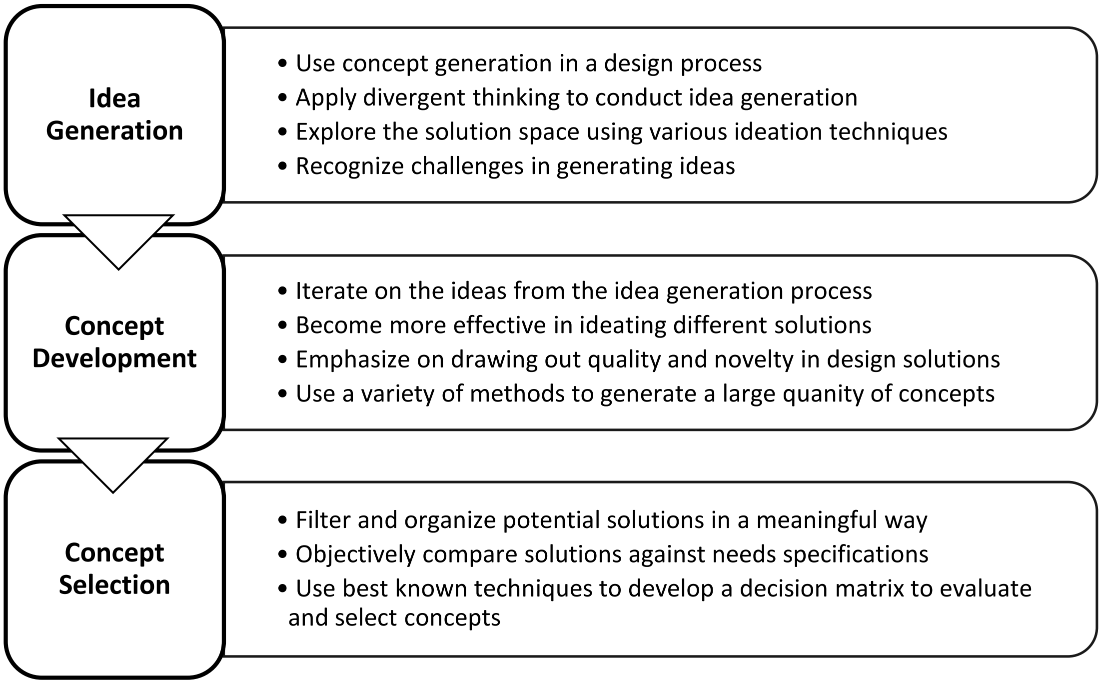

Figure 3. The learning objectives of the Center for Socially Engaged Design blocks.

Once the students completed the Learning Blocks they did a post-block design task. This time, they developed ideas for the problem statement that they had not completed during the design task with natural approaches. The study structure was identical to the previous protocol except the interview protocol included a few additional questions related to students' learning block experiences.

2.4.4 The Learning Block Intervention

The Learning Blocks were created by the Center for Socially Engaged Design to promote design skills and provide an asynchronous learning opportunity through on-demand online learning platforms coupled with one-on-one coaching sessions with experienced design consultants ("Center for Socially Engaged Design," n.d.). The blocks provide videos and/or text that highlights key principles of a particular design activity, with questions that allow students to check their understanding (Young, Daly, Hoffman, Sienko, & Gilleran, 2017). Students receive remote feedback on their answers, and once they pass, students proceed to an application opportunity, where they are provided a design scenario to apply core principles from the learning block core content. Then a coach discusses the application task with students, provides feedback, and allows the students to iterate as necessary. Finally, students complete an online reflection form on how their ideas changes and what is important to know about the topic. The Learning Block model format is summarized in Figure 4.

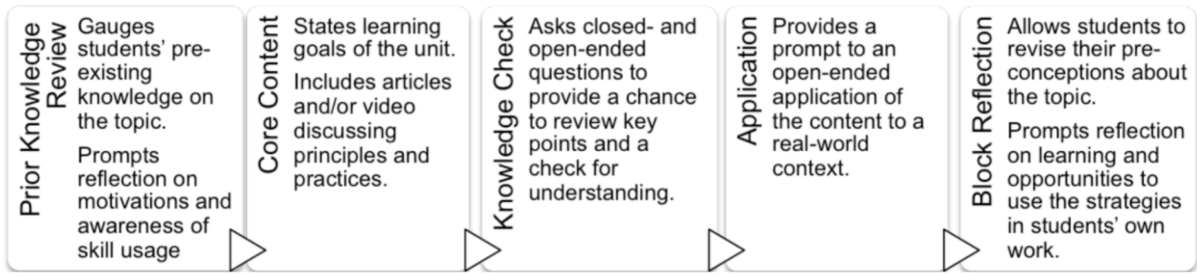

Figure 4. Center for Socially Engaged Design Learning Block Model

<u>2.4.5 Data Analysis</u>

The think-aloud and interview data were transcribed for analysis. Also, students' sketched data were matched with think-aloud data. Data were then analyzed in two different ways: 1) think-aloud and interview data were coded to uncover students' approaches and 2) sketched and think-aloud data were examined to measure outcomes of idea generation, development, and selection.

To analyze students' approaches, deductive codes were first developed based on previously documented behaviors in idea generation, development, and selection such as listing existing ideas and balancing benefits/tradeoffs in selecting ideas (Crismond & Adams, 2012). Inductive codes were added to this initial list based on recurring trends in the data (Creswell, 2013) to form the complete set of codes to describe students' behaviors. For example, an inductive code of 'self-limiting behavior: assumed requirements' was added to the codebook as a recurring pattern to describe students who came up with additional requirements that limited their idea generation. Table 2 includes the complete list of codes to describe student approaches across idea phases. After the codebook was finalized by the first two coders, a third coder independently coded the interviews and think-aloud sessions and compared all codes to the second coder. An inter-rater reliability for behavior codes was calculated as 75% among all pre-block and post- block transcripts. Values greater than 70% are typically acceptable for inter-rater reliability (Osborne, 2008). The coders discussed all discrepancies and reached full agreement prior to finalizing the findings.

Table 2. List of codes

Behavior Code	**Definition**
Self - limiting behavior: Assumed requirements	Students interpreted project requirements that were not explicitly stated in the problem statement
Ideation Techniques used (e.g. Design Heuristics, Morphological Analysis, Brainstorming, brainwriting, SCAMPER)	Student did not use an ideation technique (score 0), used at least one but did not use it clearly (score 1), intentionally used at least one as recommended (score 2)
Thought of existing solutions	Students thought or searched for existing solutions to generate ideas
Practicality of ideas	Students limited the solution space by emphasizing practicality and feasibility during idea generation
Balance benefits & tradeoffs	Students balanced benefits and tradeoffs for each design and decided the better design for which the pros outweighed the cons
Signs of idea development	Students iterated or combined ideas
Idea generation and development phase separation	Students distinguished idea generation from idea development
Used intuition	Students used intuition to evaluate ideas
Using inconsistent evaluation criteria	Students used inconsistent evaluation criteria to compare ideas
Arbitrary assignment of values	In using a decision matrix, students did not elaborate on how they

Next, students' idea generation, development, and selection outcomes were measured. We examined outcomes including quantity of total ideas, variety of total ideas, quantity of ideas developed, fixation on ideas, number of criteria used in selection, and prioritization of criteria in selection. The metrics are summarized in Table 3 and described in more detail in the following paragraphs.

Table 3. Students' idea generation, development, and selection outcomes and measurement methods

Metric	Measurement method(s)
Quantity of total ideas generated in all idea phases	Researchers counted the total ideas generated and developed
Quantity of ideas developed	Researchers counted the total number of ideas that were explicitly iterated or combined during ideation.
Variety of ideas	Researchers 1) created categories based on types of ideas and 2) created subcategories based on different sub functions.
Fixation	Researchers analyzed the first two and last two ideas generated. If one of first two or last two ideas were placed in the same types of ideas from analyzing variety of ideas, we measured it as fixation.
Number of criteria considered in idea selection	Students selected an idea based on one or multiple criteria
Prioritization of requirements and evaluation criteria	Students compared the importance of multiple criteria before comparing ideas

2.4.6 Quantity of total ideas generated in all idea phases

To measure quantity, we leveraged practices used in prior research (Linsey et al., 2005; Shah, Kulkarni, & Vargas-Hernandez, 2000). A single product solution was defined in two different ways: 1) participants clearly indicated an idea by having a sketch with descriptions of an idea (Figure 5) or 2) participants only described an idea in words but the idea covered two or more functions of the design. When students came up with single components of ideas using idea generation techniques, we did not count them as individual ideas. For example, a participant used the Mind Map to come up with various different ways to power a snow transporter such as wind power, motor, and solar power, we did not count these individual components as an idea. When the same participant used two or more components from his Mind Map to build possible solutions and sketched out the details, we counted them as ideas. Inter-rater reliability between two coders for all of the data using this approach was 94%. The coders discussed all discrepancies and reached full agreement prior to finalizing the findings.

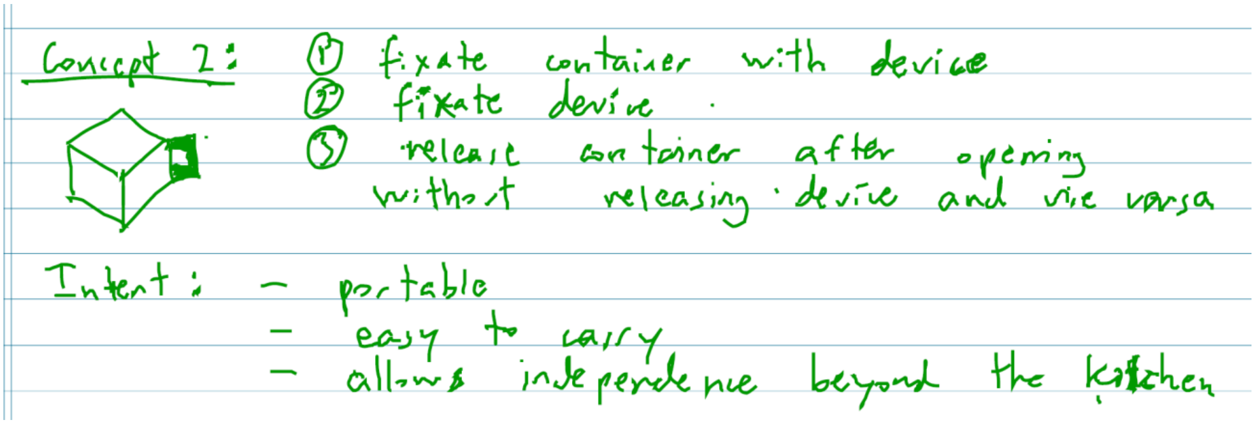

Figure 5. Example of a concept that would be considered a whole idea

2.4.7 Quantity of ideas developed

In quantifying the ideas developed, we followed the same procedure for quantifying the total number of ideas with additional criteria. Two coders only counted ideas that were explicitly indicated by students as 1) combining components of previous ideas, 2) building on previous ideas, and 3) developing ideas after initial generation. The inter-rater reliability was 83% and the coders discussed all discrepancies until they reached full agreement prior to finalizing the findings.

2.4.8 Variety of ideas

Variety of ideas were measured based on two different approaches: 1) Ideas were grouped based on key features of the design to capture different types of ideas generated. 2) Ideas were broken down into various functions or 'bins' to analyze different sub-functions of ideas that students' considered.

Each concept was classified by solution type based on the key features of the design, similar to approaches used in other studies measuring variety (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Jablokow et al., 2015). For example, in one-handed opener problem, all concepts that focused on using a handheld tool to pry open the container was classified as a type of solution that occurred several times among many participants. A coding scheme was created that consisted of exclusive categories differentiating 'obvious' concepts from unexpected concepts. For the low skill snow transporter problem, 8 different codes were created (1-ATV, 2-snowmobile, 3-snowboard, 4-snowshoes, 5-ski, 6-scooter, 7-motorcycle, 8-other). For the one-handed opener problem, 5 different codes were created (1-base/lid restraint, 2-machine (twist), 3-

handheld tool (puncture), 4-handheld tool (pry), 5-other). For both problems, the ‘other’ category represented combinations of features from multiple categories and ideas that did not fit into the above categories. For example, in the low skill snow transporter problem, any flying objects such as drones were placed in the ‘other’ category. Using two coders, inter-rater reliability for all data was 78%. The coders discussed all discrepancies and reached full agreement prior to finalizing the findings.

In the second way of measuring variety of ideas, we created categories based on various functions or ‘bins’ of ideas (Linsey et al., 2010). For example, in the low-skilled snow transporter problem, participants came up with a variety of ways to power their transporter (Table 4). Each method of powering the snow transporter would be considered a bin. Based on all the bins, we counted how many bins were considered unique, meaning they were used by a limited number of participants in this study. We counted bins that were only used by 1, 2 or 3 participants out of 10. Then we compared how many of those unique bins were used by participants during the design task with natural approaches or post-block task. Using two coders, inter-rater reliability for all data was 71%. The coders discussed all discrepancies and reached full agreement prior to finalizing the findings.

Table 4. Power source categories

Motor/ Engine	Includes propulsion ideas. Jets, rockets, turbines
Solar Energy	Collecting radiant energy emitted by the sun to power the device
Wind Energy	Capturing wind in a sail to move device
Gravity	The force that attracts an object with mass toward the center of the earth
Battery	An energy storage unit
Biological	Using an animal as a power source
Magnetic Force	Attraction or repulsion that arises between electrically charged objects
Elastic Energy	Energy stored as a result of applying a force to deform an elastic object. Energy is stored until the force is removed and the deformed object springs back to its original shape

2.4.9 Fixation

To analyze fixation, we examined the first two and last two ideas generated. If one pair of the first two or last two ideas fell in the same category of ideas, we indicated that students were fixated, and they generated same types of ideas in the beginning as well as at the end. Other studies on fixation measured number of non-redundant features of ideas to quantify fixation (Linsey et al., 2010). Similarly, our study examined redundancy of first two and last two ideas generated to measure fixation; however, we focused on redundancy of types of ideas generated instead of sub-features of ideas. For the low skill snow transporter problem, 8 different codes or types of ideas were present (1-ATV, 2-snowmobile, 3-snowboard, 4-snowshoes, 5-ski, 6-scooter, 7-motorcycle, 8-other). For the one-handed opener problem, 5 different codes or types of ideas were present (1-base/lid restraint, 2-machine (twist), 3-handheld tool (puncture), 4-handheld tool (pry), 5-other). If ideas were categorized as other, two coders created new categories and compared ideas. In coding fixation, two coders had the inter-rater reliability of 90%.

2.4.10 Number of criteria considered and prioritization of criteria in idea selection

Two coders counted the number of criteria that students considered during their idea selection and created a binary system. We categorized students into 1) a group that considered only one criterion in selecting ideas and 2) a group that considered multiple criteria. Also, we examined if students prioritized their evaluation criteria in selecting ideas. Students who prioritized their criteria either ranked criteria or assigned different weighing values to each criterion to indicate their importance. We did not evaluate the specific idea selected by students because the focus of the work was to characterize students' idea generation, development, and selection processes.

2.5 Results

The findings represent patterns in students' idea generation, development, and selection approaches as well as the types of outcomes they generated. We summarize these patterns across idea phases in Table 6 and discuss approach and outcome patterns for each idea phase in the following subsections.

Table 5. List of students' idea generation, development, and selection approaches

Natural approach	Post-learning block task approach
<u>Idea Generation Approaches</u> - Assumed additional requirements limited divergence in ideation. - Looked for existing solutions to the problem - Did not utilize any idea generation strategies - Focused on practicality of ideas	<u>Idea Generation Approaches</u> - Did not demonstrate signs of adding requirements in idea generation - Looked for existing solutions initially and generated unconventional solutions - Utilized one or two idea generation strategies - Focused on increasing the quantity of ideas
<u>Idea Generation Outcomes</u> - Generated a limited quantity and diversity of ideas - Fixated on initial ideas	<u>Idea Generation Outcomes</u> - Generated a larger quantity and diversity of ideas - Less fixated on initial ideas
<u>Idea Development Approach</u> - Showed little signs of developing ideas	<u>Idea Development Approach</u> - Separated out idea development as its own phase
<u>Idea Development Outcome</u> - Developed few ideas	<u>Idea Development Outcome</u> - Elaborated and iterated multiple ideas
<u>Idea Selection Approaches</u> - Used intuition - Using inconsistent evaluation criteria - Arbitrary assignment of values - Showed favoritism in selecting ideas	<u>Idea Selection Approaches</u> - Used a decision matrix - Used consistent evaluation criteria - Assigned arbitrary weighing criteria for Pugh Chart
<u>Idea Selection Outcomes</u> - Selected a single idea with one criterion - Did not prioritize criteria in selecting ideas	<u>Idea Selection Outcomes</u> - Considered multiple criteria in selecting the final idea - Prioritized multiple criteria

<u>2.5.1 Concept Generation Approaches</u>

2.5.1.1 Natural Concept Generation Approaches

Before going through the learning blocks, students 1) assumed additional requirements that were not explicitly described in the problem statement that limited divergence in ideation, 2) looked for existing solutions to the problem, 3) did not utilize any idea generation strategies, and 4) focused on practicality of ideas as a goal in idea generation.

When students were given a design problem, 7 out of 10 students used the stated constraints from the design problem as a guide and assumed additional requirements that were not part of the problem statement. For example, Henry was working on a one-handed opened problem and indicated an additional requirement that was not stated in the problem:

"*I'll call this design requirement.* ***Container must be fixated without use of arm*****"** (Henry)

By creating an additional requirement, Henry only came up with ideas that revolved around fixating the container. Additionally, Cathy came up with an assumed requirement not included in the problem statement. She was tasked with the low-skill snow transport problem that prompted her to design a personal transportation method on snow. The problem statement indicated that solutions should allow users to control direction and braking, but she came up with another requirement through her interpretation and assumption:

"I guess, 'Direction and braking,' ***would imply that this should be motorized****"* (Cathy).

By focusing on motorized methods of transporting on snow, Cathy limited herself from coming up with ideas that did not involve motors. Some examples of Cathy's ideas included a snow scooter with motorcycle-style hand control (Figure 6.a), an ATV with snow tires (Figure 6.b), and a snowmobile (Figure 6.c).

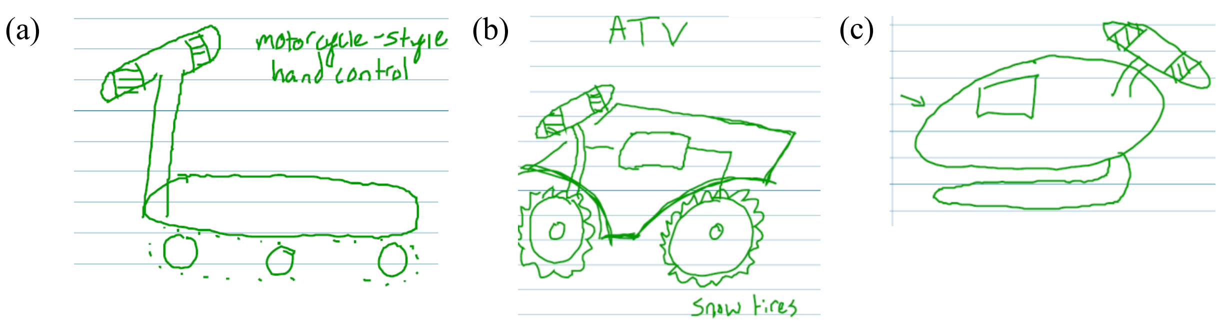

Figure 6. Examples of Cathy's initial ideas on low-skill snow transportation.

Furthermore, 8 out of 10 students relied on existing solutions and minimally diverged to consider many alternatives. Since students were allowed to use any resource they needed, they searched on Google for existing solutions to the problem. For example, Andrea who was working on one-handed container opener said,

> "*I Googled one hand opener to see if there [were] any off-the-shelf products that [are] out there. And I found some, and I borrowed some ideas from like current products, that [are] like online*" (Andrea)

None of the students using any ideation strategies to support them in considering diverse alternatives. In interviewing students after the design task with natural approaches, 6 out of 10 students indicated that they were aware of ideation techniques but did not apply them to support ideation. For example, in an interview:

> "*I remember we talked about a lot of different ways that it's possible to ideate solutions and a few of those... Remember talking about one method is the TRIZ method. And then, I remember the acronym SCAMPER. I'm not sure if I remember it correctly*." (Brian)

Students had access to the internet and they could have leveraged online resources; students knew of idea generation techniques but did not apply them.

Students also emphasized coming up with practical solutions as a goal for idea generation. For example:

> "*I think success is meeting a challenge so if ... Yeah. Yeah. I have these criteria and if my design meets those criteria, wonderful. It's successful.*" (Cathy)

By emphasizing meeting design criteria, students focused on coming up with solutions that are practical, which can lead to conventional ideas. Best practices in idea generation encourages designers to come up with novel, unconventional ideas that can be used to inspire new ideas.

2.5.1.2 Post-Block Concept Generation Approaches

After completion of the Learning Blocks, students did not assume requirements in the early phase of idea generation, looked for existing solutions initially and generated unconventional solutions later, utilized one or two idea generation tools, and focused on increasing the quantity of ideas. The combination of these approaches led to students coming up with a larger quantity of diverse ideas.

Unlike natural idea generation where students came up with assumed requirements in the beginning of the design task, 6 out of 10 students in post-block task emphasized the importance of not limiting ideas early in idea generation did not show signs of coming up with assumed requirements:

> *"It's coming up with solutions and sort of taking a question and using it to inspire solutions and not limiting your solutions. It's like an initial dump of all of your ideas, just to get those all out there"* (Brian)

Similar to the design task with natural approaches, students started idea generation with existing ideas, however, they then intentionally looked for unconventional ideas to help them diverge in idea generation. After coming up with several existing ideas, Cathy, who worked on one-handed container opener problem, looked for unconventional ways to open a jar for her 7th idea:

> "*What is the coolest way you could open a jar? Well, my go-to answer for that is to smash it, and I'm not supposed to limit myself during idea generation, something tells me that smashing it isn't a good idea. Maybe if it was a controlled smash. Is there a way to control [it]... can you puncture a jar without getting stuff in your food…* ***Now, we are going to just cut the top off*** (Figure 7)**"** (Cathy).

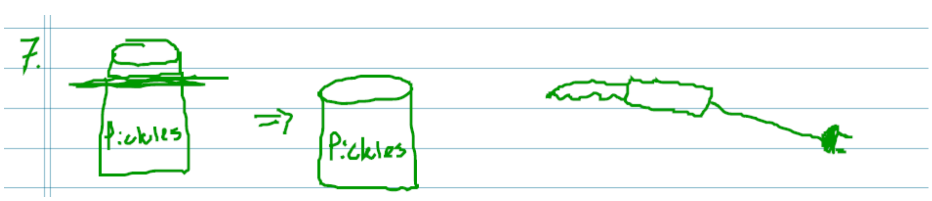

Figure 7. Cathy's idea to cut the top off using a knife to pen a container illustrates an unconventional method to open a jar

Unlike the design task with natural approaches, 8 out of 10 students were asked to utilize at least one idea generation technique, including *Design Heuristics*, Mind Mapping, Morphological Matrix, and SCAMPER. Using idea generation tools often helped students to approach idea generation in a structured way. For example, Brian was working on the snow transporter problem and used a Mind Map to generate ideas. His Mind Map incorporated central nodes that described the characteristics of his design such as power, snow movement, control direction, and braking. Then he created components for each central node. For example, he thought of different ways to power a snow transporter such as wind power, solar power, turbine, jet snow propulsion, etc., as shown in Figure 8.

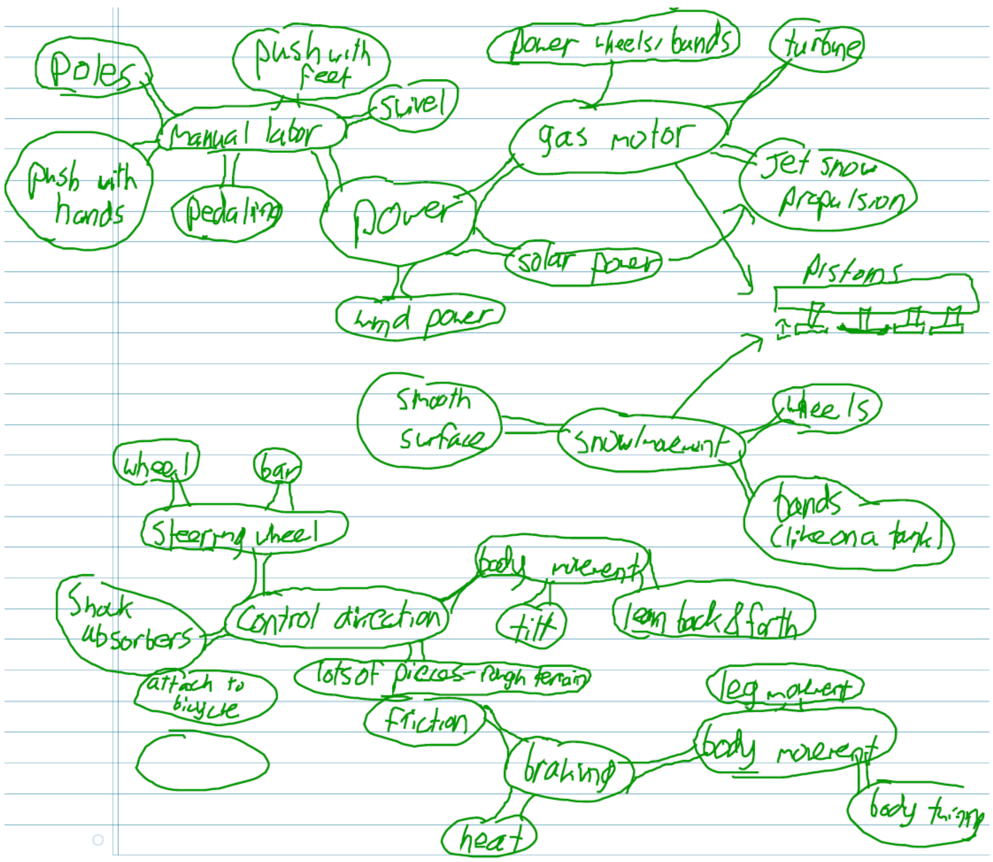

Figure 8. An example Mind Map used to generate ideas

After coming up with various different functions within the Mind Map, Brian combined multiple functions to create ideas. As seen in Figure 9, Concept (a) used wind power and smooth surface functions to create a snow sail. The user can control direction by turning the sail and brake by moving the sail away from the wind. Concept (b) used jet propulsion and smooth surface to create a snowmobile with a jet engine. By combining various functions from ideation techniques, students generated a number of concepts.

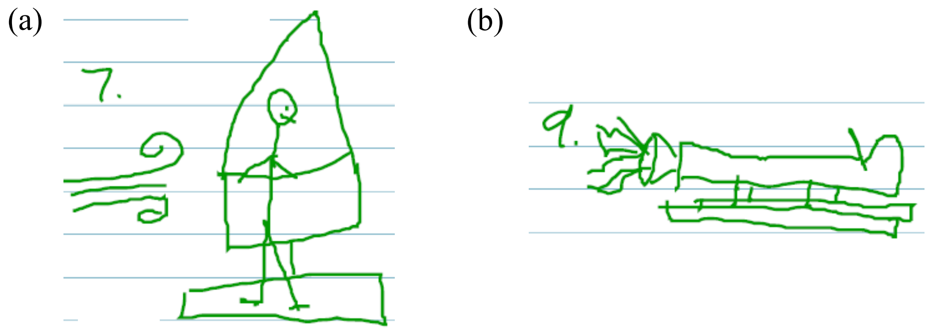

Figure 9. Ideas generated by combining components from the Mind Map. (a) Snow sail and (b) snowmobile with a jet.

In the post-block task, 10 out of 10 students articulated that coming up with a large quantity is important in idea generating. Students focused on generating a lot of ideas that may be wild and unconventional, which is considered a best practice in idea generation:

"*It's coming out with a large quantity of ideas, no matter how ridiculous*." (Henry)

Students said that they aimed to diverge to generate a large quantity of ideas and also gave themselves a target number of ideas to generate. In the post-block task, 6 out of 10 students articulated a clear goal in generating a minimum number of ideas they wanted to generate:

"*Let's say I want at least 10 ideas before I move onto the next phase.*" (Ethan)

By setting a clear quantity goal in idea generation, students generated a large quantity of ideas to ensure that they consider multiple ideas before evaluating them.

2.5.1.3 Concept Generation Outcomes

There were some notable differences in the natural and post-block ideation outcomes. Students who completed the snow transporter problem came up with an average of 4.3 (SE 1.93 concepts) and 14.8 concepts (SE 2.43 concepts) for the design task with natural approaches and post-block task, respectively with p-value of 0.07. Students who worked on one-hand container opener problem came up with an average of 4.4 (SE 0.6) and 14.6 concepts (SE 3.3) for the design task with natural approaches and post-block task, respectively with p-value of 0.04. When combining the average number of ideas generated for the two design tasks, students generated an average of 5.6 (SE 1.5) and 14.7 concepts (SE 2.7) for the design task with natural approaches and post-block task, respectively, with p-value of 0.0001 (Figure 10).

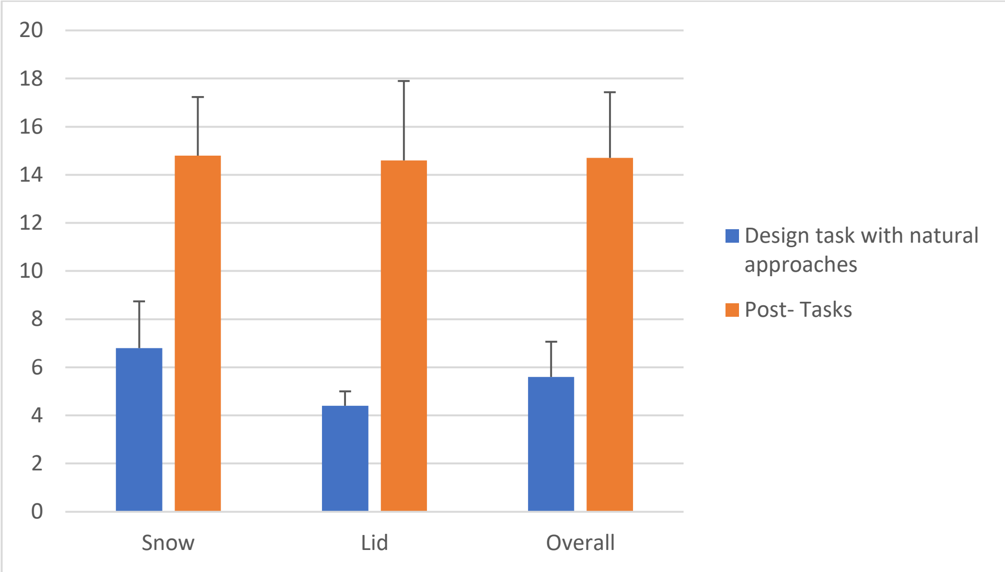

Figure 10. Average number of ideas generated in design task with natural approaches and post-block task

With regards to differences in variety, for the first variety metric we applied—idea type—students generated fewer expected concept types in the post-block task as compared to the natural ideation. For the one hand container opener problem, 41% (9 out of 22 ideas) of the concepts in the natural idea generation task and 26% (19 out of 73) ideas in the post-block task involved either base or lid being restrained and container being opened, representing the most obvious idea. Ideas in the "other" category, representing ideas that did not fit into the other categories as well as idea combinations, comprised 22% (5 out of 22 ideas) in the natural idea generation task versus 63% (46 out of 73) in post-block task. These comparisons are represented in Figure 11.a. In the snow transporter problem, 38% (13 out of 34 ideas) and 50% (37 out of 74 ideas) of the concepts were categorized as 'other' in natural idea generation and post-block task, respectively (represented in Figure 11.b).

