Developing a Design Tool for Solution Mapping: Translating Practitioners' Strategies to Support Student Engineers

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Abstract

Design processes often start with defining a problem and diverging to identify possible solutions; however, some design processes start with technologies and diverge to consider potential problems that these technologies can solve. In this latter process, engineers 'match' their technologies to problems, a term we define as "solution mapping." However, limited design strategies are available to support solution mapping. To fill this gap, we collected data from engineering practitioners on their processes for solution mapping and translated those findings to a sharable design tool for student engineers. In this paper, we describe this process, including our summary of our findings from interviews with practicing engineers who successfully identified applications for technologies they developed, and how patterns from data analysis were translated into a design tool. We also include data from pilot testing with the tool and how the pilot tests were used to refine the tool. Through this process, we were able to develop and refine an empirically-based design tool to aid solution mapping.

Introduction

In traditional problem-first design processes, engineers start with a problem and diverge to identify diverse possible solutions [1]–[5]. However, engineers may not follow this sequence; they can also develop solutions (i.e. new technologies) and diverge to identify problems to solve with these solutions [6]–[9], a term we define as "solution mapping". While solution mapping often leads to successful product development [9], engineering students are traditionally taught a more traditional problem-first process and strategies that align with the problem-first version of a design process [1]. Further, even if solution-first processes were taught, limited design strategies exist to support solution mapping in identifying problems, and limited research exists to guide the development of such strategies.

Design researchers have translated findings from their work to develop design strategies to support engineers of all levels [10]. Design tools can be developed from multiple approaches such as studying design artifacts [11]–[13] and documenting designers as they work on solving open-ended tasks [14], [15]. Although many design tools exist, limited literature exists on the process of developing design tools. Thus, we describe the process of developing a design tool to support solution mapping.

This paper describes the process of identifying design strategies from conducting semi-structured interviews with practicing engineers and going through multiple iterations to develop a tangible, accessible tool for other engineers to use in solution mapping. We also share the initial findings from pilot studies, demonstrating the usability of the tool.

Background

<u>Technology-first design processes</u>

Although, many design process models emphasize starting with a problem and identifying possible solutions [1]–[5], engineering designers often seek to leverage novel, new technologies and identify problems they can solve using those specific technologies [6]–[9]. For example, the development of 3D printers was a technology-first approach that created a platform technology with multiple applications. Also, microfluidic devices that can manupulate fluids in micro and nano level would be considered another platform technology that can have many potential applications.

Technology-first processes in design have been underexplored in the research literature. The entrepreneurship literature describes technology-first processes with three main steps: 1) technological invention, 2) opportunity recognition, and 3) approach to exploitation [8], [16]. In the first step, development of a new technology might provide new possibilities to create new products, change production processes, and serve new markets. In the opportunity recognition step, designers can identify various potential uses of the new technology to benefit their stakeholders. In the final step, designers exploit an opportunity and pursue commercializing their technology to serve the market. Although literature outlines the technology-first processes, limited guidance is available to support engineers to support engineers in recognizing opportunities.

Identifying problems to address with a given technology is not obvious and many find it challenging to recognize opportunities [8]. Currently in engineering education, limited strategies are available to support problem finding for students. Novice designers are often given problems to solve and they perceive design problems to be well-structured, straightforward tasks with necessary requirements [17]. Problem finding is considered one of the early steps in design and gaps exist in training student engineers to identify problems.

<u>Strategies for Technology-First Design Processes</u>

Limited strategies are available to support technology-first design processes. One educational method is the NSF I-Corps program, which was created to support technology advancements to commercial products [18], [19]. Engineers and scientists often develop new technologies or discover new phenonena from basic science research and seek to identify problems they can solve. Technology-first designers follow a design process as they work on ill-defined problems with many uncertainties and approach tasks with no right or wrong answers, only better or worse [20], [21].

The I-Corps participants follow the curriculum developed by Steve Blank to investigate the commercialization potential of their technology and identify various uses of technologies using a standard process that entails customer discovery to identify potential partners and meetings with investors to gain insights on developing a viable product [22]. Participants in the program are required to complete over 100 interviews with potential stakeholders to identify applications of their technologies [19]. The interviews serve as an opportunity to confirm the team's assumptions about potential applications of their technologies and develop business plans. However, in the I-Corps training, limited cognitive strategies, beyond engaging with stakeholders, are available to support designers in forming their assumptions about potential uses of their technologies.

While there are limited strategies to support technology-first design processes, there are strategies for problem-first, for example, using design ethnography to understand users and contexts to identify needs upon which a design problem statement can be developed [23], [24]. However, these strategies are not focused on the process of identifying opportunities using a technology by matching the technology to a domain to solve a problem. A designer can talk to many people from many contexts and find many problems, but not have the cognitive tools to identify and select relevant problems for which their technology could address.

<u>Design Tool Development</u>

Many design tools exist to support activites within various phases of a design process, and these tools have been developed in a variety of ways. Tools are developed by design practitioners and educators, based on what they experience in doing design and directing design. For example, brainstorming was developed as a strategy to encourage naturally-occurring ideas to be shared without judgment [25]. Tools are developed by translating theories into structured approaches. For example, SCAMPER was developed to promote creative-imaginative expression that supports idea generation in a structured manner [26].

