Cognitive strategies in solution mapping: How engineering designers identify problems for technological solutions

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Design processes sometimes begin with solutions rather than problems, particularly when new technologies spur searches for new problems to solve. Previous research on business entrepreneurship describes solution—first processes as a form of "opportunity recognition," and proposes some strategies for finding technology "match" opportunities. However, few studies have addressed the design process of how *to begin with novel technological solutions and identify problem applications. In this study, we investigated this process of* solution mapping *through an empirical study of engineering designers who had experience in successfully searching for a problem to fit their novel technological solutions. Through the analysis of qualitative interviews with 19 professional engineering designers, we identified stages and cognitive strategies in solution mapping.*

Keywords: design practice, design problems, design processes, engineering design, solution mapping

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Designers engage with ill-defined problems (Simon, 1973) that require further exploration before identifying potential solutions (Buchanan, 1992; Rittel & Webber, 1973). Prescriptive engineering design processes often emphasize defining a problem as an initial focus

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(Cross, 2008; Dieter & Schmidt, 2009; Dym & Little, 2009). In these problem-first approaches, problem exploration (Dewey, 1910) then drives a design process towards identifying a solution. A variety of strategies for problem exploration have been identified (e.g., Atman, Chimka, Bursic, & Nachtmann, 1999; Csikszentmihalyi & Getzels, 1971; Kilgore, Atman, Yasuhara, Barker, & Morozov, 2007; Murray, Studer, Daly, McKilligan, & Seifert, 2019; Studer, Daly, McKilligan, & Seifert, 2018; Stumpf & McDonnell, 1999, pp. 245–253; Wallas, 1926). All of these problem exploration processes precede and then guide the designer's search for solutions.

An alternative design process specifies problem and solution development as occurring simultaneously, termed *co-evolution* (Dorst & Cross, 2001; Maher, 2000). In co-evolution, the development of the solution occurs in interaction with the development of the problem, and vice versa (Dorst, 2019). Empirical studies of designers have confirmed that problems can continue to evolve with the identification of solutions throughout a design process (Dorst, 2019; Dorst & Cross, 2001; Wiltschnig, Christensen, & Ball, 2013).

However, in some design processes, a problem is not the first focus; instead, solutions may come first, such as when new technologies are created. For example, a chemical engineer developed a new, high-performance biopolymer that retains water; later, she found a problem application in the personal care sector: compostable infant diapers (McAlpine, 2018). This "solution-first" design process began with a technological solution and ended with the identification of a novel problem application. When such new technologies are created, they present a potential solution for existing problems. In such cases, the technological solution is well-defined and specific, though its form may be alterable. Further, the problem is neither ill-defined nor well-defined (Simon, 1973); rather, it is not defined at all. For a developing technology, the question of how to use it may be secondary, and problems it can address are not obvious (Shane, 2000). As a result, there is a need to understand how a design process beginning with a new technological solution leads to the identification of problems.

Related literature on business entrepreneurship describes a variety of social, behavioral, and cognitive activities involved in "opportunity recognition," including identifying new ventures (Baron, 2006), new solutions for known problems (Laverty & Littel, 2020), and new markets with needs (Arentz, Sautet, & Storr, 2013; Baron & Ensley, 2006; Grégoire, Barr, & Shepherd, 2009; St-Jean & Tremblay, 2011). Solution-first models in entrepreneurship have proposed goals and strategies aimed at identifying these varied opportunities in the context of business development (e.g., Danneels & Frattini, 2018; Shane, 2000; Anthony, Johnson, Altman, & Sinfield, 2008; Gruber & Tal, 2017). Building upon these models and strategies of business development, we set out to examine a solution-first design process specific to using technological solutions to address problems.

As a more specific solution-first design process, we define *solution mapping* as beginning with a novel technological solution and searching for a specific application problem. In fields like engineering, designers who develop novel technologies may then face the challenge of mapping their invention onto a very large search space of potential problems. In this study, we set out to collect rich descriptions of how to accomplish solution mapping from design practitioners with personal experience in mapping their new technologies into identified problems. More specifically, we aimed to investigate the stages and strategies reported by experienced engineering designers as they described *how* they identified potential problems for new technologies. To achieve these goals, we interviewed professional engineering designers about their successful experiences in identifying problem applications for novel technologies they had developed. The outcomes of the study will inform us about the common stages and strategies involved in a solution mapping design process.

1 Background

A variety of design processes have been identified to explain differences in how design is accomplished. A critical feature is the ordering of stages for problem identification and solution identification.

1.1 Design process models

Within fields such as engineering design, research has focused on problem–first processes (Cross, 2008; Dym & Little, 2009), where designers explore an initial problem and search for its solutions (Duncker, 1945, Figure 1a). Perhaps as a consequence, research on design processes have focused on problem exploration to first identify understandings of the problem before venturing towards solutions. Research on problem exploration (Dewey, 1910) has identified further strategies for problem development, such as deepening understanding of stakeholders (Kilgore et al., 2007), alternative problem framings (Dorst & Cross, 2001; Schön, 1984; Stumpf & McDonnell, 1999, pp. 245–253), "scoping" or "setting" a problem space (Atman et al., 1999; Dillon, 1982; Nadler, Smith, & Frey, 1989; Runco & Chand, 1995; Schön, 1983; Volkema, 1983); problem finding (Csikszentmihalyi & Getzels, 1971, 1988), and taking alternative perspectives on the problem (Murray et al., 2019; Studer et al., 2018; Wallas, 1926) (see Table 1). These problem exploration processes are often described as *preceding* and then guiding the designer's search for solutions.

In contrast to a problem-first process (Figure 1a), an alternative design process allows the development of a design problem and its potential solutions in