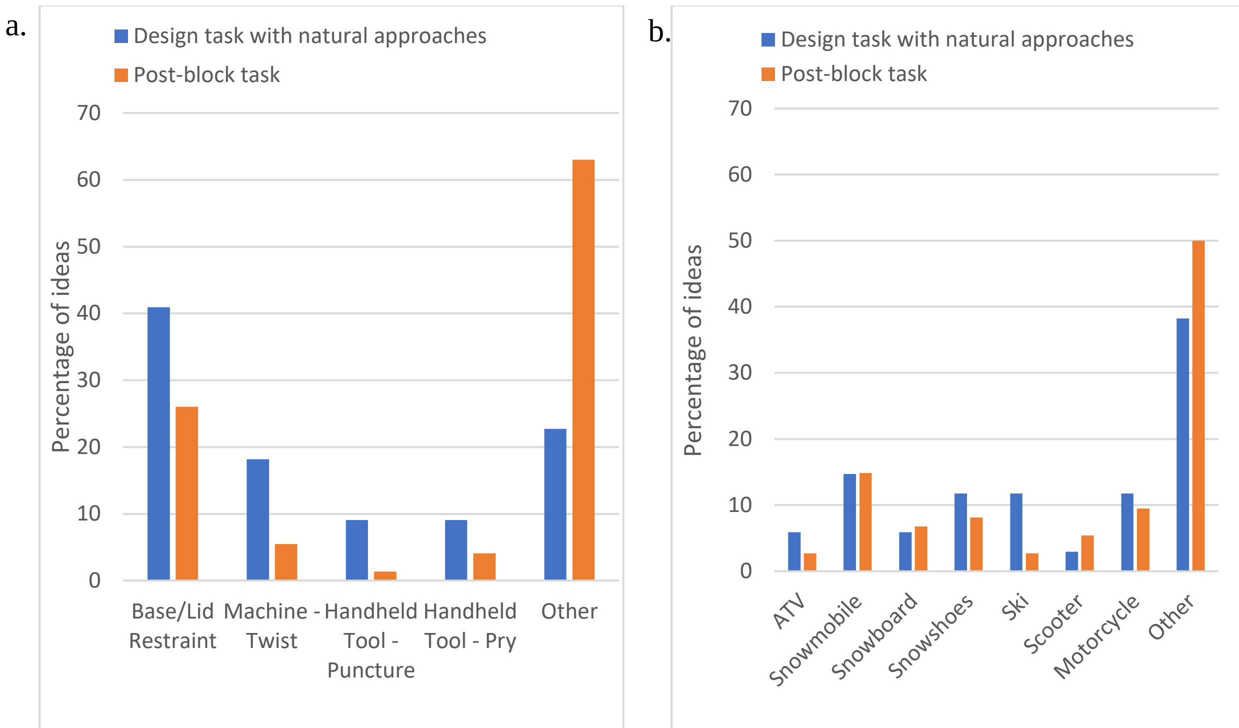

Figure 11. (a) Number of concepts grouped by solution types for the design task with natural approaches and post-block task for the one hand container opener problem. (b) Number of concepts grouped by solution types for the design task with natural approaches and post-block task for the snow transporter problem.

We saw a similar trend of more unconventional concepts generated for the post-block task when using the second variety metric we applied—the frequency of unusual features. By sorting ideas into bins of similar ideas, we found that on average, 0.8 (SE 0.4) and 1.3 (SE 0.5) bins were occupied by only one student in natural ideation and post-block task, respectively, with the p-value of 0.41. This indicates that on average, students generated less than one (0.8) unique feature during natural ideation while students came up with more than one (1.3) unique sub-feature in post-block task. On average, 1.3 (SE 0.5) and 2.8 (SE 0.6) bins were occupied by two or less students in natural idea generation and post-block tasks, respectively, with the p-value of 0.01. On average, 1.9 (SE 0.6) and 4.5 (SE 0.6) bins were occupied by three or less students in natural ideation and post-block task, respectively, with the p-value of 0.002 (Figure 12); in other words, students in natural ideation task came up with on average 1.9 features unique to three or less students while students in post-block task generated on average 4.5 sub-features unique sub-features unique to three or less students. This analysis shows that students came up with more unique features of ideas in post-block task.

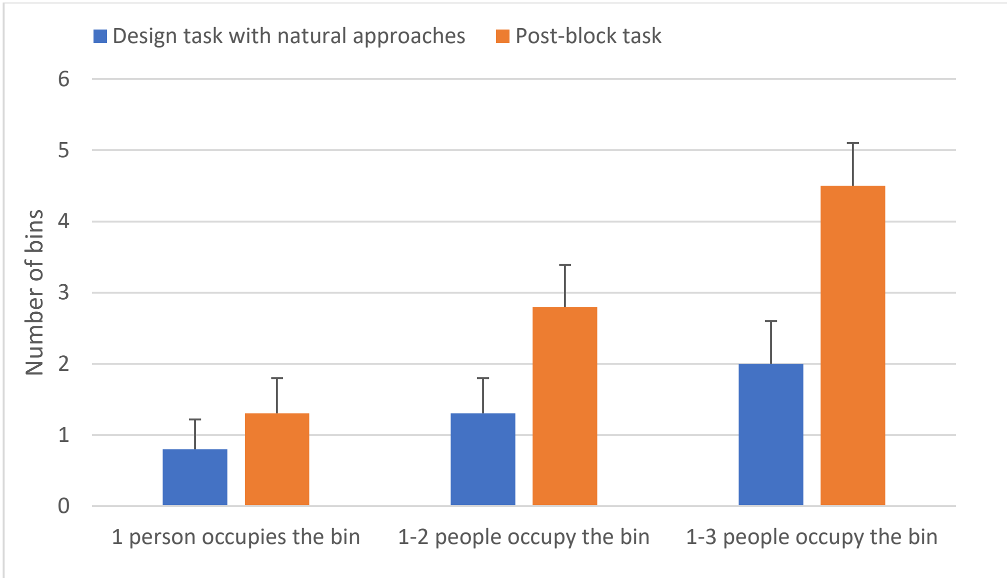

Figure 12. Number of bins occupied by 1, 1-2, or 1-3 students

Idea fixation was lower in post-block task ideas as compared to pre-block task ideas. In the pre-block task, 4 out of 10 students demonstrated fixation compared to 1 out of 10 students in post-block task. Students in the pre-block task often started generating ideas and continued to come up with same types of ideas. For example, Isaac worked on one-handed container opener for his pre-block task. His first two ideas and last two ideas emphasized restraining the base of a can to open the top (Figure 13), demonstrating that he generated same types of ideas in the beginning and end of his idea generation. In the post-block task, Henry was working on the low-skilled transportation problem. His first two ideas were snow shoes and hovercraft while his last two ideas were a tug boat with spikes and tank for heavy snow terrains. His post-task ideas varied in terms of types of ideas he generated

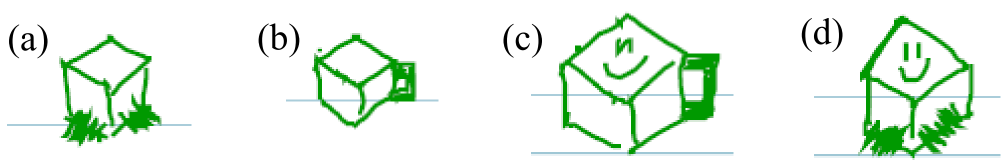

Figure 13. Henry's first two (a and b) and last two (c and d) ideas. (a) fixed device to hold the bottom of a jar, (b) portable device to hold the bottom of a jar, (c) portable and automated device to hold the jar and help you open it, and (d) fixed device to hold a jar that automatically helps you open a jar.

2.5.2 Concept Development Approaches

2.5.2.1 Natural Concept Development Approaches

In natural idea development, students showed minimal signs of developing ideas further than their initial generation. For example, Brian indicated that he did not expand on his initial ideas to make improvements:

> "*I didn't really expand on them too much, or I came up with things that I thought were problematic about them but I didn't do too much to change my design to make them better*." (Brian)

Students indicated that after they generated their ideas, they jumped into comparing and selecting ideas.

2.5.2.2 Post-Block Concept Development Approaches

In the post-block task, 10 out of 10 students intentionally developed ideas and 6 out of 10 students separated idea generation and development as two distinct phases in design. For example:

> "*Let's breakdown the process beforehand. And dividing it in terms of the blocks. Idea generation. Concept development. Concept selection. Okay, so we're on idea generation*." (Ethan)

By articulating idea development as a phase, students set aside time to build on their previous ideas. Students said that after coming up with initial ideas, they used idea development strategies such as Design Heuristics to help them build and on their initial ideas.

> "*Once I feel like I was slowing down, **I think I started switching over to development and that's when I used the design heuristic cards and shuffled them.** That's when I came up with, I think, 11 to 22 [concepts]*." (Isaac)

By having explicit idea generation and development phases, students build on their initial ideas to ultimately have a larger quantity of ideas.

2.5.2.3 Concept Development Outcomes

There were differences in the number of developed ideas students generated naturally and post-block. We counted ideas to be developed if students 1) combined components of previous ideas, 2) built on previous ideas, and 3) came back to initial ideas to further develop them. In general, students in natural idea development did not develop their initial ideas. Seven out of 10 students did not develop ideas in natural idea development while 1 out of 10 students did not develop initial ideas in the post-block task. Students who completed the snow transporter problem developed between 0 to 1 concept with an average of 0.2 (SE 0.2 concepts) during natural development; students in post-block task developed between 0 to 10 concepts with an average of 5 concepts (SE 1.58 concepts), with p-value of 0.04. Students who worked on one-hand container opener problem developed between 0 to 3 concepts with an average of 0.8 (SE 0.58) concepts in natural development; students in post-block task developed 1 to 8 concepts with an average of 4.2 concepts (SE 1.62), with p-value of 0.17. When combining the average number of ideas developed for the two design tasks, students developed an average of 0.5 (SE 0.3) and 4.6 concepts (SE 1.07) for natural development and post-block task, respectively, with p-value of 0.01. These results are represented in Figure 14.

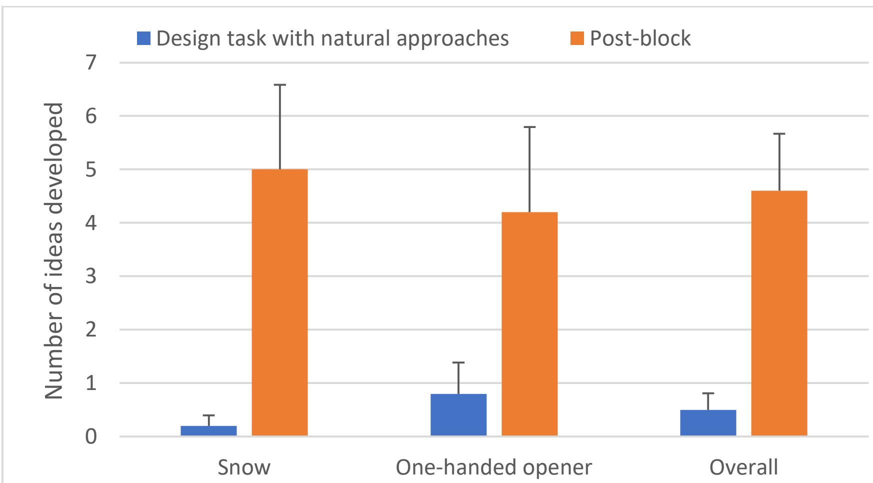

Figure 14. Quantity of developed ideas

2.5.3 Concept Selection Approaches

<u>2.5.3.1 Natural Concept Selection Approaches</u>

During the natural concept selection, students lacked structure in how they selected the most promising idea. Five out of 10 students used intuition to select ideas and they showed favoritism for ideas. Students demonstrated that they selected their best idea using their intuition without articulating why they are selecting a particular idea. For example:

> "*Basically, just either picking your best idea, or the one that you think is the best, I'd say*" (Grace)

Also, students showed favoritism and eliminated ideas that were competing with their favorite ideas without properly evaluating multiple ideas:

> "*I mean, what's going on in my head, pretty much right now, is I very much prefer my first idea with the rubber bands, or whatever. I'm just going to neglect the second idea*" (Daniel)

In selecting ideas, 9 out of 10 students came up with inconsistent lists to compare ideas in natural idea selection. For example, Henry was working on the personal transportation problem. During idea selection, Henry emphasized that his idea with treads would be good for recreation and quad copter would be safer:

> ***"****I really like number one, the treads and number four, the quad copter****.*** *I think both of these have a lot of strengths and uses and I think more use for different types of things.* ***The treads are more for recreation and the quad-copter's more for safety.*** *It depends on what you're using them for, but if* ***I have to say which one is the best solution with the design prompt in mind and saying that this is for personal use*** *and skiing and snowboarding are given as examples.* ***I think the treads are the best one for this****."* (Henry)

Henry did not use consistent criteria to compare all his ideas. He considered quad-copter as a safe design, but he did not consider safety of the tread idea. Although he listed some benefits of his ideas, he ultimately picked his tread idea for its convenience in personal use. Henry did not use clear structure in his concept selection.

In natural concept selection, when students used idea selection methods, such as Pugh Chart, their fixation, and favoritism still affected idea selection. For example, despite having evaluation criteria for Pugh Chart, students demonstrated that they were bias in rating their favorite idea and arbitrarily came up with ratings:

> *"You come up with a bunch of criteria that you want to evaluate your product with and then you assign a weight to each one of the criteria… Then you add up the numbers and get the highest rating.* ***We just come up with random numbers. If we like this design a lot, we like assign it higher scores."*** (Andrea)

Students also created a list of pros and cons to help them evaluate ideas. However, students favored ideas they perceived as having the most number of pros and minimized the effects of cons:

> "*This is already my favorite one, and the one I want to go with, but going through these pro-con lists is going to let me put a numeric value to the pros and cons of each of my design, and take my preferences out of it, which is why I'm doing this…The only two of my designs that didn't come out even with the pro and cons were the snow ATV and the snow ATV with treads.* ***I was able to decide on the one with treads because it had more pros than cons***." (Cathy)

After coming up with a list of pros and cons for her ideas, Cathy selected ideas with the most pros and least cons. She even indicated that before generating a list of pros and cons, she knew her favorite idea. At the end, she ended up picking her favorite idea with the most pros, which demonstrated that despite using concept selection methods, being attached to a favorite idea affected selecting their final idea.

2.5.3.2 Post-Block Concept Evaluation Approaches

After completing the learning blocks, students systematically organized their ideas into groups and used concept selection methods such as a Pugh Chart to select their final idea. After generating a large quantity of ideas, 5 out of 10 students grouped their ideas based on similarities. For many students, initial grouping of ideas helped them discard similar ideas before using Pugh Chart. Eight out of 10 students used Pugh Chart; students listed important criteria or requirements for their ideas. Then students often assigned weighing values for each criterion with minimal justification:

> "*I think, well, the number one is probably going to be like ease of use and I'm going to weight that as a solid five. And then I'm going to say cost because I feel like they're going to buy a lot of them. It's also important. That's a four. And then let's just like feasibility. Then that also a four and then ...we'll just say what else is important. storage ability is important. So, ease of use for the twist and pry. I think that one will get a solid ... I think that one gets a one because it is ... I mean, it's automatic but you still have to get the jar and all that to line up and that might take a little bit of difficulty.*" (Henry)

Henry came up with weighing values based on what believed to be important. After coming up with criteria and weighing values, students attempted to be objective in evaluated ideas that based on how well each idea meets the criteria. Students compared ideas and depending on the comparison, they assigned appropriate values:

> "*I think I'll use Pugh Chart and stuff to have an objective voice. I'm just not arbitrarily picking something to do. I can just go through and say, "This is why I did it that way.*" (Isaac)

Overall, in the post-block task, students attempted to be objective in selecting their idea using methods such as the Pugh Chart but their idea selection was influenced by their perception of what criteria were important in their final idea. While they showed improvement in using a structure, students struggled with coming up with fair evaluation criteria.

2.5.3.3 Concept Selection Outcomes

During natural idea selection, 4 out of 10 students selected ideas by focusing on a single criterion and they showed minimal evaluation and comparison of multiple ideas. Only 1 out of 10 students prioritized multiple criteria by ranking or providing weighing values for each criterion. David was working on the one-hand container opener problem. He selected idea based on practicality without considering or prioritizing other criteria:

> "*Alright, so my winner is the first idea, because **I think that would probably actually work. Granted a person is, you know, strong enough to open a jar.** That's the big constraint here.*" (David)

After going through the learning blocks, 8 out of 10 students considered multiple criteria and compared their ideas before choosing their final one. Also, 9 out of 10 students prioritized multiple criteria by ranking criteria or providing a weighing value for each criterion. Students heavily relied on using Pugh Chart to help them compare ideas and placed numerical values depending on their perceived quality of each idea. At the end, students added up all the values and became focused on picking the idea with the highest rating:

> "*All right. To total these up, taking the sum of the product of the weight and the scores, idea number one gets five, ten, 12 points. Number two gets ... nine, 11.*

Then number three gets 14. So objectively here, number three is the winner (Figure 15).” (Cathy)

Figure 15. Cathy’s Pugh Chart used for concept selection.
Although Cathy’s three ideas came out to be similar in the total value (12, 11, and 14 units) in her Pugh Chart, Cathy picked idea 3, which had 14 units without further questioning or reasoning her choice.

2.6 Discussion

Across all three phases of idea generation, development, and selection, mechanical engineering students demonstrated novice approaches in their natural ways. After going through the Learning Blocks, we saw substantial differences in their approaches. In the next few paragraphs, we describe how students’ approaches changed.

During idea generation, we found that in natural idea generation, students limited the alternatives they considered, created additional assumed requirements, and relied on existing solutions. This finding builds on previous research documenting challenges designers encounter in generating a large quantity of ideas (Cross, Nigel, 2001) that deviate from existing solutions (Linsey et al., 2010). Using their natural approaches, students did not leverage any idea generation strategies to support them in coming up with alternatives. Relying on existing solutions and limited use of idea generation strategies led to signs of fixation that directed students to focus on variations of similar concepts, similar to previous findings from other researchers (Jansson & Smith, 1991; Purcell & Gero, 1996). After completing the learning blocks, students adopted some of the best practices in idea generation. Students clearly articulated that generating a large quantity of ideas is important and many students set a goal to generate a specific number of ideas. Students adopted some of the ideation techniques documented in the literature such as Mind Map, Morphological Analysis, and Design Heuristics to help them generate ideas. By equipping students in idea generation techniques and teaching them best practices, students generated a greater number of ideas and came up with varying types of ideas as well, which are considered best practices (Brophy, 2001; Zenios et al., 2009). Our results mirror previous studies demonstrating the benefits of systematically applying idea generation techniques to support quantity and quality of ideas created (Daly et al., 2016; Lee et al., 2018; White, Wood, & Jensen, 2012).

In students' natural idea development, students placed minimal emphasis on developing their initial concepts and showed minimal improvements to their previous ideas. Students approached ideation as a linear path with little to no iteration, similar to findings from other research (Crismond & Adams, 2012). After completing the learning blocks, students intentionally built on their initial ideas to further develop their ideas. Students separated idea generation and development as two distinct phases; thus, students intentionally spent time building on previous ideas and combining different features of multiple ideas to create new ideas. While students made improvements, literature describes that experts iterate often and go through the idea generation and development phases multiple times (Brophy, 2001; Crismond & Adams, 2012). Although students were intentional in setting aside time to develop ideas, students did not engage in multiple cycles of development. Research has demonstrated that experienced designers engage in multiple iterations and look for new perspectives to build on previous ideas (Crismond & Adams, 2012; Gerber, 2008).

As students naturally selected ideas, students used intuition and picked a favorite idea. Students showed signs of fixation throughout the design task, similar to previous studies (Jansson & Smith, 1991; Purcell & Gero, 1996) and our study demonstrated that signs of fixation persisted through idea selection. In the post-block task, students used concept selection methods like a Pugh Chart and sought more objective evaluation, which has been a common method to support idea selection demonstrated in the literature (Pugh, 1991). Students in post-block task articulated important criteria and balanced benefits and trade-offs in selecting their idea, which are important characteristics described in the literature (Crismond & Adams, 2012; Nelson & Stolterman, 2003). However, students often arbitrary assigned numerical values to design criteria and picked the idea with the highest rating at the end. In addition to balancing benefits and trade-offs, research has demonstrated that experts use analytical methods (McKenna, Linsenmeier, & Glucksberg, 2008), back-of-the-envelope calculations (Linder & Flowers, 2001), and prototyping in selecting ideas (Lauff et al., 2018).

Although student participants had multiple design experiences through both classes and co-curricular activities, students had not adopted best practices in idea phases. This indicates that providing instructions can facilitate an update of appropriate strategies to support idea generation, development, and selection. The Learning blocks are one tool to provide support as students engage in design. The on-demand and option to learn design skills in any order may be particularly supportive for students since students in design projects will need to develop specific skills when they need them.

Overall, the Learning Blocks showed evidence in supporting students to adopt evidenced-based design practices in lessons that last 5-7 hours. In addition to this study that supported idea generation, development, and selection, another study has demonstrated the benefits of the Learning Blocks in aiding interview practices to engage with stakeholders (Young et al., 2017). The Learning Blocks will continue to evolve to include best practices in idea generation, development, and selection based on new research findings. By providing regular updates, we can ensure that students are learning and adopting most up-to-date practices.

2.6.1 Limitations

This study examined students from a single large Midwestern institution in the U.S. with educational emphasis on design in the engineering curriculum, and findings in other types of engineering programs may differ. The study was designed to gain an in-depth understanding of students' idea generation, development, and selection practices. Instead of claiming generalizability, qualitative studies emphasize transferability of the results, allowing the reader to make connections between this study and their own situation (Creswell, 2013; Patton, 2015; Saldaña, 2011). Also, in this study, students were asked to work individually and complete the task in one sitting. In practice, engineers often work on design tasks for longer periods of time and they often have opportunities to work in teams and engage with stakeholders to gain feedback throughout their tasks. Also, this study examined how students' can change their behaviors after going through a learning intervention. The study does not claim students' long-term ability to retain the information.

2.6.2 Implications

A flexible learning model that breaks down learning objectives into each phase of a design process can support design education to support successful end outcomes. For students, open-ended design experiences through co-curricular activities and internships are not sufficient to teach best practices in idea generation, development, and selection because these activities may lack explicit instruction. Many design activities emphasize achieving success at the end and may lack scaffolding to support designers through each phase of a design process. Thus, there is value in articulating clear goals within each phase and emphasizing reflection to ensure that designers are meeting their goals in each phase of their design. Breaking down design phases to provide support early in design can help engineering designers to achieve success in their overall design projects; as demonstrated in the literature, implementing best-practices is particularly important in the front-end, which includes problem definition and idea generation, because the front-end activities set the trajectory for the rest of design (Brophy, 2001; Pahl & Beitz, 1991)

In teaching design courses, instructors can leverage a flexible learning model to present materials to students when they need it. In a typical one- or two-semester design course, students work on large projects and move through their projects at different pace, making it challenging to provide relevant material at the right time for all students. By leveraging flexible learning modules that emphasize different phases of a design process, students can learn and implement relevant design practices when they need them. Additionally, since an asynchronous learning intervention has demonstrated to support junior and senior engineering students, similar learning interventions may be used to aid early practitioners to adopt best practices in different design phases.

2.7 Conclusions

This study examined students' natural approaches to idea generation, development, and selection that they had theoretically developed through their prior design experiences. These approaches were flawed, however, as students created assumed requirements that limited their divergent thinking, relied on existing solutions, generated few ideas, and selected their favorite concept at the end. After completing the Learning Blocks, students adopted some of the evidence-based design practices documented in the literature. In post-block idea generation, students minimized early evaluation, generated unconventional ideas, focused on generating a large quantity of ideas. During post-block idea development, students set aside time to iterate, combine, and build on existing ideas. Afterward, students used concept selection methods to balance benefits and tradeoffs of ideas before finalizing their idea. This study demonstrates that providing concrete lessons using asynchronous Learning Blocks can support students to develop clear approaches and goals in each phase of idea generation, development, and selection. By supporting students' design practices, we can equip students to develop innovative solutions to solve complex, open-ended design problems.

Appendix A1. Problem statements provided to the students

Low-Skill Snow Transporter Problem

Today skis and snowboards are widely used as personal transportation tools on snow. But to be able to use them, a lot of skill and experience are required that a user cannot normally learn within one day. Moreover, skis and snowboards cannot run uphill easily. It would be better if there were other options of personal tools for transportation on snow, which still allowed the user to control direction and braking, but did not require much time to learn how to use.

Design a way for individuals without lots of skill and experience skiing or snowboarding to transport themselves on snow.

Develop solutions for this problem and select a final solution at the end. **You can take as long as you need but spend a minimum of 1 hour to complete this task**. If you need any resources, please let me know.

One-Hand Opener for Lidded Food Containers Problem

The local rehabilitation center helps to treat thousands of stroke patients each year. Many individuals who have had a stroke are unable to perform bilateral tasks, meaning they have limited or no use of one upper extremity (arm/shoulder). A common issue the hospital has observed with their stroke patients is in their ability to open jars and other lidded food containers. The ability to open lidded food containers is particularly important for patients who are living on their own, in which case they often don't have help around for even basic tasks. A solution to helping them open lidded food containers with one hand would go a long way in helping the patients to maintain their independence.

Design a way for individuals who have limited or no use of one upper extremity to open a lidded food container with one hand.

Develop solutions for this problem and select a final solution at the end. **You can take as long as you need but spend a minimum of 1 hour to complete this task.** If you need any resources, please let me know.

2.8 References

Adams, R. S., & Atman, C. J. (1999). Cognitive processes in iterative design behavior. In *FIE'99 Frontiers in Education. 29th Annual Frontiers in Education Conference. Designing the Future of Science and Engineering Education. Conference Proceedings (IEEE Cat. No.99CH37011* (Vol. 1, pp. 11A6/13-11A6/18 vol.1). https://doi.org/10.1109/FIE.1999.839114

Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*(1), 1–11.

Allen, M. (1962). *Morphological Creativity: The Miracle of Your Hidden Brain Power*. New Jersey: Prentice-Hall.

Altshuller, G. (1997). *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc.

Atman, C. J., Chimka, J. R., Bursic, K. M., & Nachtmann, H. L. (1999). A comparison of freshman and senior engineering design processes. *Design Studies*, *20*(2), 131–152. https://doi.org/10.1016/S0142-694X(98)00031-3

Bailey, K. (1994). *Methods of Social Research, 4th Edition*. New York, NY: The Free Press.

Ball, L. J., Evans, J. S. B. T., & Dennis, I. (1994). Cognitive processes in engineering design: a longitudinal study. *Ergonomics*, *37*(11), 1753–1786. https://doi.org/10.1080/00140139408964950

Baucus, M. S., Norton, W. I., Baucus, D. A., & Human, S. E. (2008). Fostering Creativity and Innovation without Encouraging Unethical Behavior. *Journal of Business Ethics*, *81*(1), 97–115. https://doi.org/10.1007/s10551-007-9483-4

Brand, S. (1995). *How Buildings Learn: What Happens After They're Built*. Penguin.

Brophy, D. R. (2001). Comparing the Attributes, Activities, and Performance of Divergent, Convergent, and Combination Thinkers. *Creativity Research Journal*, *13*(3–4), 439–455.

Cardoso, C., Badke-Schaub, P., & Eris, O. (2016). Inflection moments in design discourse: How questions drive problem framing during idea generation. *Design Studies*, *46*, 59–78. https://doi.org/10.1016/j.destud.2016.07.002

Center for Socially Engaged Design. (n.d.). Retrieved September 10, 2018, from http://csed.engin.umich.edu/

Christian, J. L., Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). Design Heuristics to Support Two Modes of Idea Generation: Initiating Ideas and Transitioning Among Concepts. Presented at the Annual Conference of American Society of Engineering Education, San Antonio, Texas.

Creswell, J. W. (2013). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, *101*(4), 738–797. https://doi.org/10.1002/j.2168-9830.2012.tb01127.x

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Cross, Nigel. (2001). Design cognition: Results from protocol and other empirical studies of design activity. *Design Knowing and Learning: Cognition in Design Education*, *7*, 9–103.

Daly, S., McGowan, A., & Papalambros, P. (2013). Using qualitative research methods in engineering design research. *Proceedings of the International Conference on Engineering Design, ICED*, *2*, 203–212.

Daly, S. R., Adams, R. S., & Bodner, G. M. (2012). What Does it Mean to Design? A Qualitative Investigation of Design Professionals' Experiences. *Journal of Engineering Education*, *101*(2), 187–219.

Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). Assessing Design Heuristics for Idea Generation in an Introductory Engineering Course. *International Journal of Engineering Education*, *28*(2), 1–11.

Daly, S. R., Seifert, C. M., Yilmaz, S., & Gonzalez, R. (2016). Comparing Ideation Techniques for Beginning Designers. *Journal of Mechanical Design*, *138*(10), 101108-101108–101112. https://doi.org/10.1115/1.4034087

Diehl, M., & Stroebe, W. (1987). Productivity loss in brainstorming groups: Toward the solution of a riddle. *Journal of Personality and Social Psychology*, *53*(3), 497–509. https://doi.org/10.1037/0022-3514.53.3.497

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6

Dubberly, H. (2004). *How do you design? A compendium of Models*. San Francisco, CA: Dubberly Design Office.

Duderstadt, J. (2008). Engineering for a changing world: A roadmap to the future of engineering practice, research, and education. *Ann Arbor, MI: The Millennium Project*. Retrieved from http://milproj.dc.umich.edu/.

Eberle, R. (1995). *SCAMPER*. Waco, TX: Prufrock.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review*, *87*(3), 215–251. https://doi.org/10.1037/0033-295X.87.3.215

Ericsson, K. A., & Simon, H. A. (1993). *Protocol Analysis - Rev'd Edition: Verbal Reports as Data* (revised edition edition). Cambridge, Mass: A Bradford Book.

Ford, C. M., & Gioia, D. A. (2000). Factors Influencing Creativity in the Domain of Managerial Decision Making ,
Factors Influencing Creativity in the Domain of Managerial Decision Making. *Journal of Management*, *26*(4), 705–732. https://doi.org/10.1177/014920630002600406

Gerber, E. (2008). Developing an Idea by Throwing it Away. *Ambidextrous Magazine*. Retrieved from https://www.scholars.northwestern.edu/en/publications/developing-an-idea-by-throwing-it-away-ambidextrous-magazine

Goldschmidt, G. (1995). The designer as a team o f one. *Design Studies*, *16*(2), 189–209. https://doi.org/10.1016/0142-694X(94)00009-3

Gordon, R. (1975). *Interviewing: Strategy, Techniques and Tactics*. Illinois: Dorsey Press.

Gordon, W. J. J. (1961). *Synectics*. New York: Harper & Row.