Tools are developed from research on design artifacts. For example, TRIZ was developed from studying patterns of patented inventions [11] and these patterns have supported idea generation in classroom and industry settings [27], [28]. Additionally, Lee et al., developed and validated the usefulness of design strategies in ideation for microfluidic engineers by extracting patterns in patents [13]. The principles of DIY prototypes design was derived from an open-source database to examine key fabrication principles to reduce effort and improve quality [12]. Thus, extracting characteristics of design artifacts serves as a useful method for developing design strategies.

Design tools are also developed from studying designers' practices. In developing Design Heuristics, researchers combined studying successful products and extracting designers' approaches in a think-aloud task [14]; by studying designers as they verbalized their thought processes during an ideation task, researchers identified approaches or heuristics in ideation. In another study, a set of prototyping strategies was developed from extended observations of engineers during a product development cycle [15].

Although many design tools have been created, limited literature describes the development process of design tools. In addition to contributing a tool to support solution mapping, we describe the process of how the research data informed the development of our design tool.

Design Tool Development for Solution Mapping

We developed a design tool to aid solution mapping by: 1) interviewing 19 engineering practitioners about their solution mapping experiences, 2) extracting key strategies from the data that could be translated to an actionable approach for others to leverage, 3) ideating several possible forms the tool could take, 4) pilot testing the tools with students for usability and impact on process and outcomes, and 5) iterating on the tool based on data from the pilot tests.

<u>Semi-structured interviews with experienced engineers</u>

We first recruited and interviewed 19 engineers who have developed novel technologies and 'matched' their technologies to problems. The details of the systematic qualitative analysis can be found in our work [29]. The interviews focused on discussing specific projects they have worked on, which led to the commercialization of their technologies. Example interview questions are shown in Table 1.

Table 1. Example interview questions

Interview Focus Area	**Example Question**
Developing technology	From the beginning to the end, can you tell me about the process of developing the technology?
Recognizing opportunities	From the beginning to the end, can you tell me about how you came up with an application for your technology?
Considering alternativees	What, if any, were other opportunities and applications that you considered for this technology?

Participants had 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). Participants were recruited from a wide variety of industry sectors, including aerospace, biotechnology, energy, manufacturing, and materials. Many engineers also developed their technologies through academic research in their roles as research scientists or professors.

Table 2. Participant information

Pseudonym	Gender	Education	Position	Industry	Years of experience	Company size	Position in academia
Adam	M	PhD	Founder	Energy	22	Small	No
Bob	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
Frank	M	PhD	CEO	Energy	11	Small	No
George	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
Oliver	M	PhD	CEO	Semiconductor	9	Small	No
Peter	M	PhD	Founder	Biotechnology	36	Small	Yes
Ryan	M	PhD	Founder	Manufacturing	20	Small	Yes
Steve	M	PhD	Founder	Materials	40	Small	Yes
Tracy	F	PhD	Founder	Biosensor	18	Small	Yes
Victoria	F	MS	Manager	Manufacturing	3	Small	No

<u>Identifying Design Strategies</u>

After interviewing the 19 participants, we transcribed all recorded interviews and used an inductive coding approach [30], [31]. We identified the following trends and organized them into a chronological and logical order as shown in Figure 1. These themes were translated into 1) breaking down the technology into key characteristics, 2) describing characteristics differently or reframing the characteristics, 3) identifying multiple industry sectors, and 4) matching specific applications within industry sectors.

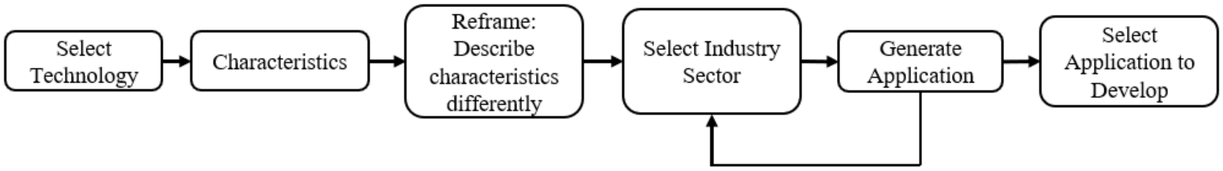


Figure 1. Principles of solution mapping drawn from expert interviews.

These experienced engineers emphasized breaking down their target technology into key characteristics and describing them in varied ways. For example, Kevin**,** who invented a new material, described his technology's key characteristics as conductive properties. Then, he described these same characteristics in different ways by focusing on ways the conductive nature of his material can create barrier properties:

> "*Like I said, the particles are electrically conductive, thermally conductive, because their platelets, if I put them in a plastic, they can create what are called barrier properties.*" (Kevin)

The engineers often reframed the key characteristics to create new functions; for example, James initially developed a laser welding technology that joined two different materials together. Using the same platform technology, he reframed the technology's function to create a laser 3D printing technology:

> *"…instead of welding, joining two materials, you are putting powder and melting it with laser to create a shape.*" (James)

By repeated attempts to reframe the key characteristics of their technologies, engineers came up with new functions, which helped them find additional potential applications. In redescribing their technologies in multiple different ways, engineers may be using synonyms and analogies of the technologies' characteristics to identify various functions.

After the engineers reframed the key characteristics of their technology, they searched for multiple broad industry sectors where it may be of use. For example, Ian developed an exoskeleton technology and initially looked for broad military, industrial, and manufacturing applications:

> "*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.*" (Ian)

Once the industry sectors were identified, the engineers reached out to stakeholders in the relevant sectors to identify specific applications for their technologies. For example, Eric identified potential applications of his new material in clothing or armor protection for the military. He then reached out to specific companies to discuss potential applications of his technology:

“*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.*” (Eric)

Based on the synthesis of principles in the interview data, we developed a tangible tool for student engineers to use in solution mapping.