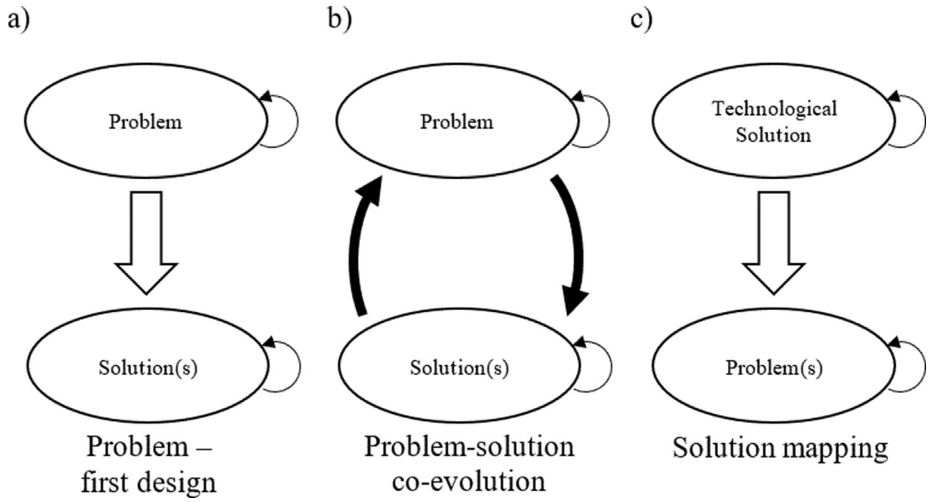

Figure 1 Three alternative design processes with problem and solution stages, but the order and direction of interaction between stages differ: a) a typical problem-first design process emphasizing defining and understanding a problem as an initial focus followed by a search for solutions (Cross, 2008): b) a process of problem-solution co-evolution, with simultaneous problem and solution development and iteration on both problem and solution spaces (Dorst, 2019); and c) a more specific solution-first process, solution mapping, *begins with a novel technological solution and is directed toward potential problems. In all three models, iteration within each stage may occur*

Table 1 Problem development strategies identified in problem-first design processes

Problem Strategies	*Definition*	*Citations*
Problem exploration	Investigate problems to determine the underlying needs to drive the search for creative solutions	(Dewey, 1910; Duncker, 1945; Wallas, 1926)
Problem framing	Alter presented problem characteristics to align with imposed frames and establishing problem boundaries	(Dorst & Cross, 2001; Schön, 1984; Stumpf & McDonnell, 1999, pp. 245–253)
Problem scoping	Set a defined problem space describing all possible problem definitions	(Atman et al., 1999; Dillon, 1982; Nadler et al., 1989; Runco & Chand, 1995; Schön, 1983; Volkema, 1983)
Problem finding	Identify a "discovered" problem by examining the presented problem with an open investigation	(Csikszentmihalyi & Getzels, 1971, 1988)
Problem perspectives	Intentionally apply different emphases, language, and viewpoints to the problem	(Murray et al., 2019; Studer et al., 2018; Wallas, 1926).
Stakeholder and context research	Integrate information about potential stakeholders and contexts of the problem to revise understandings of the real needs and constraints of people, society, the natural environment, and other aspects of context	(Kilgore et al., 2007; Norman, 1988; Salvador, Bell, & Anderson, 1999)

parallel; a potential solution can inform a redefinition of the problem, and new problem understandings push on solutions. Maher described the co-evolution of problems and solutions throughout a design process (Maher, 2000; Maher

& Tang, 2003; Poon & Maher, 1997). This *problem-solution co-evolution* model is shown in Figure 1b (Dorst, 2019; Wiltschnig et al., 2013). In this co-evolution process, bidirectional arrows represent interconnections between problem space and solution space. As designers modify the problem understanding based on their exploration of possible solutions, these solutions refocus the problem and prompt new design requirements (Maher, 1994; Wiltschnig et al., 2013).

Distinctly, solution mapping is a solution-first design process initiated by the identification of a novel technological solution (shown in Figure 1 c.). In solution mapping, a designer develops a novel technology as a solution, and then diverges to identify and consider problems that the technology might address, ending with the selection of a problem application. Novel technologies are often created without considering their purpose, requiring designers to identify problems that can be addressed with new technologies. The definitions of these three design processes are shown in Table 2.

Though implicit in publications on co-evolution, there is no apparent restriction on how the problem is developed; consequently, these same processes first identified in problem-first studies may apply equally well within a co-evolution process. In addition, strategies for solution development, such as idea generation, selection, prototyping, and testing may also occur within each of these design processes, whether beginning with a problem, co-evolving problem and solution, or beginning with a novel technology solution. We distinguish these three alternative models to highlight their differing approaches to the coordination of problem and solution design.

The literature on business entrepreneurship has also explored models of solution–first processes (Di Stefano, Gambardella, & Verona, 2012; Maine & Garnsey, 2006; Shane, 2000) where research and development of technology drives the development of new products (Di Stefano et al., 2012; Dosi, 1982). For example, the touchscreen technology first appeared as published research by Johnson at the Royal Radar Establishment UK in the mid-1960s (Johnson, 1965); then in the 1980s, Hewlett Packard used this technology to introduce the first touch screen computer. Maine & Garnsey (2006) described a process where companies match their technologies with needs in the marketplace to commercialize new products. To this formal match process, Schwartz added two more processes: a deliberate search for applications and a more passive, opportunistic match (Schwartz, 2005).

To further specify these processes, three models for technology-push in entrepreneurship have been proposed in the business development setting. Gruber and Tal (2017, p. 161) summarized approaches to agile technology development as including four general steps: (1) build a modular technology, (2) cast a wider intellectual property net, (3) take into consideration future human

Table 2 Summary of alternative design process models

Design Process Models	*Distinctive Characteristics*
Problem-first design	A design process that emphasizes defining and understanding a presented problem as a starting point, followed by a search for solutions (Cross, 2008; French, Gravdahl, & French, 1985).
Problem-solution co-evolution	An initial presented problem and its potential solutions are developed in parallel, with a change in each informing the other through iterations (Dorst, 2019; Dorst & Cross, 2001; Wiltschnig et al., 2013).
Solution mapping	A design process that begins with a novel technological solution is followed by a divergent search to identify potential problems to address.

resource needs, and (4) build and involve your stakeholder network. Gruber and Tal (2017) advised entrepreneurs to build a technology that can be adapted to multiple applications; that way, the company can pivot to exploit additional markets (Crilly, 2018). Further, in casting a wider intellectual property net, entrepreneurs should proactively protect their inventions and consider future options when making their patent claims or application fields. For human resource needs, Gruber and Tal recommended forming open-minded and agile teams with the necessary skills to flexibly develop the technology. Lastly, they suggested building stakeholder networks of investors, an advisory board, or other potential partners to help in this "agile focus" approach.

In comparison, Shane (2000) described the technology-push process as three general steps: 1) technological invention, 2) opportunity recognition, and 3) approach to exploitation. In this model, the stages are aimed towards the development of new products and serving new commercial markets. More recently, Danneels & Frattini (2018) proposed a model of "technology leveraging," where managers apply their existing technological competence to find applications for new customers. Their model follows four steps: 1) characterizing the technology by identifying its core functionality; 2) identifying potential applications; 3) selecting from among the identified applications; and, 4) choosing the best commercial entry mode. Aspects of these approaches from business development may translate to enginering design domains.