Hernandez, N. V., Schmidt, L. C., & Okudan, G. E. (2013). Systematic Ideation Effectiveness Study of TRIZ. *Journal of Mechanical Design*, *135*(10), 101009-101009–101010. https://doi.org/10.1115/1.4024976

Heslin, P. A. (2009). Better than brainstorming? Potential contextual boundary conditions to brainwriting for idea generation in organizations. *Journal of Occupational and Organizational Psychology*, *82*(1), 129–145. https://doi.org/10.1348/096317908X285642

Huang, H.-Z., Liu, Y., Li, Y., Xue, L., & Wang, Z. (2013). New evaluation methods for conceptual design selection using computational intelligence techniques. *Journal of Mechanical Science and Technology*, *27*(3), 733–746. https://doi.org/10.1007/s12206-013-0123-x

Hutchinson, S., & Wilson, H. (1992). Validity Threats in Scheduled Semistructured Research Interviews. *Nursing Research*, *41*(2), 117–119.

IDEO. (2002). *IDEO Method Cards: 51 Ways to Inspire Design*. Palo Alto: IDEO.

Jablokow, K. W., Teerlink, W., Yilmaz, S., Daly, S. R., Silk, E. M., & Wehr, C. (2015, August). *Ideation variety in mechanical design: Examining the effects of cognitive style and design heuristics*. Paper presented at the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2015), Boston, MA, USA.

Jacob, S., & Furgerson, S. (2012). Writing Interview Protocols and Conducting Interviews: Tips for Students New to the Field of Qualitative Research. *The Qualitative Report*, *17*(42), 1–10.

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11.

Kelley, T., & Littman, J. (2001). *The art of innovation*. Doubleday, NY: Currency.

Kim, E., Chung, J., Beckman, S., & Agogino, A. M. (2016). Design Roadmapping: A Framework and Case Study on Planning Development of High-Tech Products in Silicon Valley. *Journal of Mechanical Design*, *138*(10), 101106-101106–101111. https://doi.org/10.1115/1.4034221

Kim, J., & Wilemon, D. (2002). Focusing the fuzzy front-end in new product development. *R&D Management*, *32*(4), 269–279.

Kramer, J. M., Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2015). Investigating the Impacts of Design Heuristics on Idea Initiation and Development. *Advances in Engineering Education.*, *4*(4), 1–26.

Kudrowitz, B. M., & Wallace, D. (2013). Assessing the quality of ideas from prolific, early-stage product ideation. *Journal of Engineering Design*, *24*(2), 120–139. https://doi.org/10.1080/09544828.2012.676633

Lauff, C. A., Kotys-Schwartz, D., & Rentschler, M. E. (2018). What is a Prototype? What are the Roles of Prototypes in Companies? *Journal of Mechanical Design*, *140*(6), 061102-061102–061112. https://doi.org/10.1115/1.4039340

Lee, J. W., Daly, S. R., Huang-Saad, A. Y., Seifert, C. M., & Lutz, J. (2018). Using design strategies from microfluidic device patents to support idea generation. *Microfluidics and Nanofluidics*, *22*(7), 70. https://doi.org/10.1007/s10404-018-2089-6

Lee, Jin Woo, Ostrowski, A. K., Daly, S. R., Huang-Saad, A. Y., & Seifert, C. M. (2017). Extending Design Heuristics From Mechanical Engineering to a Biomedical Projects Course, V003T04A007. https://doi.org/10.1115/DETC2017-67795

Linder, B., & Flowers, W. (2001). Integrating Engineering Science and Design: A Definition and Discussion. *International Journal of Engineering Education*, *17*(4), 436–439.

Linsey, J. S., Green, M. G., Murphy, J. T., Wood, K. L., & Markman, A. B. (2005). “Collaborating To Success”: An Experimental Study of Group Idea Generation Techniques, 277–290. https://doi.org/10.1115/DETC2005-85351

Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., & Schunn, C. (2010). A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty. *Journal of Mechanical Design*, *132*(4), 041003. https://doi.org/10.1115/1.4001110

Linsey, J. S., Wood, K. L., & Markman, A. B. (2008). Increasing Innovation: Presentation and Evaluation of the Wordtree Design-by-Analogy Method, 21–32. https://doi.org/10.1115/DETC2008-49317

Liu, Y.-C., Chakrabarti, A., & Bligh, T. (2003). Towards an ‘ideal’ approach for concept generation. *Design Studies*, *24*(4), 341–355.

Louise Barriball, K., & While, A. (1994). Collecting data using a semi-structured interview: a discussion paper. *Journal of Advanced Nursing*, *19*(2), 328–335. https://doi.org/10.1111/j.1365-2648.1994.tb01088.x

Marsh, E. (1993). *Hierarchical Decision Making in Machine Design*.

McKenna, A., Linsenmeier, R., & Glucksberg, M. (2008). Characterizing computational adaptive expertise. *ASEE Annual Conference and Exposition, Conference Proceedings*. Retrieved from https://asu.pure.elsevier.com/en/publications/characterizing-computational-adaptive-expertise-2

McMahon, K., Ruggeri, A., Kämmer, J. E., & Katsikopoulos, K. V. (2016). Beyond Idea Generation: The Power of Groups in Developing Ideas. *Creativity Research Journal*, *28*(3), 247–257. https://doi.org/10.1080/10400419.2016.1195637

Nelson, H. G., & Stolterman, E. (2003). *The Design Way: Intentional Change in an Unpredictable World : Foundations and Fundamentals of Design Competence*. Educational Technology.

Osborn, A. F. (1963). *Applied imagination: Principles and procedures of creative problem-solving* (3rd Rev Edition). Buffalo, NY: Scribner.

Osborne, J. (2008). *Best practices in quantitative methods*. Thousand Oaks, CA: Sage.

Ostrowski, A., Lee, J. W., Daly, S., Huang-Saad, A., & Seifert, C. (2017). Design in Biomedical Engineering: Student Applications of Design Heuristics as a Tool for Idea Generation. In *American Society for Engineering Education*. Columbus, Ohio.

Pahl, G., & Beitz, W. (1991). *Engineering Design: A Systematic Approach*. Berlin: Springer.

Patton, M. (2015). *Qualitative Research & Evaluation Methods: Integrating Theory and Practice* (4th ed.). Thousand Oaks, CA: SAGE Publications.

Pugh, S. (1991). *Total Design: Integrated Methods for Successful Product Engineering*. Wokingham, England ; Reading, Mass: Addison-Wesley.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies*, *17*(4), 363–383. https://doi.org/10.1016/S0142-694X(96)00023-3

Rechkemmer, A., Makhlouf, M., Wenger, J., Silk, E., Daly, S., McKilligan, S., & Jablokow, K. (2017). Examining the Effect of a Paradigm-Relatedness Problem-Framing Tool on Idea Generation. In *American Society for Engineering Education*. Columbus, OH.

Rietzschel, E. F., Nijstad, B. A., & Stroebe, W. (2006). Productivity is not enough: A comparison of interactive and nominal brainstorming groups on idea generation and selection. *Journal of Experimental Social Psychology*, *42*(2), 244–251. https://doi.org/10.1016/j.jesp.2005.04.005

Rowe, P. (1987). *Design thinking*. Cambridge, MA: The MIT Press.

Rubenson, D. L., & Runco, M. A. (n.d.). The Psychoeconomic View of Creative Work in Groups and Organizations. *Creativity and Innovation Management*, *4*(4), 232–241. https://doi.org/10.1111/j.1467-8691.1995.tb00228.x

Saldaña, J. (2011). *Fundamentals of Qualitative Research*. Oxford University Press, USA.

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign*, *4*(1), 5–18. https://doi.org/10.1080/15710880701875068

Sevier, D. C., Jablokow, K., McKilligan, S., Daly, S. R., Baker, I. N., & Silk, E. M. (2017). Towards the Development of an Elaboration Metric for Concept Sketches, V003T04A006. https://doi.org/10.1115/DETC2017-67375

Shah, J. J., Kulkarni, S. V., & Vargas-Hernandez, N. (2000). Evaluation of idea generation methods for conceptual design: Effectiveness metrics and design of experiments. *Journal of Mechanical Design*, *122*(4), 377. https://doi.org/10.1115/1.1315592

Shah, J. J., Vargas-Hernandez, N., & Smith, S. M. (2003). Metrics for measuring ideation effectiveness. *Design Studies*, *24*(2), 111–134.

Shah, J. J., Vargas-Hernandez, N., Summers, J. D., & Kulkarni, S. (2001). Collaborative Sketching (C-Sketch) — An Idea Generation Technique for Engineering Design. *The Journal of Creative Behavior*, *35*(3), 168–198. https://doi.org/10.1002/j.2162-6057.2001.tb01045.x

Sheppard, S., Macatangay, K., Colby, A., & Sullivan, W. (2009). *Educating engineers: Design for the future of the field*. San Francisco: Jossey-Bass.

Toh, C. A., & Miller, S. R. (2015). How engineering teams select design concepts: A view through the lens of creativity. *Design Studies*, *38*, 111–138. https://doi.org/10.1016/j.destud.2015.03.001

Ullman, D. G., Dietterich, T. G., & Stauffer, L. A. (1988). A model of the mechanical design process based on empirical data. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, *2*(01), 33–52.

van Someren, M. W., Barnard, Y. F., & Sandberg, J. a. C. (1994). *The think aloud method: a practical approach to modelling cognitive processes*. LondenAcademic Press0127142703978012714270 8. Retrieved from https://dare.uva.nl/search?identifier=7fef37d5-8ead-44c6-af62-0feeea18d445

White, C. K., Wood, K. L., & Jensen, D. (2012). From Brainstorming to C-Sketch to Principles of Historical Innovators: Ideation Techniques to Enhance Student Creativity. *Journal of STEM Education: Innovations and Research*, *13*(5). Retrieved from http://www.jstem.org/index.php/JSTEM/article/view/1621

Youmans, R. J., & Arciszewski, T. (2014). Design fixation: Classifications and modern methods of prevention. *AI EDAM*, *28*(2), 129–137. https://doi.org/10.1017/S0890060414000043

Young, M. R., Daly, S. R., Hoffman, S. L., Sienko, K. H., & Gilleran, M. A. (2017). Assessment of a Novel Learning Block Model for Engineering Design Skill Development: A Case Example for Engineering Design Interviewing. Presented at the 2017 ASEE Annual Conference & Exposition, Columbus, OH. Retrieved from https://peer.asee.org/assessment-of-a-novel-learning-block-model-for-engineering-design-skill-development-a-case-example-for-engineering-design-interviewing

Zenios, S., Makower, J., Yock, P., Brinton, T. J., Kumar, U. N., Denend, L., & Krummel, T. M. (2009). *Biodesign: The Process of Innovating Medical Technologies* (1 edition). Cambridge, UK ; New York: Cambridge University Press.

Chapter 3: Start with Solutions or Problems? Design Processes in Academia and Industry

3.1 Abstract

Sharing design outcomes between academia and industry links the latest research to product development and innovation. As academia and industry have different constraints due to their environmental contexts, their design processes likely differ. To investigate these processes, we focus on exploring front-end design processes for academic and industry designers developing medical devices in a qualitative study. Our findings show that industry engineers describe the design process sequence as "problem definition, solution exploration, detail design, evaluation, and communication." Academic engineers, in contrast, describe their process as beginning with solution methods, then searching for problems and evaluating the compatibility between problems and solution methods (the "solution mapping process," and finally communicating their findings through publications. Understanding their differing processes can facilitate knowledge sharing and promote collaboration between academia and industry.

3.2 Introduction

Innovation in engineering design may be facilitated by collaborations between industry and academics (Gelijns & Their, 2002). Academic connections with industry may maximize the potential to develop innovative ideas and methods for commercial products (National Science Foundation, 2010). Universities have been an important source of creating new knowledge and contributing to economic growth as they support industrial innovation (Aghion, Dewatripont, & Stein 2008; Gibbons & Johnston, 1974; Nelson, 1986). Recently, there has been an increasing call for companies to outsource early-stage design innovations to start-ups and academic labs (Gura, 2015). However, there is a mismatch between technologies developed in academic labs and commercialization in industry (Huang-Saad, Fay, & Sheridan 2016). To facilitate collaboration, the cultural gap between industry and academia needs to be bridged to better understand each other's needs (Berman, 2008). Much of the literature on research links between academia and industry has concentrated on research commercialization, technology transfer, patents, and publication rights (Fulop & Couchman, 2006; Kruss, 2006; Lawson, 2013; Meagher & Copeland, 2006); however, there has been little research on design processes in academic versus industrial settings and it is unknown whether these two design organizations – academic and industry labs – follow the same or different design processes. Following a good design process can streamline the development of successful products (Dubberly, 2004), and optimizing design processes improves outcomes (Ottosson, 2001; Soosay & Hyland, 2004). To improve the end products, the processes themselves need continual refinement and redesign (Dubberly, 2004). It is important to understand design practices of academia and industry to maximize collaboration because ideas and technologies that have been successfully transferred from academia to industry have contributed to innovative outcomes (Grimpe & Hussinger, 2013).

As context is a key driver in design decision making, the goal of our work was to investigate differences in design processes based on their organizational context in academia and industry. The focus of our work was to explore front-end design processes, which include problem definition and concept generation (Zhang & Doll, 2001). A gap exists in divergent and convergent design processes at the design stage when the problem and solution are most open and evolving (as is the case in the design front-end) (Dorst & Cross, 2001), as well as the contextual factors that promote convergence and divergence in design processes. Additionally, the front-end of the design process has the largest potential for changes and improvements with the least effort because it focuses on conceptual rather than implemented designs (Cooper, 1993; Verganti, 1997). To investigate front-end design processes in academic and industry settings, we conducted semi-structured interviews of practicing designers in academia and industry. To limit variations in the results that could arise from disciplinary differences, we selected medical device designs.

Understanding front-end design processes of academic and industry practitioners can help to identify areas to further promote collaboration and optimize the strengths of academia and industry. Academic practitioners not only create new knowledge but also engage in translational research to develop technologies for commercialization. Industry often collaborates with academia to leverage new knowledge and technologies developed in academia. Understanding the design processes in these two settings is important for deciding where and when resources should be allocated and how to promote collaboration on design between industry and academia.

3.2.1 The Context of a Design Process

The organizational context of a design environment influences design processes and approaches (Pahl & Beitz, 1991) due to many constraints on decision-making processes, such as project timelines, expertise, and resources (Blessing & Chakrabarti, 2009; Goncher & Johri, 2015; Jonassen, 2000; Kilgore et al., 2007). Design is a situated and social process affected by its context rather than an isolated or well-defined condition (Bucciarelli 1994). On an organizational level, financial and resource limitations are known to constrain design practices (Bruce, Cooper, & Vazquez, 1999). Conflicts within companies have also been observed to affect design processes, such as a culture of competition among design, engineering and marketing departments (Cooper & Press, 1995) or resistance from senior management based on tradition-bound behaviors (Bruce, Cooper, and Vazquez, 1999). Team conflicts that are poorly managed can damage design outcomes (Greer, & Jehn, 2012) and lead to an increase in uncertainty (Paletz, Chan, & Schunn, 2017).

Better understanding of different organizational contexts provides opportunities to improve design processes (Johns, 2001; Rousseau & Fried, 2001). However, little is known about how context influences design approaches and outcomes. Academia and industry settings place different constraints on design processes and on innovation in design. Academic and industry professionals often have different goals, interests, and timelines that inform their behaviors (Bloedon & Stokes, 1994). These different contexts may both limit and facilitate different design choices and outcomes (Newell & Simon, 1972; Stokes, 2001).

3.2.2 Designing in academic contexts

Practitioners developing medical devices in industry and academic settings engage in design processes frequently as they develop novel device designs to address open-ended, ill-defined problems. Design has been defined as the search for solutions to ambiguous and ill-defined problems with many uncertainties (Cross, 2008; Jonassen, 2000; Visser, 2006). Design by academic practitioners was defined by Goel and Pirolli (1992) articulation of 12 features to describe the characteristics of a design task. For example, engineering designers in academia are bounded by non-negotiable constraints (such as the laws of thermodynamics and biological principles) as well as negotiable ones (such as social dynamics in work environment and political constraints in academia). Engineering designers in academia further demonstrate design characteristics by approaching problems with no right or wrong answers, only better or worse, and continuing to iterate and receive feedback on their work. A case can be made that much of the work of engineering designers in academia can be classified as aligning with characteristics that define design.

Design processes overlap with other complex processes in which practitioners likely engage. For example, research—a systematic investigation into a subject to increase knowledge (OECD, 2015) and technology transfer—further development and commercialization of scientific findings (Journal of Technology Transfer, n.d.) have some commonalities with design, such as ill-defined problems, better or worse answers instead of right or wrong, iterative feedback loops, and high costs associated with every action. While many engineering designers in academia also engage in research and technology transfer, the focus of this research was design decision making in line with traditional design process activities as outlined by Goel & Pirolli (1992). We posit that applying a design lens to these complex activities contributes to a deeper understanding of decision making in these ill-defined contexts.

3.3 Methods

3.3.1 Research Questions

The focus of this qualitative study was to investigate design processes in academia and industry sectors in medical device design. Our project addressed the following research questions:

- What similarities and differences exist in front-end design processes in industry and academia?
- What constraints contribute to design processes based on these settings?

3.3.2 Participants

A total of ten academic (A1-A10) and eleven industry engineers (I1-I11) in the field of medical device design participated in this study (Table 6). The engineers were recruited via email explaining the purpose of our research project. Additional engineers were recruited through a snowball sampling approach (Biernacki & Waldorf 1981). Academic engineers were employed in two large Midwestern U.S. universities in positions including graduate student researchers, postdoctoral researchers, research scientists, and professors. Academic engineers had 4 to 20 years (average = 10.75 years) of experience in research and design. Industry engineers were recruited from companies in the Midwest, East Coast and West Coast of the U.S. The engineers worked in company ranging from small (less than 50 employees), and medium (between 50-249 employees) to large (greater than or equal to 250 employees) sizes. Most of the industry engineers first started working in academia before transitioning into industry, and had an average of 5.5 years of experience in academia and 3.7 years in industry.

Table 6. Participants' information for Academic (A) and Industrial (I) Engineers

(*) indicates engineers with start-up experience while in academia

Participant	Gender	Highest Education	Size of the institution/company	Years in academia	Years in industry
A1	M	Ph.D.	Large	20*	0
A2	M	Ph.D.	Large	16*	0
A3	M	Ph.D.	Large	13	0
A4	M	Ph.D.	Large	7	0
A5	M	Ph.D.	Large	12	0
A6	M	Ph.D.	Large	10	0
A7	M	Ph.D.	Large	16	0
A8	F	Ph.D.	Large	4.5	0
A9	M	M.S.	Large	4	0
A10	M	M.S.	Large	5	0
I1	M	PhD	Medium	14	2
I2	M	B.S.	Small	2	3
I3	F	Ph.D.	Large	4.5	3
I4	M	B.S.	Small	0	3
I5	F	M.S.	Medium	4	6.5
I6	M	Ph.D.	Large	9*	1
I7	M	Ph.D.	Large	8	6
I8	M	Ph.D.	Large	5	10
I9	M	Ph.D.	Small	9	1
I10	M	Ph.D.	Large	2	3
I11	M	Ph.D.	Small	4	2.5

3.3.3 Data collection

Data were collected in individual semi-structured interviews with academic and industry engineers. Participation was voluntary and confidential, and no payment was provided. This approach allowed exploring the perceptions and opinions of the engineers and enabled probing for more information (Louise, Barriball, & While, 1994). Probing can be a valuable tool in ensuring reliability of the data because it can allow for clarification of responses (Hutchinson & Wilson, 1992), and elicit complete information (Bailey, 1994; Gordon, 1975). Probing also helps in recalling information for questions involving memory (Smith, 1992).

The interview questions were developed through multiple iterations. Three pilot interviews were conducted to test the interview protocol and ensure clarity of questions, and were not included in the analysis. Open-ended questions suitable for both contexts were developed based on the steps of an engineering design process, and emphasized problem exploration, idea generation, evaluation, iteration, and communication (Table 7). The interview protocol also included questions to identify constraints and goals affecting their processes. To encourage storytelling, our interview protocol asked a participant to give us an example of a specific project that he/she worked on and all the questions probed for details of that specific experience. One interviewer conducted all of the interviews in-person or video call. Interviews were between 30 and 90 minutes, and were audio-recorded for analysis. In qualitative studies, the participant numbers are generally small due to the in-depth interview process (Patton, 2001; Saldaña, 2011). Many design studies have made use of in-depth questioning to explore engineers' experiences (Björklund, 2013; Crilly, 2015; Daly, Adams, et al., 2012).

Table 7. Main categories and example interview questions.

Interview Focus Area	**Example question(s)**
Background	How long have you been working in your field?
Overview	Can you tell me about one device you developed and give me an overview of the process?
Problem exploration	From the experience that you just shared, what was the main goal that you started with? What did you envision the final outcome of this project to be?
Idea generation	How did you come up with the solution to address the question? Did you have any alternative solutions to the problem that you were trying to solve?
Evaluation and iteration	Did you refine your device to make improvements throughout the process?

	How did you know to make those changes?
Final outcome	At the end, how did you know that you were finished?
Critical constraints	Thinking about the project as a whole, what criteria or constraints were important to your device?
Environment/setting	How did the academic university or industry setting affect the choices and approaches?

3.3.4 Data analysis

We transcribed all recorded interviews and used an inductive coding approach (Boyatzis, 1998; Creswell, 2013) to analyze the transcripts. The codes were developed based on emergent patterns established through interpretations of detailed reviews of the raw data to determine themes and allow observations to emerge from the data (Thomas, 2006). During the analysis, identified themes were continuously compared to newly emergent themes and revised throughout the analysis process (Boeije, 2002).

Categories and subsets of inductive codes were developed based on known design processes and constraints; for example, one category was *problem definition*. An example code was *freedom to pursue an idea,* indicated by this participant statement:

"I guess the university had the freedom to just go off on a tangent" (Participant A1).

Another category was *idea generation,* and an example code under this category was *limited alternatives*. This code captured statements indicating that a participant did not consider alternative solutions, such as:

"Let me think about, did we have alternative solutions? I don't think I came up with something else" (Participant A5).

The final codebook included all of the categories and codes identified, as well as frequency counts for each code by the participant type (industry or academic designer). The following section provides the major themes evident in the interview responses.

3.4 Findings

A key finding from comparing the two sets of responses was that academic and industry engineers had *different* design processes for problem definition and solution generation. The differences in the design processes in these two contexts are illustrated in Figure 16. Industry engineers' processes paralleled a "traditional" design process sequence, including problem definition, concept generation, detailed design, evaluation, and communication. Industry engineers also iterated between problem definition and solution generation to refine their problems and requirements. In the detailed design phase, industry engineers expressed the need to minimize risks of an extended timeline by selecting promising and practical solutions that were also user friendly and manufacturable. Industry engineers stated that they focused on developing marketable products that would satisfy their users and stakeholders.

In contrast, academic engineers began their design process with concept generation, then turned to problem definition, and then to detailed design, evaluation, and communication (see Figure 16). Academic engineers did not *consider multiple solutions* during concept generation; instead, they described their focus as using existing, set solutions, and searching for problems that the set solutions could solve. If a defined problem could not be addressed with their set solution, they moved on to different problems. Academic engineers stated that they looked for novel problems to solve, and their aim was to demonstrate proof of concept that would lead to scholarly publications.

The constraints and goals described by engineers for their design projects in academia and industry were also different, which led to differing emphases on their final devices. Industry engineers described their goal as developing products that would be profitable and satisfy the requirements of their stakeholders, which led to emphasis on usability and manufacturability. Academic engineers described leveraging their specific, technical expertise to provide solutions to open questions, leading to new knowledge suitable for scientific publication. This led to focusing on demonstrating proof of concept for the feasibility of an idea without emphasis on usability and manufacturability. In the following sections, we elaborate on these findings, and provide interview excerpts as evidence for these themes.

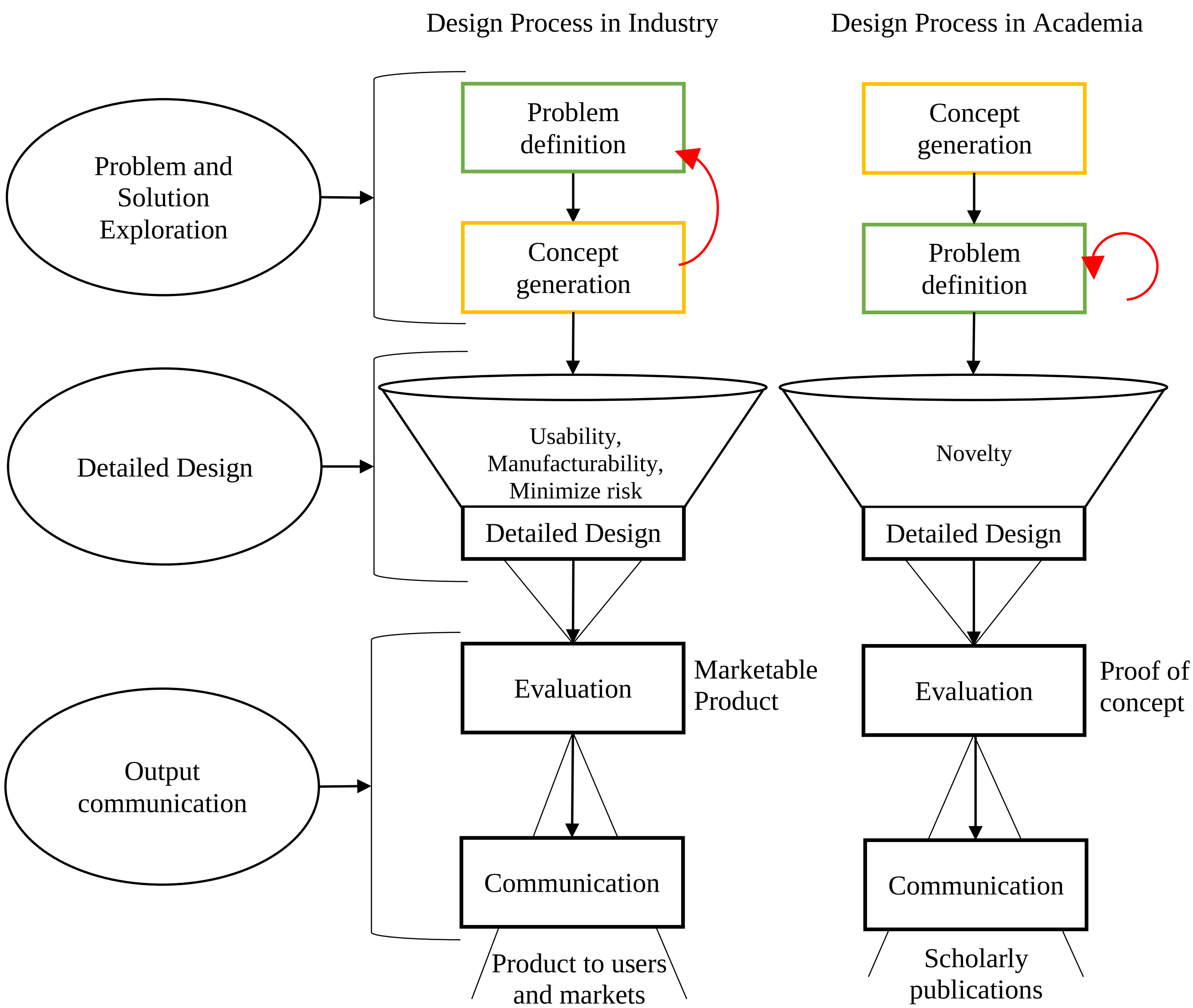

Figure 16. Overview of common elements in the design processes described in industry and academic contexts.

3.4.1 Problem definition and solution generation in industry and academia

Engineers in the two settings differed in their stated goals for their design processes. Industry engineers stated that they were motivated to solve problems that would generate profit.

In contrast, academic engineers said they had the freedom to choose problems without considering profit.

Industry engineers described their design process as starting with a defined problem. Typically, problems were provided for them by higher management or marketing, and their next step was to generate solutions to solve those problems (the standard design process sequence; (Dubberly, 2004)). In contrast, academic engineers started their design process with a preselected solution concept in the form of an existing technology or specific expertise in their field. Next, they looked for open (unsolved) problems that the specified solution might address. As seen in Figure 16, this process flips the first two stages of the design process because the solution is determined prior to identifying the problem.

In addition, industry engineers described iterations on defining the problem and finding a solution based on the capabilities and technologies available at their companies. In contrast, academic engineers described finding problems where they could apply an existing solution. In the concept generation phase, industry engineers searched for multiple, diverse solutions while \academic engineers considered few or no alternative solutions, and focused on leveraging their expertise and making minor adjustments to existing solutions. Academic engineers stated they were motivated to answer scientific questions using their specified devices; thus, having their own solution was sufficient, and they did not seek better or alternative solutions (see Table 8).

Table 8. Comparison of strategies used by engineers in academic and industry setting in the problem definition and concept generation phases.

	Industry	**Academia**
Problem Definition		
Identifying problems	Given	Chosen
Iterating	Problems and solutions	Finding problems
Concept Generation		
Generating concepts	Considered multiple, diverse solutions	Considered few or no alternative solutions

Consulting help	Experts in companies and academic researchers	Lab members and collaborators
Searching the literature for ideas	Important	Important
Maximizing expertise	Not emphasized	Emphasized

3.4.1.1 Problem definition in industry

Industry engineers reported starting with problems identified by their marketing departments or higher management. These problems were based on known customer needs. The engineers iterated on problem definition and concept generation stages to refine design requirements. For example, one industry engineer stated:

> *"The business side will […] go out and then determine there's a customer need… when [you have a condition], right? I'll make a go from that example. The marketing team comes and says, "Hey, we need to know [someone has a condition]. Here's my customer need"* (Participant I10).

Similar to Participant I10, Participant I5 emphasized the importance of customer needs as her primary focus in defining problems:

> *"[A] big driver is our customers. If the customer says, "[…] here's my situation […] I have this special need," then we can work with the customer to try to address their needs"* (Participant I5).

Industry engineers also indicated that once they were given a problem, marketing and engineering teams collaborated to iterate on problem definitions and potential solutions based on the capabilities and limitations of resources at their companies. The design process did not typically progress linearly in a single cycle from problem definition to concept generation in industry. Participant I10 emphasized this process of understanding the feasibility of a project for their company by iterating on possible solutions and redefining problems with multiple departments within the company:

> *"Everybody gives input into what they think they can do to achieve this […] Once marketing understands there is a possibility that this can be done, then what marketing will do is they'll go out again […] Marketing comes back and says the average customer is going to be your average consumer. A person at home. They don't want a finger prick. They want it done in 5 minutes. They prefer urine or saliva. They want it easy to read. That gets more defined into a customer-needs document"* (Participant I10).

Participant I4 repeated this need to iterate on possible solutions and redefine problems in the early stage of design as an important aspect of his process:

> *"Let's get something that works that we can go and test with our users and find out what's important and then refine, instead of trying to do everything in one shot"* (Participant I4).

In their descriptions of iterating on possible solutions and redefining problems, industry engineers emphasized the importance of refining their problems early. This process of defining problems was largely driven by the goal of identifying profitable problems. As one participant stated:

> *"The marketing team will define that market segment. We could make a billion dollars in ten years…"* (Participant I10).

The problem defined by the company needed to fit into known market needs, and be likely to provide financial rewards when the problem is addressed.

