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A solution in search of problems: a cognitive tool for solution mapping to promote divergent thinking

Jin Woo Lee [a], Shanna R. Daly[b], Aileen Huang-Saad[c], Gabriella Rodriguez[d], Quinton DeVries[e] and Colleen M. Seifert[f]

[a]Department of Mechanical Engineering, California State University Fullerton, Fullerton, CA, USA; [b]Department of Mechanical, University of Michigan, Ann Arbor, MI, USA; [c]Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA; [d]Department of Electrical Engineering, University of Michigan, Ann Arbor, MI, USA; [e]School of Information, University of Michigan, Ann Arbor, MI, USA; [f]Department of Psychology, University of Michigan, Ann Arbor, MI, USA

ABSTRACT

Engineering design processes are often defined as beginning with a problem and diverging to generate possible solutions; however, design processes can start with a newly developed technological solution, followed by a divergent search for potential problem applications it can solve, termed 'solution mapping'. Building on previous research where engineering practitioners described their successful strategies for solution mapping, we created a tool to support solution mapping and tested its impact with engineering students. In a single session, graduate and advanced undergraduate engineering students were presented with a novel technology and worked to identify potential problem applications for it. Comparing students using the Solution Mapping Design Tool to two control groups, more diverse problem applications were produced when using the tool. Considering diverse options is an important feature of design processes shown to promote creativity and innovation. With this successful proof of concept, future work on solution mapping will identify how to support engineers seeking problem applications by making use of new technologies.

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1. Introduction

Prescriptive engineering design processes documented in the literature define an initial problem as a starting point (Cross 2008; Dym and Little 2009; Dieter and Schmidt 2009), proceeding next to understand the context and the needs of the stakeholders, generate potential solutions, select options for prototyping, conduct testing and refining, and evaluate the solution (Kilgore et al. 2007; Studer et al. 2018). However, a problem is not always an initial focus in engineering design. Engineers who develop a novel technology may 'reverse' this problem-first design process by beginning with the solution and exploring potential problem applications. In this 'flipped' process, called *solution mapping*, the engineer aims to match a technological solution with a problem application, exploring multiple potential

CONTACT Jin Woo Lee jinlee@fullerton.edu Department of Mechanical Engineering, California State University Fullerton, 800 N. State College Blvd., E-100, Fullerton, CA, USA

problems that can be solved with a new technology (Lee 2019; Lee et al. 2018a; Lee et al. 2020a; Lee et al. 2020b). For newly-developed technologies, identifying problems they can address is not obvious. Shane (Shane 2000) noted that although many people are exposed to information about a new invention, very few opportunities to use a technology are discovered, and these are not easily identifiable from simple knowledge of the technology. These challenges suggest the need for design tools and training, but engineering design currently lacks both for solution mapping.

Successful design tools have been developed to support other design processes, such as concept generation in problem-first processes, and studies have demonstrated the efficacy of leveraging design tools to aid engineers (Daly et al. 2016; Hernandez et al. 2013; Lee et al. 2018c; Lee et al. 2018d). Empirically-based design tool development has been guided by analyses of patents and design artefacts (Lee et al. 2018c; Altshuller 1997; Camburn et al. 2015) as well as by investigations of patterns in approaches to open-ended design tasks (Daly et al. 2012; Lauff et al. 2018). Many design tools have been developed to support problem-first design processes, but no evidence-based design tools are currently available to guide engineers in solution mapping.

Previous work on solution mapping has identified several cognitive strategies shared by engineering practitioners who successfully identified problem applications for new technologies (Lee et al. 2020a; Lee 2019; Lee et al. 2019). The use of cognitive strategies in the form of specific, experience-based guidelines to support decision making have been shown to be representative of expertise (Sternberg et al. 2003). The Solution Mapping Design Tool for divergent thinking about technology problem applications was developed (Lee et al. 2020a; Lee et al. 2019). Divergent thinking, a necessary component of creativity (Kudrowitz and Dippo 2013; Guilford 1967; Baer 2014), is defined as considering alternatives, making unexpected combinations, and identifying connections among remote associations (Guilford 1967) (Treffinger et al. 2002). In design, practicing divergent thinking to generate multiple, diverse ideas has been shown to increase the potential for innovative outcomes (Brophy 2001). In this study, we investigated the impact of the Solution Mapping Design Tool on divergent thinking when searching for technology problem applications.

2. Related work

2.1. Solution first processes

Within engineering design, few studies have examined solution-first design processes. However, some studies have suggested a design process similar to solution mapping. For example, a study of bio-inspired design observed that designers sometimes begin with a mechanism seen in biological systems and search for engineering problems where it can be applied (Helms et al. 2009). Other studies describe a process starting with an existing product in the marketplace and, through 'reverse engineering,' identifying its mechanisms and making improvements based on the perceived market defects or envisioned evolution (Otto and Wood 2001). The literature suggests that by analysing a product to identify its components, reverse engineering can help better understand the needs of the application (Keller et al. 1999). While these alternative design processes also begin with a known solution, they retain some problem definition through the existing product or biological system in the form of what the solution is designed 'for.'

Literature in entrepreneurship has examined solution-first processes, described as 'technology-push,' approaches, where research and development of new technologies can drive product development (Di Stefano et al. 2012) For example, Maine and Garnsey (Maine and Garnsey 2006) described that generic technologies, such as new materials, could be developed into a new product by matching them to needs in the market. The entrepreneurship literature has described solution-first approaches more broadly as 'opportunity recognition' processes to identify a potential market or need. Opportunity recognition reports have mainly focused on the activity of business entrepreneurs aimed towards market and stakeholder needs and the commercialisation process. However, some studies define opportunities with regard to new technology by beginning with a technological invention and recognising an opportunity for its use and an approach to its exploitation (Shane 2000; Grégoire et al. 2009).

We have defined solution mapping as a more specific form of opportunity recognition focused on a newly developed technology without an evident purpose; through divergent thinking processes, possible problems to solve using the technology are identified (Lee et al. 2020a; Lee 2019; Lee et al. 2019). For example, an engineer developed an organic photodetector as he focused on creating materials for electronics. He later identified an application to create a lighting system that changes colour and intensity in real-time in sync with the sun's position, providing daylight in spaces deprived of windows and skylights (Allen 2015). When a new technology is created, it is an opportunity to solve problems; most centrally to solution mapping, the technology lacks a general purpose, but has a great fit to a constrained problem. For example, the creation of a 'not very sticky' adhesive at 3M presented a generic opportunity as a fixative and it was later used to solve the problem of marking places on paper. This fixative on Post-It Notes was a classic example of solution mapping: a specific technology is matched to a previously unrelated problem through a divergent design process leading to discovery. This solution mapping design process clearly differs from problem-first design processes because the problems are initially undefined.