1.2 *Strategies for recognizing technology opportunities*

Even with an innovative technology, it is often not obvious *how* to recognize opportunities for applications; as Shane (2000) describes, different individuals may identify different opportunities, and some are unique. Researchers in entrepreneurship have identified a variety of strategies for recognizing opportunities through empirical studies with entrepreneurs, summarized in Table 3. However, these strategies are set within business development, a much broader set of potential opportunities (e.g., finding investment partners and new markets) rather than solely technology applications.

Table 3 Opportunity recognition strategies identified in business entrepreneurship

Strategy	*Description*	*Empirical Evidence*	*Source*
Find jobs to be done	Identify jobs for which existing solutions are ineffective or nonexistent	Surveyed entrepreneurs	(Anthony et al., 2008, p. 108)
Create mentor and social networks	Find mentors to guide in identifying opportunities. Also, exchange information between individuals.	Surveyed novice entrepreneurs	(St-Jean and Tremblay, 2011)
Pattern detection	Recognize opportunities for new ventures using connections between events and patterns	Surveyed novice and experienced entrepreneurs	(Baron & Ensley, 2006)
Apply prior knowledge	Leverage prior knowledge, developed through individuals' unique life experiences, to find opportunities	A controlled experiment with entrepreneurs	(Arentz et al., 2013)
Structural alignment	Make comparisons of objects and identify possible opportunities from the comparisons.	Think-aloud protocol studies of entrepreneurs	(Grégoire et al., 2009)
Hypothesis testing	Develop potential market opportunities as hypotheses and test them with potential customers	Summary of entrepreneurs' approaches	(Blank & Dorf, 2012, p. 24)

These strategies provide varied approaches to developing potential opportunities. For example, the *jobs to be done* strategy (Anthony et al., 2008, p.108) emphasizes that customers "hire" products to do jobs they need done in their lives. Similarly, the strategy of *hypothesis testing* (Blank & Dorf, 2012, p. 24) suggests positing opportunities as hypotheses to be tested through market research. A third strategy involves eliciting information from other people: St-Jean and Tremblay (2011) identified *mentors and social networks* as playing a positive role in recognizing opportunities by providing new information and supporting decision-making.

The three other identified strategies for recognizing opportunities focus on making informational connections. As Baron & Ensley (2006) described, entrepreneurs "*connect the dots*" between seemingly unrelated events, and then detect patterns in these connections to identify new products or services to pursue. Similarly, Arentz et al. (2013) recommended identifying opportunities through leveraging *prior knowledge* developed through unique life experiences. The third connection strategy, *structural alignment,* suggests comparing products and identifying opportunities from it (Grégoire et al., 2009). These strategies provide general direction on identifying problem applications for technologies.

Cognitive strategies in solution mapping

However, these strategies for recognizing business opportunities apply to a broad range of activities, such as identifying investment funding, human resources, intellectual property, and market opportunities (Arentz et al., 2013; Gruber & Tal, 2017; Baron & Ensley, 2006; St-Jean & Tremblay, 2011; Grégoire et al., 2009). A systematic review of research in entrepreneurship concluded that the field of opportunity recognition is underexplored and fragmented (Hansen, Shrader, & Monllor, 2011; Mary George, Parida, Lahti, & Wincent, 2016), with an evolving understanding as entrepreneurs leverage different processes (Schwartz, Teach, & Birch, 2005). Adding a focus on the technological solution may suggest other strategies related to identifying problem applications. More specific information on *how* to find potential technology applications may advance understanding and provide additional direction specific to these types of opportunities. In addition, these previous studies have collected evidence from entrepreneurs rather than technology designers. A study examining design processes that build toward applications of technological solutions may uncover *how* designers can use such strategies to support their successful designs.

1.3 Solution mapping in engineering design

Engineering designers focusing on novel technologies may need more specific strategies for solution mapping. Because most training and experiences in engineering design involve problem–first processes, engineers have been underprepared to approach designing of new technology-based solutions and identifying problem applications. To address this gap, the National Science Foundation I-Corps program was developed based on entrepreneurship practices by Blank and Dorf (2012) to encourage designers to identify potential problem applications for new technologies, described in detail by Huang-Saad, Fay, and Sheridan (2016) and Nnakwe, Cooch, and Huang-Saad (2018). In this program, participants receive support from mentors and social networks for identifying potential customers for their new technology. I-Corps engineering designers engage in 6–8 weeks of training, and complete over 100 interviews with potential stakeholders to confirm their assumptions about how identified problems map onto new technologies. However, the I-Corps program can offer only limited guidance on solution mapping processes because few studies and empirically-based guidelines are available. Within engineering design, the dominant model is problem-first design (Simon, 1996); however, some research on bio-inspired design has observed that designers sometimes begin with a biological mechanism and identify problems where it may be applied (Helms, Vattam, & Goel, 2009).

A common approach to identifying design strategies has been to extract strategies from the performance of expert designers. For example, idea generation strategies have been identified through interviews and observation of practicing designers (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Yilmaz

& Seifert, 2011). Prior research has shown that intentional application of cognitive strategies supports successful design outcomes (Brown & Goslar, 1986; Lawson, 1979; Navarro-Prieto, Scaife, & Rogers, 1999), and can support designers in divergent thinking (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Hernandez, Schmidt, & Okudan, 2013; Lee, Daly, Huang-Saad, Seifert, & Lutz, 2018; Lee, Daly, & Vadakumcherry, 2018). A similar study of cognitive strategies evident in engineering design processes may provide specific, experience-based guidance for solution mapping. Our previous work on solution mapping suggests guidance is needed: during the early phases of technological invention, engineering designers focused on functional advancement (including improved performance and reduced cost) without identifying applications for their technologies (Lee et al., 2018).

2 Methods

2.1 Research goal

The research aimed to describe how solution mapping – starting from a technology to identifying a problem application – took place in the context of engineering design. Our project addressed this research question: What cognitive strategies do engineering designers use to identify problem applications for novel technologies?

2.2 Participants

The study included 19 engineering designers from varied engineering fields who had been successful at developing their novel technologies and identifying problem applications, with success defined as developing commercial products or receiving external funding for the commercialization of their technologies. All participants were involved in the development of the technologies for which they sought problems they could solve. The sample size was appropriate for the in-depth data collection required and consistent with other qualitative studies (Borrego, Douglas, & Amelink, 2009; Creswell, 2017, p. 186; Patton, 2001, p. 242). As a qualitative study, the results provide evidence of observed patterns but are not intended to generalize to other settings. Instead, this study offers specific patterns identified across individuals performing similar engineering design tasks.