3.4.1.2 Problem definition in academia

The design process for academic engineers began with actively seeking problems that they could address with their technical expertise or existing solutions. Academic engineers also reported that they had the flexibility to choose and change problems if a proposed problem could not be addressed with their solutions. As technology experts, academic engineers commonly looked for problems that they could solve through new collaboration opportunities. Participant A2 stated that he was openly looking for problems to address using a specific device as the solution method:

"I just wanted to get some experience in the biology lab and talk to biologists, so I didn't care if it was [a topic] or something else. I just wanted to find basically a good application of [my device] … so it had a practical use" (Participant A2).

In defining problems to solve, academic engineers often looked for collaboration opportunities through discussions with biologists and clinicians. Academic engineers frequently mentioned that biologists and clinicians knew of "good problems" that could not be addressed with any existing solutions. For example, Participant A4 described the benefit of collaborating with biologists and clinicians in identifying problems:

"[Clinicians or biologists] have this question, and it's very important and [clinicians or biologists] cannot answer it. Based on my experience there are a lot of these kind of questions. But as an engineer, we don't know. [Engineers] don't know [clinicians or biologists] need this kind of tool. So, talking or the discussion between the clinicians is very helpful, or biologists" (Participant A4).

Several academic engineers described flexibility in choosing problems based on their solutions, and mentioned the possibility of choosing to move on to different projects. Academic engineers were not bound by specific problems they needed to solve. For example, one academic participant stated:

"If it didn't work, we weren't going to fiddle around with it [...] We were excited because it was a good fit, but if it didn't fit, we probably wouldn't have worked too much on alternatives. It's a great application, but we weren't that interested in the application" (Participant A1).

Participant A1 was not restricted to solving this one problem. If his technical expertise was not right for the problem, he would not have continued to work on the project. Instead, he planned to move on to a different question that his solution expertise could address. Participant A4 also indicated his freedom to move to different problems depending on his interests. If he did not find interesting problems to address with his solution, he could switch direction and look for new problems in a different domain:

> *"There's no ending line.... When you start to notice there are not many interesting things…you stop doing it. You start to switch to a new direction"* (Participant A4).

This freedom to switch problems was considered a primary factor driving the process of problem definition for academic engineers, and was reported by 8 out of 10 academic engineers. For example, Participant A7 reported:

> *"When you are working in university, you can work on anything. Whenever you see a possibility you can go ahead and try it out"* (Participant A7).

The flexibility of defining their own problems allowed academic engineers to switch directions based on their interests, and to look for potential collaboration opportunities based on their own expertise.

3.4.1.3 Concept generation in industry

In the concept generation phase, industry engineers searched for multiple solutions that would meet customer requirements and address problems. Industry engineers relied on reading the literature and collaborating with experts to gain knowledge about possible solutions. Instead of a single solution, industry engineers looked for many possible solutions. As one industry participant stated:

> *"We had several brainstorming sessions where we thought of several different approaches. This one seemed to work the best, and we pursued it more, but yeah. We had a lot of different ideas, some of them were just not too good."* (Participant I2).

Participant I2 considered many different technologies before deciding on a final solution concept. Similarly, Participant I1 also considered multiple alternatives that best addressed his needs:

> *"You can do it in a magnetic way, you can do it in an optical way, you can do it in an electro kinetic way, or you can do it just by hydrodynamic ways so you just create some configurations, geometry. At the end, what they care is I start from a [blood] sample"* (Participant I1).

In searching for possible solutions, 9 out of 11 engineers in industry mentioned that they generated ideas by reading the academic literature. Industry engineers frequently scanned the literature to find methods that might work to address their needs:

> *"I did a literature [search] of all the different ways that channels are closed… We went through and said, "Well, that kind of gets what we want." We looked at everything that's available"* (Participant I4).

In addition, industry engineers actively collaborated with experts both within their companies and in academia:

> *"The company has people with different talent: optics, electronics. For that part, I don't need to worry about. Again, when I think about or decide, those people can help me to prepare the prototype in order to test"* (Participant I7).

By consulting with other experts, industry engineers were able to think of ideas outside of their own current technical capabilities. When required expertise was not available within their company, they reached out to universities for help. As one participant noted:

> *"[Company] will also help us to establish connections with [a] university, if we need anything, any help, or if we want to look into any technologies, professors have […] already developed"* (Participant I1).

Since industry engineers reported focusing on coming up with various alternatives to solve their problems, they actively engaged in searching broadly within the literature, and consulted with experts in their companies and academic labs. As a result of following more traditional design processes, industry engineers reported considering a wider range of possible solutions.

3.4.1.4 Concept generation in academia

Academic engineers reported starting with specific solutions or content expertise first, before looking for problems to address. Solution specifics were often narrowly predefined before academic engineers started their projects, which led them to consider few or no alternative solutions. One academic stated:

> *"We kind of have a hammer almost ready, and then, if a good application comes up that matches this, then we can tweak and do something towards that"* (Participant A1).

For example, a specific expertise such as using a device to sort small particles based on size and affinity would be set as the desired solution. Thus, more specific solutions were considered just within this category. In other cases, academic engineers reported setting exact technical solutions before beginning their search for problems. For example, one reported:

> *"We discovered this effect and we asked ourselves well how can they use this now for a biological [application] out there?"* (Participant A3).

Academic engineers typically described their design process as matching their solution with a new problem; as a result, they reduced effort towards searching for different or better solutions. Eight out of 10 academic engineers indicated that they did not consider *any* alternative solutions. Even the other two engineers who said they did consider alternatives did not provide details about alternatives identified. When asked whether they considered alternative solutions, most academic engineers responded that they had a single solution they had developed using their expertise, or that they made minor adjustments to an existing technology to address the problem. A common response was that no alternative solutions were considered:

> *"Let me think about, did we have alternative solutions? I don't think I came up with something else"* (Participant A5).

Participant A5 was satisfied with a single solution because his solution addressed the problem he had identified; so, he did not find it necessary to come up with alternatives. In another case, Participant A10 focused on using an existing technology in his lab, and he made small adjustments to it to fit his new problem:

> *"I basically just tinkered with the original design. We came up with the [channel dimension change], and we came up with maybe different methods too for the [fabrication] part […] Other than that, we didn't play around with it too much. We got it to work and that was the most important thing. We just went with that"* (Participant A10).

Participant A10 made minor changes to his existing technology by adjusting the dimensions and fabrication method for his device; but, the core idea stayed the same. When the device was functional and addressed his needs, it was done. The tendency to stay within their expertise and goal of answering scientific questions often resulted in considering one solution. For example, Participant A3 indicated that when he thought of solutions for his project, his mind automatically went to solutions that used his own expertise:

> *"Whenever I'm thinking about making devices my mind is automatically going to go to things that can be made using laser cutting, soft lithography or possibly micromilling because those are the tools that I have in my lab. Someone who has a background in silicon micro-machining might think of devices and techniques that exploit silicon as the channel material. Your perspective obviously comes from what your background is […] That definitely limits the type of projects that you do. I won't say limit because I could go ahead and do a silicon based project for example, but when you're envisioning ideas, your mind always goes to things that it knows already"* (Participant A3).

In addition, academic engineers were more concerned about answering problems and making measurements with their devices instead of generating commercial products. As long as the devices they designed were demonstrably capable of addressing the problem, they were satisfactory. Academic engineers were attempting to show that their solution could address a specific problem and felt that finding the best solution was less important; for example, Participant A7 indicated the importance of focusing on a successful solution rather than focusing on optimizing the device:

> *"If this one works pretty well I probably wouldn't even bother to try another. Because I mean the ultimate goal is to measure the thing. If I can measure it pretty well in this way, I wouldn't want to try some other method"* (Participant A7).

Participant A7 implied that if a device worked as intended and allowed him to collect sufficient data, he did not have to consider alternative solutions. His emphasis was on developing *one* solution to adequately solve a problem instead of developing the *best* solution.

In thinking about solutions, academia engineers relied on their previous experiences, published research in the scientific literature, and influence from lab members. For example, Participant A4 emphasized the importance of reading the literature to help him think of ideas and gain new knowledge:

> *"The literature reading is very, very important, because the idea, or the solution, doesn't come out of nowhere. It comes out of your experience, your knowledge. So you have to have that base, in order to make innovations. The very first thing is to read. Read intensively, even sometimes the paper doesn't look very relevant. Maybe [it] can spark your ideas"* (Participant A4).

This participant described his existing expertise based on past experience and the academic literature as key. Also, the influence of their lab members and collaborators working on similar problems was reported to affect their solutions:

> *"Maybe I would have come up with a different design if I didn't have these two important discussions with my lab mates"* (Participant A7).

In sum, academic engineers minimally explored their solution space, and were influenced by research studies in the literature and lab members who interacted with them about their projects.

3.4.2 Detailed design in industry and academia

In the detailed design phase, designers work on a concept to develop and "flesh out" its potential qualities. Industry engineers emphasized the importance of minimizing the risk of extended timelines by choosing promising solutions; however, academic engineers did not emphasize risks or timelines. In addition, industry engineers focused on usability and manufacturability to develop marketable products and generate profit. However, academic engineers did not emphasize usability or manufacturability because a conceptual solution with demonstrated success was adequate to answer new scientific questions (See Table 9).

Table 9. Comparison of strategies used by industry and academic engineers in the detail design phase.

	Industry	**Academia**

Detailed Design		
Taking risks	Minimized by selecting promising solutions	Not addressed
Focusing on usability	Important	Not an emphasis
Focusing on manufacturability	Important	Not an emphasis
Having strict timelines	Important	Not an emphasis
Having competitions	Served as important benchmarks	Not an emphasis

3.4.2.1 Detailed design in industry

In the detailed design phase, industry engineers emphasized the importance of creating manufacturable and user-friendly devices. Their products needed to be better than competing devices, and attractive to end users and stakeholders. For example, Participant I4 indicated that she focused on the usability of her device to have an advantage over her competitors' devices:

> *"I think that's an area where some of our competitors and a lot of the academic labs have generated some very high quality results, there's a big gap there in terms of getting to something that's usable…We looked at everything that's available and said, 'How can we do this, that enables our users'"* (Participant I4).

In addition, manufacturability and reliability were important considerations to development in industry. For example, Participant I10 indicated the importance of ensuring that when a device left the "proof of concept" stage, it needed to be ready for mass production:

> *"Once you leave this proof of concept phase, that's when you really start digging into the weeds like all right, I can do this once, now can I make 1,000 of them. Can I make 10,000 of them and can they all work the same… That's really how that process works. Once you show that you can do this on a 10,000 scale, then it's like all right… Now let's make a million of them and have them work, all million."* (Participant I10)

In addition, several industry engineers were concerned about "risky" ideas that would be difficult to achieve and require a long development time:

> *"You propose a possible solution, and then you characterize that, mostly in terms of risk, resources and reward. Right? How likely is it that this solution that you propose is actually going to work?[…] That's maybe a nice idea but it's just, there's no way it's going to work […] I've proposed something to my supervisor where [he] said, yeah, that looks like it would provide a lot of reward, but the technical risk is very high, I don't think it's going to work, or it's not going to work easily"* (Participant I8).

Industry engineers had the tendency to look for solutions that would be feasible and practical when developing them into products. Time and resource constraints were primary constraints in the detailed design phase. For example, Participant I5 emphasized the need to allocate his time and prioritize his effort in developing a product:

> *"There's always a time limit. It's really important to assess what's the best use of your time. You might run into something where you say, 'Oh, that might be cool to try,' but then, later down the road, you might have some time to pursue it. Or you might just have to say, "Okay, well, I don't have time for that, and it wouldn't be worth pursuing because something else has priority." The biggest issue is usually just time"* (Participant I5).

Participant I5 discussed minimizing the risk involved when testing out more ideas would potentially extend his timeline. Though he saw opportunities to pursue an interesting idea, he decided it was not practical because of the time required. Likewise, Participant I2 indicated limited time and company funding as the main constraints in product development:

> *"The amount of time that we had to explore different options, I feel, was kind of limited because basically, company funding; we are trying to get a product out faster rather than just learn about (devices)"* (Participant I2).

Industry engineers also frequently mentioned comparing their devices to their competitors' products:

> *"We know what the product needs to do based on what our competitors can do. Is it sensitive enough? What do these other kits do? We need to be that good or better. Is it reproducible? What do these other kits do? We look at what all the competitors do and when we're better than them, as soon as we hit that goal we stop development in that area and then we'll be there"* (Participant I11).

Industry engineers talked about "benchmarking" their competitors' devices, and aimed to produce even better devices themselves.

3.4.2.2 Detailed design in academia

Since academic engineers focused on generating new scientific knowledge, there was very little discussion of making their devices user-friendly and easy to manufacture. Four out of 10 engineers acknowledged that manufacturability was lacking in their current work:

> *"It just requires a lot of training and patience to build the device and it's not easy to get a person that is interested and motivated to follow the procedures of the device because it's so difficult. To them, it would be frustrating if they need to fail ten times before they get the first success"* (Participant A9).

Academic engineers described building only a few devices to demonstrate proof of concept. Their devices were often very difficult to manufacture, and required extensive training to fabricate. In addition to manufacturing, usability was not emphasized in the academics' designs. Four out of 10 academic engineers reported that usability needed improvement before multiple users could handle the device outside of their research lab:

> *"It would require probably to change the setup a little bit in terms of how easy it was to put together and to assemble. For me, it was easy because I did it almost every day, but it takes some time if you're a first-time user and things like that"* (Participant A10).

Since academic engineers who had developed devices were also their initial users, usability in design was minimized. Their goal was to answer novel research questions rather than delivering a robust device for end users:

"Now, the goal of most of the good studies is not to have a device in the end. The goal is to answer a question that cannot be answered with other tools." (Participant A4).

Academic engineers emphasized the functionality of the devices to answer new research questions, leading them to minimize usability and manufacturability. Financial limitations also played a large role in shaping design approaches:

"My adviser is not a rich guy regarding to the research funding. When I decide my experiment, I couldn't spend [a] single dollar without [a] reason… I always have to make plans before I order the chip and not to waste any single chip for my measurement which was really stressful" (Participant A8).

In addition to research funding, the capabilities of equipment in their labs sometimes limited the academic engineers' approaches:

"Of course you need to know the capability of the instruments in the clean room. Sometimes you require very small features, sometimes you need multiple layers… and sometimes you need some compatibility with some chemicals. All these you need to consider, otherwise, if you want ... I want a channel here, but it's not feasible to fabricate it. And also you need to consider sometimes even your design, it's achievable, I would say, but it's very, very complicated process" (Participant A4).

Academic engineers' device designs were limited by the capabilities of the equipment available for academic engineers' use.

3.4.3 Output communication in industry and academia

In the evaluation and communication phases, industry engineers focused on delivering a product with an emphasis on satisfying stakeholders, and academic engineers emphasized presenting proof of concept (See Table 10). Both industry and academic engineers emphasized publishing scientific papers as an important part of communicating their results. However, industry engineers were not required to publish and their publications were used to advertise their products; in contrast, academic engineers perceived publishing scientific papers as their main goal.

Table 10. Comparison of strategies used by industry and academia engineers in the evaluation and communication phases.

	Industry	**Academia**
Evaluation		
Delivering a device	Sellable product	Proof of concept that would lead to publications
Communication		
Publishing a journal paper	Used to advertise their product	End goal of developing a device
Communication with stakeholders and end users of the device	Important emphasis	Not very important

3.4.3.1 Evaluation in industry

The evaluation stage includes finalizing and testing a design. All industry engineers focused on developing tangible products. Industry engineers sought to create products that would be sold to address customers' needs:

> *"It needs to be a product for sale. That's our driving force, our goal. We're making a product that's going to be on the market soon."* (Participant I11).

From beginning to the end, industry engineers focused on developing products for sale.

3.4.3.2 Evaluation in academia

Academic engineers emphasized demonstrating "proof of concept" and sharing knowledge about potential applications:

> *"The milestone is that we treat the product with different drugs so that it can behave differently, and if we can tell the difference using our device, meaning that we can prove this device has a clinical potential, and we've done that. So that was a milestone"* (Participant A7).

Unlike industry engineers, academic engineers did not emphasize developing marketable products at the end.

3.4.3.3 Communication in industry

Industry engineers focused on reaching out to their end users and stakeholders to validate their devices, and placed less emphasis on scientific publications. Industry engineers ensured that all design requirements were met, and that their customers were satisfied with their products:

> *"Now you'll have done hundreds of testing for each functional performance to assure that this design produces repeatability and reproducibility, then you take that final design to the customer again and [do] a human factor study. You assess with the panel of customers whether that design that you created... that you're ready to launch [and] really meets all of the requirements that they wanted. […] to make sure that when you do release this product, that people will pay for it."* (Participant I3).

The majority of industry engineers reported that publishing was not a requirement because it does not necessarily contribute to product development. However, some industry engineers indicated that publishing scientific papers helped them gain publicity for their work:

> *"Part of it is advertising. People would read your paper and read that oh, you used these kits from this company or this is how these kits work from this company, that's really neat"* (Participant I11).

3.4.3.4 Communication in academia

Academic engineers focused on publishing their results in scientific journals, and placed minimal emphasis on stakeholders. The end deliverable for academics was demonstrating that their devices can generate data for publications. Instead of focusing on building devices, they emphasized gaining new knowledge:

> *"I guess the sign to finish is because, at the end, we publish a paper. We do what we need to and if we finished all the experiments, then we are done. It is more publication driven"* (Participant A5).

Likewise, Participant A8 described the goal as submitting a manuscript to publish her work. Once she had sufficient data for her project to wrap up a complete story, it was time to end her project:

"When I almost finished my project, I feel there is not many questions coming in for my specific project. I feel like, 'Oh, it might be almost like wrapping up with that. Maybe my story is complete enough to tell other people and they can get some like understanding for my project.' I think that might be my intuition that my project will be almost finish with that… Finally, I send my manuscript and get accepted" (Participant A8).

Obtaining sufficient data for publications was considered an important goal. Academic engineers expressed the importance of solving problems, but placed very little emphasis on how the information and concepts could be transferred to other users. For example:

"This is a research scale and I just try to pinpoint or solve the practical problem in my own known problems. If it happens that… [the] concept is being used in, let's say hospital or other area, it is not my business" (Participant A5).

This perspective demonstrated that academic engineers placed less emphasis on considering the end users of their publications and devices than did unlike industry engineers.

3.5 Discussion

3.5.1 Design processes in academia and industry

Problem exploration includes both divergent processes in identifying alternative problem perspectives and convergent processes in selecting one to pursue to solution (Yilmaz et al., 2014; Studer et al., 2018). While industry engineers followed a typical design process with problem definition followed by a search for multiple solutions, academic engineers reversed this process by searching only for problems to fit their existing solutions. Academic engineers emphasized problem finding rather than solution generation by beginning their process with a candidate solution – in the form of a technical device, specific technology or area of expertise – in mind. Then, academic engineers looked for problems that could be addressed using their specific solution. If their expertise could not solve a given problem, they moved on to consider a different problem. The end goal for the academics' projects was to collect sufficient data to show a solution was adequate, leading to scientific publication. Academic engineers followed a "technology push" model (Di Stefano, Gambardella, and Verona 2012) that leveraged existing technologies and identified problems that could be solved using those technologies. *Technology* *push* serves as an important source of innovation because it brings radical changes that are dissimilar from prior inventions (Norman and Verganti 2014). Ullman (1992) suggested that the majority of design projects are driven by a realized problem or market space, and the design process for technology-driven projects may be different (Thomas, Culley, & Dekoninck, 2007). Our findings for the academic engineers display an example of a technology-driven process, and demonstrate that successful design processes do not have to start with the problem definition phase.

The design process in industry closely mirrored the default model of design, following the sequence of problem definition, solution exploration, evaluation and communication (Cross 2008; Pahl and Beitz 1991). Industry engineers began projects with pre-defined problems after studying the market and customer needs. Subsequently, marketing and engineering departments iterated on problem definitions and solution generation to define requirements based on the capabilities of their companies (Dorst and Cross 2001). During the concept generation stage, industry engineers diverged to search for multiple, diverse solution ideas. Also, industry engineers depended heavily on the academic literature to inform them about solutions from the established pool of technologies and methods. In addition, industry engineers collaborated often with other experts within their companies and with academic researchers with content expertise. The differing environments for industry and academic engineers were associated with different design processes.

3.5.2 Constraints and goals that influenced design decisions

The key goal described by academic engineers was collecting sufficient data using their solution for scientific publication**.** Academic engineers employed their designed device to answer scientific questions, and they took a minimalist approach to the design considerations of user-friendliness and manufacturability. Also, the academic engineers felt their environment was unconstrained in exploring the problem space, which may have encouraged them to stay within their solution expertise and search instead for problems. In addition, academic researchers expressed feeling free to stop a project and move on to a different project if needed. These contextual differences for academic engineers influenced their relative lack of explorations for alternative solutions. Past research supports this finding that structure and cultural norms associated with different design settings can shape problem spaces (Daly, McKilligan, Murphy, & Ostrowski, 2016).

Industry engineers described their focused as developing profitable devices, and described their goals as designing physical products that were user-friendly, manufacturable, and reliable, and that met known customer needs. Industry engineers explored a diverse set of potential solutions for their problems in order to select the best solution**.** At the same time, industry engineers felt they could not fully explore and test solutions due to strict timelines and resource limitations; consequently, they looked for promising but practical solutions. Time management is one of the most influential constraints in design processes (Goncher & Johri, 2015). In the end, industry engineers chose solutions that would meet all the user requirements for their problems while including features for usability, reliability, and manufacturability to give them an advantage over competitors' products. With different goals and contextual constraints, the design processes described by academic and industry engineers prioritized different aspects of design.

3.6 Design practice contributions and implications

This paper aligns the discourse between research, technology transfer, and design processes across engineering settings. Academic research labs push the boundaries of current understanding to produce new knowledge. Particularly in medical device development, academic engineers study basic scientific principles and engage in translational research by collaborating across disciplines to identify important clinical applications for devices (Mark et al., 2010). Medical devices may go through a technology transfer process from initial proof of concept to commercialization to market. However, currently, there is a mismatch between the technologies developed in academia and commercialization in industry. Academic universities are responsible for scientific discoveries and development of new technologies, but there are limited approaches to transition these discoveries outside of universities (Huang-Saad, Fay, & Sheridan, 2016). With a better mutual understanding of the constraints and goals of academic and industry engineers, both may become better informed about alternative design processes and can intentionally and strategically change their processes as needed. For example, an academic researcher who wants to commercialize their work may focus on understanding possible stakeholders and develop their device with added usability features.

Additionally, by understanding the strengths and focus areas of design in academic and industry settings, engineers from both sectors can improve communication and collaboration. Knowing the design processes being used in the related sector will help those creating new scientific publications (academic engineers) and those making use of them (academic and industry engineers). In academic design processes, innovation appears to arise from the "technology push," while in industry's design processes, new ideas enter through the "market pull" (Di Stefano et al., 2012). Academia generates technology push by developing new solution methods and identifying their qualities and potential applications. At the same time, industry introduces new problems by constantly identifying problems and needs, and searching for promising solution methods. Collaboration can help to overcome the barrier of commercializing work, with industry providing resources and questions to academic research (Lee 2000; Mansfield 1995; Siegel, Waldman, & Link 2003), and industry benefitting from leveraging solutions from academia.

These results also indicate the value of academic publications that consider their industry audience by providing specific information about the transferability of solutions. Information required in technical problem solving is costly to acquire, transfer, and use in a new location (von Hippel, 1994). While academia focuses on publishing new knowledge and demonstrating "proof of concept," during the research process, scientists often fail, and face many difficulties in building a successful device. Including development information is important and relevant to industry as they attempt to make use of new solutions. Those in industry may not have specific expertise in an area, but may want to apply a new technology shared in the literature. By facilitating information transfer to end users with details on development, new findings may be more readily accessible, and more successfully translated for use.

There is also an opportunity to strengthen the connection between the academic engineers' goal of proof of concept and industry's desire to use mature concepts that can be commercialized. It may be risky for industry to translate academic research findings into commercial devices because it would require additional development time. Instead, academic researchers could further identify and define the potential applications, and develop the technology to the point that industry can make use of it for commercialization (Huang-Saad, Fay, & Sheridan, 2016). Contributions made by innovation and new technology are largely determined by the rate and manner of innovation diffusion to the relevant populations (Hall 2004). Technologies developed in academia may need to be further developed for industry to adopt them. Academic researchers may learn more about how to foster the commercialization of technology by participating in programs such as the National Science Foundation Innovation Corps (Blank, 2011).

Understanding contextual influences on their design processes may help engineers select and use design tools in both academia and industry. For example, academic researchers typically seek out problems that match their solution expertise, and can benefit from the literature focusing on identifying problems and opportunities using existing technologies (Baron 2006), and may benefit from tools aimed at reframing problems (Studer et al., 2016). Industry professionals focus on generating diverse solutions for their problems, and may benefit from implementing proven ideation methods to support creative thinking and problem solving (Altshuller, 1997; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Linsey, 2007).

While other research has shown that many components of design are context independent such as addressing open ended problems, and freedom in possible outcomes(Daly, Adams, et al., 2012; Goel & Pirolli, 1992; Jonassen, 2000; Zimring & Craig, 2001), the present study is the first to show how design processes differ based on the contextual constraints in academic and industry settings. Industry engineers followed a traditional design process starting with a problem and exploring potential solutions, while academic engineers followed a technology push model (Di Stefano, Gambardella, & Verona, 2012) by developing new technologies to solve multiple problems. These findings may transfer to academic engineers in various disciplines who follow similar practices with fixed solutions and matches to problems are explored. In recent years, engineers have developed innovative technologies with multiple applications (e.g. graphene, 3D printing, and shape memory alloy) (Mohd Jani et al., 2014; Shen et al., 2012; Ventola, 2014). Mechanical and materials engineers may seek to leverage various characteristics of these technologies through exploring potential problems to solve. To better support designers with expertise in increasingly specific technologies, further research is needed to understand how designers identify important applications for their technologies.

3.7 Limitations and future work

The findings from this study are drawn from reports of a small number of engineers, as is typical in qualitative studies with interview data. In addition, engineers in one specific field, biomedical devices, served as the sample, and findings in other fields may differ. Further studies outside of this engineering field would help to generalize these findings to other design disciplines. The present study was designed to gain an in-depth understanding of engineers' experiences within this specific engineering domain (Saldaña 2011). In addition, this study did not explore differences among engineers, such as demographics and time in the field, and other differences among engineers may influence the results. Furthermore, this study relied on semi-structured interviews of self-reported experiences, which can lead to a bias in responses and in omissions of pertinent information. Though the interview question categories were the same, the was some variation in probing questions based on the content discovered in the interviews. Finally, analysis of the interview data was done by a single coder. Further studies with direct observations of design practices would be helpful in validating these findings.

3.8 Conclusion

This study explored differences in design processes between academic and industry engineers in developing medical devices. Two different types of design processes were observed. Industry engineers described their process as identifying problems, seeking out varied solutions, choosing the best of multiple, alternative solutions, and developing concepts into final products. The main goal espoused in industry was to create a device that filled a known commercial need. In contrast, academic engineers described their goal as maximizing leverage from their specific expertise and device technologies. Academic engineers started with their solution method and searched instead for problems, then evaluated the fit between a problem and their solution method, finally producing a "proof of concept" in order to publish their results. The findings from the interviews establish that these design processes are distinctly different for academia and industry. By documenting differences in design processes, this study provides an understanding of how design process differs in these two contexts, providing opportunities for better collaboration between academia and industry and encouraging both to consider their alternative choices in the design process.

3.9 References

Aghion, P., Dewatripont, M., & Stein, J. C. (2008). Academic freedom, private-sector focus, and the process of innovation. *The RAND Journal of Economics*, *39*(3), 617–635. https://doi.org/10.1111/j.1756-2171.2008.00031.x

Altshuller, G. (1997). *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc.

Bailey, K. (1994). *Methods of Social Research, 4th Edition*. New York, NY: The Free Press.

Baron, R. A. (2006). Opportunity Recognition as Pattern Recognition: How Entrepreneurs “Connect the Dots” to Identify New Business Opportunities. *The Academy of Management Perspectives*, *20*(1), 104–119. https://doi.org/10.5465/AMP.2006.19873412

Berman, J. (2008). Connecting with industry: bridging the divide. *Journal of Higher Education Policy and Management*, *30*(2), 165–174.

Biernacki, P., & Waldorf, D. (1981). Snowball Sampling: Problems and Techniques of Chain Referral Sampling. *Sociological Methods & Research*, *10*(2), 141–163. https://doi.org/10.1177/004912418101000205

Björklund, T. A. (2013). Initial mental representations of design problems: Differences between experts and novices. *Design Studies*, *34*(2), 135–160. https://doi.org/10.1016/j.destud.2012.08.005

Blank, S. (2011). Embrace failure to start up success. *Nature News*, *477*(7363), 133–133. https://doi.org/10.1038/477133a

Blessing, L., & Chakrabarti, A. (2009). DRM: A Design Research Methodology. In *DRM, a Design Research Methodology* (pp. 13–42). Springer London. https://doi.org/10.1007/978-1-84882-587-1_2

Bloedon, R. V., & Stokes, D. R. (1994). Making University/Industry Collaborative Research Succeed. *Research-Technology Management*, *37*(2), 44–48. https://doi.org/10.1080/08956308.1994.11670969

Boeije, H. (2002). A Purposeful Approach to the Constant Comparative Method in the Analysis of Qualitative Interviews. *Quality and Quantity*, *36*(4), 391–409. https://doi.org/10.1023/A:1020909529486

Borrego, M., Douglas, E. P., & Amelink, C. T. (2009). Quantitative, Qualitative, and Mixed Research Methods in Engineering Education. *Journal of Engineering Education*, *98*(1), 53–66. https://doi.org/10.1002/j.2168-9830.2009.tb01005.x

Boyatzis, R. E. (1998). *Transforming Qualitative Information: Thematic Analysis and Code Development*. SAGE.

Bruce, M., Cooper, R., & Vazquez, D. (1999). Effective design management for small businesses. *Design Studies*, *20*(3), 297–315. https://doi.org/10.1016/S0142-694X(98)00022-2

Greer, L. L., & Jehn, K. A. (2012). The paradox of intragroup conflict: A meta-analysis. *Journal of Applied Psychology*, *97*(2), 360–390. https://doi.org/10.1037/a0024844

Cooper, R. (1993). *Winning At New Products: Accelerating The Process From Idea To Launch* (Second). New York: Basic Books.

Creswell, J. W. (2013). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies*, *38*, 54–91. https://doi.org/10.1016/j.destud.2015.01.002

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Daly, S., McKilligan, S., Murphy, L., & Ostrowski, A. (2016). Tracing Problem Evolution: Factors that Impact Design Problem Definition. In *Design Thinking Research Symposium (DTRS)*. Copenhagen, Denmark.

Daly, S. R., Adams, R. S., & Bodner, G. M. (2012). What Does it Mean to Design? A Qualitative Investigation of Design Professionals' Experiences. *Journal of Engineering Education*, *101*(2), 187–219.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design Heuristics in Engineering Concept Generation. *Journal of Engineering Education, 101*(4), 601–629.

Di Stefano, G., Gambardella, A., & Verona, G. (2012). Technology push and demand pull perspectives in innovation studies: Current findings and future research directions. *Research Policy, 41*(8), 1283–1295. https://doi.org/10.1016/j.respol.2012.03.021

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6

Dubberly, H. (2004). *How do you design? A compendium of Models*. San Francisco, CA: Dubberly Design Office.