2.2. Development of design tools and strategies for divergent thinking

Design tools and strategies have been developed to support divergent thinking in the early stages of design, and successfully promote the consideration of multiple, diverse options leading to more creative and innovative outcomes (Lee et al. 2018c; Daly et al. 2012; Kudrowitz and Dippo 2013; Brophy 2001; Shah et al. 2000; Linsey 2007). Idea generation tools aimed primarily at problem-first processes have been developed using several different methods. One approach in creating design tools derived from studying successful design outcomes; for example, TRIZ was developed by studying patterns in over 40,000 patents to create a set of 40 strategies supporting concept generation (Altshuller 1997). The effectiveness of TRIZ was examined in one ideation study where students improved in generating ideas with higher variety and novelty compared to a control group (Hernandez et al. 2013). Similarly, a set of ideation strategies in microfluidics was developed by extracting patterns evident in patents; in a study with advanced engineering students, the use of the microfluidic design strategies resulted in more varied and creative ideas during concept generation (Lee et al. 2018c). These design tools have been proven to be effective at improving fluency and flexibility when used in problem-first design scenarios.

Other design tools have been developed through empirical studies of designers' work processes. Synectics, a problem-solving methodology, was derived from audio and video recording meetings dealing with obstacles and arriving at creative solutions (Gordon 1961). Synectics emphasises problem-solving using analogies to generate solutions, as does design-by-analogy (Linsey 2007; Tomko et al. 2015). Design-by-analogy was developed to guide designers in linguistically representing the design problem that can support divergent thinking by creating novel analogies and analogous domains (Linsey 2007; Linsey et al. 2008; Fu et al. 2015; Linsey et al. 2012). However, design-by-analogy has been developed and tested to promote generating novel solutions for a problem, not for using a solution to generate possible problem applications.

While brainstorming is common in group design, it is sometimes practiced with its original guidelines to generate as many ideas as possible, minimise evaluation while generating, and build on previous ideas (Osborn 1963; Osborn 1942). However, brainstorming does not provide specific directions for creating novel ideas. *Design Heuristics* were developed by identifying designers' generation strategies as they worked through open-ended problems in think-aloud sessions (Daly et al. 2012) and *Design Heuristics* have been documented to support students and professional designers in generating creative solutions to problems (Yilmaz et al. 2016; Lee et al. 2018b). As designers verbalised their thought processes, researchers captured specific strategies used to introduce variation in the potential solutions generated. This suggests that engineers who have successfully identified problem applications of a novel technology may offer alternative or more specific strategies for solution mapping.

Researchers in entrepreneurship have identified a variety of strategies for recognising opportunities through empirical studies of entrepreneurs. Baron and Ensley (Lee et al. 2018b) described that entrepreneurs 'connect the dots' between seemingly unrelated events and detect meaningful patterns to identify new product opportunities. However, the 'connect the dots' strategy provides limited guidance on how to identify meaningful patterns. Arentz and colleagues (Baron 2006) stated that leveraging prior knowledge developed from past experiences can help in identifying opportunities. This strategy is challenging to use because it does not specify which prior knowledge should be considered. These strategies in entrepreneurship can benefit from having prescriptive guidance on how to find potential problem applications for technologies.

An educational approach to identify potential problem applications of technologies was established by the National Science Foundation's I-Corps program (Arentz et al. 2013; Nnakwe et al. 2018). I-Corps participants follow a curriculum developed by Steve Blank to investigate different uses and commercialisation potential for their technology (Robinson 2012). The standard process entails customer discovery to identify potential partners, and meetings with business investors to gain insights about developing a viable product. In the curriculum, participants are required to complete over 100 interviews with potential stakeholders to understand the needs that their technology can fill. The interviews serve as a good opportunity to confirm or deny their assumptions about possible uses of their technologies. However, in the I-Corps program, there are limited strategies provided to support designers in forming initial assumptions about potential problem applications for their technology to support solution mapping. Thus, we aimed to develop and examine the effectiveness of a design tool to support solution mapping.

To identify potential strategies for identifying problem applications for a new technology, empirical evidence from successful solution mapping design cases were collected in a recent study (Lee 2019; Lee et al. 2020a; Lee et al. 2020b). Through interviews with engineers who developed novel technologies and successfully matched them to problem applications, a set of cognitive strategies for solution mapping was identified. Cognitive strategies are specific experience-based guidelines identified in practices that appear helpful to good outcomes (Blank and Dorf 2012), and using these strategies has been shown to be highly advantageous in diverse settings (Riel 1996; Brown and Goslar 1986; Lawson 1979). Cognitive strategies in approaching design tasks have been developed into explicit design approaches that can be adopted by others (Lee et al. 2018c; Daly et al. 2012; Brown and Goslar 1986).

Beginning with these empirically-derived guidelines, we formulated a design tool to support engineers as they attempted solution mapping. The purpose of the tool is to promote divergent thinking by helping engineers consider multiple, diverse problem applications for a technology. The tool was designed to follow the process observed in successful engineering designers working with new technological solutions: (1) break down the technology into key characteristics; (2) identify enabling functions based on these characteristics; (3) search in multiple industry sectors; and (4) identify specific needs (Lee et al. 2020a; Lee 2019; Lee et al. 2019). While evident in expert solution mapping, no instruction on this alternative design process or instructional strategies yet exists.

To implement the tool, we created a solution mapping process within a single design session. Given a technology, the engineers are guided through a sequence of steps where they analyse the technology's key characteristics as enabling functions. Then, they consider a list of industry sectors in order to survey a broad range of problem application areas. Finally, they propose multiple problems where the technology may be of use. The Solution Mapping Design Tool resulted from a series of pilot tests designed to ensure it was easy to understand and apply to novel technologies. It was also considered through several different technologies to ensure the tool's language was suitably independent of a specific technology.

In the study, we compared the impact of the use of the Solution Mapping Design Tool to two control groups. One group was provided only the list of industry sectors also used in the tool. This comparison would allow us to determine whether the information about sectors was sufficient to motivate problem discovery apart from the tool. The true control group completed the same solution mapping task without any assistance.