The engineering designers were recruited via email from existing contact networks. Additional engineering designers were recruited through snowball sampling from their acquaintances (Biernacki & Waldorf, 1981). Engineering designers were from companies in California, Arizona, Michigan, Pennsylvania, and New York, and held positions such as founder, application manager, and CEO. Participant experience ranged from 3 to 49 years (average = 20.6 years) in small (less than 50 employees) or large companies (greater than

Table 4 Participant information

Engineer	*Gender*	*Degree*	*Position*	*Industry*	*Years in field*	*Company size*
Adam	M	PhD	Founder	Energy	22	Small
Bert	M	PhD	Founder	Sensor	10	Small
Carl	M	MS	Founder	Aerospace	9	Small
Diane	F	BS	Product Specialist	Biotechnology	3	Large
Eric	M	PhD	Founder	Biotechnology	18	Small
Felipe	M	PhD	CEO	Energy	11	Small
Gabriel	M	PhD	Founder	Electromagnetic technology	20	Small
Harris	M	PhD	Founder	Electromagnetic technology	49	Small
Ian	M	PhD	Founder	Robotics	8	Small
James	M	PhD	Founder	Manufacturing	44	Small
Kevin	M	PhD	Founder	Materials	44	Small
Larry	M	PhD	Founder	Manufacturing	7	Small
Michael	M	BS	Manager	Energy	41	Large
Orlando	M	PhD	CEO	Semiconductor	9	Small
Peter	M	PhD	Founder	Biotechnology	36	Small
Raul	M	PhD	Founder	Manufacturing	20	Small
Steve	M	PhD	Founder	Materials	40	Small
Trisha	F	PhD	Founder	Biosensor	18	Small
Victoria	F	MS	Manager	Manufacturing	3	Small

1000 employees). The engineering designers worked in a variety of industry sectors, including energy, biotechnology, aerospace, manufacturing, and materials, as shown in Table 4 with pseudonyms. Many had launched companies with technologies they developed in their academic research, making them into commercial applications, and 11 out of 19 participants continued to hold positions in academia as professors or research scientists. Participation in the interview was voluntary and confidential, and no payment was provided.

2.3 Data collection

We collected semi-structured interviews with engineering designers focused on discussing their solution mapping experiences. 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 (see protocol in Appendix A). The questions were developed through multiple iterations, and two pilot interviews were conducted to address focus and clarity. Pilot tests are important in minimizing flaws, limitations, or other weaknesses within the interview protocol, and allowing researchers to make necessary changes before the implementation of the research study (Kvale, 2007, p. 46; Saldaña, 2011).

Probing questions were used to gain additional information during the interviews (Louise Barriball & While, 1994). Probing is an important tool in ensuring the reliability of the data because it allows for clarification of responses (Hutchinson & Wilson, 1992) and elicits more complete information

(Bailey, 1994, p. 194). Further, probing helps in recalling information for questions that involve the memory of past events (Smith, 1992).

For consistency, all interviews were conducted over 2 months by one interviewer trained in qualitative research methods. Interviews were conducted on the phone or in-person, and lasted 30–90 min. All interviews were recorded and transcribed for analysis.

2.4 *Data analysis*

Two researchers with a background in engineering design reviewed a subset of interview transcripts to develop an inductive codebook of possible cognitive strategies in participants' descriptions of their experiences. Following the recommendations from Creswell (2017) and Saldaña (2011), the transcribed interviews were analyzed for emergent themes through iterative, detailed readings of the raw interview transcripts. During this development of the inductive codebook, the set of codes was revised to improve accuracy in representations, in alignment with the recommendations from Boeije (2002). For example, one strategy, *emphasize different or multiple descriptions of the solution characteristics,* was coded when an engineering designer described leveraging more than one characteristic of his technology while attempting to identify a problem application (portions italicized for emphasis):

> "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*."

Because the engineering designer described multiple features of the new technology, his comment appeared to follow this strategy. In some instances, engineering designers used multiple strategies in a statement and more than one code was assigned to a given interview statement. After multiple iterations, the codebook was finalized, and the same two researchers independently coded the rest of the transcripts. Their percent agreement was over 90%, greater than the 70% level acceptable for inter-rater reliability (Osborne, 2008, p. 32). The coders discussed all discrepancies to a consensus to complete the coding analysis.

Next, two researchers created concept maps following each engineering designer's described stages of solution mapping. We then compared these maps to identify common patterns across participants. We used these comparisons to create a master solution mapping framework representing sequences of common stages and cognitive strategies in identifying problem applications for new technologies.

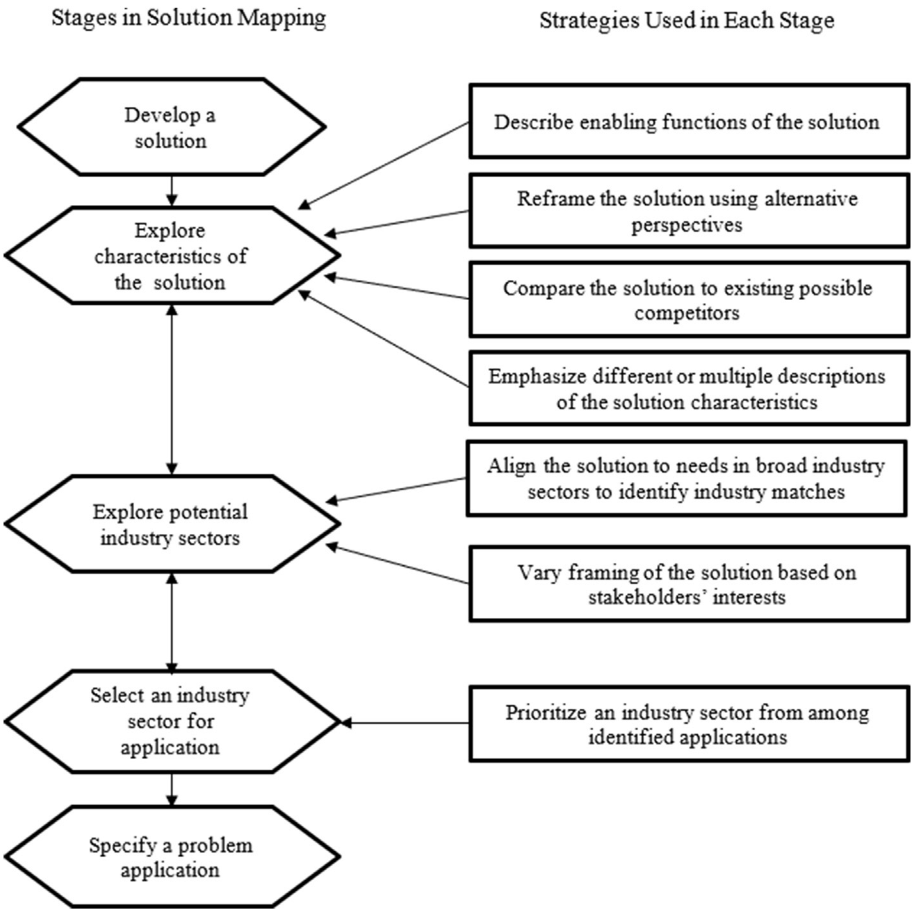

Figure 2 Findings from observations of solution mapping accounts across 19 participants. Stages in Solution Mapping are shown on the left, and cognitive strategies that appeared in these stages are on the right. Double arrows between stages indicate that the participants reported iteration across these stages throughout solution mapping