Fulop, L., & Couchman, P. K. (2006). Facing up to the risks in commercially focused university–industry R&D partnerships. *Higher Education Research & Development*, *25*(2), 163–177. https://doi.org/10.1080/07294360600610396

Gelijns, A. C., & Thier, S. O. (2002). Medical Innovation and Institutional Interdependence: Rethinking University-Industry Connections. *JAMA*, *287*(1), 72–77. https://doi.org/10.1001/jama.287.1.72

Gibbons, M., & Johnston, R. (1974). The roles of science in technological innovation. *Research Policy*, *3*(3), 220–242. https://doi.org/10.1016/0048-7333(74)90008-0

Goncher, A., & Johri, A. (2015). Contextual Constraining of Student Design Practices. *Journal of Engineering Education*, *104*(3), 252–278. https://doi.org/10.1002/jee.20079

Gordon, R. (1975). *Interviewing: Strategy, Techniques and Tactics*. Illinois: Dorsey Press.

Grimpe, C., & Hussinger, K. (2013). Formal and Informal Knowledge and Technology Transfer from Academia to Industry: Complementarity Effects and Innovation Performance. *Industry and Innovation*, *20*(8), 683–700. https://doi.org/10.1080/13662716.2013.856620

Gura, T. (2015). Got a startup? Rent a bench. *Science*, *348*(6240), 1196–1199. https://doi.org/10.1126/science.348.6240.1196

Hall, B. H. (2004). *Innovation and Diffusion* (Working Paper No. 10212). National Bureau of Economic Research. https://doi.org/10.3386/w10212

Huang-Saad, A., Fay, J., & Sheridan, L. (2016). Closing the divide: accelerating technology commercialization by catalyzing the university entrepreneurial ecosystem with I-Corps™. *The Journal of Technology Transfer*, 1–21. https://doi.org/10.1007/s10961-016-9531-2

Hutchinson, S., & Wilson, H. (1992). Validity Threats in Scheduled Semistructured Research Interviews. *Nursing Research*, *41*(2), 117–119.

Johns, G. (2001). In praise of context. *Journal of Organizational Behavior*, *22*(1), 31–42. https://doi.org/10.1002/job.80

Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development*, *48*(4), 63–85. https://doi.org/10.1007/BF02300500

Journal of Technology Transfer. (n.d.). Retrieved May 14, 2018, from http://www.springer.com/business+%26+management/journal/10961

Kilgore, D., Atman, C. J., Yasuhara, K., Barker, T. J., & Morozov, A. (2007). Considering Context: A Study of First-Year Engineering Students. *Journal of Engineering Education; Washington*, *96*(4), 321–334.

Kruss, G. (2006). Tensions in Facilitating Higher Education-Industry Research Partnerships in High Technology Fields in South Africa. *Journal of Higher Education Policy and Management*, *28*(1), 31–44. https://doi.org/10.1080/13600800500283775

Lawson, C. (2013). Academic patenting: the importance of industry support. *The Journal of Technology Transfer*, *38*(4), 509–535.

Lee, Y. S. (2000). The Sustainability of University-Industry Research Collaboration: An Empirical Assessment. *The Journal of Technology Transfer*, *25*(2), 111–133. https://doi.org/10.1023/A:1007895322042

Linsey, J. S. (2007). *Design-by-analogy and representation of innovative engineering concept generation* (PhD Dissertation). University of Texas, Austin, TX.

Louise Barriball, K., & While, A. (1994). Collecting data using a semi-structured interview: a discussion paper. *Journal of Advanced Nursing*, *19*(2), 328–335. https://doi.org/10.1111/j.1365-2648.1994.tb01088.x

Mansfield, E. (1995). Academic Research Underlying Industrial Innovations: Sources, Characteristics, and Financing. *The Review of Economics and Statistics*, *77*(1), 55–65. https://doi.org/10.2307/2109992

Mark, D., Haeberle, S., Roth, G., Stetten, F. von, & Zengerle, R. (2010). Microfluidic lab-on-a-chip platforms: requirements, characteristics and applications. *Chemical Society Reviews*, *39*(3), 1153–1182. https://doi.org/10.1039/B820557B

Meagher, T., & Copeland, R. (2006). Patent Issues Facing Universities. *Research Management Review*, *15*(2), 1–13.

Mohd Jani, J., Leary, M., Subic, A., & Gibson, M. A. (2014). A review of shape memory alloy research, applications and opportunities. *Materials & Design (1980-2015)*, *56*, 1078–1113. https://doi.org/10.1016/j.matdes.2013.11.084

National Science Foundation. (2010). The Role of the National Science Foundation in the Innovation Ecosystem.

Nelson, R. R. (1986). Institutions Supporting Technical Advance in Industry. *The American Economic Review*, *76*(2), 186–189.

Newell, A., & Simon, H. A. (1972). *Human Problem Solving*. Englewood Cliffs, N.J: Prentice-Hall.

Norman, D. A., & Verganti, R. (2014). Incremental and radical innovation: Design research vs. technology and meaning change. *Design Issues*, *30*(1), 78–96. https://doi.org/10.1162/DESI_a_00250

OECD. (2015). *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific, Technological and Innovation Activities*. Paris: OECD.

Ottosson, S. (2001). Dynamic concept development - A key for future profitable innovations and new product variants. In *International Conference on Engineering Design* (pp. 331–338). Glasgow.

Pahl, G., & Beitz, W. (1991). *Engineering Design: A Systematic Approach*. Berlin: Springer.

Paletz, S. B. F., Chan, J., & Schunn, C. D. (2017). The dynamics of micro-conflicts and uncertainty in successful and unsuccessful design teams. *Design Studies*, *50*, 39–69. https://doi.org/10.1016/j.destud.2017.02.002

Patton, M. Q. (2001). *Qualitative Research & Evaluation Methods* (3rd edition). Thousand Oaks, CA: SAGE.

Rousseau, D. M., & Fried, Y. (2001). Location, location, location: contextualizing organizational research*. *Journal of Organizational Behavior*, *22*(1), 1–13. https://doi.org/10.1002/job.78

Saldaña, J. (2011). *Fundamentals of Qualitative Research*. Oxford University Press, USA.

Shen, H., Zhang, L., Liu, M., & Zhang, Z. (2012). Biomedical Applications of Graphene. *Theranostics*, *2*(3), 283–294. https://doi.org/10.7150/thno.3642

Siegel, D. S., Waldman, D., & Link, A. (2003). Assessing the impact of organizational practices on the relative productivity of university technology transfer offices: an exploratory study. *Research Policy*, *32*(1), 27–48. https://doi.org/10.1016/S0048-7333(01)00196-2

Smith, L. (1992). Ethical issues in interviewing*. *Journal of Advanced Nursing*, *17*(1), 98–103. https://doi.org/10.1111/j.1365-2648.1992.tb01823.x

Soosay, C. A., & Hyland, P. W. (2004). Driving innovation in logistics: Case studies in distribution centres. *Creativity and Innovation Management*, *13*(1), 41–51. https://doi.org/10.1111/j.1467-8691.2004.00292.x

Stokes, P. D. (2001). Variability, constraints, and creativity: Shedding light on Claude Monet. *American Psychologist*, *56*(4), 355–359. https://doi.org/10.1037/0003-066X.56.4.355

Studer, J. A., Yilmaz, S., Daly, S. R., & Seifert, C. M. (2016). Cognitive Heuristics in Defining Engineering Design Problems, V007T06A009. https://doi.org/10.1115/DETC2016-59942

Thomas, D. R. (2006). A General Inductive Approach for Analyzing Qualitative Evaluation Data. *American Journal of Evaluation*, *27*(2), 237–246. https://doi.org/10.1177/1098214005283748

Thomas, T., Culley, S., & Dekoninck. (2007). Creativity in the Engineering Design Process. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Ullman, D. . (1992). *The mechanical design process*. New York, NY: McGraw-Hill.

Ventola, C. L. (2014). Medical Applications for 3D Printing: Current and Projected Uses. *Pharmacy and Therapeutics*, *39*(10), 704–711.

Verganti, R. (1997). Leveraging on systemic learning to manage the early phases of product innovation projects. *R&D Management*, *27*(4), 377–392. https://doi.org/10.1111/1467-9310.00072

Visser, W. (2006). *The cognitive artifacts of designing*. Lawrence Erlbaum Associates. Retrieved from https://hal.inria.fr/inria-00526069

von Hippel, E. (1994). “Sticky Information” and the Locus of Problem Solving: Implications for Innovation. *Management Science*, *40*(4), 429–439. https://doi.org/10.1287/mnsc.40.4.429

Yilmaz, S., Daly, S. R., Jablokow, K. W., Silk, E. M., & Rosenberg, M. N. (2014, June). *Investigating impacts on the ideation flexibility of engineers*. Paper presented at the American Society for Engineering Education (ASEE) Annual Conference, Indianapolis, IN, USA.

Zhang, Q., & Doll, W. (2001). The fuzzy front end and success of new product development: a causal model. *European Journal of Innovation Management*, *4*(2), 95–112. https://doi.org/10.1108/14601060110390602

Chapter 4: Cognitive Strategies in Solution Mapping

4.1 Abstract

Typically, design processes are described as starting with an initial problem; however, this does not acknowledge "technology-first" design processes, where designers develop technologies without awareness of problems they can solve; then, designers need a process to identify specific problems that might be solved with their new technologies. We define this type of design process as *solution mapping* because it represents an opposing process to problem solving. Research studies often address traditional problem-first design processes; thus, limited information is available to guide empirically-based strategies for supporting solution mapping. This study focused on identifying the cognitive strategies used by engineering practitioners who have been successful in solution mapping; that is, developing technologies and later identifying problems they can solve with their technologies. The study involved a qualitative analysis of interview data collected with expert designers recalling their solution mapping experiences. Our findings articulate a collection of cognitive strategies that form multiple pathways for practitioners to use in identifying problems for their technological solutions. In one identified pathway, engineers initially broke down their technologies into key characteristics, identified enabling functions, and aligned them with the potential needs of multiple industry sectors. In another pathway, engineers used multiple perspectives to gain novel functions for their technologies and then engaged with a series of stakeholders from varied industry sectors to identify specific needs. Understanding and developing explicit cognitive strategies in the solution mapping process can support engineers as they "flip" the design process.

4.2 Introduction

Design processes typically start with defining a problem and then diverging to identify possible solutions, called "problem-first" processes (Cross, 2008a; Dubberly, 2004; Eide, Jenison, Northup, & Mickelson, 2011; Ertas & Jones, 1996; French, Gravdahl, & French, 1985).

However, “technology-first” processes have been identified where designers develop solutions and look for problems they address (Thomas, Culley, & Dekoninck, 2007). However, technology-first designers sometimes develop novel technologies, and later work to identify problem applications of it to solve problems, am alternative design process we define as *solution mapping* (see Figure 17). For example, the discovery of graphene (a very thin, strong, and light form of carbon), created a design process with a search for multiple problem applications.

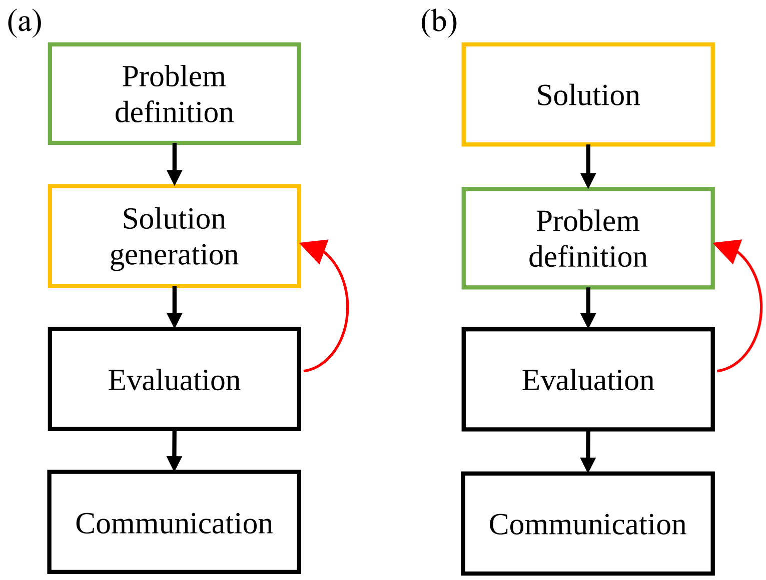

Figure 17. Comparison of (a) a traditional “problem-first” design process (Cross, 2008) with (b) a *solution mapping* design process showing differences in the first two stages.

Design research has focused on developing strategies to identify solutions in problem-first processes (e.g., Altshuller, 1997; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Lee, Daly, Huang-Saad, Seifert, & Lutz, 2018; Linsey, Markman, & Wood, 2012), and less empirical evidence is available on how to support solution mapping practices. In contexts where solution mapping occurs, such as problem applications of new technology, engineers are encouraged to make assumptions about potential problem applications of their technologies and then to test those assumptions by engaging with potential stakeholders (Huang-Saad, Fay, & Sheridan, 2016; Nnakwe, Cooch, & Huang-Saad, 2018). Strategies for solution mapping often arise in the entrepreneurship space as more engineers develop technologies leading to the formation of startups. However, technology-first design is not just an entrepreneurship activity; in fact, many engineers may engage in solution mapping in varied career contexts.

In this paper, we seek to contribute to our understanding of the solution mapping process by identifying a set of cognitive strategies to support designers in finding problem applications of technologies. Previous studies have demonstrated that empirically-based cognitive strategies can support designers in idea generation (Daly, Yilmaz, et al., 2012; Hernandez, Schmidt, & Okudan, 2013; Lee, Daly, Huang-Saad, Seifert, & Lutz, 2018; Lee, Daly, & Vadakumcherry, 2018) because they provide explicit directions for attempting a design process. Often, cognitive strategies for design capture implicit knowledge derived from designers' experiences (Yilmaz et al., 2016; Schunn, Mcgregor, & Saner, 2005) and have limited accessibility.

Because few prior studies have identified cognitive strategies in solution mapping, this study was designed to investigate cognitive strategies of professional engineers engaged in solution mapping. To identify cognitive strategies used by designers, we conducted semi-structured interviews focusing on uncovering each step in expert practitioners' solution mapping processes. These informants were identified based on their experience with successfully developing novel technologies and identifying problems their technology could solve. Understanding practitioner behaviors can assist in the development of sharable useful in supporting other engineering designers engaging in technology-first design processes.

4.3 Background

4.4 Design Processes Starting with Solutions

Models of the design process emphasize starting with a realized need and then identifying possible solutions (Cross, 2008a; Dubberly, 2004; Eide et al., 2011; Ertas & Jones, 1996; French et al., 1985); however, in solution mapping, designers often seek to leverage novel technologies as solutions, and must identify problems they can solve using those specific technologies (Thomas et al., 2007). In technological invention, development of a new technology provides opportunities to create new products and serve new markets. Shane (2000) breaks down a technology-first process into three steps: 1) technological invention, 2) opportunity recognition, and 3) approach to exploitation. After identifying a technology, designers recognize opportunities to use the new technology in a new problem application. In the final step of solution mapping, designers exploit an opportunity and pursue commercialization of their technology.

Solution mapping is a valuable process because a new technology can provide opportunities for the creation of innovative products (Norman & Verganti, 2014); however, there are challenges in the solution mapping process. In previous work, we found that during the early phase of technological invention, engineering designers may focus on functional advancement (including improved performance and reduced cost) without identifying applications for their technology (Lee, Daly, Huang-Saad, & Seifert, 2018). Even with a very innovative technology, identifying problems it can address is not obvious and no instruction on this process is offered in engineering education; as a consequence, many designers find it challenging to recognize opportunities in the form of unsolved problems (Shane, 2000). Thus, it is imperative to develop ways to support designers in identifying varied uses for their novel technologies en route to commercializing their technologies in the form of innovative products.

4.5 Problem Exploration Strategies

In the typical engineering classroom, designers are presented with a design brief laying out a specified problem to solve; in other settings, designers explore problems and then settle on a definition within one possible perspective (Csikszentmihalyi & Getzels, 1971; Getzels, 1979; Studer, Daly, McKilligan, & Seifert, 2018). In addition, the problem may "co-evolve" during the creation of a solution, resulting in further changes in problem definition (Dorst & Cross, 2001). Among the patterns of change during problem exploration, common approaches include taking a problem defined by someone else (in particular, from existing products) (Cross, 2008b). Another approach is exploring and defining a novel problem through design research such as ethnography (Bucciarelli, 1988; Mohedas, Daly, & Sienko, 2014; Salvador, Bell, & Anderson, 1999). Where making observations and conducting in-depth interviews can help designers uncover needs and new views of the problem. Prior research on problem exploration has focused on this problem-first, divergent process, and identified strategies to generate alternative perspectives on problems (Studer et al., 2018) such as the "five whys" strategy (Bulsuk, 2011).

However, the solution mapping design process requires a new understanding of problem exploration. Since design processes are different for problem-first and solution mapping processes, existing problem finding strategies may not apply within solution mapping where the search for a problem is driven by the existing solution (in the form of new technology). In solution mapping, a gap exists in the literature around available strategies to support problem exploration within solution mapping. There have been efforts to encourage solution mapping. For example, the NSF I-Corps program was developed. Using a curriculum developed by Steve Blank at Stanford University as its foundation (Blank & Dorf, 2012; Nnakwe et al., 2018), engineers and scientists in the program investigate the commercialization potential of their new technologies. I-Corps participants form teams, engage in 6-8 weeks of training, and complete at least 100 interviews with potential stakeholders who may benefit from their technologies. I-Corps offers business mentors to help build networks and business practices. Customer interviews serve as an opportunity to confirm the team's assumptions about how identified problems map onto their new technologies (Blank & Dorf, 2012). Through this interview process, participants are encouraged to explore numerous problems across industries and disciplines but little to no guidance is provided on how to navigate the potential problem space.

Little attention has been devoted to research on the solution mapping process, and how designers form initial assumptions about potential problems to match their specific technologies. Cognitive strategies are defined as specific, experience-based guidelines to help designers make good decisions (Riel, 1996), and prior research has shown that cognitive strategies are highly advantageous in design in multiple settings (Brown & Goslar, 1986; Lawson, 1979; Navarro-Prieto, Scaife, & Rogers, 1999). In particular, empirical studies have demonstrated that cognitive strategies used by experienced designers can be identified and developed into explicit design strategies useful to other designers. (Altshuller, 1997; Daly et al., 2012; Hernandez et al., 2013; Lawson, 1979; Lee, Daly, Huang-Saad, Seifert, et al., 2018) . Thus, the goal of this research was to identify cognitive strategies used by successful designers in mapping a new technological solutions onto new problem applications.

4.4 Method

4.4.1 Research Questions

The focus of this study was to investigate front-end design processes of technology-driven innovation in engineering design. Our project addressed this research question:

- What cognitive strategies are used to identify applications of novel technologies?

4.4.2 Participants

The study included a total of 19 engineers from varied fields of engineering (see Table 11). Engineers who had developed a novel technology in multiple problem applications were recruited via email. Additional engineers were recruited through snowball sampling among their acquaintances (Biernacki & Waldorf, 1981). Many design studies make use of in-depth interviews to gain understanding of engineers' experiences (Björklund, 2013; Crilly, 2015; S. Daly, McGowan, & Papalambros, 2013; Daly, Adams, & Bodner, 2012; Goldschmidt, 1995). In qualitative studies, the participant numbers are generally small due to the in-depth interview process (Borrego, Douglas, & Amelink, 2009; Creswell, 2013; Patton, 2001; Saldaña, 2011). All participants were selected from companies in California, Arizona, Michigan, Pennsylvania, and New York and held positions including founders, application managers, and CEOs. Engineers had from 3 to 49 years of experience (average = 20.6 years) and worked in small (less than 50 employees) or large companies (greater than 1000 employees). The participants worked in a wide variety of industry sectors, including energy, biotechnology, aerospace, manufacturing, and materials. Participation was voluntary and confidential, and no payment was provided for participation. Many participants launched companies translating their academic research to commercial applications, and 11 out of 19 participants continued to hold positions in academia as professors or research scientists.

Table 11. Participant information

Pseudonym	Gender	Education	Position	Industry	Years of experience	Company size	Position in academia
Adam	M	PhD	Founder	Energy	22	Small	No
Bert	M	PhD	Founder	Sensor	10	Small	Yes
Carl	M	MS	Founder	Aerospace	9	Small	No
Diane	F	BS	Product Specialist	Biotechnology	3	Large	No
Eric	M	PhD	Founder	Biotechnology	18	Small	Yes
Felipe	M	PhD	CEO	Energy	11	Small	No

Gabriel	M	PhD	Founder	Electromagnetic wave technology	20	Small	Yes
Harris	M	PhD	Founder	Electromagnetic wave technology	49	Small	Yes
Ian	M	PhD	Founder	Robotics	8	Small	No
James	M	PhD	Founder	Manufacturing	44	Small	Yes
Kevin	M	PhD	Founder	Materials	44	Small	Yes
Larry	M	PhD	Founder	Manufacturing	7	Small	Yes
Michael	M	BS	Manager	Energy	41	Large	No
Orlando	M	PhD	CEO	Semiconductor	9	Small	No
Peter	M	PhD	Founder	Biotechnology	36	Small	Yes
Raul	M	PhD	Founder	Manufacturing	20	Small	Yes
Steve	M	PhD	Founder	Materials	40	Small	Yes
Trisha	F	PhD	Founder	Biosensor	18	Small	Yes
Victoria	F	MS	Manager	Manufacturing	3	Small	No

4.4.3 Data Collection

Data were collected through semi-structured interviews, which allowed exploring the perceptions and opinions of the engineers and enabled probing questions to gain additional information (Louise, Barriball & While, 1994). Probing is an important tool in ensuring reliability of the data because it can allow for clarification of responses (Hutchinson & Wilson, 1992) and elicit more complete information (Bailey, 1994; Gordon, 1975). Further, probing helps in recalling information for questions that involve memory for past events (Smith, 1992).

The interview questions were focused on discussing the processes involved in their design work on specific products (shown in Table 12). The content of the interview questions was guided by the problem exploration and opportunity recognition literature (Shane, 2000; Studer et al., 2018). Most of the questions focused on how participants developed their technologies and identified problem applications for them. The questions were developed through multiple iterations with two pilot interviews to address their clarity. Pilot tests are important in ensuring there are no flaws, limitations, or other weaknesses within the interview protocol, and to allow researchers to make necessary changes prior to the implementation of the research study (Kvale, 2007; Saldaña, 2011).

Table 12. Sample of questions from the beginning, middle, and end of the interview schedule.

Sample Interview Questions
From the beginning to the end, can you tell me about the process of developing the technology?
From the beginning to the end, can you tell me about how you came up with an application for your technology?
What sources helped you in identifying this application?
What, if any, were other opportunities and applications that you considered for this technology?

For consistency, all interviews were conducted over a 2-month period by one interviewer who was trained in qualitative methods of research. Interviews were conducted on the phone or in-person, lasting 30 to 90 minutes. All interviews were recorded and transcribed for analysis.

4.4.4 Data Analysis

Transcribed interviews were analyzed for emergent themes (Boyatzis, 1998; Creswell, 2013; Saldaña, 2011). The inductive codes were identified as patterns by the first author through interpretations made by iterative, detailed readings of the raw interview transcripts. Emphasis was placed on identifying the strategies common across participants. During the analysis, identified themes were compared with newly emergent themes, and codes were revised throughout the process to present accurate representations (Boeije, 2002). The final codes are shown in Table 13. Using this code list, the transcripts were considered independently by two coders trained in engineering design. The percent of agreement between the two coders was over 90%, greater than the 70% level typically acceptable for inter-rater reliability (Osborne, 2008). The coders discussed all discrepancies to consensus to complete the coding analysis.

Table 13. List of eight inductive codes identified in transcript analysis.

Code	Description
Explores multiple industries	Sought specific industries to implement the technology
Reframes solution to identify new functions	Used a different way to describe what their product can do, in turn discovering new applications
Breaks down technology into superior characteristics	Identified superior characteristics of the technology
Describes technology with enabling functions	Described what the technology can do in action verbs
Compares technology to existing technologies	Compared their technology to existing technologies and competitors to find application
Changes speech depending on audience	Based on types of customers, they had to change or reframe how they describe their technology
Uses different or multiple functions	Emphasized different functions or multiple functions to match technology with industry sectors
Prioritizes/sorts viable industry sectors and applications	After identifying multiple potential applications, prioritized industry sectors and specific applications to pursue

4.5 Results

Using the coding analysis results, we identified three different pathways evident in the solution mapping processes observed. Some participants took more than one pathway in their extended process of identifying applications of their technologies. Following a *Function Pathway* (Figure 18), 18 out of 19 participants first developed their descriptions of the characteristics or functions enabled by their new technology. Their strategies were captured in two themes: *break down their technology into key characteristics* and/or *describe the technology with action verbs*. In a second *Reframing Pathway* (Figure 18), 3 out of 19 participants changed their description of the new technology when they *reframed their technology functions* using different perspectives. Two out of 19 participants followed an *Analogy Pathway* (Figure 18) by comparing their new technology with existing, similar technologies to find applications. Later in all pathways, participants describe a common process of identifying multiple industry sectors by aligning characteristics of their technologies with possible needs in the industries. Then, participants engaged with individual stakeholders in these prioritized industry sectors, and varied how they described their technologies for each type of stakeholder in order to aid identifying connections to specific industry applications. The three pathways represent specified patterns of actions as cognitive strategies applied during the solution mapping process. We summarize these findings in Figure 18 and discuss them in the following subsections.

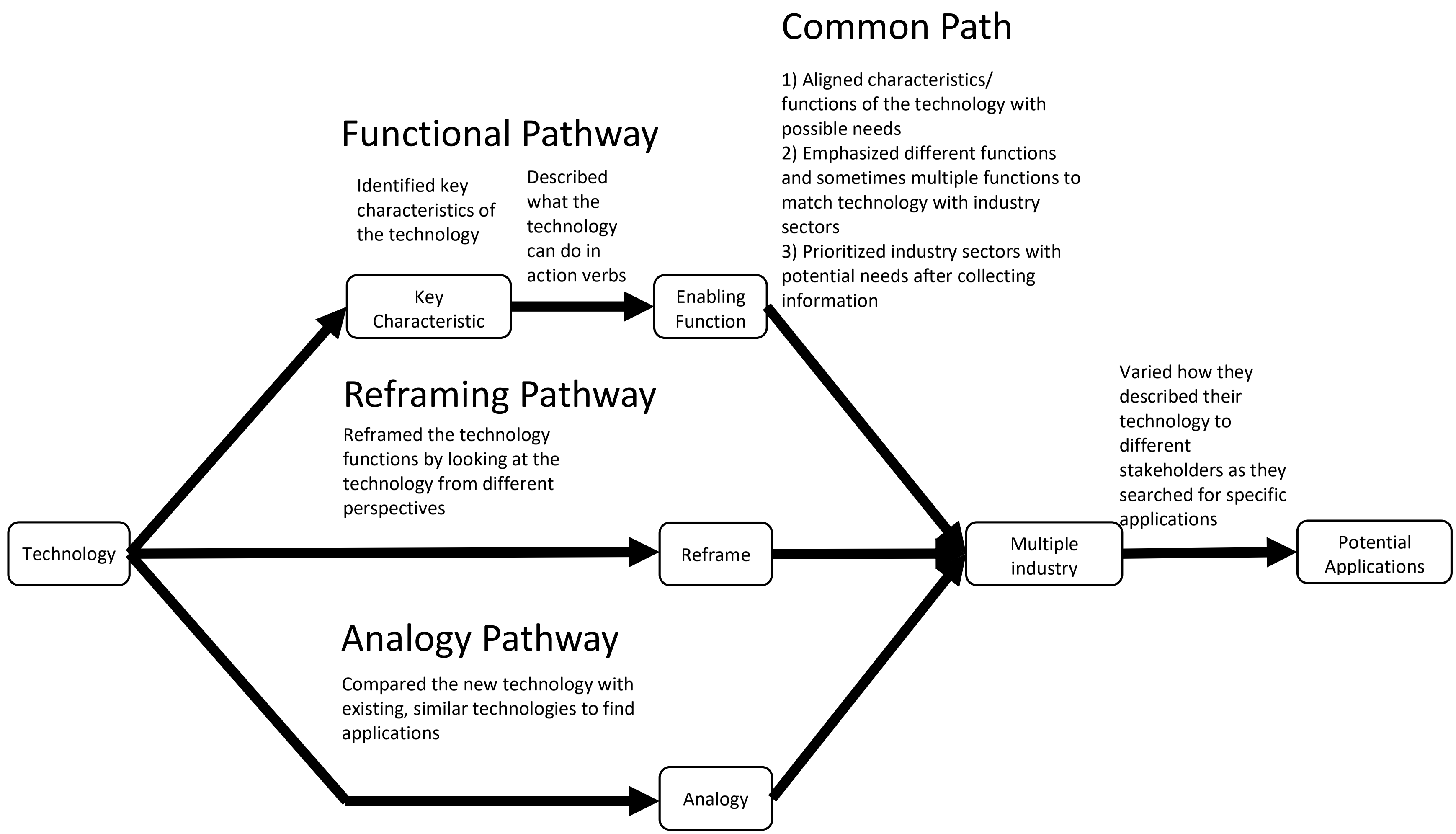

Figure 18. The process of matching a technology to applications and cognitive strategies used in each stage. Engineers identified key characteristics of the technology, described enabiling functions, matched industry sectors, and talked with specific stakeholders within those industries to find applications.

4.5.1 Functional Pathway

4.5.1.1 Engineering identified key characteristics of their technologies

Before identifying problem applications of technologies, designers broke down their technologies into key characteristics in layman's terms. Designers communicated the key characteristics of their technologies without using technical jargon. In addition, engineers emphasized the superior characteristics of their technologies compared to other technologies. For example, Victoria described her company's 3D printing technology as achieving a higher strength compared to existing 3D printing technologies:

> "*…(A traditional 3D printer has) good strength in the X-Y direction, and very low strength in the Z direction, so a lot of parts fail very quickly. And so with using this…technology, we're able to, with some materials, match injection molding strength.*" (Victoria)

Similarly, Adam emphasized characteristics of his battery technology compared to his competitors':

> "*It was, **how could we develop technology that was superior to our competitors so that we could stay in the market place?**... The strength of our technology... We were focused on … fuel cells. We used the basic ceramic know-how, initially, on how to make them small.*" (Adam)

By emphasizing their technology's superior functions, engineers sought to identify problem applications where their new technology provided needed advantages.

4.5.1.2 Engineering designers identified enabling functions using action verbs from key characteristics

After describing key characteristics of technologies, designers used action verbs to describe enabling functions of their technologies. For example, Eric described one of the characteristics of his technology as a porous material. Because of the porosity, his technology allowed him to collect and retain liquid specimen:

"*Because it's a* ***porous material****...in fact we were able* ***to collect the specimen*** *and completely dissolve the hydrogel, and recover 95% of the specimen.*" (Eric)

Similarly, Kevin emphasized what his technology can do based on its characteristics:

"*The particles are* ***electrically conductive, thermally conductive****… if I put them in a plastic,* ***they can create what are called barrier properties****.*" (Kevin)

4.5.1.3 Engineering designers emphasized different characteristics of their technologies and sometimes multiple characteristics at the same time in order to find problem applications.