Tool Development

Based on our interviews and multiple iterations, we created a design tool (see Figure 2). We describe the process of tool development below.

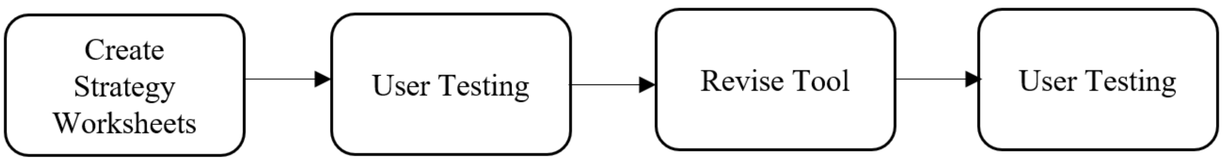
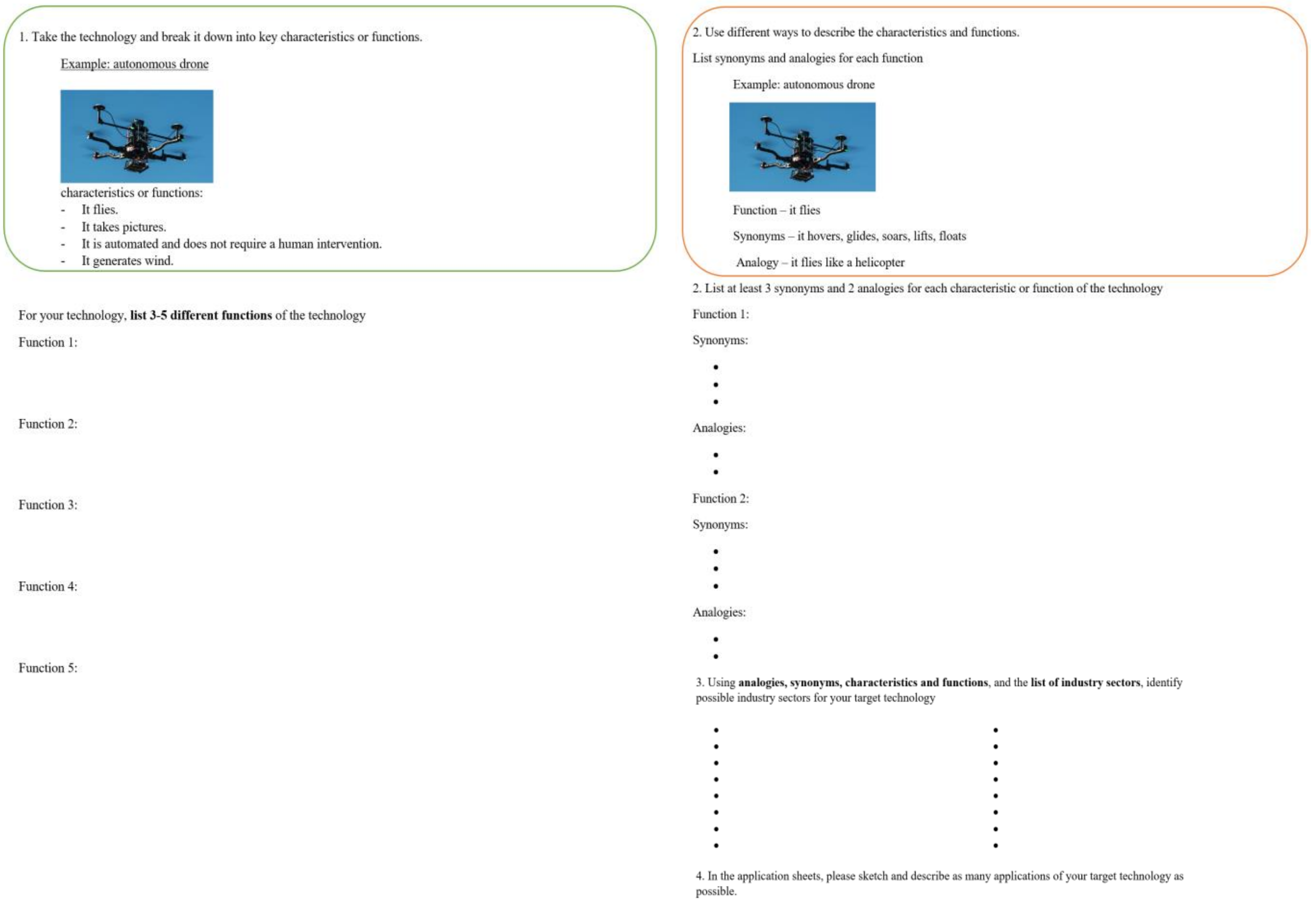


Figure 2. Overview of the changes and pilot tests necessary to develop the design tool

We developed the tool in the form of worksheets with step-by-step instructions and examples to provide ordered scaffolding (Figure 3). The tool broke the strategies down into 4 steps: 1) break down the technology into key characteristics, 2) describe the key characteristics with synonyms and draw analogies, 3) identify multiple industry sectors, and 4) match specific applications within industry sectors.