3 *Findings*

We observed five stages in solution mapping and seven different cognitive strategies. Figure 2 represents the stages identified and the associated cognitive strategies for particular stages. The solution mapping stages provide a framework for discussing general approaches to solution mapping. The majority of participants reported experiences that moved through all five stages identified for solution mapping: 1) identify a solution, 2) explore characteristics of the solution, 3) explore potential industry sectors, 4) select an industry sector for application, and 5) specify a problem application. However, 7 out of 19 participants did not engage in all five stages. Six participants omitted the third stage, *explore potential industry sectors*. These participants explored the characteristics of their solutions and then had a specific industry sector in mind for

Table 5 Themes coded representing cognitive strategies in solution mapping

Solution Mapping Strategies	*Frequency Across Interviews (n = 19)*	*Description*
Describe enabling functions of the solution	14	Translate the key characteristics of what the technology can do using action verbs to describe these enabling functions.
Emphasize different or multiple descriptions of the solution characteristics	12	Emphasize different functions (and sometimes multiple functions) to generate alternative descriptions of the solution qualities.
Reframe the solution using alternative perspectives	4	Reframe the solution's functions using alternative perspectives to better understand their capabilities.
Compare the solution to existing possible competitors	3	Compare the technology to potential competitors' technologies to consider the viability of problem applications.
Align the solution to needs in broad industry sectors to identify industry matches	13	Align key characteristics or functions of the solution with possible needs in multiple, broad industry sectors before identifying specific problem applications.
Vary framing of the solution based on stakeholders' interests	4	Change or reframe technology description based on different types of stakeholders to connect with stakeholders in varied industry sectors who may be interested.
Prioritize industry sectors from among identified applications	12	Prioritize industry sectors and applications after identifying multiple potential industry sectors to converge on a few applications to pursue.

potential applications, thus they limited their divergence in exploring multiple industry sectors.

The identified strategies describe how participants generated potential problem applications from known solutions, as shown in Table 5. All participants used more than one strategy, and they repeated stages iteratively in identifying problem applications for their technologies. In the remainder of the findings section, we describe the discovered strategies within each stage of solution mapping and how they were leveraged in participants' experiences.

3.1 Stage 1: Develop a solution

Participants described early work in their solution mapping experiences as developing a solution, described by 18 out of 19 participants. Participants started with a solution without having a clear problem application to pursue. For example, Carl created a new drone technology and described that identifying problems came after the technology development:

> "*We were a solution looking for a problem*, so we started the company … *We never set out and said [the industry] has problems*. We need to go solve those. We were like we've got a cool device. How can this benefit somebody?"

Cognitive strategies were not captured during the first stage of *develop a solution*, as participants described their initial process of technology development before pursuing problem applications.

3.2 Stage 2: Explore characteristics of the solution

In the second stage of solution mapping, participants explored characteristics of the solutions to better understand their capabilities, demonstrated by 18 out of 19 participants. Participants emphasized exploring key characteristics of their technologies without using technical jargon. For example, Diane described her technology as a sensor that can measure oxygen level:

> "*[The technology] measures the oxygen that is being released from the skin* … Since the skin is the lowest in priority on the oxygen delivery chain, meaning that the body will send oxygen first to major organs, and then to the skin last. So if you have any type of circulatory issues, you'll see it in the skin first because your body is prioritizing."

Four cognitive strategies were emphasized by participants in their experiences exploring the characteristics of solutions: 1) *describe enabling functions of the solution*, 2) *emphasize different (or multiple) descriptions of the solution characteristics*, 3) *reframe the solution using alternative perspectives*, and 4) *compare the solution to existing possible competitors*.

3.2.1 Strategy: Describe enabling functions of the solution

Participants identified the enabling functions of their solutions. They identified key characteristics of their solutions and translated those characteristics into enabling functions. 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 a 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."

Kevin created a new type of micro material that has conductive properties. He not only described his technology's characteristics, but he also took a step further to focus on what the technology could do:

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

Participants appeared to explore the functions their solutions might afford through deeper consideration of their capabilities.

3.2.2 *Strategy: Emphasize different or multiple descriptions of the solution characteristics*

The solution had multiple unique, different characteristics. Participants focused on different characteristics to consider multiple problem applications for their solutions. By considering multiple characteristics and functions, participants diversified potential problem applications for their solutions. For example, Kevin developed a new material that was thin, large, lightweight, and stiff. By focusing on the thin and large characteristics, he searched for problem applications in water filtration by controlling in spaces and opening between the material. 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 [to use for filtration]* … 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."

Participants often combined multiple characteristics of their solutions to identify problem applications. By using different combinations of key characteristics, participants sought to identify more, varying problem applications that may be addressed by their solutions. For example, Larry developed a new type of 3D printer and leveraged both abilities to print small features and conducting materials to identify problem applications in hearing aid companies:

> "*It involves small features right. It involves conducting materials, which we can print … So like say we also talked to hearing aid companies*. Same thing, small with conducting materials. We talked to the automotive industry because they sometimes need sensors, print on sensors for testing their components, products or even sometimes making internal tools."

By combining multiple characteristics of their solutions, participants searched for problem applications that could take the most advantage of their solutions' functions.

3.2.3 Strategy: Reframe the solution using alternative perspectives

Four out of 19 participants changed their descriptions of the solution when they reframed the solution using alternative perspectives. Instead of solely focusing on the known functions, participants identified new functions for their solutions by reframing them using alternative perspectives to better understand their capabilities. By creating alternative functions by reframing their solutions, participants were able to pivot and identify new problem applications. For example, James initially developed a laser welding technology. Instead of focusing on the welding function to identify problem applications, he considered alternative functions for his technology. Using similar principles as welding, he created a 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 the laser to create a shape*. That's laser cladding. That's how I got started."

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.

Raul also created a different function for a solution that was mainly used to clean surfaces by dissolving oil. He considered a completely different way of using his solution. Instead of focusing on cleaning surfaces, he considered ways to deliver oil to surfaces with the same technology:

> "He was just talking about using [a technology] to dissolve oil. Like when you clean semi-conductor wafers, or he was talking about decaffeinating coffee. He was talking about dry cleaning clothes. These are all kind of clean applications where you don't want to put toxic stuff to remove oil from tight spaces, difficult spaces, and [this technology] has been very good at that. That's what he was talking about. *He wanted to remove oil from surfaces, and I needed to deliver oil to surfaces, but, the same thing. If it dissolves, it dissolves, and I made that connection really fast*."