3. Method

In this study, our research aimed to test the Solution Mapping Design Tool developed from studies of engineers' solution mapping cognitive strategies (Lee et al. 2020a; Lee 2019; Lee et al. 2019) to examine its effects on supporting divergent thinking in the search for problem applications. The present study explored the following research questions:

1. Are there differences in the quantity of applications identified by engineering students using the Solution Mapping Design Tool compared to other information instruction or no instruction?
2. How does the Solution Mapping Design Tool impact the diversity of identified applications?

3.1. Materials

The Solution Mapping Design Tool was developed from a study of 19 engineering professionals (Lee et al. 2020a; Lee 2019; Lee et al. 2019) who developed novel technologies and then, identified one or more problem applications in a wide variety of industry sectors, including energy, biotechnology, aerospace, manufacturing, and materials. To develop the tool, a graduate student trained in qualitative research methods conducted semi-structured interviews with engineering professionals that aimed to identify cognitive strategies used to find problem applications for technologies. The engineering professionals had experience being successful at developing novel technologies and identifying problem applications, with success defined as developing commercial products or receiving external funding for commercialisation. The semi-structured interviews were designed to examine specific patterns identified across individuals performing solution mapping.

The semi-structured interview data revealed cognitive strategies in solution mapping and a sub-set of the cognitive strategies was translated into a two-part design tool. The first part of the tool provides scaffolding for exploring the technology (as shown in Figure 1). The tool worksheet guides students in (1) identifying key characteristics of a technology, (2) examining its enabling functions, (3) identifying areas for potential use, and (4) designing specific applications of a technology. The second part of the tool includes industry information in the form of a page of listing industry sectors from the North American Industry Classification System (as shown in Appendix A1). This two-part design tool was pilot-tested with 15 engineering students and we iterated on its design multiple times to ensure clarity and usability. The pilot test participants received $25 for approximately 1.5 h of their time. The pilot tests prompted additional iterations of the solution mapping tool to ensure clarity for the users. Thus, the results from the pilot tests were not included in the data analysis as the tool itself was modified after the initial testing.

3.2. Data collection

Data collection proceeded through four major stages as represented in Figure 2.

Students were recruited by email to participate in a single experimental session of approximately 1.5 h through engineering department listservs at a large Midwestern university. A total of 93 engineering students (54 male and 39 female; 68 advanced undergraduate and 25 graduate level; and 63 in mechanical engineering and 30 in non-mechanical (e.g. biomechanical engineering)) participated in the study. All participants received $25 as compensation for their participation.

Students were assigned at random to one of three group sessions: (1) a control group, where no additional information was provided ($N = 32$); (2) a second control group where only a list of Industry Sectors was provided (Appendix A1; $N = 28$), and (3) a Solution Mapping Design Tool group that was given both the list of Industry Sectors and scaffolding to guide the solution mapping process ($N = 33$). These groups were roughly proportional to the demographics of the group as a whole.

The students were directed to work individually to 'identify diverse problem applications for a new technology and to generate as many problem applications as possible' in 60 min. A graduate student with prior teaching experience conducted all the study sessions through a PowerPoint presentation for consistency. An introduction to solution mapping

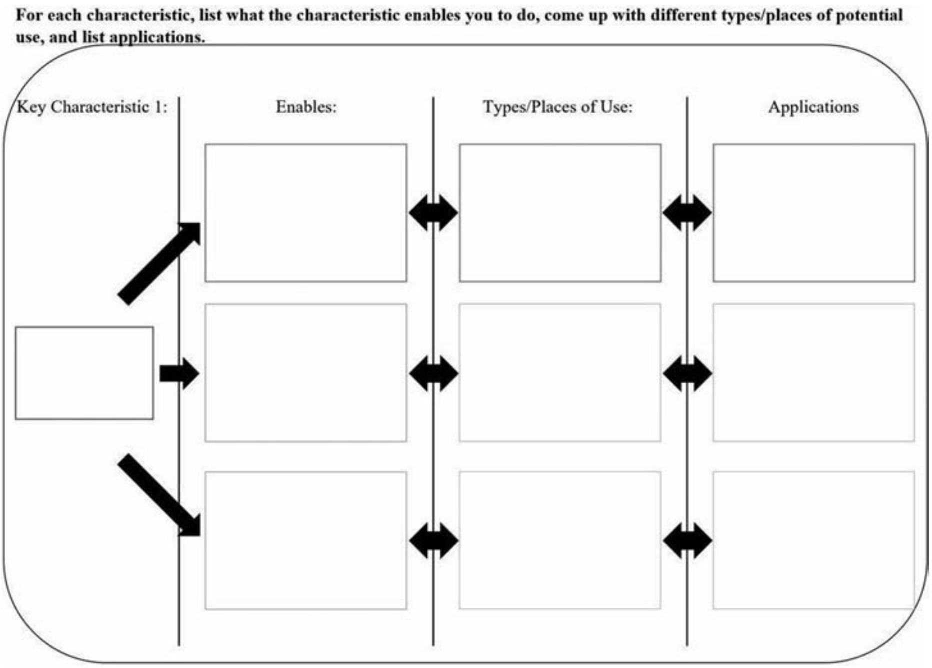


Figure 1. Solution Mapping Design Tool Part 1.

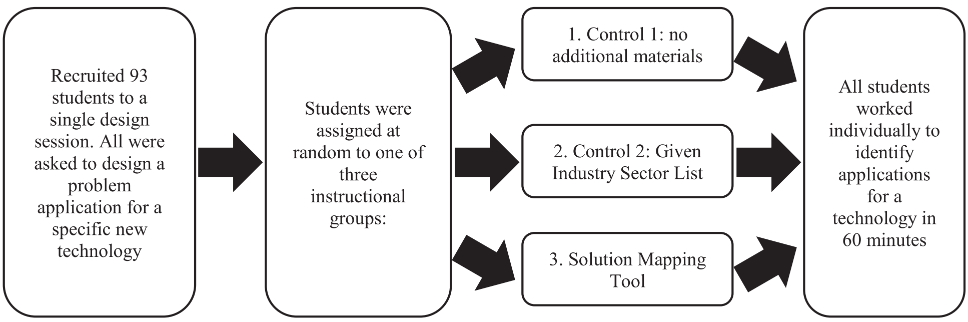


Figure 2. Data collection overview.

was presented for the first 5 min, and students had the opportunity to ask questions. All groups were then directed to identify potential problem applications for 'shape memory alloys.' This novel mechanical engineering technology was selected through a pretest to ensure its accessibility for undergraduate engineering students. This prompt was presented to all students in the study:

3.3. *Shape memory alloy*

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

Identify potential applications of shape memory alloys.