1. Take the technology and break it down into key characteristics or functions.

Example: autonomous drone

characteristics or functions:
- It flies.
- It takes pictures.
- It is automated and does not require a human intervention.
- It generates wind.

For your technology, **list 3-5 different functions** of the technology

Function 1:

Function 2:

Function 3:

Function 4:

Function 5:

2. Use different ways to describe the characteristics and functions.

List synonyms and analogies for each function

Example: autonomous drone

Function – it flies

Synonyms – it hovers, glides, soars, lifts, floats

Analogy – it flies like a helicopter

2. List at least 3 synonyms and 2 analogies for each characteristic or function of the technology

Function 1:

Synonyms:
-
-
-

Analogies:
-
-

Function 2:

Synonyms:
-
-
-

Analogies:
-
-

3. Using **analogies, synonyms, characteristics and functions**, and the **list of industry sectors**, identify possible industry sectors for your target technology

4. In the application sheets, please sketch and describe as many applications of your target technology as possible.

Figure 3. The initial design tool as worksheet.

<u>User testing 1</u>

We first tested the design tool to assess its usability. The study was designed as a single session experiment. First, we gathered a list of recent technologies with multiple applications. We tested the problem statements for example technologies including graphene, drone, quantum dots, aerogel, 3D printing, hydrogel, and shape memory alloys (see Figure 4). Then, we tested these problem statements and filtered them based on three criteria: 1) accessibility of the technology, 2) non-obviousness of applications, and 3) limited number of characteristics. For accessibility, we selected technology would be understandable with a short explanation and familiar to undergraduate students in engineering. For example, optical tweezers were not selected because it is used in more narrow research applications. We also selected technology without obvious existing applications. For example, ultrasound is used in multiple applications including medical imaging, welding, and structural testing, and our user tests revealed that students fixated on these medical imaging applications. Last, we selected technology with no more than three identified characteristics to avoid an overwhelming number of applications. For example, graphene has a many characteristics, such as high opacity, high thermal conductivity, high strength, biocompatibility, etc. Using graphene may lead to many, varied applications. After four user tests and using these filtering criteria, we narrowed the list to two technologies: 1) shape memory alloys, and 2) hydrogel.

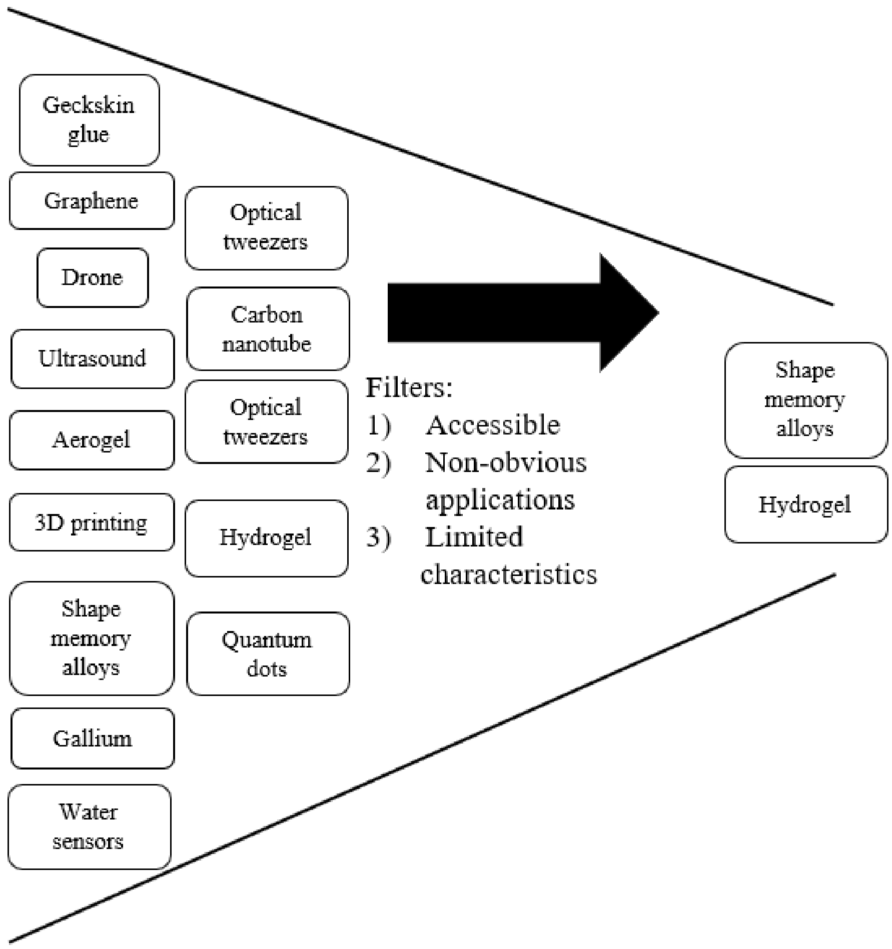


Figure 4. Selection process for technologies used in testing the solution mapping design tool

After selecting two possible technologies for the experiment, we tested the tool with the shape memory alloy problem statement. The control group included 6 participants (1 postdoctoral researcher, 3 graduate students, 2 juniors) and the intervention group included 7 participants (1 postdoctoral researcher, 3 graduate students, and 3 juniors). The control group was instructed to come up with as many applications of shape memory alloys as they could within 60 minutes. The intervention group was given the design tool for solution mapping and a 7-page list of industry sectors from the North American Industry Classification System. They were also instructed to come up with many applications in 60 minutes plus an additional 10 minutes to spend learning the design tool.