3.2.4 Strategy: Compare the solution to existing possible competitors

Three out of 19 participants compared their solutions to existing possible competitors to find additional characteristics of their solutions and find problem applications. For example, Adam, who developed a new type of battery technology, identified potential problem applications of his own technology by comparing key characteristics of his technology with his competitors and identifying applications that his competitors did not adequately address:

"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 … [battery technology]. We used the basic … know-how, initially, *on how to make them small … 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 the customer liked the idea of [our type of solution] 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."

Victoria's company developed a new type of 3D printing technology that set them apart from the existing approaches. Many existing 3D printing technologies have low strength in the Z (height) direction as features are created by building weaker bonds in the Z direction. Victoria emphasized her technology as achieving a higher strength compared to existing 3D printing technologies and identified unique applications for their new technology:

"*… [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*."

By understanding the novel characteristics of their technologies compared to their competitors' technologies, participants identified different uses for their solutions.

3.3 Stage 3: Explore potential industry sectors

After exploring characteristics of the solution to better understand its capabilities, 13 out of 19 participants explored potential industry sectors. For example, Ian developed an exoskeleton technology and considered all possible industry sectors that might use his technology before narrowing down choices:

"*There's a lot of excitement around the military and industrial applications of exoskeleton technology. You're starting to see a lot of focus on developing exos for manufacturing applications*. So, we're considering all of it …

Two cognitive strategies emerged during the stage of exploring potential industry sectors: 1) *align the solution to needs in broad industry sectors to identify* *industry matches*, and 2) *vary framing of the solution based on stakeholders' interests*.

3.3.1 Strategy: Align the solution to needs in broad industry sectors to identify industry matches

Participants aligned their solutions' capabilities with the 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 required data that his drone could 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."

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

3.3.2 Strategy: Vary framing of the solution based on stakeholders' interests

Participants intentionally varied how they engaged with multiple stakeholders to identify potential industry sectors for applications. For example, Diane's company developed a technology with a wide range of problem applications but she focused on medical problem 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 at*. If it would be beneficial for them, that kind of thing."

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 technology to stakeholders from various industries to identify specific problem applications.

Larry developed a 3D printer that could print composite materials. He prioritized various sectors and engaged with stakeholders within those industries to find a fit:

> "Because I print composite material … So, of course, you've got the automotive industry, which uses 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 … The 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."

Participants emphasized the importance of having the ability to vary how they engaged with stakeholders to identify problem applications within specific sectors.

3.4 Stage 4: Select an industry sector for application

Before identifying specific problem applications of their solutions, participants identified broad industry sectors that could potentially benefit from their technologies and then selected an industry sector to pursue. For example, Bert developed a novel sensor that could be used in multiple areas, but settled on pursuing automotive problem applications:

> "You know through just reading the papers and the articles out there, you'll be able to understand some potential applications of the technology and that's how I basically got introduced to the applications of the technology to great extent. But again … the application was for navigation purposes for being able to detect … As I said, it's a radar technology to be able to detect and see targets at different ranges and the different sizes. That was the core of what it was capable of doing, and you know for navigation sensors there are different markets, *and one of which was autonomous cars*."

Participants used the cognitive strategy, *Prioritize industry sectors from among viable identified applications,* to help them select a particular industry sector.

3.4.1 Strategy: Prioritize industry sectors from among viable identified applications

Participants prioritized industry sectors that appeared to be good matches to their solutions based on two factors: 1) providing value to the specific industry using their solutions, and 2) aligning the industry sectors with their knowledge and training. For example, Carl developed a drone but did not have a clear problem application. He considered many different industry sectors and prioritized one industry that he could provide value:

> "*We were looking at cell towers and power and oil and gas and boats and shipyards. 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 [this industry] and really focused on adding value to [this industry]*."

Carl was initially searching for broad problem applications to address with his solution. After searching broad industry sectors, he prioritized the power and energy industries as his main targets and found a problem application in using his autonomous drone to support a specific industry sector. Many other participants demonstrated a similar approach. Eric considered several different problem applications in multiple industry sectors. He initially focused on developing a consumer product using his new material. However, due to his limited understanding of developing consumer products, he decided to prioritize developing a product related to his core expertise in biotechnology. Thus, he focused on developing a DNA testing kit using the same material he considered for creating a consumer product:

> "It has all those properties of strength, of light, and so, and use that for building a surfboard. So that's really how we started, and we did some prototyping of part of the [consumer product] … *but ultimately I have very little knowledge of consumer products … so they thought it would be better if I find an application that will be closer to what my core expertise was [in biotechnology]*. So one program we have was in DNA forensics, so we were the first one to bring what we call rapid DNA testing."

Participants appeared to prioritize an industry sector based on their knowledge and training, recognizing that multiple applications could have been possible, but those with the highest familiarity might have led to greater success for them.

3.5 Stage 5: Specify problem application

After selecting a specific industry sector, participants considered several problem applications within that sector, but all participants ultimately focused on one application to pursue. For example, Gabriel narrowed down to finding applications within wireless technology using his solution. His team focused on a specific application within the wireless industry:

> "There are other applications we want to pursue, but we are earlier stage, *so we made a decision that we should focus, at least initially, trying to develop one of the applications into maturity before we spread ourselves into too many areas*. So we kind of made a strategic decision."

Participants focused on developing a single product and focused on applying their technology on one application instead of pursuing multiple applications at the same time. No cognitive strategies were articulated in the last stage as they selected the application.

4 Discussion

4.1 Contributions and connections to research literature

This study identified 1) five stages and 2) seven cognitive strategies in solution mapping used by engineering designers. The stages of solution mapping we identified complement findings from previous studies in business entrepreneurship. For example, the first stage and last stage – "identify a solution" and "specify a problem application" – were identified by Shane (2000) and Danneels & Frattini (2018) in entrepreneurship opportunity recognition work. The second stage of a solution mapping process we observed – identifying the solution characteristics – was also noted by Danneels & Frattini (2018), and the third stage we identified – exploring industry sectors – has been described by Maine & Garnsey (2006). While the results parallel the models in entrepreneurship, there were important differences in the processes we observed.