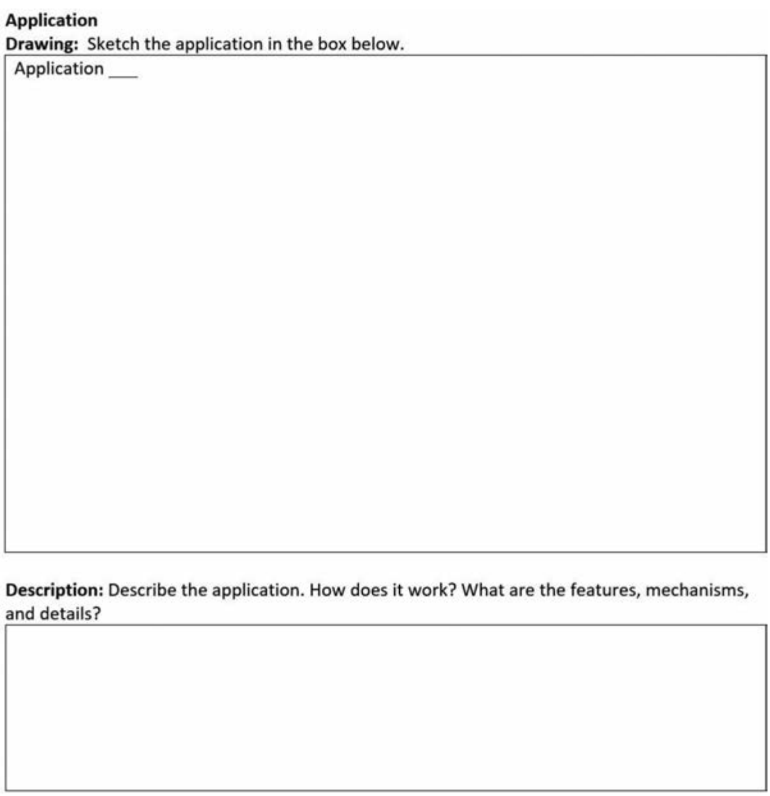
Please spend 1 h to complete this task.

Blank sheets were given to students to document the problem applications they generated, and students were prompted to both sketch and describe their problem applications (as shown in Figure 3). The design sheets were collected at the end for analysis.

3.4. Data analysis

Drawings from the design sheets were scanned and the associated written descriptions were transcribed. The size of the drawings was adjusted to be similar for all designs to clearly present them to the coders. An example of a student's sheet with a transcribed description is shown in Figure 4.

The analysis of each participant's collection of ideas focused on two criteria associated with divergent thinking in design (Daly et al. 2016; Navarro-Prieto et al. 1999) and creativity research (Guilford 1967; Kudrowitz and Wallace 2013; Amabile 1982): (1) fluency (total



Application
Drawing: Sketch the application in the box below.

Application ___

Description: Describe the application. How does it work? What are the features, mechanisms, and details?

Figure 3. Concept sheets for individual problem application ideas.

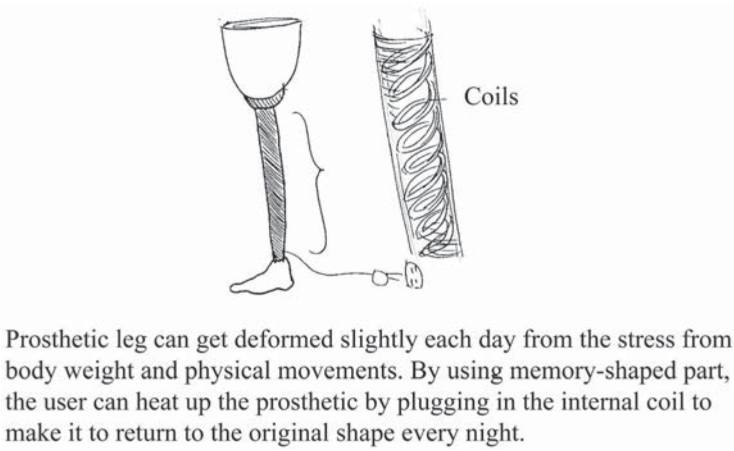


Figure 4. Example of a problem application with a design sketch and transcribed description.

quantity) and (2) flexibility (diversity of applications). To measure the quantity of ideas in a participant's set, we counted the total number of problem applications generated, indicated by the number of individual sheets they completed.

We measured the diversity of each student's collection of ideas using two means: (1) functions, and (2) industry sectors. We examined variations in *how* the shape memory alloys were used (functions) and *where* they were applied (industry sectors). The list of industry sectors was modified to serve as codes to identify variations in application areas (Appendix A2). In examining diversity, each problem application was labelled with only one function and industry sector. Researchers quantified the number of unique functions and industry sectors considered by each participant. The code list of functions was generated inductively through multiple iterations of three coders. For example, one student considered using the shape memory alloy to design an automobile body (as shown in Figure 5). If dented, it could be heated to remove the dent. This problem application function was categorised as 'motor vehicle and parts' industry and 'self-repair' function. The list of different functions for shape memory alloys generated during the analysis is shown in Appendix A3.

Two independent coders then categorised every application design for the industry sector and function. The percent agreement was 86% for industry sectors and 84% for functions, greater than the 70% level typically accepted for inter-rater reliability (Wilson et al. 1954). The researchers discussed all discrepancies until there was a consensus.

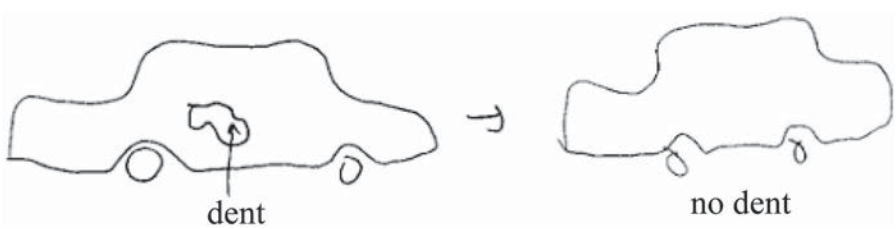


Figure 5. Example of an application of shape memory alloy that was categorised as 'motor vehicle and parts' industry and 'self-repair' function.