<u>User testing findings</u>

After the study, we asked participants about the usability of the design tool and clarity of instructions. Several participants noted that they faced challenges in coming up with synonyms and analogies based on the characteristics of the technology. Some participants spent more than

30 min listing synonyms before generating applications, suggesting more focused prompts to guide them in using the tool may be helpful (Figure 5).

We also noted that participants made limited use of the industry sectors list. We provided a 7 page list of industry sectors; however, participants often did not read the entire list. Instead, they focused on the first two pages, suggesting a more condensed list of industry sectors may prove to be more user-friendly.

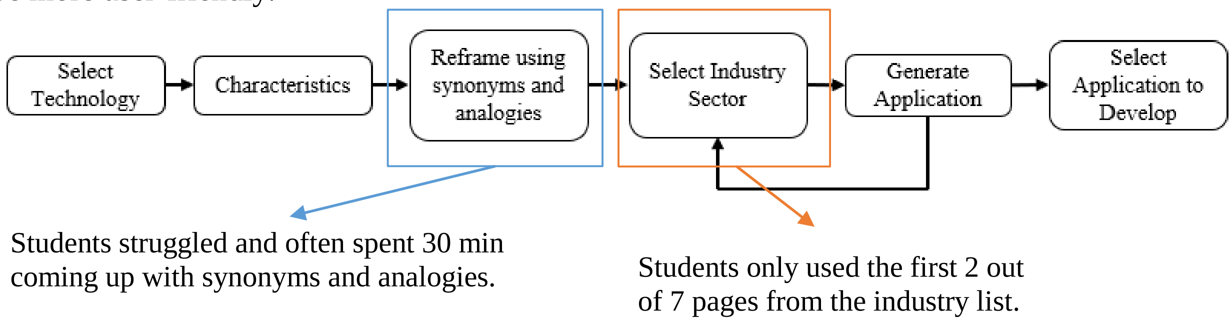


Figure 5. Challenges identified in implementing the first user testing of the design tool.

<u>User Testing Measures</u>

The control group generated an average of 7.1 applications (SE 1.4) and the intervention group generated 9.8 (SE 1.4) applications within 1 hour (truncated to equate generation time) and 11.3 (SE 1.6) applications within 1 hour and 10 minutes (as seen in Figure 6). This study supported our conclusion that the intervention may help participants generate more applications of shape memory alloys.

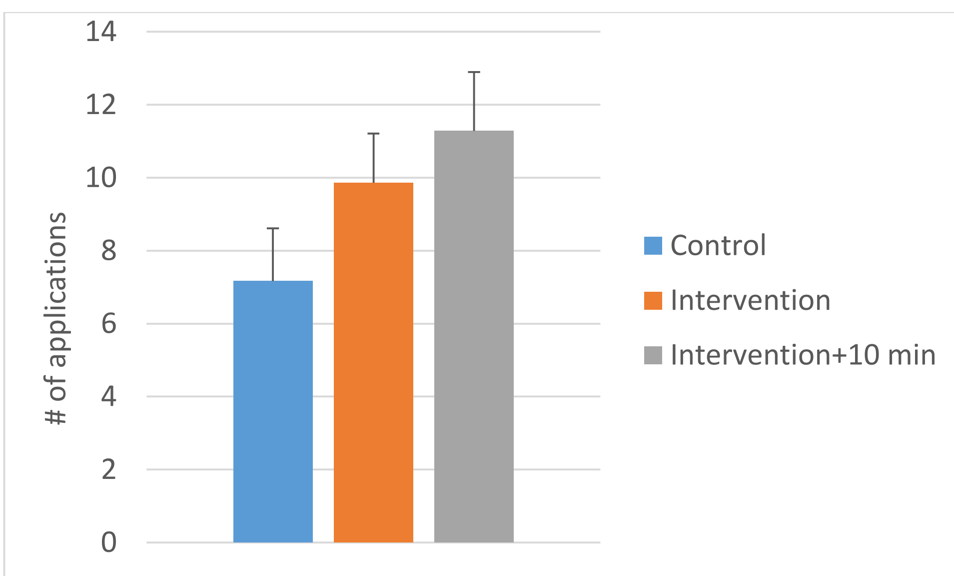


Figure 6. Quantity of applications generated in the control and intervention groups.

We also examined the types of applications generated. In general, many of the control group applications focused on household products with shape memory alloys. For example, participants came up with armor (Figure 7.a), a key (Figure 7.b), and a screw driver tip (Figure 7.c) that could return to its original shape after being deformed. In the intervention group, participants generated more broad applications for shape memory alloys; participants thought of using shape memory alloys to create a self-repairing satellite (Figure 7.d), a shape-changing cage for different sized animals (Figure 7.e), and a reusable writing material (Figure 7.f). We noted that many participants in the control group focused on applications in consumer household products while participants in the intervention group generated applications in more varied industry sectors.