In solution mapping, engineering designers 'fixated' on particular technologies and developed them in-depth, similar to prior studies in design fixation where designers stick with a particular solution idea and continue to refine it (Crilly, 2019). However, unlike previous fixation studies, engineering designers in this study demonstrated divergence in problem exploration by considering problems in multiple, unrelated areas as they searched to identify problems to match their technologies. Although several of the stages of solution mapping have been discovered by other scholars, our contribution lies in articulating each stage in solution mapping and aligning cognitive strategies used in these stages; we have identified ways engineering designers identified potential problem applications using novel technologies.

Cognitive strategies for solution mapping were uncovered starting in the second design stage, *Explore characteristics of the solution* where engineering designers "fleshed out" the qualities of the solution. Four solution mapping strategies were associated with this stage. The most frequent strategy was, *describe enabling functions of the solution*. This strategy appears related to using functional decomposition to generate solutions, described in Eck (2011) and Umeda, Ishii, Yoshioka, Shimomura, and Tomiyama (1996). Identifying enabling functions is similar to the recommended entrepreneurship practice of identifying key characteristics (Anthony et al., 2008, p. 108; Gruber & Tal, 2017), and bio-inspired design practices of understanding mechanisms in biology before identifying applications (Helms et al., 2009) Our findings support these recommendations and further specify a solution mapping strategy to describe key functional characteristics of the solution.

A second strategy identified for exploring characteristics of the solution was, *emphasize different or multiple descriptions of the solution characteristics*. By considering multiple characteristics and functions, engineering designers diverged in their thinking about the solutions, and therefore in potential problem applications for their solutions. Engineering designers also combined multiple characteristics or functions of their solutions to identify new problem applications. Prior research has documented combining characteristics or functions as a source of divergent ideas during design (Mohan, Shah, Narsale, & Khorshidi, 2014). In our study, the engineering designers at times combined functions identified in their solutions to take advantage of multiple functions and to identify new solution descriptions. Emphasizing and combining solution features to identify new problem applications is a novel strategy not seen in the entrepreneurship literature.

A third strategy identified for exploring the solution was, *reframe the solution using alternative perspectives*. By taking multiple, alternative perspectives towards their solutions, engineering designers reported identifying new, varied functions instead of focusing on those previously identified. Perspective-taking allows one to move away from one viewpoint and take on another person's view (Ackermann, 2012). Perspective-taking in solution mapping may support engineering designers as they attempt to understand their own creation − the solution technology − by generating alternative views of its functions. Taking new perspectives helped some engineers to pivot in new directions; more generally, the entrepreneurship literature recommends pivoting as a valuable strategy promoting flexible thinking (Crilly, 2018; Gruber & Tal, 2017).

Finally, engineering designers followed the strategy, *compare the solution to existing possible competitors*. Considering other related solutions was sometimes useful in identifying additional specific characteristics of their solutions. Engineering designers mentioned comparing their solutions to other solutions in the same general category, such as "batteries" or "3D printers." By understanding the novel characteristics of their technologies compared to competitors' technologies, engineering designers were able to identify different uses for their solutions. This strategy is similar to the *structural alignment* strategy identified in the entrepreneurship literature (Grégoire et al., 2009); however, in that context, comparisons of products within marketing categories were proposed. Whereas in this study, engineering designers aligned the key characteristics of solutions. Across these four strategies to deepen understanding of the solution, their use during solution mapping identifies specific cognitive tasks used by engineering designers to enrich their solution descriptions.

In the third stage identified in the solution mapping process, *explore potential industry sectors*, two solution mapping strategies were evident. Engineering designers identified multiple industry sectors that might benefit from their solution by *aligning the solution to needs in broad industry sectors to identify industry matches*. The strategy of alignment across problems and solutions rests on perceptions of similarity between two or more objects, described by (Day & Gentner, 2007; Keane & Fintan, 2001; Markman & Gentner, 1993; Grégoire, Barr, & Shepherd, 2009). Additionally, Maine & Garnsey (2006) described product-market fit in entrepreneurship by aligning characteristics and functions in a technology-to-market matching process. In our study, engineering designers were observed to perform a more specific type of structural alignment where they "mapped" the key features of their solutions with aspects of needs evident in specific industry sectors.

Another strategy in identifying industry sectors focused on *varying framing of the solution based on stakeholders' interests*. Engineering designers changed how they described their solutions to various stakeholders to find connections to multiple industry sectors. Through stakeholder engagement, engineering designers spent time learning about problems within multiple industry sectors, and identified the clear needs of their stakeholders, which is a common practice in problem exploration within human-centered design research (Brown, 2009, p. 39; Kelley & Littman, 2001, p. 6; Miaskiewicz & Kozar, 2011).

In the fourth stage identified in solution mapping, the strategy, *prioritize industry sectors from among identified applications* was evident. From the interviews, some engineering designers' competencies and experiences were involved in selecting their final application sector. More generally, using prior knowledge based on personal experiences was identified in the entrepreneurship literature (Arentz et al., 2013).

In sum, the seven solution mapping strategies identified in our study were tied to specific properties of solutions; consequently, exploration involved specific questions regarding material properties, capacities, qualities, and functional characteristics of their solutions. This focus on properties suggests that the physical nature of novel technologies plays a large role in driving the search for problem applications. In addition, expertise within specific industry sectors appeared to heavily influence solution mapping approaches. In all cases in the study, the engineering designers intended to identify products where the new technologies "fit" existing problem applications, and they were dependent on their own or others' (such as stakeholders') knowledge of specific sectors.

The findings from this study build on existing literature and share some commonalities with more general strategies identified in entrepreneurship settings. Similar to entrepreneurs, engineering designers reported comparing their solutions to competitors (Baron & Ensley, 2006). Both groups also aligned key solution characteristics to industry sector problems (Grégoire et al., 2009) and engaged with external stakeholders (mentors) in identifying problem applications (St-Jean & Tremblay, 2011). Our study also provided some evidence of personal prior knowledge contributions in prioritizing an application area, while an individual's contributions in initially finding opportunities are more generally noted within entrepreneurship (Arentz et al., 2013). These commonalities suggest solution mapping is related to a broader range of tasks in opportunity recognition within entrepreneurship, where the link between solution and problem application is only the first step in developing a viable business.

However, other strategies from the entrepreneurship literature, such as "jobs to be done" (Anthony et al., 2008, p. 108) were not evident in this study of engineering designers. In addition, the key strategies identified in our findings regarding the exploration of the solution – describing enabling functions, emphasizing different or multiple descriptions, and reframing with alternative perspectives – have not appeared previously in the entrepreneurship literature. These differences suggest that some solution mapping strategies may be specific to designers with an in-depth understanding of the technologies. The technology-leveraging model (Danneels & Frattini, 2018) does share surface similarities with the solution mapping process, such as the "characterize the technology" stage. However, the other three stages proposed in their model were not observed in our study. Further research is needed to develop relationships between the opportunity recognition processes identified in business entrepreneurship and engineering design processes such as solution mapping. As the creation of new technologies increases, developing our understanding of design processes involving technology is increasingly important. In addition, the strategies identified from this study in the context of novel technology development may apply to other, non-technology solution–first processes in business and other fields.