Many technologies had multiple unique, different characteristics. Engineers focused on different characteristics to consider multiple problem applications of their technologies. For example, Kevin developed a new material that is thin, large, light weight, and stiff. By focusing on the thin and large characteristics, he searched for problem applications in water filtration. At the same time, by leveraging stiff and lightweight characteristics, he looked for automotive problem applications of his material:

"*I described the (material) and said that they're very* ***thin and very large.*** *So we investigated a method to cause them to be produced with fixed spaces between them…****If it was the right size and I used very, very small marble, nothing would get through except the water…*** *I've mentioned the energy storage area. The vehicle area, the wind area, and so forth. There you're talking about you want* ***to make structures that are very stiff and very lightweight and then be able to have these other properties in them as well.*** *For example, in a vehicle, you like to have very thermally conductive materials in some applications under the hood. You'd like to have lightweight materials that perform structurally and they absorb the impact and so forth in the body.*" (Kevin)

Designers often combined multiple characteristics of their technologies to identify applications. For example, Eric leveraged both density and insulation characteristics to look for applications that require bullet-proof, high insulation applications such an army vehicle:

"*It was a* ***bullet proof material, again, because of the density of the material.*** *It's a very good* ***insulation material, so that insulation is known, but it was also very***

light material that we can wear, *so you can do armor protection. So we started to discuss with some of the companies making those products, either the clothing, wearable system, but we talked also with one of the largest companies making at that time the Humvee vehicle for the army, where they needed to do the insulation, for example, in the door of the vehicle*." (Eric)

By combining multiple characteristics of their technologies, engineers looked for problem applications that could take the most advantage of their technologies' functions.

4.5.2 Reframing Pathway

4.5.2.1 Engineering designers reframed their technology functions by looking at the technology from different perspectives to identify different potential uses.

In addition to understanding the enabling functions based on key characteristics of their technologies, designers identified new functions for their technologies by reframing them using alternative perspectives to better understand their capabilities. For example, James initially developed a laser welding technology that later became laser cladding, or laser 3D printing technology.

"*Technology is what do you call ... laser welding of titanium…* ***but instead of welding, joining two materials, you are putting powder and melting it with laser to create a shape****. That's laser cladding. That's how I got started.*" (James)

By shifting his perspective from laser welding (focused on joining two materials together) to laser cladding (creating new shapes by melting powder), James created a new and different function for his technology.

4.5.3 Analogy Pathway

4.5.3.1 Engineering designers compared characteristics and enabling functions of their technologies with competitors' technologies to identify applications.

After understanding the key characteristics and enabling functions of their technologies, some engineers looked toward competitors' technologies and their applications. Adam identified potential applications of his own technology:

"***We had a competitor who was very successful in adjacent market space…They put them into (a list of) applications. They worked fine, except, when they didn't***

> ***work fine. Then they had problems. We would meet with, talk to various people who had purchased these and deployed them, and learned what challenges they'd run into.*** *Then, mentally, we would have our own personal mental list as to whether or not we could overcome the shortcomings. If we could, then we knew that customer liked the idea of a fuel driven solution, fuel cell, and that the customer was okay with something at that price point. We knew they ultimately had a special application where other things wouldn't work. We knew if we could provide a slightly differentiated solution, that solves their existing problems, they would most likely be willing to adopt.*" (Adam)

By understanding different uses of the competitors' technologies, engineers identified different uses for their own technologies.

<u>4.5.4 Common Path</u>

4.5.4.1 Engineering designers aligned characteristics/functions of the technology with possible needs of industries.

Engineers aligned their technologies' capabilities with possible needs of industries. For example, Carl developed an autonomous drone that can take images to collect data. He was looking for industry sectors that require data that his drone can collect:

> "*Honestly we just brainstormed and threw a bunch of stuff on the board and* ***were like where is it hard to get a camera that you want data****? I think at the time a bridge had fallen down, and we were talking about infrastructure, and maybe these* ***bridges would fall down less if they had better data to analyze****, but it's hard to get those pictures.*" (Carl)

By aligning the characteristics and functions of his technology and possible needs of various industry sectors, Carl identified the infrastructure industry as a possible area to find applications for his autonomous drone.

4.5.4.2 Engineering designers prioritized and filtered industry sectors as possible uses of their technology.

Before identifying specific applications of their technologies, engineers identified broad industry sectors that can potentially benefit from their technologies, and then filtered to remove candidates and prioritized sectors that appeared to be good matches to their technologies. For example, Carl developed an autonomous drone but did not have a clear application. He considered many different industry sectors:

> "*We were a solution looking for a problem, so we started the company. Well, the very first pitch we ever gave when we went to San Francisco and pitched to that alumni. The very first pitch we gave, we said we're gonna build military and we're gonna build industrial inspection, and we're gonna build a hobby grade one. We're gonna build it across the whole board… Oh yeah. We were looking at cell towers and power and oil and gas and boats and ship yards. And we were looking at traffic monitoring. We were looking at search and rescue applications. We talked to the state police and fire departments and who else? I even spoke a lot to the* military *through one of the innovation groups… We're looking at other things inside of power. Power distribution, like high voltage transmission lines. We've still considered stuff like Telecom, cell towers and other large structures that you need to fly close to, but so far we're really focused on wind and really focused on adding value to the analytics of wind."* (Carl)

Carl was initially searching for broad problems to address with his technology. After searching broad industry sectors, he prioritized the power and energy industries as his main targets, and found an application in using his autonomous drones to support the wind power industry. Many other engineers demonstrated a similar approach. Ian developed an exoskeleton technology and considered all possible industry sectors that might use his technology:

> "*There's a lot of excitement around the military and industrial applications of exoskeleton technology. You're starting to see a lot of focus developing exos for manufacturing applications. So, we're considering all of it… We're entering this field that's at such an early stage, it's just a huge amount of opportunity. And there's certainly more opportunity than we have time to explore. So, we have to choose very carefully where we decide to spend our energy."* (Ian)

4.5.4.3 Engineering designers identified specific applications within various industries talking to multiple different stakeholders and varying how they describe their technologies.

After identifying promising industry sectors, engineers did a deep dive into specific sectors to look for applications of their technologies. As engineers engaged with various individual stakeholders within multiple industry sectors, they intentionally varied how they spoke about their technology based on different audiences. For example, Diane's company developed a technology with a wide range of applications but they were focusing on medical applications:

> "*But you definitely need to change how you speak based on who your audience is. For example, for this cold-calling I was speaking* ***mostly to someone in materials acquisition. So typically they don't have a technology based background.*** *They probably don't have too much of a medical based background…So you need to put it in somewhat simpler terms. On the other hand,* ***if you're talking to doctors you need to give them more of a medical based background. Talk to them more about the diagnoses, talk about reimbursement, talk about the large patient base…*** *If you're talking to more* ***research customers, you need to talk about the technology specifically what frequency it works it****. If it would be beneficial for them, that kind of thing.*" (Diane)

Diane had to vary her description of the benefits of using her technology based on different types of stakeholders, such as doctors and researchers.

Similarly, Larry needed to have the ability to explain his technologies to stakeholders from various industries to identify specific applications. Larry developed a 3D printer that can print composite material. He prioritized various sectors and talked with stakeholders within those industries to find a fit:

> "*Because I print composite material…So, of course, you've got automotive industry, which using a lot more composite material than before. Some cars literally have pretty much all the structural ... I should say non-structural components with composite materials. I mean the frames, you need metal. That's for sure. But they're talking about interior, car casing, even some of the internal*

parts that people cannot touch within the hood, composite materials. So the need of composite materials for automotive can be growing rapidly… Drone industry is increasing as well. Wind turbines, green energy, same thing. And of course, we've got medical, which is the prosthetic industry that we're talking about. To be fair with you, we do not know which one works better than the other. ***At the beginning, we talked to all of them…*** *What's the application? I have no idea.* ***You talk to them and they will tell you. You pretty much tell them the technology and if it fits with what they care in their mind, they will keep talking to you****. If it doesn't fit anything, they will be polite and keep talking to you for three to five minutes and get you away. As simple as that.*” (Larry)

Engineers started out searching broadly across potential sectors that can use their technologies, and identified a shorter list of sectors to prioritize. Then, they identified and talked with individual stakeholders within each of those industries to find specific problem applications.

4.6 Discussion

A successful design process does not always start with a problem. Although many design processes focus on this typical design process starting with a problem and coming up with a solution (Cross, 2008a; Dubberly, 2004; Eide et al., 2011; Ertas & Jones, 1996; French et al., 1985), engineering designers in this study focused instead on using their technologies as solutions and identifying new problems they can solve. This process is described in the entrepreneurship literature as “opportunity recognition” (Shane, 2000). In the present study, we identified specific cognitive strategies used by engineers working with new technologies in a process of *solution mapping*, to match technologies to problem applications.

Engineering designers in the study demonstrated a number of cognitive strategies used to understand and expand their own understanding of the varied capabilities of their new technologies. The most common strategy observed was identifying the superior characteristics of their new technology compared to existing technologies, similar to the functional decomposition strategy documented in idea generation in design (Eck, 2011; Umeda, Ishii, Yoshioka, Shimomura, & Tomiyama, 1996). However, functional decomposition has previously been used to identify functional requirements for a problem in order to generate multiple solutions. In this study, designers instead used functional decomposition of their new technologies to identify novel or superior functions which may match the needs in specific problems.

Designers also combined multiple characteristics or functions of their technologies to identify applications. Prior research has documented combining characteristics or functions during generation of new solutions to a problem (Mohan, Shah, Narsale, & Khorshidi, 2014). In our study, designers instead combined functions of their technologies to understand how to take advantage of multiple functions in order to identify new problems where their solutions are maximally effective.

Another strategy identified was to focus on taking multiple, alternative perspectives towards their technologies in order to consider each of the new technology's functions and capabilities. Perspective taking allows one to move away from one's own viewpoint and take on another person's view (Ackermann, 2012). Perspective taking in solution mapping may support designers in understanding their own technology better by generating different alternative views of its functions, aiding in identifying its applications.

Our study revealed that designers compared their technologies with other existing technologies in order to understand potential applications. In the business and entrepreneurship literature, the comparison of new technologies with existing technologies to identify applications is called a "fast-follower" strategy (Kim, 2012), and engineering designers in our study engaged in similar approaches.

Many engineering designers identified multiple industry sectors that may benefit from using their technologies by aligning (mapping) key characteristics of their technologies with potential needs of various industry sectors. The use of analogy involves creating alignments across instances based on perceptions of similarity between two or more objects (c.f. Day & Gentner, 2007; Keane et al., 1994; Markman & Gentner, 1993; Gregoire, Barr & Shepherd, 2010). In our study, engineering designers were observed to perform a specific type of analogical comparison where they "mapped" or "aligned" the key features of their technologies with needs evidence in specific industry sectors.

Engineering designers did a "deep dive" into each sector to help them identify specific applications of their technologies. This involved learning about the problems within a section by interviewing and engaging with individual stakeholders. In particular, the designers met with various different types of stakeholders in an industry sector and explained their technology in layman's terms in order to find connections. By engaging with stakeholders, engineers sought to identify clear needs of their stakeholders, which is a common approach used in human-centered design (Brown, 2009; Kelley & Littman, 2001; Miaskiewicz & Kozar, 2011). Our findings demonstrate that engineering designers are selective in their search for problem applications, and suggest that the solution mapping process is not well understood or supported in their previous training; instead, they viewed their experience as a novel and challenging problem of their own to solve by looking for a 'match' between their technology and a problem.

4.7 Limitations

The findings from this study are drawn from a small number of participants' interviews, limiting generalizability. Qualitative studies focus on in-depth understanding of participants' experiences to identify meaning (Creswell, 2013; Patton, 2001; Saldaña, 2011). In-depth studies using small sample sizes are common in design research (e.g., Cardoso, Badke-Schaub, & Eris, 2016; Daly, Adams, et al., 2012; Damen & Toh, 2017; Goldschmidt, 1995; Goucher-Lambert, Moss, & Cagan, 2016; Starkey, McKay, Hunter, & Miller, 2016) and provide valuable insights into design processes.

This study identified several cognitive strategies based on a sample of participants across multiple industry sectors. Certainly, additional cognitive strategies may be evident by studying a larger sample size in more domains. A long-term research goal is to develop a collection of such strategies demonstrated in varied design contexts in order to aid divergent thinking during the solution mapping process with new technologies. Future studies can help to identify additional cognitive strategies to support solution mapping.

4.8 Implications

This paper identified cognitive strategies in solution mapping using interviews of experienced engineers. Ideally, these cognitive strategies may be applied by other designers engaged in the process of solution mapping. To support this, design tools may be created for designers following a technology-first design process. Currently, no such tools are available. Other design tools have been demonstrated to support novice and experienced engineers in specific phases of a design process (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Hernandez et al., 2013; Lee, Daly, Huang-Saad, Seifert, et al., 2018); therefore, a tool including the cognitive strategies identified in this study may be helpful to support both novice and experienced engineers as they perform solution mapping.

The results of this study identify a role for engineering education in preparing designers for solution mapping processes. Based on our findings, we anticipate developing design courses or modules that collaborate with technology inventors to identify various different uses of new technologies. We envision a teachable set of strategies translating the observed findings into accessible design tools to support engineering students and practitioners in solution mapping. As demonstrated in this study, design processes do not always start with problems and designers may start with a technology. Lessons on solution mapping can support designers to be equipped with different tools and approaches to design. With these design tools, engineering students and practitioners can learn ways to explore multiple applications of novel technologies, increasing their knowledge of how to perform solution mapping and their confidence in undertaking the process, potentially leading to more innovative products.

4.9 Conclusion

This study explored cognitive strategies in identifying problem applications in a technology-centered design process; in solution mapping, engineers leverage new, novel technologies by searching for problems that 'match' their technologies' advantages. The findings from this qualitative study show that engineering designers break down their technologies into superior characteristics, identify enabling functions, take multiple perspectives to understand alternative functions, and compare their technologies with existing, similar technologies in order to better understand the opportunities provided in their own new technologies. Then, engineers identified broad industry sectors that might leverage their technologies through aligning the characteristics of their technologies with specific needs in various industries. To investigate these matches, engineers engaged with individual stakeholders within those industries to identify specific problems and needs. The observed cognitive strategies may be translated into explicit design tools to support designers in identifying alternative problems for their existing solutions.

4.10 References

Ackermann, E. (2012, November 12). Perspective-Taking and Object Construction: Two Keys to Learning. https://doi.org/10.4324/9780203053492-8

Altshuller, G. (1997). *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc.

Bailey, K. (1994). *Methods of Social Research, 4th Edition*. New York, NY: The Free Press.

Biernacki, P., & Waldorf, D. (1981). Snowball Sampling: Problems and Techniques of Chain Referral Sampling. *Sociological Methods & Research*, *10*(2), 141–163. https://doi.org/10.1177/004912418101000205

Björklund, T. A. (2013). Initial mental representations of design problems: Differences between experts and novices. *Design Studies*, *34*(2), 135–160. https://doi.org/10.1016/j.destud.2012.08.005

Blank, S., & Dorf, B. (2012). *The Startup Owner's Manual: The Step-By-Step Guide for Building a Great Company* (1 edition). Pescadero, Calif: K & S Ranch.

Borrego, M., Douglas, E. P., & Amelink, C. T. (2009). Quantitative, Qualitative, and Mixed Research Methods in Engineering Education. *Journal of Engineering Education*, *98*(1), 53–66. https://doi.org/10.1002/j.2168-9830.2009.tb01005.x

Boyatzis, R. E. (1998). *Transforming Qualitative Information: Thematic Analysis and Code Development*. SAGE.

Brown, S. W., & Goslar, M. D. (1986). Decision support systems: advantages in consumer marketing settings. *Journal of Consumer Marketing, 3*(3), 43–50. https://doi.org/10.1108/eb008169

Brown, T. (2009). *Change by Design: How Design Thinking Transforms Organizations and Inspires Innovation*. New York: HarperBusiness.

Bucciarelli, L. L. (1988). An ethnographic perspective on engineering design. *Design Studies, 9*, 159–168.

Bulsuk. (2011). An Introduction to 5-why. Retrieved March 15, 2019, from https://www.bulsuk.com/2009/03/5-why-finding-root-causes.html

Cardoso, C., Badke-Schaub, P., & Eris, O. (2016). Inflection moments in design discourse: How questions drive problem framing during idea generation. *Design Studies*, *46*, 59–78. https://doi.org/10.1016/j.destud.2016.07.002

Creswell, J. W. (2013). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies*, *38*, 54–91. https://doi.org/10.1016/j.destud.2015.01.002

Cross, N. (2008a). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Cross, N. (2008b). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Csikszentmihalyi, M., & Getzels, J. W. (1971). Discovery-oriented behavior and the originality of creative products: A study with artists. *Journal of Personality and Social Psychology*, *19*(1), 47–52. https://doi.org/10.1037/h0031106

Daly, S., McGowan, A., & Papalambros, P. (2013). Using qualitative research methods in engineering design research. *Proceedings of the International Conference on Engineering Design, ICED*, *2*, 203–212.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design heuristics in engineering concept generation. *Journal of Engineering Education*, *101*(4), 601–629. https://doi.org/10.1002/j.2168-9830.2012.tb01121.x

Daly, Shanna R., Adams, R. S., & Bodner, G. M. (2012). What Does it Mean to Design? A Qualitative Investigation of Design Professionals' Experiences. *Journal of Engineering Education*, *101*(2), 187–219.

Daly, Shanna R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). Assessing Design Heuristics for Idea Generation in an Introductory Engineering Course. *International Journal of Engineering Education*, *28*(2), 1–11.

Damen, N. B., & Toh, C. A. (2017). Designing for Trust: Understanding the Role of Agent Gender and Location on User Perceptions of Trust in Home Automation, V007T06A044. https://doi.org/10.1115/DETC2017-68349

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6

Dubberly, H. (2004). *How do you design*. A compendium of Models.

Eck, D. van. (2011). *Functional Decomposition: On Rationality and Incommensurability in Engineering*.

Eide, A., Jenison, R., Northup, L., & Mickelson, S. (2011). *Engineering Fundamentals and Problem Solving* (6 edition). New York, NY: McGraw-Hill Education.

Ertas, A., & Jones, J. C. (1996). *The Engineering Design Process* (2 edition). New York etc.: Wiley.

French, M., Gravdahl, J., & French, M. J. (1985). *Conceptual design for engineers*. London: Design Council.

Getzels, J. W. (1979). Problem Finding: a Theoretical Note. *Cognitive Science*, *3*, 167–172.

Goldschmidt, G. (1995). The designer as a team o f one. *Design Studies*, *16*(2), 189–209. https://doi.org/10.1016/0142-694X(94)00009-3

Gordon, R. (1975). *Interviewing: Strategy, Techniques and Tactics*. Illinois: Dorsey Press.

Goucher-Lambert, K., Moss, J., & Cagan, J. (2016). Using Neuroimaging to Understand Moral Product Preference Judgments Involving Sustainability, V007T06A023. https://doi.org/10.1115/DETC2016-59406

Hernandez, N. V., Schmidt, L. C., & Okudan, G. E. (2013). Systematic Ideation Effectiveness Study of TRIZ. *Journal of Mechanical Design*, *135*(10), 101009-101009–101010. https://doi.org/10.1115/1.4024976

Huang-Saad, A., Fay, J., & Sheridan, L. (2016). Closing the divide: accelerating technology commercialization by catalyzing the university entrepreneurial ecosystem with I-Corps™. *The Journal of Technology Transfer*, 1–21. https://doi.org/10.1007/s10961-016-9531-2

Hutchinson, S., & Wilson, H. (1992). Validity Threats in Scheduled Semistructured Research Interviews. *Nursing Research*, *41*(2), 117–119.

Kelley, T., & Littman, J. (2001). *The art of innovation*. Doubleday, NY: Currency.

Kim, S.-Y. (2012). Transitioning from fast-follower to innovator: The institutional foundations of the Korean telecommunications sector. *Review of International Political Economy*, *19*(1), 140–168. https://doi.org/10.1080/09692290.2010.503125

Kvale, S. (2007). *Doing interviews*. Thousand Oaks, CA: Sage Publications Ltd.

Lawson, B. R. (1979). Cognitive Strategies in Architectural Design. *Ergonomics*, *22*(1), 59–68. https://doi.org/10.1080/00140137908924589

Lee, J. W., Daly, S., Huang-Saad, A., & Seifert, C. (2018). Divergence in Problems Rather Than Solutions: Design Processes of Microfluidic Engineers in Academia. In *ASME 2018 International Design Engineering Technical Conferences (IDETC)*. Quebec City, Canada.

Lee, J. W., Daly, S. R., Huang-Saad, A. Y., Seifert, C. M., & Lutz, J. (2018). Using design strategies from microfluidic device patents to support idea generation. *Microfluidics and Nanofluidics*, *22*(7), 70. https://doi.org/10.1007/s10404-018-2089-6

Lee, J. W., Daly, S. R., & Vadakumcherry, V. (2018). Exploring Students' Product Design Concept Generation and Development Practices. In *American Society for Engineering Education*. Salt Lake City, UT.

Linsey, J. S., Markman, A. B., & Wood, K. L. (2012). Design by Analogy: A Study of the WordTree Method for Problem Re-Representation. *Journal of Mechanical Design*, *134*(4), 041009-041009–041012. https://doi.org/10.1115/1.4006145

Louise Barriball, K., & While, A. (1994). Collecting data using a semi-structured interview: a discussion paper. *Journal of Advanced Nursing*, *19*(2), 328–335. https://doi.org/10.1111/j.1365-2648.1994.tb01088.x

Miaskiewicz, T., & Kozar, K. A. (2011). Personas and user-centered design: How can personas benefit product design processes? *Design Studies*, *32*(5), 417–430. https://doi.org/10.1016/j.destud.2011.03.003

Mohan, M., Shah, J. J., Narsale, S., & Khorshidi, M. (2014). Capturing Ideation Paths for Discovery of Design Exploration Strategies in Conceptual Engineering Design. In J. S. Gero (Ed.), *Design Computing and Cognition '12* (pp. 589–604). Springer Netherlands.

Mohedas, I., Daly, S., & Sienko, K. (2014). Design Ethnography in Capstone Design: Investigating Student Use and Perceptions. *International Journal of Engineering Education*, *30*(4), 888–900.

Navarro-Prieto, R., Scaife, M., & Rogers, Y. (1999). Cognitive Strategies in Web Searching. In *5th Conference on Human Factors and the Web*. Maryland. Retrieved from https://www.researchgate.net/publication/239061211_Cognitive_Strategies_in_Web_Searching

Nnakwe, C. C., Cooch, N., & Huang-Saad, A. (2018). Investing in Academic Technology Innovation and Entrepreneurship: Moving Beyond Research Funding through the NSF I-

CORPS; Program. *Technology & Innovation*, *19*(4), 773–786. https://doi.org/info:doi/10.21300/19.4.2018.773

Norman, D. A., & Verganti, R. (2014). Incremental and radical innovation: Design research vs. technology and meaning change. *Design Issues*, *30*(1), 78–96. https://doi.org/10.1162/DESI_a_00250

Osborne, J. (2008). *Best practices in quantitative methods*. Thousand Oaks, CA: Sage.

Patton, M. Q. (2001). *Qualitative Research & Evaluation Methods* (3rd edition). Thousand Oaks, CA: SAGE.

Riel, A. J. (1996). *Object-Oriented Design Heuristics* (1st ed.). Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc.

Saldaña, J. (2011). *Fundamentals of Qualitative Research*. Oxford University Press, USA.

Salvador, T., Bell, G., & Anderson, K. (1999). Design Ethnography. *Design Management Journal (Former Series)*, *10*(4), 35–41. https://doi.org/10.1111/j.1948-7169.1999.tb00274.x

Schunn, C. D., Mcgregor, M. U., & Saner, L. D. (2005). Expertise in ill-defined problem-solving domains as effective strategy use. *Memory & Cognition*, *33*(8), 1377–1387. https://doi.org/10.3758/BF03193370

Shane, S. (2000). Prior Knowledge and the Discovery of Entrepreneurial Opportunities. *Organization Science*, *11*(4), 448–469. https://doi.org/10.1287/orsc.11.4.448.14602

Smith, L. (1992). Ethical issues in interviewing*. *Journal of Advanced Nursing*, *17*(1), 98–103. https://doi.org/10.1111/j.1365-2648.1992.tb01823.x

Starkey, E. M., McKay, A. S., Hunter, S. T., & Miller, S. R. (2016). Let’s Get Physical? The Impact of Dissection Modality on Engineering Student Design Learning, V003T04A015. https://doi.org/10.1115/DETC2016-60364

Studer, J. A., Daly, S. R., McKilligan, S., & Seifert, C. M. (2018). Evidence of problem exploration in creative designs. *AI EDAM*, *32*(4), 415–430. https://doi.org/10.1017/S0890060418000124

Thomas, T., Culley, S., & Dekoninck. (2007). Creativity in the Engineering Design Process. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Umeda, Y., Ishii, M., Yoshioka, M., Shimomura, Y., & Tomiyama, T. (1996). Supporting conceptual design based on the function-behavior-state modeler. *AI EDAM*, *10*(4), 275–288. https://doi.org/10.1017/S0890060400001621

Chapter 5: Cognitive design tool for divergent thinking in solution mapping

5.1 Abstract

Design processes usually start with defining an initial problem and then diverge to generate possible solutions; however, some design processes start with novel technologies and diverge to consider potential problems that these technologies can solve. We define the latter process as "solution mapping," to capture how engineering designers 'match' their novel technologies to existing problems. A recent qualitative study of engineering practitioners identified cognitive strategies evident in successful cases of solution mapping. In this study, we examined the applicability and impact of these solution mapping strategies embedded in a design tool. An empirical study with engineering students showed that tool use resulted in the identification of more diverse problem applications for a technology. The tool appears to help novice designers learn how to engage with the solution mapping process.

5.2 Introduction

In traditional problem-first design processes, engineers identify an initial problem and consider multiple possible solutions to address the problem (Cross, 2008; Dubberly, 2004; Eide, Jenison, Northup, & Mickelson, 2011; Ertas & Jones, 1996; French, Gravdahl, & French, 1985). However, in some design processes, engineers have been known to reverse this process: They develop a novel technology first and then consider multiple problems they can solve with their technology (Baron, 2006; Lee, Daly, Huang-Saad, & Seifert, 2018; Shane, 2000; Thomas, Culley, & Dekoninck, 2007), a process we call *solution mapping*. While solution mapping is common in engineering and entrepreneurship (Baron, 2006; Shane, 2000; Thomas et al., 2007), engineering students are often taught only problem-first design processes. Even if solution-first approaches are considered by educators, there are few evidence-based design tools to guide designers in solution mapping processes.

Design researchers have developed a variety of design tools to support engineers throughout a design process (Blessing & Chakrabarti, 2009). Design researchers utilized multiple approaches in developing design tools, including studying design artifacts (Altshuller, 1997; Camburn et al., 2015; Lee, Daly, Huang-Saad, Seifert, & Lutz, 2018), and documenting designers as they work on solving open-ended tasks (Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Lauff, Kotys-Schwartz, & Rentschler, 2018). Studies have demonstrated the efficacy of leveraging design tools to aid design practices (Daly, Seifert, Yilmaz, & Gonzalez, 2016; Hernandez, Schmidt, & Okudan, 2013; Lee, Daly, Huang-Saad, Seifert, et al., 2018; Lee, Daly, & Vadakumcherry, 2018). However, no studies have examined a design tool for solution mapping.

In a previous study (Lee et al., to be submitted), I identified cognitive strategies through a qualitative study of solution mapping with engineering practitioners who successfully identified problems for their new technologies. Cognitive strategies are specific experience-based guidelines that help designers make good decisions and using cognitive strategies is highly advantageous (Brown & Goslar, 1986; Lawson, 1979; Navarro-Prieto, Scaife, & Rogers, 1999). The present study develops these cognitive strategies for solution mapping as an accessible design tool to support engineers. The tool is then tested through an empirical study of student engineers to determine its effectiveness in supporting solution mapping.

5.3 Background

5.3.1 Design processes starting with solutions

Although design process models typically starting with a problem leading to a solution (Cross, 2008; Dubberly, 2004; Eide et al., 2011; Ertas & Jones, 1996; French et al., 1985), designers sometimes develop a novel technology as a solution and then diverge to consider various problems served by their technology (Baron, 2006; Lee et al., 2018; Shane, 2000; Thomas et al., 2007). For example, the development of 3D printers was a technology-first approach where a novel technology was developed before potential problem applications were identified. Also, microfluidic device technology to precisely control microliter volumes of fluid has been created, and engineers continue to search for applications of this technology (Blow, 2007). Although the technology-first process differs from the typical problem-first process, technology-first designers also follow key principles of design as they map a well-specified solution onto multiple and diverse alternative problems where there is no right or wrong answer to find better matches (Goel & Pirolli, 1992; Jonassen, 2000; Visser, 2006).

Technology-first design processes seek to exploit new patents or make use of interesting mechanisms (Thomas et al., 2007). In entrepreneurship, technology-first processes are broken down into three key steps: 1) technological invention, 2) opportunity recognition, and 3) approach to exploitation (Grégoire, Barr, & Shepherd, 2009; Shane, 2000). By developing new technologies with unique capabilities, designers create new possibilities to develop novel products, change production processes, and generate new market opportunities. In opportunity recognition, designers identify multiple potential uses for their new technologies to fit markets and stakeholder needs. In a last step, designers exploit an opportunity and pursue commercializing their technologies into products. However, it is often challenging to identify different uses for a technology because recognizing opportunities is not obvious (Shane, 2000). In business cases, studies have demonstrated that there are multiple factors contributing to the opportunity recognition process, including prior knowledge, expertise, and mentorship (Baron, 2006; Shane, 2000; St-Jean & Tremblay, 2011).

Within the design research literature, there are few studies addressing solution mapping as a process. While engineering designers in particular face the need for solution mapping whenever new technology is invented, they are rarely prepared to do so. Engineering education in academic programs does not include specific instruction on solution mapping, and there are few evidence-based guidelines for training. A qualitative study of successful solution mapping experiences identified a set of cognitive strategies. These guidelines may be useful in training novice designers about the solution mapping process. However, no studies have investigated specific design tools to support solution mapping.

5.3.2 Development of design tools

Many design tools have been developed using varied approaches to support engineers in various phases of design. Tools have been developed by translating design theories into structured approaches; for example, SCAMPER was developed to promote creative concept generation through structured prompts (Eberle, 1995).

Another approach to developing design tools is to study successful design artifacts. For example, TRIZ was developed by studying patterns in over 40,000 patents to create a set of 40 strategies supporting concept generation (Altshuller, 1997). Similarly, a set of design strategies in microfluidics was developed by extracting patterns in patents (Lee, Daly, Huang-Saad, Seifert, et al., 2018). The principles of DIY prototypes were also developed by analyzing key fabrication principles in prototypes from an open-source database (Camburn et al., 2015).

Design tools have also been developed through empirical studies of designers' practices. Prototyping tools were developed from observing and interviewing engineering practitioners for an extended period (Lauff et al., 2018). In another study, *Design Heuristics* were developed by identifying designers' approaches as they worked through an open-ended problem in a think-aloud protocol (Daly, Yilmaz, et al., 2012). Lee and colleagues (Lee et al., 2019) identified cognitive strategies in solution mapping by interviewing engineering professionals. This approach appears promising for the development of a design tool for solution mapping.