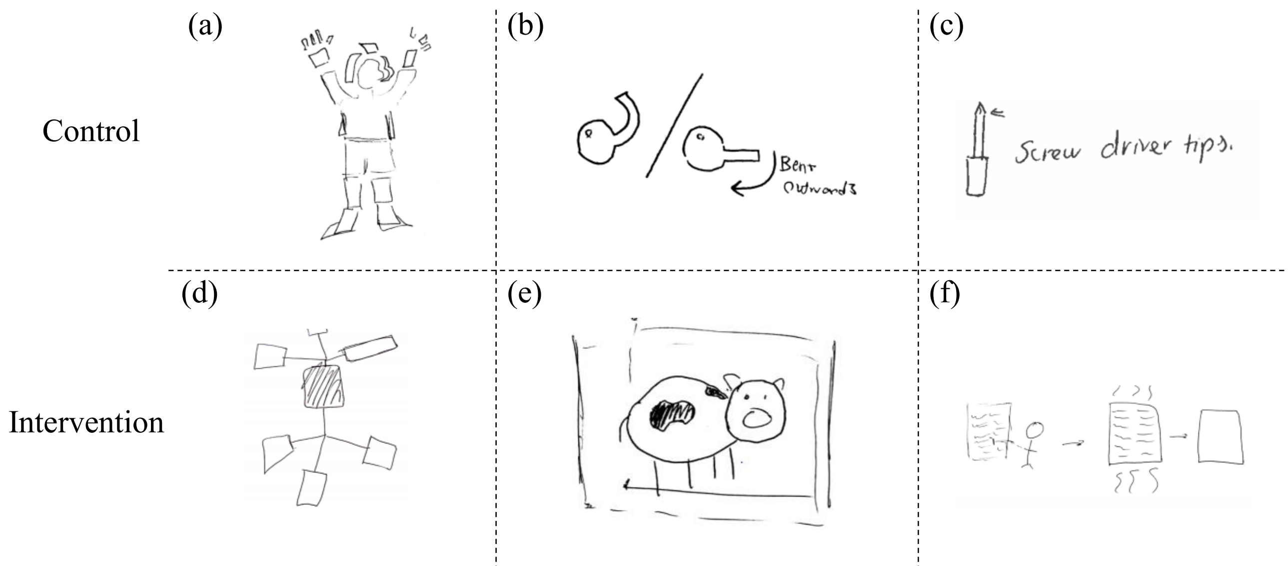


Figure 7. Examples of applications generated in control (a) armor, (b) key, (c) screw driver tip, and intervention groups: (d) self-repairing satellite, (e) animal cage, (f) reusable writing material.

<u>Revising the Tool</u>

The user testing study 1 revealed that participants struggled to come up with synonyms and analogies for a technology's functions. To provide better guidance, we re-examined the original interview data to better understand how practitioners redescribed their technologies. We identified "enabling functions" in the engineers' descriptions of key characteristics rather than synonyms. For example, Adam initially developed a small battery system, and he identified the enabling new function as portability:

> "*By making them small, we were able to make them portable. By making them portable, we were able to open up new markets for things like drones and soldier-born fuel cell systems."* (Adam)

To revise the tool, we changed the strategy, "describe key characteristics with synonyms," with "describe enabling functions," and we removed the instruction to "draw analogies."

We also shortened the list of industry sectors from a 7-page list to a single page of broader industry sectors from the North American Industry Classification System. This more general list may suit the search for application areas without overwhelming students with too many alternatives to consider.

User Test 2 with Revised Tool

A second user testing study was conducted with two graduate students to examine usability. One student found it difficult to go through the protocol in a linear path, moving from worksheet sections on characteristics, enabling functions, industry sectors and then specific applications. Instead, she jumped from describing the key characteristics of the technology to direct applications, and sometimes struggled to use the industry sectors list. To provide more freedom for students to identify their own process, we revised the worksheets and tool to allow participants to go through the prompts in any order (as seen in Figure 8). With this change, we finalized our design tool.