A one-way analysis of variance (ANOVA) compared the three instructional groups on the outcome measures of the quantity of application designs and diversity measures of industry sectors and functions considered. ANOVA is used to analyse the differences among group means in a sample (Osborne 2008). The assumption of homogeneity of variance was not violated and Tukey's honestly significant difference (HSD) post hoc test was used. Additionally, we analysed the effects of major (mechanical versus non-mechanical engineering students), gender (male versus female), and grade level (undergraduate versus graduate student) using Wilk's lambda tests in multivariate analysis of variance (MANOVA) on the outcome measures of the quantity of applications, industry sectors, and functions. MANOVA tests multiple dependent variables to examine the effects of the measured dependent variables (Girden 1992). We used the error rate of alpha $= 0.05$ for both ANOVA and MANOVA.

4. Results

As a check on our assumptions, we compared the results for students divided based on demographic groups. There were no significant differences in either the quantity or diversity measures when comparing mechanical and non-mechanical engineering students ($p = 0.109$), male and female students ($p = 0.787$), and advanced undergraduate and graduate students ($p = 0.183$), across all three groups. Thus, we present the results in the following subsections by tool condition (full Solution Mapping Design Tool, the control group with a list of industry sectors only, and the control group).

4.1. Quantity of applications

In total, 93 students generated 824 applications across all three conditions, with each participant generating between 3 and 15 applications. There were no significant differences in

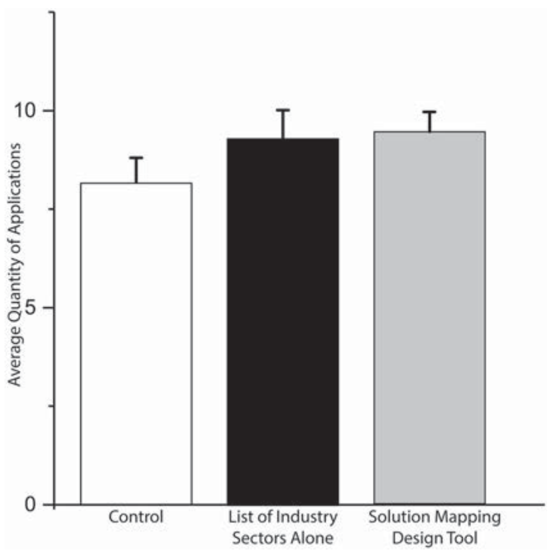


Figure 6. The average quantity of applications generated by the control group (left) compared to the list of industry sectors alone and Solution Mapping Design Tool groups.

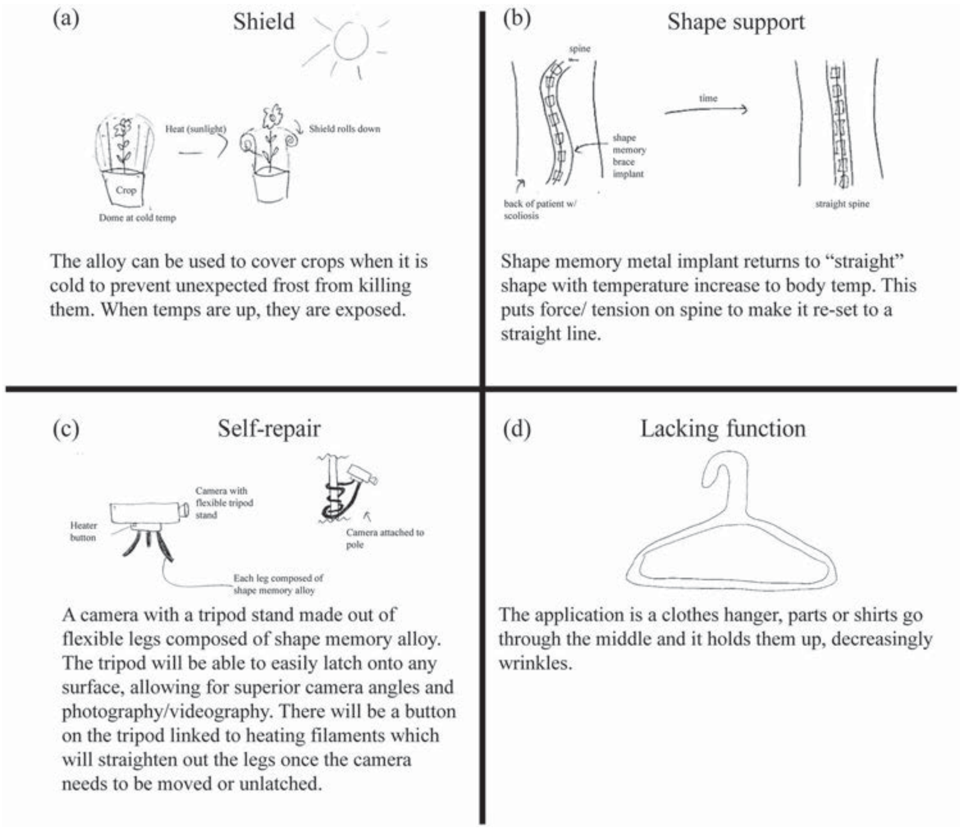


Figure 7. Examples of functional variation in students' shape alloy designs: (a) Shield function: An alloy dome covers crops in cold temperatures and opens when warm. (b) Shapesupport function: A spinal brace implant made of a shape memory alloy for treating scoliosis. (c) Self-repair function: An alloy is used for flexible tripod legs that can easily latch onto any surface and be removed by pressing a button to heat the alloy and change its shape. (d) Lacking function: A clothes hanger made of a shape memory alloy.

the quantity of applications generated among the groups. The Solution Mapping Design Tool group generated the most applications ($M = 9.33$), and the Industry Information group generated slightly fewer ($M = 9.21$). However, neither the Industry Information group ($p = 0.396$), nor the Solution Mapping Tool group ($p = 0.295$) were significantly different from the control group (see Figure 6).