4.2 Limitations

For this study, we selected successful engineering designers who had developed commercial products or obtained external funding for the commercialization of their novel technologies. Because we interviewed successful engineering designers, we considered only positive cases that had convinced investors to further develop their products. Ideally, additional studies would compare these findings to those in cases where engineering designers failed to find successful problem applications, allowing observation of whether the strategies uncovered in this study predict success. Further, additional strategies may be discovered by examining a larger number of cases.

Our study did not explore differences among participants such as years of experience, types of technology, differences in industries, and demographics. Additionally, our study sample included only 3 females, which is not sufficient to represent the diverse demographics represented in professional engineering. While we included participants working in multiple industry sectors, additional cognitive strategies may be evident if the diversity of industry sectors was increased. 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 solution mapping. Further studies might compare these results from engineering designers to other design domains. With larger samples, exploring how features of the solution, designers, industries, and interactions impact solution mapping may serve to contextualize these findings. Examining a wider sample of designers would be informative about the variety of approaches to solution mapping in design.

4.3 Implications

This study contributes novel findings to the design literature by identifying stages and cognitive strategies to support solution mapping. By interviewing successful engineering designers, we have identified design stages and common cognitive strategies in mapping new solutions to problem applications. Viewing solution–first processes through a design lens can facilitate connections across disciplinary areas and provide language that resonates with engineering and design communities. Furthermore, it can support design practitioners and students in broadening the strategies they leverage in their work.

To support designers and students in using these cognitive strategies in solution mapping, new design tools could be created. Other design tools have been shown to support novice and experienced engineers in specific phases of design work (Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Hernandez, Schmidt, & Okudan, 2013; Lee, Daly, Huang-Saad, Seifert, & Lutz, 2018); consequently, a tool can provide scaffolding for exploring potential problem applications. This tool can guide engineers in identifying key characteristics of solutions and enabling functions, and provide a list of industry sectors to consider in multiple domains. Such a tool may serve as a guide to engineers in the National Science Foundation (NSF) I-Corps program, supporting their training on how to develop potential problem applications for new technologies (Huang-Saad et al., 2016; Nnakwe et al., 2018). Such a design tool would allow designers to think through the steps in solution mapping using these strategies to gain experience with the solution mapping process.

The results of this study also identify a role in design education for preparing engineering designers to perform solution mapping. Very few opportunities are provided in traditional engineering curricula to experience a solution-first design process. Providing training and guidance may better prepare engineers to approach solution-first design when opportunities arise. In proof of this concept, a pilot study examined how engineering students use the strategies found in this study to generate more diverse problem applications for a technology (Lee, 2019). The engineering designers in the study reported only one or just a few experiences with solution mapping; more generally, the frequency of experience with solution mapping among engineering designers is unknown. Programs like the NSF I-Corps document interest from engineering designers in learning about the identification and development of applications for new technologies. However, engineering designers are not currently well prepared for this solution-first design task (Lee, 2019). Because this design process is not currently a part of engineering education, it may be helpful to prepare future engineering designers by providing experience with these and other potential strategies.

With the solution mapping strategies identified, engineering students and practitioners may gain greater familiarity with exploring multiple problem applications for novel technological solutions, and develop their skills for future solution mapping as professional engineering designers. Given the importance and promise of new technology development, building solution mapping skills for engineering designers is a reasonable educational investment. As the successful engineering designers in our study demonstrated, the under-explored design process of solution mapping accomplishes a non-obvious match between new technologies and important problem applications, leading to more innovative products.

5 Conclusion

This study explored a solution-mapping design process where a novel technology initiates a search for appropriate problem applications it can address. The resulting process model identified five stages and seven associated strategies in the identification of problem applications from technological solutions, defined as *solution mapping*. The findings from this qualitative study show that engineering designers share common design stages and cognitive strategies while designing with different technologies and applications. While these findings shared features with opportunity recognition in business entrepreneurship, there were many findings unique to this study. This suggests the process of recognizing an opportunity for applying technological solutions may depend on the designer's knowledge and approaches. The observed stages and cognitive strategies may be translated into an explicit design tool to support designers in mapping their new technological solutions onto important, unsolved problems. Finally, these findings suggest the coordination of problem and solution stages in design processes have important consequences for how design is accomplished.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. List of interview questions

- What is your technical expertise?
  - How did you develop your expertise?
  - How long have you been working in your field?
- What is a new technology that you have developed (that has been commercialized)? If more than one, choose one to discuss.
  - I will now ask you a series of questions about the specific example you just described.
- From the beginning to the end, can you tell me about the process of developing the technology in that example?
  - From the experience that you just shared, what was the main purpose or motivation in developing the technology?
  - How did you come up with it?
  - Why was this important?
  - How, if at all, did the goal evolve or change over time.
  - What were the strengths of your technology?
  - What were the challenges of developing your technology?
  - What point are you in the development process? (If they're still working on it)
- 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?
  - Can you tell me about how you found a possible application you could pursue?
  - Did you have a "eureka moment"?

- At what point did you decide that this was the specific application of your technology to pursue?
- What were the challenges in using your technology for this application?
- What, if any, were other opportunities and applications that you considered for this technology?
  - How different were they from each other?
  - What did the search for another application look like?
  - Why did you discard some of these possible applications?
- What would have encouraged you to explore additional opportunities and applications for your technology?
- Was there an instance that you wanted to pursue a different application but could not for any reason?
- Do you still look for additional opportunities to pursue?
  - Can you tell me about a time that you actively searched for another application?
- Looking at the experience as a whole, can you sketch out the sequence of significant milestones in identifying the application for your technology?
  - Do you feel this application of your technology is a success?
- If you were to start over from the beginning, would you do anything differently?
- Tell me about your work environment at the time, and how it may have affected your choices and approaches in recognizing and pursuing opportunities using your technology?
  - Where were you in your career when you pursued this opportunity?
- How did the people you worked with effect your choices in recognizing and pursuing opportunities?
- What knowledge was most useful in helping you figure out your application?
- What competing technologies were you aware of for your application?
- What else may have influenced your choices in recognizing applications for your technology?
- Was there a time that you considered a different application using the same technology?
- Looking at the process as a whole, what is your advice for those who have a new technology and are looking for an application?
- Is there anything else that you would like to share to help us get a better picture of how you recognized applications for your technology?

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