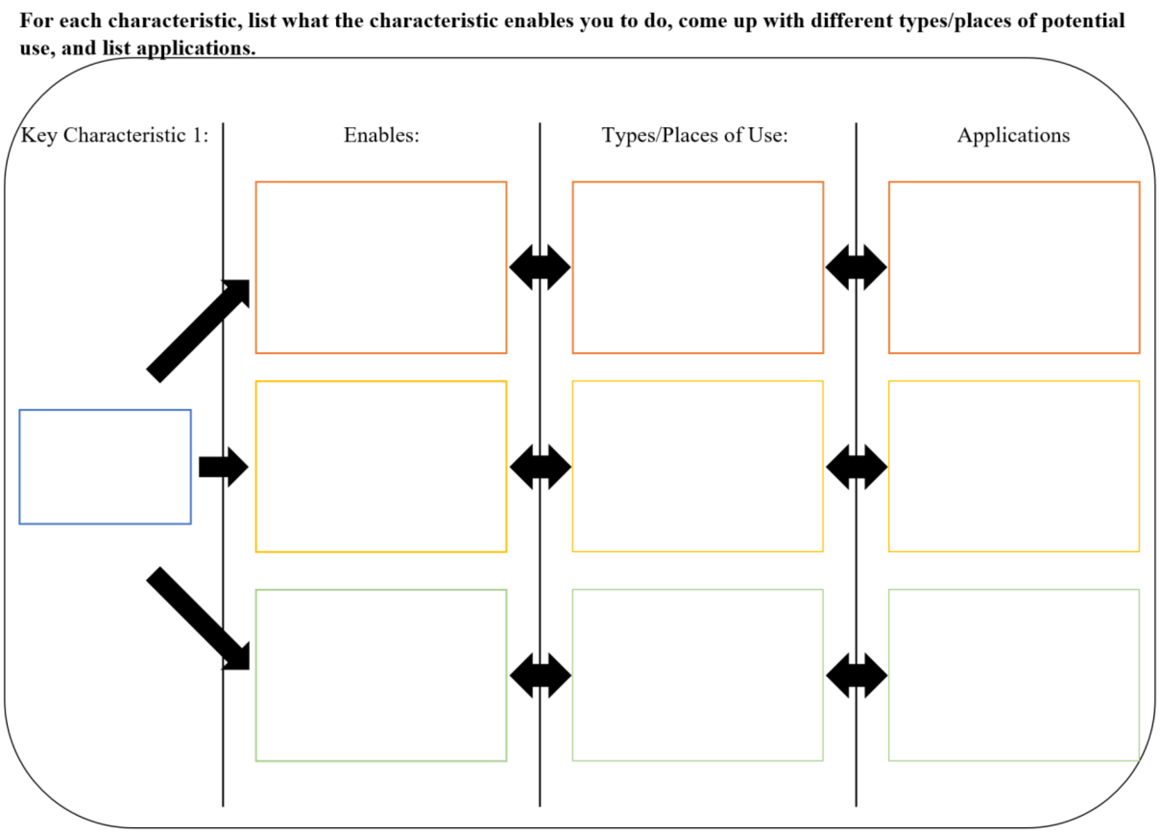


Figure 8. Finalized design tool

Discussion

This paper describes the process of studying practicing engineers' design strategies to develop an evidenced-based design tool for solution mapping. From interviews with engineering practitioners with experience in solution mapping, we gained an in-depth understanding of how engineers identified problems for applying their novel technology solutions. Often, experienced engineers have accumulated implicit knowledge derived from their experiences that help them navigate through the design tasks [32]. Other research has demonstrated the usefulness of studying experienced engineers' practices through observation and think-aloud protocols and translating their practices into tangible tools [14], [15].

We identified the key strategies for a solution mapping process, and created a worksheet tool to structure the process for engineering students. After developing this initial tool, we conducted a series of user studies to test the adequacy of the tool and measure outcomes. These studies informed our decisions to revise the tool in several specific ways. For example, our user tests using showed that participants struggled to come up with redescriptions of technology characteristics with our "synonyms and analogies" instruction. This prompted us to revise the tool by reexamining the interview data. We identified the redescription strategy as focused on enabling technology functions, and revised the tool to provide better direction toward identifying these characteristics.

In studying the outcomes of tool use, our user studies showed that engineering students can use our design tool to guide them towards a larger number of diverse applications for a given new technology. By creating a tool to support students in performing solution mapping, students will be able to engage in this alternative design process. Other research has demonstrated that design tools can provide guidance and direction in different phases of design to improve success [28], [33], [34]. This new design tool for solution mapping will provide students with the opportunity to experience a wider range of design important to new technology development.

Design tools have been identified to support other steps in a design process and achieve better outcomes [13], [14], [28]. This approach of studying experienced engineers' practices and developing parallel educational interventions through user testing can produce effective pedagogy that equips engineering students with the necessary design skills to support their own design practices.

Limitations

The identified strategies for a solution mapping process are based on a small sample of 19 interviews with experienced engineers. Because innovations based on new technologies are more challenging, access to engineers' experiences with the process are more difficult to study. A larger sample of engineers working on technology applications may uncover additional strategies. Also, while semi-structured interviews provide an in-depth understanding of engineers' experiences, participants' self-reports may leave out pertinent details, especially since many of these engineers were retelling their past rather than present design experiences. Additional studies may be needed to support these findings through concurrent reports. Finally, the user testing involved small sample sizes for an experimental study testing the usefulness of the design tool. While smaller samples are typical of user testing for interfaces, they do not allow statistical comparisons; instead, obvious differences and problems are noted and assessed for tool revision. This approach focuses on the process of iterating and changing the tool to improve its usability by addressing identified findings. A larger study is necessary to empirically validate the usefulness of the final design tool.

Conclusion

Although many design process models begin with an identified problem and follow through to its solution, a alternative model arises with the discovery of new technology. In these cases, designers appear to start with a solution (their new technology) and then identify existing problems where they can apply their new solution, a process we define as, "solution mapping." Little previous research has identified how design processes occur in these situations, and no tools are available to support student engineers in developing their solution mapping skills. To address this need, we describe our research on identifying successful strategies from experienced engineers and translating their strategies into a tangible tool to support student engineers. We interviewed experienced engineers engaged in solution mapping and identified patterns in the their approaches to use as strategies. Through multiple iterations of user testing, we further refined and developed the design tool for accessibility and usability by student engineers. The findings show that the tool is effective in supporting students in the solution mapping process. Students who used the design tool generated a larger quantity of diverse applications for a new technology. Our research demonstrates a process educators can use to identify practice strategies and translate them into tangible tools to support engineering instruction.

References

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

[2] H. Dubberly, *How do you design*. A compendium of Models, 2004.

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

[4] A. Ertas and J. C. Jones, *The Engineering Design Process*, 2 edition. New York etc.: Wiley, 1996.

[5] M. French, J. Gravdahl, and M. J. French, *Conceptual design for engineers*. London: Design Council, 1985.

[6] R. A. Baron, "Opportunity Recognition as Pattern Recognition: How Entrepreneurs 'Connect the Dots' to Identify New Business Opportunities," *Acad. Manag. Perspect.*, vol. 20, no. 1, pp. 104–119, Feb. 2006.