4.2. Analysis of diversity: functions

Students' applications for shape memory alloys included diverse functional uses, as shown in Figure 7. For example, a 'shield' concept used a shape memory alloy to cover crops in cold weather and prevent unexpected loss from frosts (see Figure 7(a)). The shield could roll down at high temperatures to expose the crops to sunlight. Another student designed an alloy implant that returned to its original shape based on body temperature (see Figure 7(b)). This application, described as 'shape support,' may be used to straighten the spine of a patient with scoliosis. Another student created a design with an alloy as flexible tripod

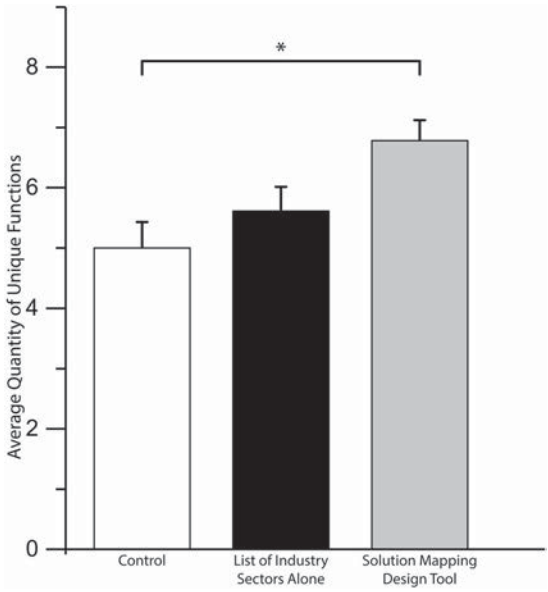


Figure 8. The average number of shape memory alloy functions considered by each participant in the control, Industry Information, and Solution Mapping Design Tool groups. $*p < 0.05$.

legs for a camera (see Figure 7(c)). The tripod can easily latch onto any surface, allowing for superior camera angles. A button on the tripod links to a heating element to straighten the legs or unlatch, as a 'self-repair' function. Some students did not indicate a specific function for the shape memory, and were coded as 'lacking function.' For example, this shape memory alloy as a clothes hanger (see Figure 7(d)) did not describe leveraging the unique characteristics of the alloy.

As shown in Figure 8, the three instructional groups differed in the number of different functions identified for the shape memory alloy. The Solution Mapping Design Tool group ($M = 6.76$) produced more diverse design functions than the control group ($M = 4.97$; $p = 0.004$) and Industry Information group ($M = 5.57$; $p = 0.098$). No significant difference was observed between the control and Industry Information groups ($p = 0.545$).

4.3. Analysis of diversity: industry sectors

Students generated a diverse set of industry sector applications for shape memory alloys in the study. An example of the industry sector 'shipping and storage equipment' uses a shape memory alloy to create durable crates for shipping that can be compressed for easy storage (Figure 9(a)). Another student generated an application to use a shape memory alloy as a pipe for oil extraction that closes shut, in case of accidents, labelled as 'oil and gas' industry (Figure 9(b)). A student proposed using a shape memory alloy as reusable wires for a chicken coop, which was labelled as 'agriculture and forestry support' (Figure 9(c)). Another student used a shape memory alloy as a switch for circuits with changing temperatures. However, since the student did not indicate where the switch will be used, we coded this as 'unspecified' industry (Figure 9(d)).

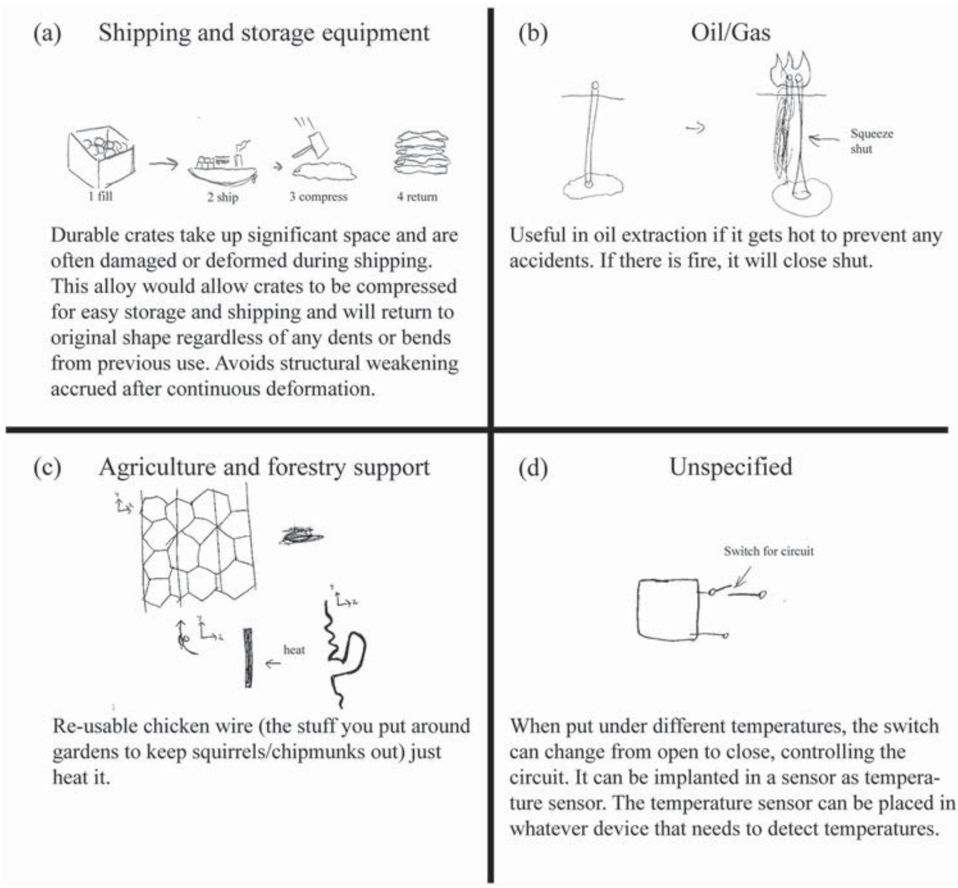


Figure 9. (a) Shipping and storage equipment – crates for shipping and storage. (b) Oil and gas – a pipe made of a shape memory alloy that can close, in case of fire. (c) Agriculture and forestry support – reusable chicken coop wires. (d) Unspecified – a switch for a circuit.

The control ($M = 6.19$) and Industry Information ($M = 7.11$) groups covered fewer industry sectors than the Solution Mapping Design Tool group ($M = 7.61$). This difference between control and Solution Mapping Design Tool groups was significant ($p = 0.039$). No significant difference was observed between control and Industry Information ($p = 0.274$) groups. Figure 10 summarises these results.