5.3.3 Supporting technology-first design

An educational approach to solution mapping with expert practitioners has been established in the National Science Foundation's I-Corps program, created to support technology advancements to commercial products (Nnakwe, Cooch, & Huang-Saad, 2018; Robinson, 2012). Engineers and scientists often develop new technologies with improved functions, discover new phenonema from basic science research, or devise a generational advance in existing technologies. To use their inventions, designers need to identify problems their new technology can solve in order to enter the market. I-Corps participants follow a curriculum developed by Steve Blank to investivate different uses and commercialization potential for their technology (Blank & Dorf, 2012). The standard process entails customer discovery to identify potential partners, and meetings with business investors to gain insights about developing a viable product. In the curriculum, participants are required to complete over 100 interviews with potential stakeholders to understand needs that their technology can fill. The interviews serve as a good opportunity to confirm or deny their assumptions about possible uses of their technologies. However, in the I-Corps program, there are few strategies provided to support designers in forming initial assumptions about potential problem applications for their technologies.

To support designers in identifying potential uses of technology, empirical evidence about successful cases were collected in a qualitative study by Lee and colleagues (Lee et al., to be submitted). Through interviews with engineering designers who developed novel technologies and successfully matched them to problems, a set of cognitive strategies in solution mapping was identified. Cognitive strategies are specific experience-based guidelines identified in practitioners that appear to help make good decisions (Riel, 1996), and using cognitive strategies is highly advantageous in diverse settings (Brown & Goslar, 1986; Lawson, 1979; Navarro-Prieto, Scaife, & Rogers, 1999). These cognitive strategies in approaching design can be developed into explicit design strategies that can be adopted by others (Altshuller, 1997; Daly et al., 2012; Hernandez et al., 2013; Lawson, 1979; Lee, Daly, Huang-Saad, Seifert, et al., 2018). The solution mapping strategies identified include methods such as breaking down technologies into key characteristics, identifying enabling functions based on characteristics, searching for multiple industry sectors, and engaging with stakeholders from various industry sectors to identify specific needs (Lee et al., 2019). These strategies have not been validated to support solution mapping; in this study, our research aim was to identify how a solution mapping design tool affects the search for problem applications for a new technology.

5.4 Methods

My project was guided by the following research questions:

1. How does the solution mapping tool affect the quantity of applications?

2. How does the solution mapping tool impact the diversity of applications?

5.4.1 Participants

Participants were 61 3rd year undergraduate, 4th year undergraduate, and graduate students in an engineering program at a large Midwestern University. Students were asked to participate in a single session and received $25 as compensation.

5.4.2 Data Collection

Students were assigned at random to one of the three groups: A) control with no interventions (N = 21), B) intervention with industry sectors (N = 19), and C) intervention with industry sectors and the solution mapping design tool (N = 21).

A graduate student with prior teaching experience conducted the three study sessions on consecutive days. PowerPoint presentations were used to guide the sessions for consistency. In each session, students were asked to work individually to identify varied applications for a new technology and to generate as many problem applications as possible. The technology chosen for the study was “shape memory alloys” for all three groups, which represents a mechanical engineering technology accessible for undergraduate students. The technology prompt was developed by identifying platform technologies with multiple applications documented in the literature, developing multiple technology prompts, and piloting selected prompts with undergraduate engineering students. The prompt used in the study is shown in Appendix A2.

Students were asked not to consult with other students and not to use any outside resources. Blank sheets were given to students to document their applications, which prompted students to both sketch and describe their applications in words. For all groups, an introduction to solution mapping was discussed for the first 5 minutes and students had the opportunity to ask questions for the next 5 minutes. All groups were instructed to come up with as many applications as possible for the technology in the prompt. The control group followed this procedure for 60 minutes. Intervention 1 group followed the same procedure with the addition of a provided one-page condensed list of industry sectors taken from the North American Industry Classification System (see Appendix A3). Intervention 2 group was given the same industry sectors list and the solution mapping tool (see Appendix A4) with written instructions for use. Students in the Intervention 2 group were instructed to mark an X on their worksheet at 60 minutes in order to record their progress as in other groups; in addition, they were given an additional 10 minutes to compensate for added time needed to learn to use the tool.

5.4.3 Data Analysis

The application sheets were collected and written descriptions were transcribed. The size of the drawings was adjusted to be similar for all applications. An example of a concept sheet is shown in Figure 19. In total, the 61 students generated 561 problem applications across all three conditions, with each participant generating between 3 and 20 applications.

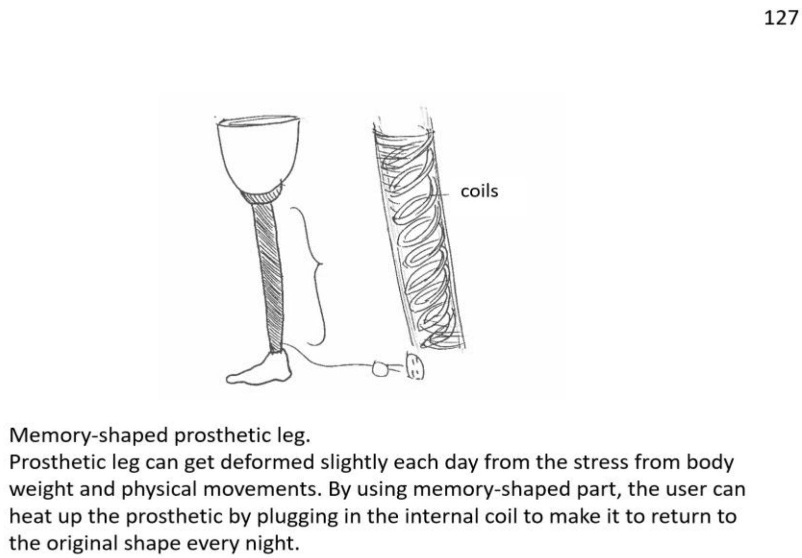

Figure 19. Example of a concept sheet with design sketch and transcribed written comments.

The analysis assessed all the applications generated for quantity and diversity, common assessments of ideation success in design (Daly, Seifert, Yilmaz, & Gonzalez, 2016; Kudrowitz & Wallace, 2013) and in creativity research (Amabile, 1982; Wilson, Guilford, Christensen, & Lewis, 1954). To measure quantity, we counted the total number of applications generated by each participant. For the Intervention Group 2, we assessed quantity of applications after 60 minutes and after 70 minutes (the additional time suggested for learning to use the mapping tool). In establishing idea diversity, we examined variations in industry sectors selected and in the functions of shape memory alloys described across all applications generated by a student. Two independent coders categorized every application, and the percent agreement was 86% for the list of industry sectors and 84% for the list functions, greater than the 70% level typically accepted for inter-rater reliability (Osborne, 2008).

One-way analysis of variance (ANOVA) was conducted to compare the three groups (and the longer session for Intervention Group 2) on the two outcome measures. We used the error rate of alpha = 0.1 and 0.05.

5.5 Results

5.5.1 Analysis of quantity of applications

The average of number of concepts generated is shown in Fig. 20. For quantity of applications, no significant differences emerged among the groups. The Intervention 2 group with extended time generated the most applications (M = 10.57), and the Intervention 1 group the fewest (M = 8.10). However, compared to performance of the control group (M = 8.95), neither the Intervention 1 group with the industry sector list ($p = 0.45$), the Intervention 2 group with industry sector list and mapping tool (M = 9.52; $p = 0.61$), nor the Intervention 2 group with extended time ($p = 0.18$) were significantly different in number of applications generated.

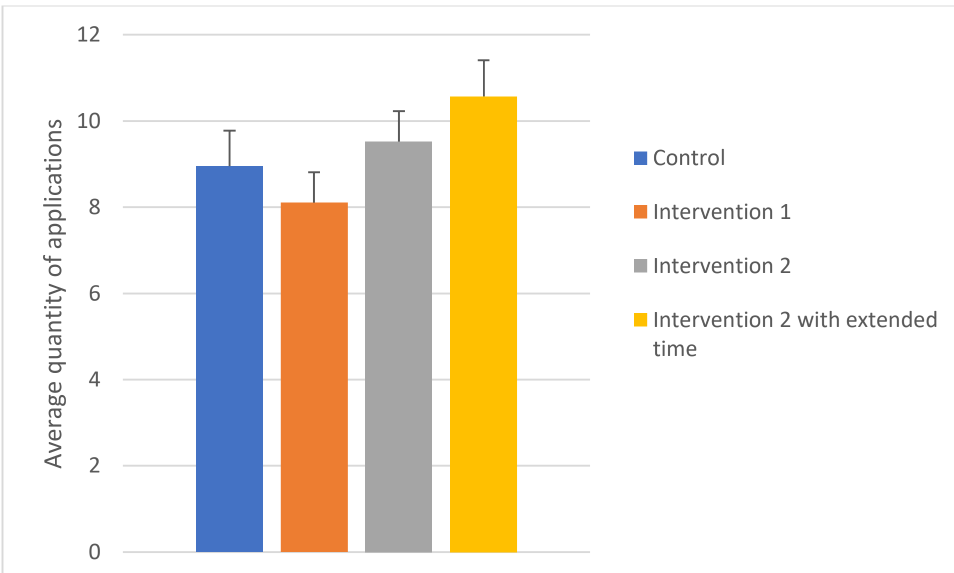

Figure 20. The quantity of applications generated by the control group (left) compared to those with the interventions.

5.5.2 Analysis of diversity of applications: Functions

I categorized every application into a target function and quantified the number of unique functions that each participant considered (see Figure 21). There was significant difference between the Control group and the Intervention 2 group (with industry sector list and mapping tool when an extra ten minutes was allotted ($p = 0.03$; for 60 minutes of work time, the difference was not significant, $p = 0.14$). No significant difference was observed between Control and Intervention 1 groups ($p = 0.12$).

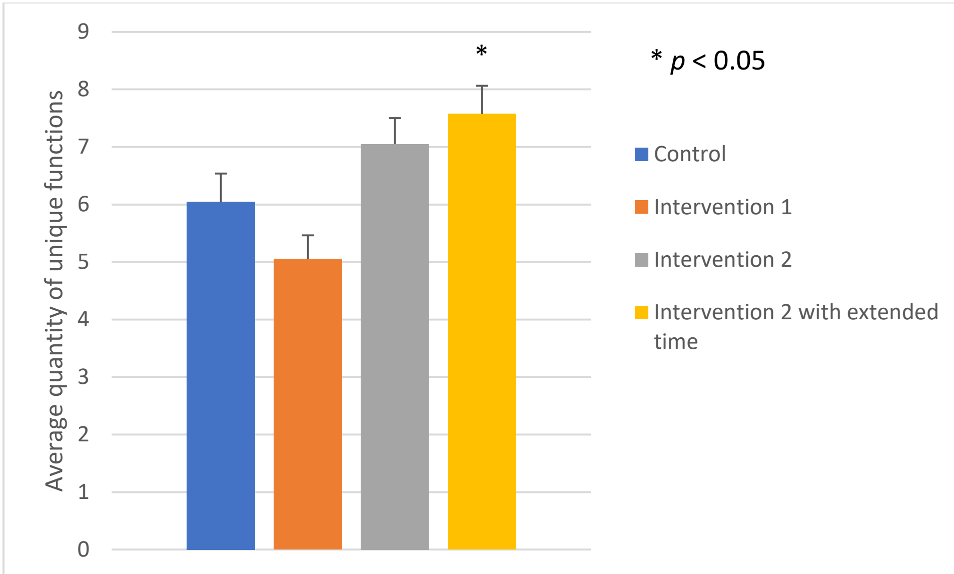

Figure 21. Average number of unique shape memory alloy functions considered in applications.

Students generated applications for shape memory alloys with varied functional uses. One student used a shape memory alloy to create a clothes hanger, but did not leverage the unique characteristics of the alloy, coded as "lacking function" (see Figure 22.a). Another student generated an application to use an alloy implant that returns to its original shape based on body temperature. This application can add force to straighten the spine of a patient with scoliosis, coded as "shape support" (Figure 22.b). Noted as "self-repair," a student generated an application to use an alloy as flexible tripod legs for a camera. The tripod would be able to easily latch onto any surface, allowing for superior camera angles. A button on the tripod would link to a heating element on the legs to straighten the tripod to be moved or unlatched (Figure 22.c). Indicated as "shield," another student used a shape memory alloy to cover crops in cold weather to prevent unexpected loss from frosts. The shield rolls down when temperatures are high to expose the crops to sunlight (Figure 22.d).

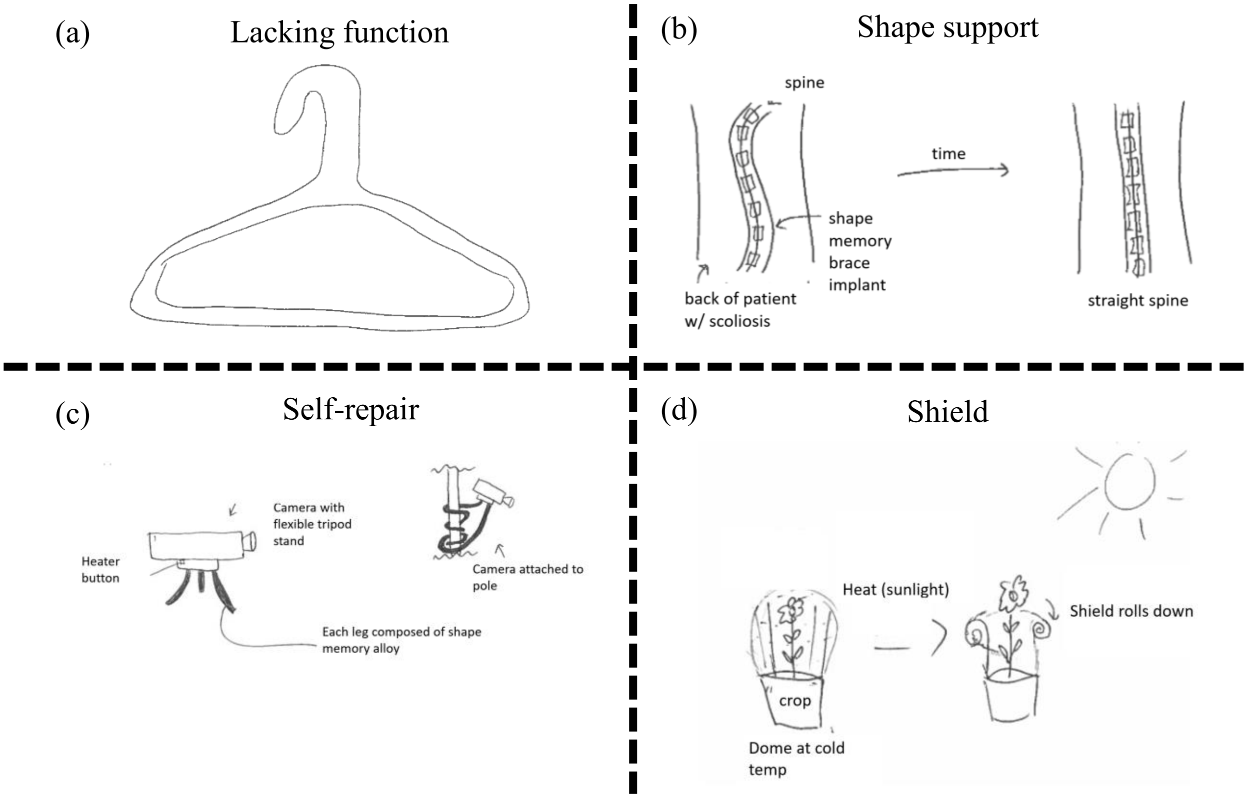

Figure 22. (a) Lacking function: a clothes hanger made of a shape memory alloy. (b) Shape support function: A spinal brace implant made of a shape memory alloy for treating scoliosis. (c) Shield function: A shape memory alloy dome to cover crops in cold temperatures and open in warm temperatures.

5.5.3 Analysis of diversity of applications: Industry sectors

I categorized every application into an industry sector and quantified the number of unique industry sectors that each participant considered (as seen in Figure 23). The control group (M = 6.95; SE = 0.48) and Intervention 1 group (industry sector list; M = 6.79; SE = 0.40) covered fewer industry sectors than the Intervention 2 group (with industry sector list and mapping tool) with either the same (M = 8.00; SE = 0.50) or extended time (M = 8.52, SE = 0.56). This difference between Control and Intervention 2 groups was significant only for the extended time measure ($p = 0.04$). No significant difference was observed between Control and Intervention 1 groups.

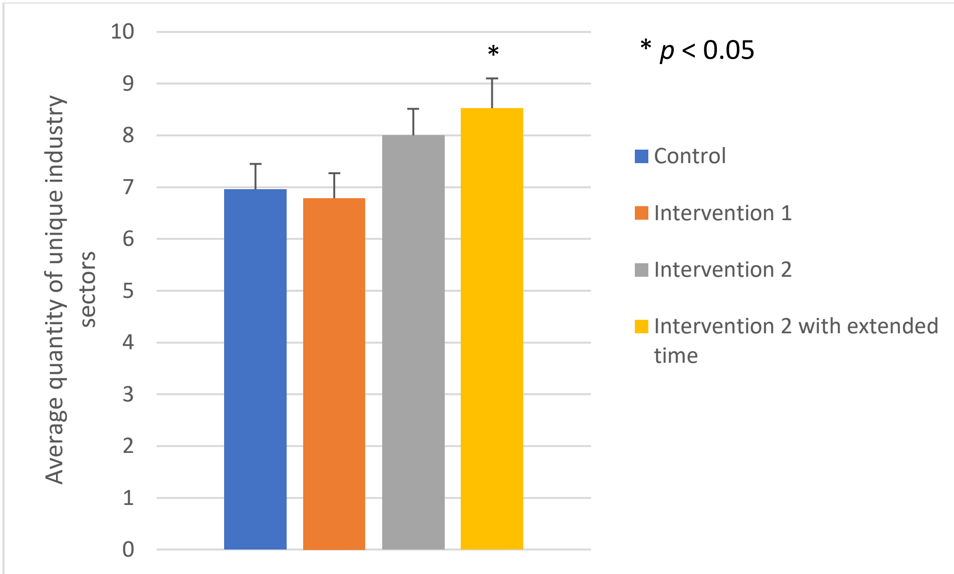

Figure 23. Average number of unique industry sectors considered by each participant.

Students generated a diverse set of industry sector applications for shape memory alloys in the study (for examples, see Figure 24). One student used a shape memory alloy as a switch for circuits with changing temperatures. However, since the student did not indicate where the switch will be used, we coded this as “unspecified” industry (Figure 24.a). Another student generated an application to use a shape memory alloy as a pipe for oil extraction that will close shut in case of accidents, coded as “oil and gas” industry (Figure 24.b). A student proposed using a shape memory alloy as reusable wires for a chicken coup, coded as “agriculture and forestry support” (Figure 24.c). Noted as “storage equipment,” a student thought of using a shape memory alloy to create durable crates for shipping that can be compressed for easy storage (Figure 24.d).

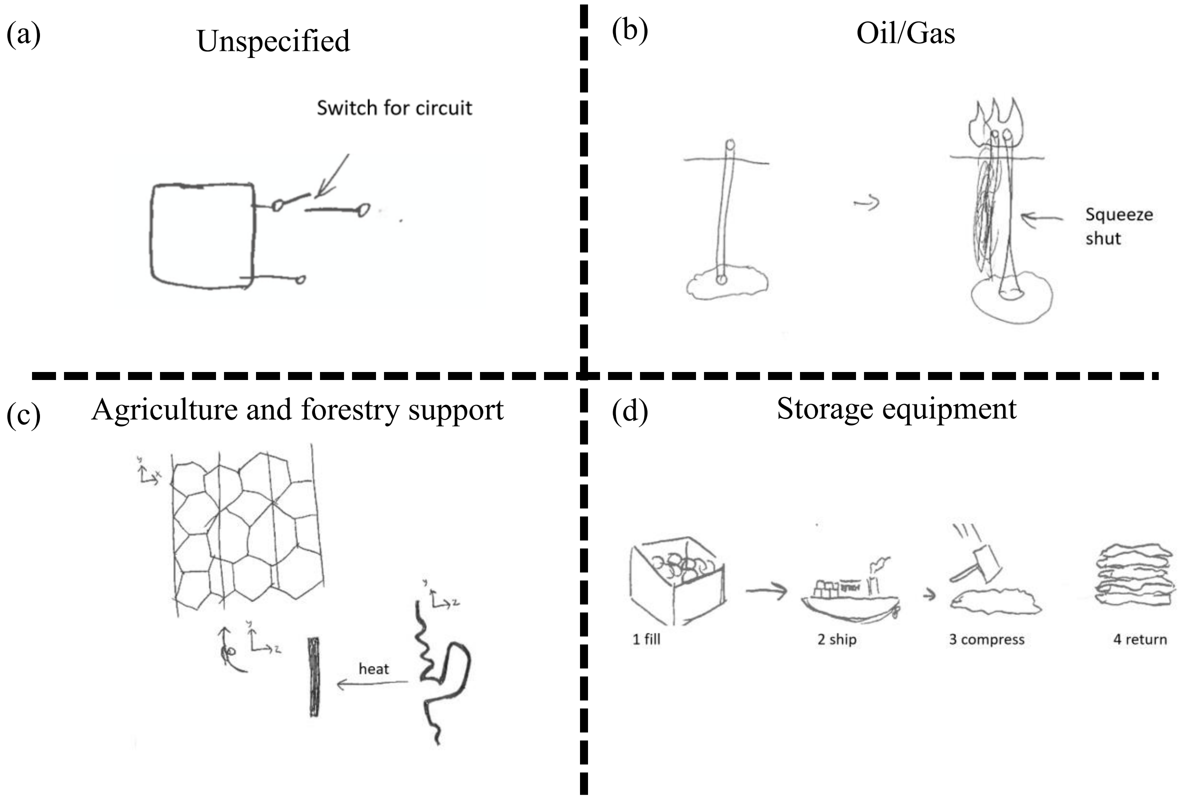

Figure 24. (a) Unspecified – a switch for circuit. (b) Oil and gas – a pipe made of a shape memory alloy that can close in case of fire. (c) Agriculture and forestry support – reusable chicken coup wires. (d) Storage equipment – crates for shipping and storage.

5.6 Discussion

The solution mapping tool was shown to support divergent thinking in generating problem applications of a novel technology. Given an industry sector list and the solution mapping tool, students were able to break down the technology into key characteristics and enabling functions, and generated applications with more varied functions and industry sectors. The findings are compromised by the problem of adding time to compensate for the provided tools. Those given only the industry sector lists likely took time from their solution mapping process to review the list; as a result, they generated fewer applications. Similarly, the intervention including the sector list and the solution mapping tool required additional time to understand these supports; when given ten minutes of extra time, performance in this group was the best across the measures. Prior research documents the benefits of using design tools to support divergent thinking during concept generation, and demonstrates that design tools may increase creativity, diversity, and quantity of concepts considered (Daly et al., 2016; Hernandez et al., 2013; Lee, Daly, Huang-Saad, Seifert, et al., 2018; Lee, Daly, & Vadakumcherry, 2018). This study was the first to examine the effectiveness of a design tool for solution mapping, and the results support the conclusion that this new form of design aid is also effective.

We also found that providing information without scaffolding the design process may not be beneficial. In this case, we provided a list of industry sectors and asked our participants to identify different uses of a technology in multiple industry sectors. However, participants did not generate more diverse applications with the list of industry sectors alone. When participants were given a list of industry sectors and the solution mapping design tool that provided cognitive scaffolding of identifying applications of a technology, participants considered more diverse uses of a technology. While previous research has demonstrated the benefits of using cognitive strategies in supporting design practices (Altshuller, 1997; Daly et al., 2012; Hernandez et al., 2013; Lawson, 1979; Lee, Daly, Huang-Saad, Seifert, et al., 2018), our study documents the efficacy of leveraging cognitive strategies to aid solution mapping.

We did not observe differences in the quantity of applications generated across the groups. One explanation is that participants using the solution mapping design tool simply require additional time to learn to use the design tool. The group provided with only an industry sector list produced fewer applications than any other group; so, the added time to learn about provided tools may result in less time to work on the design problem. Even so, the engineering students in the study were able to generate applications for a novel technology with minimal instruction even though it was the first time they had encountered the solution mapping process. This suggests students are able to understand the solution mapping process, and can consider potential problem applications without in-depth knowledge of the technology. Of course, more expertise may improve performance on the task.

5.7 Limitations

This study examined engineering students from a single large institution in the U.S., and findings in other educational settings may vary. Also, my study tested the usefulness of the solution mapping tool using one technology. I will need to test the solution mapping design tool with multiple technologies to determine how the type of solution impacts the mapping process. In addition, other findings may be uncovered if a larger sample size is collected.

In this study, students were asked to work individually to generate applications of a technology in a single session without use of outside resources. These circumstances are not reflective of practitioners' experiences with solution mapping for their own technologies. Practitioners spend extended periods of time to identify applications of their technologies, and often have opportunities to work in teams who can support them in solution mapping. Also, practitioners frequently engage with stakeholders to gain feedback throughout their design processes. Additional studies are needed to examine how the solution mapping design tool can support designers in practice.

5.8 Implications

These results have implications in engineering practice and education. When engineering practitioners search for applications of their technologies, current methods may not be sufficient. Engineers can benefit from explicit instructions providing guidance in solution mapping. By using the cognitive design tool in this study, practitioners may be able to come up with a more diverse set of applications to consider for their technologies.

Current engineering education curricula do not include solution mapping processes. Previous studies of entrepreneurs (Shane, 2000) and engineers (Lee et al., 2019) have demonstrated that novel technologies are invented without clear problem applications in mind. Design curricula emphasize "problem-first" design processes that encourage problem definition before diverging to consider potential solutions. The strategies for solution mapping capture in the tool may be useful in creating a lesson or learning module to teach technology-first design processes.

5.9 Conclusions

Design processes often start with a specific technology and diverge to consider problems it can solve, an alternative design process we call *solution mapping*. No tools have previously been available and empirically validated as supporting designers in solution mapping. The solution mapping tool developed through interviewing engineering practitioners was successful in helping students generate a more diverse set of applications for a given technology. This study demonstrates the usefulness of the solution mapping design tool in a controlled experiment with student engineers. The findings show that the tool is effective in leading students to consider diverse alternative applications of a technology. Because solution mapping is a design process beginning with a solution instead of a problem, support of its stages through the use of a design tool may be especially important.

Appendix A2. Problem statement

Shape Memory Alloy

A shape-memory alloy is an alloy that remembers its original shape. When it is deformed, it can return to its pre-deformed shape when heated. The transformation temperature can be adjusted to be between -100ºC to 200ºC through changing the alloy composition. The two main types of shape-memory alloys are copper-aluminum-nickel and nickel-titanium. These compositions can be manufactured to almost any shape and size. The yield strength of shape-memory alloys is lower than that of conventional steel, but some compositions have a higher yield strength than plastic or aluminum.

Identify potential applications of shape memory alloys.

Please spend 1 hour to complete this task.

Appendix A3. List of industry sectors

AGRICULTURE, FORESTRY, FISHING AND HUNTING
Crop production
Animal production and aquaculture
Agriculture and forestry support activities

MINING, QUARRYING, AND OIL AND GAS EXTRACTION
Oil and gas extraction
Mining, except oil and gas
Support activities for mining

UTILITIES
Utilities

CONSTRUCTION
Construction of buildings
Heavy and civil engineering construction
Specialty trade contractors

MANUFACTURING
Food manufacturing
Beverage and tobacco product manufacturing
Textile mills
Textile product mills
Apparel manufacturing
Leather and allied product manufacturing
Wood product manufacturing
Paper manufacturing
Printing and related support activities
Petroleum and coal products manufacturing
Chemical manufacturing
Plastics and rubber products manufacturing
Nonmetallic mineral product manufacturing
Primary metal manufacturing
Fabricated metal product
Machinery manufacturing
Computer and electronic product manufacturing
Electrical equipment and appliance mfg.
Transportation equipment manufacturing
Furniture and related product manufacturing
Miscellaneous manufacturing

WHOLESALE TRADE
Merchant wholesalers, durable goods
Merchant wholesalers, nondurable goods
Electronic markets and agents and Brokers

RETAIL TRADE
Motor vehicle and parts dealers
Furniture and home furnishings stores
Electronics and appliance stores
Building material and garden supply stores
Food and beverage stores
Health and personal care stores
Gasoline stations
Clothing and clothing accessories stores
Sports, hobby, music instrument, book stores
General merchandise stores
Miscellaneous store retailers
Nonstore retailers

TRANSPORTATION AND WAREHOUSING
Air transportation
Rail transportation
Water transportation
Truck transportation
Transit and ground passenger transportation
Pipeline transportation
Scenic and sightseeing transportation
Support activities for transportation
Postal service
Couriers and messengers
Warehousing and storage

INFORMATION
Publishing industries, except Internet
Motion picture and sound recording industries
Broadcasting, except Internet
Telecommunications
Data processing, hosting and related services
Other information services

FINANCE AND INSURANCE
Monetary authorities-central bank
Credit intermediation and related activities
Securities, commodity contracts, investments
Insurance carriers and related activities
Funds, trusts, and other financial vehicles

REAL ESTATE AND RENTAL AND LEASING
Real estate
Rental and leasing services
Lessors of nonfinancial intangible Assets

PROFESSIONAL AND TECHNICAL SERVICES
Professional and technical services

MANAGEMENT OF COMPANIES AND ENTERPRISES
Management of companies and enterprises

ADMINISTRATIVE AND WASTE SERVICES
Administrative and support services
Waste management and Remediation services

EDUCATIONAL SERVICES
Educational services

HEALTH CARE AND SOCIAL ASSISTANCE
Ambulatory health care services
Hospitals
Nursing and residential care facilities
Social assistance

ARTS, ENTERTAINMENT, AND RECREATION
Performing arts and spectator sports
Museums, historical sites, zoos, and parks
Amusements, gambling, and Recreation

ACCOMMODATION AND FOOD SERVICES
Accommodation
Food services and drinking places

OTHER SERVICES, EXCEPT PUBLIC ADMINISTRATION
Repair and maintenance
Personal and laundry services
Membership associations and org.
Private households

PUBLIC ADMINISTRATION
Executive, legislative and general Government
Justice, public order, and safety activities
Administration of human resource programs
Administration of environmental programs
Community and housing program administration
Administration of economic programs
Space research and technology
National security and international affairs

Appendix A4. Solution mapping design tool

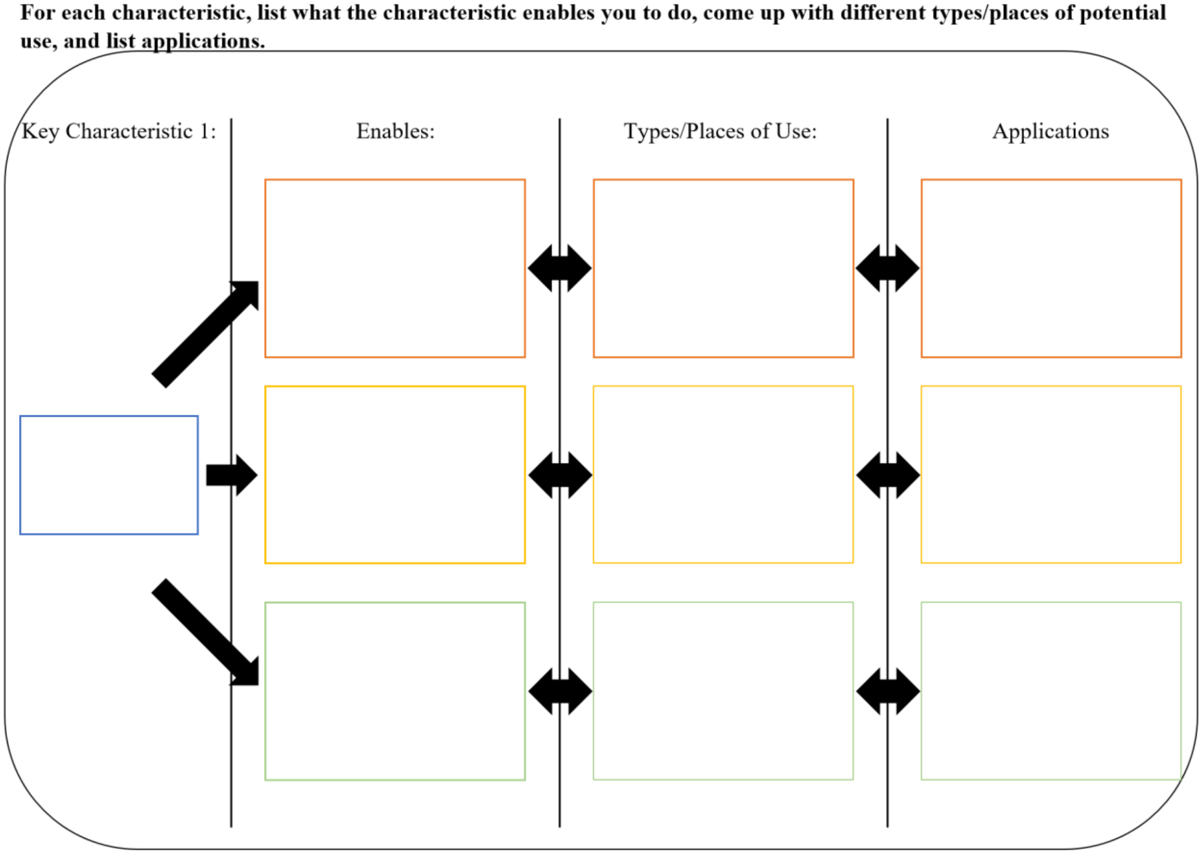

Figure 25. Solution mapping design tool for students

5.10 References

Altshuller, G. (1997). *40 principles: TRIZ keys to technical innovation*. Worcester, Mass.: Technical Innovation Center, Inc.