[7] J. W. Lee, S. Daly, A. Huang-Saad, and C. Seifert, "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, 2018.

[8] S. Shane, "Prior Knowledge and the Discovery of Entrepreneurial Opportunities," *Organ. Sci.*, vol. 11, no. 4, pp. 448–469, Aug. 2000.

[9] T. Thomas, S. Culley, and Dekoninck, "Creativity in the Engineering Design Process," *Guidel. Decis. Support Method Adapt. NPD Process.*, 2007.

[10] L. Blessing and A. Chakrabarti, "DRM: A Design Research Methodology," in *DRM, a Design Research Methodology*, Springer London, 2009, pp. 13–42.

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

[12] B. A. Camburn *et al.*, "The Way Makers Prototype: Principles of DIY Design," presented at the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2015, p. V007T06A004-V007T06A004.

[13] J. W. Lee, S. R. Daly, A. Y. Huang-Saad, C. M. Seifert, and J. Lutz, "Using design strategies from microfluidic device patents to support idea generation," *Microfluid. Nanofluidics*, vol. 22, no. 7, p. 70, Jul. 2018.

[14] S. R. Daly, S. Yilmaz, J. L. Christian, C. M. Seifert, and R. Gonzalez, “Design heuristics in engineering concept generation,” *J. Eng. Educ.*, vol. 101, no. 4, pp. 601–629, Oct. 2012.
[15] C. A. Lauff, D. Kotys-Schwartz, and M. E. Rentschler, “What is a Prototype? What are the Roles of Prototypes in Companies?,” *J. Mech. Des.*, vol. 140, no. 6, pp. 061102-061102–12, Mar. 2018.
[16] D. A. Grégoire, P. S. Barr, and D. A. Shepherd, “Cognitive Processes of Opportunity Recognition: The Role of Structural Alignment,” *Organ. Sci.*, vol. 21, no. 2, pp. 413–431, Jul. 2009.
[17] D. P. Crismond and R. S. Adams, “The informed design teaching and learning matrix,” *J. Eng. Educ.*, vol. 101, no. 4, pp. 738–797, Oct. 2012.
[18] Robinson, “I-Corps and the Business of Great Science,” *JOM*, vol. 64, no. 10, pp. 1132–1133, Oct. 2012.
[19] C. C. Nnakwe, N. Cooch, and A. Huang-Saad, “Investing in Academic Technology Innovation and Entrepreneurship: Moving Beyond Research Funding through the NSF I-CORPS; Program,” *Technol. Innov.*, vol. 19, no. 4, pp. 773–786, Jun. 2018.
[20] V. Goel and P. Pirolli, “The structure of Design Problem Spaces,” *Cogn. Sci.*, vol. 16, no. 3, pp. 395–429, Jul. 1992.
[21] D. H. Jonassen, “Toward a design theory of problem solving,” *Educ. Technol. Res. Dev.*, vol. 48, no. 4, pp. 63–85, Dec. 2000.
[22] S. Blank and B. Dorf, *The Startup Owner’s Manual: The Step-By-Step Guide for Building a Great Company*, 1 edition. Pescadero, Calif: K & S Ranch, 2012.
[23] I. Mohedas, S. Daly, and K. Sienko, “Design Ethnography in Capstone Design: Investigating Student Use and Perceptions,” *Int. J. Eng. Educ.*, vol. 30, no. 4, pp. 888–900, 2014.
[24] T. Salvador, G. Bell, and K. Anderson, “Design Ethnography,” *Des. Manag. J. Former Ser.*, vol. 10, no. 4, pp. 35–41, Oct. 1999.
[25] A. F. Osborn, *Applied imagination: principles and procedures of creative thinking*, 3rd, revised ed. Charles Scribner’s Sons, 1957.
[26] R. Eberle, *SCAMPER*. Waco, TX: Prufrock, 1995.
[27] G. Cascini and P. Rissone, “Plastics design: integrating TRIZ creativity and semantic knowledge portals,” *J. Eng. Des.*, vol. 15, no. 4, pp. 405–424, Aug. 2004.
[28] N. V. Hernandez, L. C. Schmidt, and G. E. Okudan, “Systematic Ideation Effectiveness Study of TRIZ,” *J. Mech. Des.*, vol. 135, no. 10, pp. 101009-101009–10, Sep. 2013.
[29] J. W. Lee, S. Daly, A. Huang-Saad, C. Seifert, and G. Rodriguez, “Cognitive Strategies in Solution Mapping: How Engineers Identify Problems with Solutions,” To be submitted.
[30] R. E. Boyatzis, *Transforming Qualitative Information: Thematic Analysis and Code Development*. SAGE, 1998.
[31] J. W. Creswell, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications, 2013.
[32] C. D. Schunn, M. U. Mcgregor, and L. D. Saner, “Expertise in ill-defined problem-solving domains as effective strategy use,” *Mem. Cognit.*, vol. 33, no. 8, pp. 1377–1387, Dec. 2005.
[33] J. W. Lee, S. R. Daly, and V. Vadakumcherry, “Exploring Students’ Product Design Concept Generation and Development Practices,” in *American Society for Engineering Education*, Salt Lake City, UT, 2018.

[34] J. W. Lee, A. Ostrowski, S. R. Daly, A. Huang-Saad, and C. M. Seifert, "Idea generation in biomedical engineering courses using Design Heuristics," *Eur. J. Eng. Educ.*, vol. 0, no. 0, pp. 1–19, Sep. 2018.