5. Discussion

The Solution Mapping Design Tool was shown to support divergent thinking in generating problem applications for a novel technology. Using the Solution Mapping Design Tool, engineering students were able to break down the technology into its key characteristics and enabling functions, allowing them to generate problem applications with more diverse functions and industry areas. Prior research has documented the benefits of using design tools to support divergent thinking during concept generation to increase diversity, and quantity of concepts considered (Daly et al. 2016; Hernandez et al. 2013; Lee et al. 2018c;

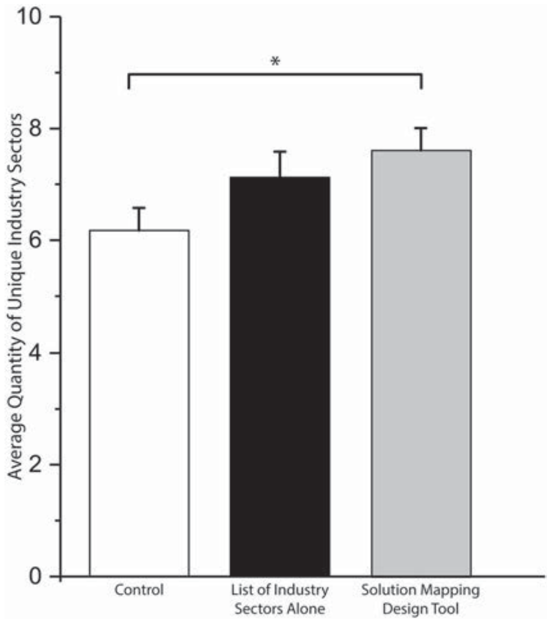


Figure 10. Average number of industry sectors considered by each participant in different groups. $* p < 0.05$

Lee et al. 2018d). This study is the first to examine the effectiveness of a design tool for solution mapping, and the findings support the conclusion that this new design tool provides scaffolding for students in considering diverse problem applications for a new technology.

The Solution Mapping Design Tool provided cognitive scaffolding beyond reminding students of industry sectors for application. We found that just providing information about the range of potential industrial sectors was not, by itself, beneficial. When provided with the list of industry sectors alone, engineering students did not generate as many diverse applications for the technology. The findings show that both information about industry areas and the scaffolding provided by the tool for solution mapping were required to generate more diverse mappings. Students who were given the complete Solution Mapping Design Tool, including the list of industry sectors, generated more diverse applications than when the industry sectors were provided alone. The Solution Mapping Design Tool appears to be helpful in guiding students through the technology analysis so that they can make use of the industry sector list provided. While previous research has demonstrated the benefits of cognitive strategies as tools to support design (Hernandez et al. 2013; Lee et al. 2018c; Altshuller 1997; Daly et al. 2012; Brown and Goslar 1986), our study documents the efficacy of leveraging cognitive strategies specifically to aid solution mapping processes.

The quantity of applications generated was similar across the three groups. One explanation is that the single session study provided a relatively short amount of time to work on solution mapping. Participants using the solution mapping tool may require additional time to learn to use it, resulting in less time to work on their designs. Comparing any instructional approach will tend to result in a reduced amount of time to work on designs compared to a control group. In addition, the one-session study may be affected by students' need to 'exhaust' their own initial ideas before using the provided tool, limiting the ability to detect the impact of its use (Chatfield and Collins 1981).

Overall, the engineering students in the study were able to generate more diverse applications for a novel technology using the Solution Mapping Design Tool compared to students given information about industry sectors or a control group. The Solution Mapping Design Tool was effective with minimal instruction even though the students had not encountered the solution mapping process in previous instruction or training. Students' ability to successfully perform solution mapping through the use of the tool within a single session suggests students can grasp the very different design process of solution mapping. The experience with alternative design processes may hold further benefits for engineering students in considering their potential as designers who can identify both new problem applications and new technology solutions, leading to more flexible design competencies.

5.1. Limitations

This study examined engineering students from a single large institution in the U.S., and findings in other educational settings may differ. The sample demographics were also limited, with fewer females and no information collected about ethnicity. Also, the study tested the Solution Mapping Design Tool using one example of new technology. Further studies are necessary to explore solution mapping with more technologies to determine how their qualities may impact the effectiveness of the solution mapping tool. Another limitation is that the quality and feasibility of problem applications were not assessed in this study. Because our aim was to assess divergent thinking, we measured whether students considered multiple, diverse concepts rather than evaluating their feasibility, as in concept generation (Linsey et al. 2012). For our study of solution mapping, we examined solution mapping in a single design session focusing on the early phases of conceptual design. With longer sessions, more information about feasibility may be available for future studies.

In our single-session study, students were asked to work individually to generate problem applications for a technology without the use of outside resources. The design session in our study may differ from practice settings in work contexts such as group design. In practice, engineers likely spend extended periods working to identify problem applications for their technologies, often have opportunities to consult with others, including stakeholders, and access resources and work in teams to accomplish solution mapping. Additional studies are needed to examine how the Solution Mapping Design Tool can support engineers in design practice.

5.2. Implications

The Solution Mapping Design Tool was developed from studies of engineering professionals' successful design practices when performing solution mapping; that is, working from a discovered technology towards an application problem through divergent thinking. Because instruction on solution mapping is limited in existing engineering curricula, engineering students are underprepared to engage in a solution mapping process. The cognitive strategies for solution mapping embodied in the tool were useful in supporting engineering students in divergent thinking about problem applications, and may provide key information for lessons or learning modules on solution mapping.

We anticipate that solution mapping can be taught within engineering design courses, from the first year to senior capstone courses, in a relatively short amount of time. Participants in this study learned and applied solution mapping within a single session, requiring minimal instruction. A proposed lesson plan might include a short introduction on what solution mapping is, a description of how the Solution Mapping Design Tool was developed from empirical findings, and practice using the tool with a novel technology.

The Solution Mapping Design Tool may also be useful for engineering practitioners as they seek to identify multiple or alternative problem applications for a known technology or for technologies developed with other problem applications. In previous studies, engineering designers described the considerable difficulty in navigating the 'backward' task of starting with a novel solution and searching for potential application problems across domains. The importance of divergent thinking was illustrated in every solution mapping experience 'in the wild.' For each engineer, the process of solution mapping was a new design process with limited available support. However, our findings suggest the Solution Mapping Design Tool could be used to support engineering practitioners when the need for solution mapping arises. Rather than struggle to diversify their search on their own, the Solution Mapping Design Tool provides scaffolding and training, such as in workshops with other engineering designers, which may help them succeed.