Amabile, T. M. (1982). Social psychology of creativity: A consensual assessment technique. *Journal of Personality and Social Psychology*, *43*(5), 997–1013.

Baron, R. A. (2006). Opportunity Recognition as Pattern Recognition: How Entrepreneurs "Connect the Dots" to Identify New Business Opportunities. *The Academy of Management Perspectives*, *20*(1), 104–119. https://doi.org/10.5465/AMP.2006.19873412

Blessing, L., & Chakrabarti, A. (2009). DRM: A Design Research Methodology. In *DRM, a Design Research Methodology* (pp. 13–42). Springer London. https://doi.org/10.1007/978-1-84882-587-1_2

Blow, N. (2007). Microfluidics: in search of a killer application. *Nature Methods*, *4*, 665–670. https://doi.org/10.1038/nmeth0807-665

Brown, S. W., & Goslar, M. D. (1986). Decision support systems: advantages in consumer marketing settings. *Journal of Consumer Marketing*, *3*(3), 43–50. https://doi.org/10.1108/eb008169

Camburn, B. A., Sng, K. H., Perez, K. B., Otto, K., Wood, K. L., Jensen, D., & Crawford, R. (2015). The Way Makers Prototype: Principles of DIY Design (p. V007T06A004-V007T06A004). Presented at the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers. https://doi.org/10.1115/DETC2015-46295

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design heuristics in engineering concept generation. *Journal of Engineering Education*, *101*(4), 601–629. https://doi.org/10.1002/j.2168-9830.2012.tb01121.x

Daly, Shanna R., Seifert, C. M., Yilmaz, S., & Gonzalez, R. (2016). Comparing Ideation Techniques for Beginning Designers. *Journal of Mechanical Design*, *138*(10), 101108-101108–101112. https://doi.org/10.1115/1.4034087

Dubberly, H. (2004). *How do you design*. A compendium of Models.

Eberle, R. (1995). *SCAMPER*. Waco, TX: Prufrock.

Eide, A., Jenison, R., Northup, L., & Mickelson, S. (2011). *Engineering Fundamentals and Problem Solving* (6 edition). New York, NY: McGraw-Hill Education.

Ertas, A., & Jones, J. C. (1996). *The Engineering Design Process* (2 edition). New York etc.: Wiley.

French, M., Gravdahl, J., & French, M. J. (1985). *Conceptual design for engineers*. London: Design Council.

Goel, V., & Pirolli, P. (1992). The structure of Design Problem Spaces. *Cognitive Science*, *16*(3), 395–429. https://doi.org/10.1207/s15516709cog1603_3

Grégoire, D. A., Barr, P. S., & Shepherd, D. A. (2009). Cognitive Processes of Opportunity Recognition: The Role of Structural Alignment. *Organization Science*, *21*(2), 413–431. https://doi.org/10.1287/orsc.1090.0462

Hernandez, N. V., Schmidt, L. C., & Okudan, G. E. (2013). Systematic Ideation Effectiveness Study of TRIZ. *Journal of Mechanical Design*, *135*(10), 101009-101009–101010. https://doi.org/10.1115/1.4024976

Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development*, *48*(4), 63–85. https://doi.org/10.1007/BF02300500

Kudrowitz, B. M., & Wallace, D. (2013). Assessing the quality of ideas from prolific, early-stage product ideation. *Journal of Engineering Design*, *24*(2), 120–139. https://doi.org/10.1080/09544828.2012.676633

Lauff, C. A., Kotys-Schwartz, D., & Rentschler, M. E. (2018). What is a Prototype? What are the Roles of Prototypes in Companies? *Journal of Mechanical Design*, *140*(6), 061102-061102–061112. https://doi.org/10.1115/1.4039340

Lawson, B. R. (1979). Cognitive Strategies in Architectural Design. *Ergonomics*, *22*(1), 59–68. https://doi.org/10.1080/00140137908924589

Lee, J. W., Daly, S., Huang-Saad, A., & Seifert, C. (2018). Divergence in Problems Rather Than Solutions: Design Processes of Microfluidic Engineers in Academia. In *ASME 2018 International Design Engineering Technical Conferences (IDETC)*. Quebec City, Canada.

Lee, J. W., Daly, S., Huang-Saad, A., Seifert, C., & Rodriguez, G. (To be submitted). Cognitive Strategies in Solution Mapping: How Engineers Identify Problems with Solutions.

Lee, J. W., Daly, S. R., Huang-Saad, A. Y., Seifert, C. M., & Lutz, J. (2018). Using design strategies from microfluidic device patents to support idea generation. *Microfluidics and Nanofluidics*, *22*(7), 70. https://doi.org/10.1007/s10404-018-2089-6

Lee, J. W., Daly, S. R., & Vadakumcherry, V. (2018). Exploring Students' Product Design Concept Generation and Development Practices. In *American Society for Engineering Education*. Salt Lake City, UT.

Navarro-Prieto, R., Scaife, M., & Rogers, Y. (1999). Cognitive Strategies in Web Searching. In *5th Conference on Human Factors and the Web*. Maryland. Retrieved from https://www.researchgate.net/publication/239061211_Cognitive_Strategies_in_Web_Searching

Nnakwe, C. C., Cooch, N., & Huang-Saad, A. (2018). Investing in Academic Technology Innovation and Entrepreneurship: Moving Beyond Research Funding through the NSF I-CORPS; Program. *Technology & Innovation*, *19*(4), 773–786. https://doi.org/info:doi/10.21300/19.4.2018.773

Osborne, J. (2008). *Best practices in quantitative methods*. Thousand Oaks, CA: Sage.

Riel, A. J. (1996). *Object-Oriented Design Heuristics* (1st ed.). Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc.

Robinson. (2012). I-Corps and the Business of Great Science. *JOM*, *64*(10), 1132–1133. https://doi.org/10.1007/s11837-012-0446-6

Shane, S. (2000). Prior Knowledge and the Discovery of Entrepreneurial Opportunities. *Organization Science*, *11*(4), 448–469. https://doi.org/10.1287/orsc.11.4.448.14602

St-Jean, E., & Tremblay, M. (2011). OPPORTUNITY RECOGNITION FOR NOVICE ENTREPRENEURS: THE BENEFITS OF LEARNING WITH A MENTOR, *17*(2), 13.

Thomas, T., Culley, S., & Dekoninck. (2007). Creativity in the Engineering Design Process. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Wilson, R. C., Guilford, J. P., Christensen, P. R., & Lewis, D. J. (1954). A factor-analytic study of creative-thinking abilities. *Psychometrika*, *19*(4), 297–311. https://doi.org/10.1007/BF02289230

Chapter 6 Discussion: Contributions, implications and future work

6.1. Overview

Across my research, I have focused on divergent thinking in design. Within concept generation, I studied novice engineers' divergent thinking approaches as impacted by a learning intervention; by providing explicit scaffolding, I demonstrated that novice engineers may shift their concept generation behaviors to be more aligned with documented best practices. Within solution mapping, I defined a new form of the design process specific to invented technology: How does design happen when the solution and not the problem is specified in the first stage? I investigated this form of divergent thinking through semi-structured interviews and identified specific cognitive strategies. These strategies were then developed as a solution mapping design tool, and tested and validated to support divergent thinking for novice engineers. In this chapter, I discuss the intersections of my studies and synthesize overall conclusions.

6.2 Discussion

6.2.1 Successful design processes can start with a problem or a solution

Following a sound design process is crucial in developing an innovative product. My studies document design processes with multiple pathways to achieve successful outcomes. I have documented two different design process models in Chapters 3 and 4: 1) problem-first and 2) technology-first. The problem-first design process models follow the sequence of defining the problem, generating potential solutions, evaluating the solutions, and communicating the outcomes, consistent with design process models presented commonly in the literature (Cross, 2008; Dubberly, 2004; Eide, Jenison, Northup, & Mickelson, 2011; Ertas & Jones, 1996; French, Gravdahl, & French, 1985). My contribution lies in pushing against the traditional design process model and identifying an alternative pathway that starts with a solution. These technology-first design processes reverse the "traditional" design process sequence (Lee, Daly, Huang-Saad, & Seifert, 2018; Thomas, Culley, & Dekoninck, 2007). Engineers can develop new, novel technologies without having clear problems to address, defined as *solution mapping* in this dissertation. Although previous research in business has documented the overall process of technology-first entrepreneurship, I articulated a more detailed process of how designers leverage new technologies to recognize opportunities. In Chapter 3, I demonstrated that academic designers often followed a “technology-first” design model and searched for applications of their technologies. Furthermore, engineering designers at successful companies that have commercial products or have received venture capital funding also followed a “technology-first” design process model. In particular, in Chapter 4, I demonstrated that designers from a wide variety of engineering fields -- including biotechnology, robotics, aerospace, and manufacturing -- developed technologies before identifying problems, indicating that “technology-first” processes may not be unique to one discipline or field.

The importance of understanding multiple design pathways is that engineering designers can select and optimize design tools to help them reach their end goals. Designers can be reflective about their design approaches to ensure that they are leveraging various tools appropriate for their design contexts.

6.2.2 Design is driven by context in industry, academia, or start-up

Across my studies in Chapters 3 and 4, I learned that independently of discipline, design processes are driven by their placement in industry, academia, or start-up companies. Although all engineers in Chapter 3 had similar expertise in microfluidics, engineers working in large companies followed a “problem-first” approach, while engineers working in academic labs approached design processes with “technology-first” models. Engineers working in large companies were often given problems to solve by management or marketing, where teams of researchers identified profitable market opportunities. After identifying these opportunities, engineers were asked to come up with solutions to address these problems, and were minimally involved in the initial problem definition phase. Regardless of their expertise, engineers in large companies searched for multiple potential solutions that could address the problems. On the other hand, engineers in academia were not provided with problems to solve. Instead, they used their core technologies and searched for problems, following a “technology-first” model. Often, engineers in academia were working alone or in small teams, which may have limited their ability to broadly search for problems and diversify their potential solutions.

In Chapter 4, I also found that engineers in many start-up companies also followed "technology-first" design processes. Engineers in startup companies indicated that they had to "wear many hats" due to limited resources and personnel. For example, an engineer in a small company was developing the technology, identifying problems to solve, and running the administration duties of his company. Also, startup companies relied on federal and private investments before commercializing their technologies to make a profit. Engineers from startup companies indicated that at times, they ran out of money during the technology development and had to reach out to investors to obtain additional funds. Because of these financial and resource constraints, engineers prioritized leveraging their technologies to solve problems that would lead them to a commercially viable product as soon as possible. Similarly, research has shown that the context of a design process influences designers approaches and decision-making due to constraints that impact design (Blessing & Chakrabarti, 2009; Goncher & Johri, 2015; Jonassen, 2000; Kilgore, Atman, Yasuhara, Barker, & Morozov, 2007); particularly, financial resource limitations have been demonstrated to constrain design practices (Bruce, Cooper, & Vazquez, 1999).

Better understanding of different contextual factors impacting design can provide opportunities to improve design processes. Engineers may benefit from awareness of their approaches in different settings to understand limitations, and potential opportunities. By increasing awareness, engineers can better manage design processes to achieve success.

6.2.3 Human-centered design and technology-centered design

While prior research has highlighted tensions between human-centered and technology-centered design approaches (Krippendorff, 2005), in my research, engineers engaged in solution mapping combined principles of both technology and human-centered design. They heavily emphasized developing novel technologies; at the same time, they practiced important principles of human-centered design such as engaging with stakeholders and interviewing potential users. Often, human-centered and technology-centered approaches are addressed separately in research. Human-centered design emphasizes meeting the needs of all stakeholders in product development and end usage (Krippendorff, 2005). Human-centered designers often conduct ethnographic studies and connect with users to empathize and understand their true needs (Kelley & Littman, 2001). In contrast, technology-centered design is often defined as a design process that focuses on the technology development that lacks an understanding of the users' needs (Krippendorff, 2005; Hoffman et al., 2002).

Successful innovations connect technology-centered and human-centered design. New technology development can lead to creating market opportunities, new design processes, and innovative ways of addressing problems. New technologies must be implemented with an understanding of the stakeholders' needs. Engineers should not emphasize technology or human-centered design as their primary approach; rather, engineers should leverage principles from both design models to aid their design processes.

6.2.4 Factors affecting designers in divergent thinking

Previously, few studies have documented the contextual drivers that influence engagement in divergent thinking within engineers' design approaches. In my research, I articulated specific factors across both solution mapping and concept generation processes that facilitated or hindered divergent thinking. Engineers engaged in solution mapping (studies in Chapters 3 and 4) were affected by previous experiences and prior knowledge. For example, one designer who developed a new material with multiple uses had a background in medical device development. Although he identified an application of his material in developing a consumer product, he did not pursue this application because he did not have expertise in consumer product development. Instead, he searched for an application to use his material to develop medical devices. Engineers sometimes eliminated possible opportunities to use their novel technologies because they often limited themselves to diverge only within their expertise. Research has documented various factors affecting solution mapping, such as expertise, networking, and prior experience (Arentz, Sautet, & Storr, 2013; Baron, 2006; Ma, Huang, & Shenkar, 2011). My research confirms that engineers engaged in solution mapping may be hindered by expertise and prior experience.

Mechanical engineers performing concept generation were also affected by prior knowledge and relied too often on existing solutions. Engineers eliminated concepts outside of their expertise and limited their divergence; for example, novice designers indicated that they would not consider concepts if they had limited understanding of those concepts. Also, engineers searched for existing concepts and borrowed features of similar solutions that were familiar. Novice engineers relied on their prior knowledge from previous projects or searched for similar concepts online instead of generating unique, diverse concepts. Literature has documented challenges in concept generation from fixation on existing concepts and limited divergence (Cross, 2001; Jansson & Smith, 1991; Purcell & Gero, 1996). In addition to documenting similar fixation behaviors, my research added to this literature by capturing some causes of fixation, such as generating false design requirements that restrict the diversity of concepts and limiting risk tasking by focusing on concepts that have been demonstrated to work.

Understanding clear factors affecting divergent thinking is important because design is a situated and social process affected by its context (Bucciarelli, 1994); design contexts may both limit and facilitate design choices (Newell & Simon, 1972; Stokes, 2001). Engineers should be guided in understanding the effects of contextual factors to ensure that they are maximizing their use of successful design strategies.

6.2.5 Supporting divergent thinking in concept generation and solution mapping

My dissertation contributes to the development and testing of design tools in concept generation and solution mapping for the support of engineers as they diverge in their design processes. The concept generation tool in Chapter 2 was a combination of best practices documented in the literature; similarly, the new solution mapping tool was derived from empirically-based findings from practitioners' approaches.

In concept generation, few studies have examined approaches of upper level students who will soon be engineering practitioners. Previous concept generation studies have aimed to study specific behaviors; for example, many concept generation studies examined the effects of fixation and interventions to mitigate it (Crilly, 2015; Jansson & Smith, 1991; Linsey et al., 2010). Other studies looked at the effects of best practices in supporting concept generation (Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Hernandez, Schmidt, & Okudan, 2013; Linsey, Markman, & Wood, 2012). My dissertation examined how upper level students employed best practices in their concept generation, development, and selection processes, and the impact of an online learning intervention (umich.catalog.instructure.com/browse/csed/) in supporting advanced design approaches. By using a think-aloud protocol method, I captured specific changes in students' behaviors during their design tasks. By providing a learning intervention, students learned these best practices to help them succeed in their design tasks.

My dissertation work has also led to the development of an evidence-based cognitive design tool that supports divergent thinking in solution mapping. Engineers engaged in solution mapping lack clear cognitive strategies to aid them in identifying applications of their technologies. Previous literature has recommended that designers stay alert, be open to opportunities, recognize patterns, and find mentors to help them identify opportunities (Arentz et al., 2013; Baron, 2006; St-Jean & Tremblay, 2011). However, these are not strategies that individual engineers can easily use. Other educational methods such as the National Science Foundation's I-Corps program can support solution mapping processes (Nnakwe, Cooch, & Huang-Saad, 2018; Robinson, 2012). The I-Corps participants are immersed in a 4-6 week training program and complete many interviews with potential stakeholders to understand potential uses for their technology. However, the I-Corps program is not accessible to everyone, and additional scaffolding is needed to support solution mapping. The solution mapping tool developed from my dissertation supports divergent thinking, and led students to considering more diverse possibilities (Chapter 5).

My dissertation has led to the first empirically-based design tool for solution mapping that is accessible and easy to use with minimal instruction. Design educators need only to spend about 10 minutes on instruction about using the solution mapping tool. In addition, the learning intervention to support concept generation takes approximately 6 hours to complete, and has direct benefits in helping students to adopt documented best practices.

6.3 Implications

6.3.1 Scaffolding front-end design

The findings from my dissertation suggest that design instructors should provide explicit instruction on concept generation and solution mapping to allow engineers to aim for specific goals within these phases. Breaking down design phases to provide support early, particularly in the front-end phases, can support engineers in achieving overall success because decisions made at the front-end of design has been demonstrated to set a trajectory for the rest of the design process (Pahl & Beitz, 1991).

In concept generation, designers are encouraged to come up with creative solutions to problems (Cross, 2008). By providing detailed instructions within concept generation, such as creating a goal for the quantity of concepts, minimizing evaluation until all the concepts are generated, and leveraging concept generation strategies, designers are more likely to be successful. When designers generate a large quantity of concepts by setting a goal, designers are more likely to come across novel, unconventional concepts. Kudrowitz et al. (2013) found that the initial few concepts are conventional, existing ones and designers diverge to consider more unique concepts after exhausting the obvious concepts. If designers evaluate their concepts early, they may limit the types of concepts generated. In Chapter 2, engineering designers assumed additional requirements and evaluated their concepts as they were generating them. Evaluation of ideas led to filtering concepts early in the concept generation stage, which may limit the quantity and diversity of alternative ideas. Engineering design educators can incorporate multiple concept generation strategies in their lessons to help students identify strategies that work well in supporting their own divergent thinking. Concept generation strategies such as brainstorming, brainwriting, mind mapping, and *Design Heuristics* can aid designers in generating a large quantity of diverse concepts to help them explore the solution space.

Engineering design educators should also make use of my solution mapping design tool to provide scaffolding in solution mapping. Currently, engineers are encouraged to assume possible applications of their technology and validate their assumptions by interviewing and engaging with stakeholders (Nnakwe et al., 2018; Robinson, 2012). However, no support has been available to aid designers in the process of diverging to consider possible applications of their technologies. My dissertation research identified specific cognitive strategies such as breaking down technologies into key characteristics, identifying enabling functions, aligning key characteristics with industry sectors, and comparing new technologies with existing technologies. Engineering educators can provide explicit instructions in solution mapping using my design tool and engineers may generate more diverse applications of their technologies that can lead to successful “matching” of technologies to possible uses.

6.3.2 Design process awareness

An important implication of my work is that design instructors need to promote students’ awareness of multiple acceptable pathways through design processes. Although many design process models start with a problem and then search for solutions, design processes do not have to start with a problem. Rather, engineers can develop a novel technology and apply that specific technological solution to solve a variety of different problems. Instructors should promote a broad understanding of design processes and how they may vary. Emphasizing design awareness can help engineers to approach open-ended design tasks with strategies and confidence in hand. By understanding different design processes based on contextual constraints, engineers can better select and leverage design tools to help them achieve design success. For example, engineers in academia and startup companies may seek out problems that match their solution expertise and may benefit from design tools that emphasize problem finding and reframing problems. By being aware of design approaches, engineers can intentionally reflect upon and improve their design decisions and become better designers.

6.4 Limitations

Limitations of my collected empirical work include 1) sample sizes that may limit statistical findings and generalizable claims, and 2) individual and time-restricted design tasks. Chapter 3 and 4 employed small numbers of professional engineers in various fields, as is typical in qualitative studies with interview data. These individuals with success in finding applications of new technology are also challenging to identify and access. Small sample sizes reduce the generalizability of the findings in multiple contexts. However, these studies were designed to gain an in-depth understanding of engineers' experiences based on a specific context (Saldaña, 2011). As in other qualitative work, I aimed to establish transferability to allow the reader to make connections between the study and his or her own situation based on descriptions of the context (Borrego, Douglas, & Amelink, 2009). With an in-depth understanding of engineers' practices based on my qualitative studies, others can build on this work to generalize the findings to new contexts.

Another limitation was the task settings for the empirical studies in Chapters 2 and 5. Students were asked to work individually on a new design task and to complete it in an hour. In practice, engineers often work on design tasks for much longer periods of time, with opportunities to iterate, and a context with teamwork and external resources. Because of the isolated test environments for these design studies, participants did not complete steps such as engaging with potential stakeholders to gain feedback throughout their work. However, the goal of both studies was to identify the impact of specific behaviors within design. Consequently, we examined a small portion of a design process by providing explicit tasks to complete within a short time period. This approach was sufficient to identify factors that did impact design outcomes, but may not have captured other important variables that play important roles in divergent thinking in design.

6.5 Future Work

Two areas of future work include 1) identifying additional strategies in solution mapping and 2) understanding concept development approaches.

6.5.1 Solution Mapping

Chapter 4 has shown that expert engineering designers have solution mapping strategies they use to "match" their technologies with potential problem applications. The work in Chapter 4 leveraged semi-structured interviews to identify cognitive strategies by relyingd on participants' self-reported experiences. Although semi-structured interviews offer an in-depth understanding of engineers' experiences (Saldaña, 2011), engineers may have had biases in their responses as they retold their experiences occurred several years ago. For example, they may forget attempts that were unsuccessful as they recount the story of the incidents leading to their success. Thus, additional ethnographic and think-aloud studies are needed to triangulate my findings from Chapter 4.

My future work can leverage ethnographic methods to observe engineers for extended periods of time as they engage in solution mapping. Many new startups and technology-focused companies engage in solution mapping at pitch competitions and at the National Science Foundation's I-Corps program. With helpful connections, I may be able to observe practitioners as they approach the solution mapping process for the first time, and as they engage with stakeholders and look for opportunities for their technologies. While longitudinal observations would take months to complete, I am interested in capturing how solution mapping approaches change based on feedback they receive during the process.

Additional directions to pursue include leveraging think-aloud protocol studies to identify additional solution mapping strategies and triangulate my findings from Chapter 4. Think-aloud approaches capture processes and ideas as they occur rather than through long-term memories (Ericsson & Simon, 1980, 1993). This provides more accurate access to thought processes as a participant works through a design task, potentially revealing the changing strategies and approaches in solution mapping.

6.5.2 Concept Development

My future work can examine best practices in concept development. My work from Chapter 2 has shown that novice engineers expend minimal effort in concept development because they focus on initial concept generation and then quickly shift their focus to concept selection. Many prior studies have investigated practices in concept generation as well as concept selection across the novice to expert spectrum. However, little work has examined the concept development practices of engineers with varied levels of experience. I would like to begin by examining expert practices in concept development using observations and interviews.

To understand concept development practices, I would first conduct semi-structured interviews with engineers who have been involved in the product development process from beginning to the end. These interviews would focus on identifying patterns and behaviors of engineers as they develop their initial concepts by synthesizing existing ideas, selecting components of ideas, and eliminating some ideas. I would like to study how engineers approach concept development in order to document successful practices that helped them develop their successful ideas. Next, I would like to go into greater depth in concept development practices by conducting observational studies. The initial semi-structured interviews will aid in narrowing the focus for the later observations to explore possible themes that arise from the phenomena.

Across these studies, the common theme of divergent thinking processes in design take different forms to play differing roles in design processes. However, in all cases, it appears that engineers in particular feel challenged by the need to open their training to many different possibilities rather than one correct one. In practice, engineering designers face ill-defined problems often, and their ability to address problems and create new alternative solutions represents the best of engineering practice. It is my hope that the studies reported here will serve to add support to those practices and provide training to improve design processes “in the wild.”

6.6 References

Blessing, L., & Chakrabarti, A. (2009). DRM: A Design Research Methodology. In *DRM, a Design Research Methodology* (pp. 13–42). Springer London. https://doi.org/10.1007/978-1-84882-587-1_2

Borrego, M., Douglas, E. P., & Amelink, C. T. (2009). Quantitative, Qualitative, and Mixed Research Methods in Engineering Education. *Journal of Engineering Education*, *98*(1), 53–66. https://doi.org/10.1002/j.2168-9830.2009.tb01005.x

Bruce, M., Cooper, R., & Vazquez, D. (1999). Effective design management for small businesses. *Design Studies*, *20*(3), 297–315. https://doi.org/10.1016/S0142-694X(98)00022-2

Bucciarelli, L. L. (1994). *Designing engineers*. Cambridge, MA: MIT Press.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies*, *38*, 54–91. https://doi.org/10.1016/j.destud.2015.01.002

Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity. In C. Eastman, W. Newstatter, & M. McCracken (Eds.), *Design Knowing and Learning: Cognition in Design Education* (pp. 79–103). Oxford, UK: Elsevier.

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design* (4th ed.). West Sussex, England: Wiley.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design heuristics in engineering concept generation. *Journal of Engineering Education*, *101*(4), 601–629. https://doi.org/10.1002/j.2168-9830.2012.tb01121.x

Dubberly, H. (2004). *How do you design? A compendium of Models*. San Francisco, CA: Dubberly Design Office.

Eide, A., Jenison, R., Northup, L., & Mickelson, S. (2011). *Engineering Fundamentals and Problem Solving* (6 edition). New York, NY: McGraw-Hill Education.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review*, *87*(3), 215–251. https://doi.org/10.1037/0033-295X.87.3.215

Ericsson, K. A., & Simon, H. A. (1993). *Protocol Analysis - Rev'd Edition: Verbal Reports as Data* (revised edition edition). Cambridge, Mass: A Bradford Book.

Ertas, A., & Jones, J. C. (1996). *The Engineering Design Process* (2 edition). New York etc.: Wiley.

French, M., Gravdahl, J., & French, M. J. (1985). *Conceptual design for engineers*. London: Design Council.

Goncher, A., & Johri, A. (2015). Contextual Constraining of Student Design Practices. *Journal of Engineering Education*, *104*(3), 252–278. https://doi.org/10.1002/jee.20079

Hernandez, N. V., Schmidt, L. C., & Okudan, G. E. (2013). Systematic Ideation Effectiveness Study of TRIZ. *Journal of Mechanical Design*, *135*(10), 101009-101009–101010. https://doi.org/10.1115/1.4024976

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11.

Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development*, *48*(4), 63–85. https://doi.org/10.1007/BF02300500

Kelley, T., & Littman, J. (2001). *The art of innovation*. Doubleday, NY: Currency.

Kilgore, D., Atman, C. J., Yasuhara, K., Barker, T. J., & Morozov, A. (2007). Considering Context: A Study of First-Year Engineering Students. *Journal of Engineering Education; Washington*, *96*(4), 321–334.

Krippendorff, K. (2005). *The Semantic Turn: A New Foundation for Design* (1 edition). Boca Raton: CRC Press.

Kudrowitz, B., & Dippo, C. (2013). When Does a Paper Clip Become a Sundial? Exploring the Progression of Originality in the Alternative Uses Test. *Journal of Integrated Design and Process Science*, *17*(4), 3–18. https://doi.org/10.3233/jid-2013-0018

Lee, J. W., Daly, S., Huang-Saad, A., & Seifert, C. (2018). Divergence in Problems Rather Than Solutions: Design Processes of Microfluidic Engineers in Academia. In *ASME 2018 International Design Engineering Technical Conferences (IDETC)*. Quebec City, Canada.

Linsey, J. S., Markman, A. B., & Wood, K. L. (2012). Design by Analogy: A Study of the WordTree Method for Problem Re-Representation. *Journal of Mechanical Design*, *134*(4), 041009-041009–041012. https://doi.org/10.1115/1.4006145

Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., & Schunn, C. (2010). A study of design fixation, its mitigation and perception in engineering design faculty. *Journal of Mechanical Design*, *132*(4), 041003. https://doi.org/10.1115/1.4001110

Newell, A., & Simon, H. A. (1972). *Human Problem Solving*. Englewood Cliffs, N.J: Prentice-Hall.

Nnakwe, C. C., Cooch, N., & Huang-Saad, A. (2018). Investing in Academic Technology Innovation and Entrepreneurship: Moving Beyond Research Funding through the NSF I-CORPS; Program. *Technology & Innovation*, *19*(4), 773–786. https://doi.org/info:doi/10.21300/19.4.2018.773

Pahl, G., & Beitz, W. (1991). *Engineering Design: A Systematic Approach*. Berlin: Springer.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies*, *17*(4), 363–383. https://doi.org/10.1016/S0142-694X(96)00023-3

Robinson. (2012). I-Corps and the Business of Great Science. *JOM*, *64*(10), 1132–1133. https://doi.org/10.1007/s11837-012-0446-6

Saldaña, J. (2011). *Fundamentals of Qualitative Research*. Oxford University Press, USA.

Stokes, P. D. (2001). Variability, constraints, and creativity: Shedding light on Claude Monet. *American Psychologist*, *56*(4), 355–359. https://doi.org/10.1037/0003-066X.56.4.355

Thomas, T., Culley, S., & Dekoninck. (2007). Creativity in the Engineering Design Process. *Guidelines for a Decision Support Method Adapted to NPD Processes*.