Further, the tool may prompt engineering practitioners to maximise their divergence in thinking about unique applications, and expand their search to differing uses for their technology. By encouraging divergent thinking, the Solution Mapping Design Tool may help engineers more fully explore design spaces by prompting their consideration of more diverse options before pursuing selected problem applications. The experience gained by practice in solution mapping processes for multiple technology examples will be beneficial for engineers who are currently forced to struggle alone in the 'backward' process of solution-first design.

6. Conclusions

Design processes sometimes begin with a specific technology in hand and diverge to consider problems it may solve, a design process called *solution mapping* (Lee et al. 2020a; Lee 2019; Lee et al. 2019). However, it is difficult for engineers to identify potential problem applications for a technology, and limited support has been available to aid engineers in solution mapping. In this study, we tested a new design tool based on empirical evidence from successful engineering practitioners. The Solution Mapping Design Tool was shown to support engineering students in generating alternative applications through divergent thinking, leading to the identification of multiple problem applications for a given technology. Engaging in divergent thinking is important in generating diverse, non-obvious, and creative solutions in the early stages of design; in this study, we found that the same divergent thinking process is helpful when searching for problems. The Solution Mapping Design Tool supported design processes through two components: (1) an analysis scaffold to aid engineers in breaking down potential functions for a technology; and (2) a broad list of industry sectors to prompt consideration of a wide range of application areas. The findings show that combining these into the Solution Mapping Design Tool provides effective support for engineering students in considering diverse problem applications for a novel technology. Supporting solution mapping through the use of a cognitive tool may be especially important for student engineers as they learn an alternative design process in solution-first design (Gray et al. 2019).

Disclosure statement

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ORCID

Jin Woo Lee http://orcid.org/0000-0001-5387-1668

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Appendix

Table A1. List of industry sectors provided to two groups of engineering students.

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

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

UTILITIES
Utilities

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

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

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

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

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

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

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

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

PROFESSIONAL AND TECHNICAL SERVICES
Professional and technical services

MANAGEMENT OF COMPANIES AND ENTERPRISES
Management of companies and enterprises

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

EDUCATIONAL SERVICES
Educational services

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

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

ACCOMMODATION AND FOOD SERVICES
Accommodation
Food services and drinking places

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

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

Table A2. List of industry sectors considered by participants.

Industry sector	Description
Aerospace and parts	Parts for air and space travel.
Agriculture and forestry	Agriculture and forestry related helping to protect and maintain plants.
Pet/feed store supplies	Supplies found in pet and feed stores designed for the care of domesticated animals.
Arts and entertainment	Supplies that relate to art as entertainment and recreation.
Clothing/accessories	Common clothing items (also textiles) and jewellery.
Construction and building	Construction materials for new buildings, renovations, and small fix ups.
Dental	Applications specific to dental hygiene and maintenance.
Educational and demonstrational	Using the alloy for research and demonstrational classroom equipment.
Consumer electronics and parts	Consumer electronics and any parts inside, that attaches to, or modifies, or protects, or enhances electronics.
Encryption	Non-visible data protection used as a security feature.
Energy	Applications that produce or maintain energy (as in utilities).
Medical	Medical applications used inside or outside the body to protect, align, or strengthen a specific body part.
Fire Security	Helping to detect and suppress or provide escape from fire.
Food and Bev	Produces objects that stores or comes into contact with food and/or drinks
Furniture	Furniture that can be found in a home or office
Manufacturing parts	Parts found in the assembly of products, molds/casts, levers, etc.
Locksmith industry	Installation of mechanical locks and doors and safes for everyday use.
Motor vehicle and parts	Produce parts for the assembly of, safety of, and repair of automobiles
Office Supplies	Supplies found in and around the office.
Oil and Gas	Used in the extraction and movement of oil and gas.
Sports/Recreation	Equipment for sports and other outdoor recreation activities.
Shipping and storing	Meant to store or transport products.
Unspecified	Application had no specific industry.
Waste and recycling	Having to do with the waste and recycling processes.
Weapons/Defense	With intent to harm others or defend oneself from the harm of others, i.e. military applications.
Railroad and parts	Parts for the assembly of, safety of, and repair of railroads
Nautical and parts	Parts for the assembly of, safety of, and repair of nautical vessels

Table A3. List of functions considered for shape memory alloy use.

Function	Description
Binding	The function of the alloy is to bring items together via adhering or coupling.
Customising	The alloy is used for personalisation and one form is more useful to one individual.
Decorating	The alloy is used to create a ornament/decoration for the home.
Demonstrating	The alloy is used for teaching, educating, prototyping, and modelling.
Fitting into a small space	The alloy is used to be placed into a tight area then shaped
Indicating	When the alloy is 'activated,' there is a state change to indicated activation
Lacking function	The description and/or application's purpose was unclear
Existing as multiple states	The alloy is used as multiple states and one state is not more useful than others
Patching to cover a hole	The alloy is used to patch or cover a hole.
Protecting from non-natural/expected forces	The application is used as protection in situations where impact is expected.
Restoring back to desired state	The alloy will be restored back to its original shape
Reusing/recycling for other purposes	The alloy can be shaped and reused/recycled for other purposes.
Self-repairing	The alloy will go back to its original state due to natural heating (ie heat from the sun)
Sensing (binary fashion ie. on/off)	When the alloy is activated it simply indicates a change.
Supporting shape to resist forces	The alloy is used to align or resist external forces helping the object to keep its natural optimised shape.
Shielding the user	The alloy shields the user from forces seen in natural world such as hail, fire, lava.
Optimising to fit into storage space	The alloy allows for folding, bending, condensing of the object to maximise space utilisation.
Strengthen the object with the alloy	The alloy is used to make an object physically stronger.
Switching from one state to another	When the alloy is 'activated,' it causes a change (affects its surroundings not just itself)
Weighing an object down	The alloy is used to make an object physically heavier.
Utilising material properties	The alloy is used to for the intended purpose of the object (i.e. a screwdriver to move a screw)
Energy storing	The alloy stores potential energy in its shape and releases with the temperature change.