Tackling the 'right' problem: Investigating cognitive strategies used in understanding design problems

by

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DEDICATION

I would like to dedicate this thesis to my parents for all their love and support and for teaching me the importance of nourishing your mind, body, and soul and to never give up on the things you're passionate about, no matter how hard it may seem.

I would also like thank my brother, Jorden, for pointing me in the right direction of pursuing my Master's degree at Iowa State University, my boyfriend, Adam, for being my rock and providing me with the motivation I needed to finish strong, and the rest of my friends and family, for always being the most supportive people in the room.

TABLE OF CONTENTS

Page

LIST OF FIGURES v

LIST OF TABLES vi

ACKNOWLEDGMENTS vii

ABSTRACT viii

CHAPTER 1. INTRODUCTION 1

- Problem Exploration in Engineering Design 2
- Heuristic Use in Engineering Design 5
- Research Motivation 7
- Thesis Structure 8
- References 9

CHAPTER 2. INVESTIGATING THE USE OF COGNITIVE HEURISTICS IN THE EXPLORATION OF ENGINEERING DESIGN PROBLEMS 13

- Abstract 13
- Introduction 13
- Methods 20
- Results 29
- Discussion 43
- Conclusion 47
- References 47

CHAPTER 3. CASE STUDIES OF PROBLEM EXPLORATION PROCESSES IN ENGINEERING DESIGN 51

- Abstract 51
- Introduction 51
- Background 52
- Existing Strategies for Problem Exploration 55
- Problem Exploration Heuristics 57
- Research Questions 58
- Research Methods 59
- Results 64
- Discussion 86
- Conclusions 91
- References 92

CHAPTER 4. CONCLUSIONS 96

Illustration of Problem Exploration Heuristics Use 98
Limitations and Recommendations for Future Work 101
References 103

APPENDIX A. IRB APPROVAL 104

APPENDIX B. PROBLEM EXPLORATION HEURISTICS 105

APPENDIX C. INFORMED CONSENT DOCUMENT 110

LIST OF FIGURES

Page

Figure 1 Synthesized definitions of problem finding, problem framing, and problem defining 15

Figure 2 Illustration of the Problem Exploration Heuristic Extraction Method....... 24

Figure 3 Demonstration of how the designer used the heuristic Break down the desired goal 33

Figure 4 Demonstration of how the designer appeared to use the heuristic Expand the primary stakeholder group 35

Figure 5 Demonstration of how the designer used the heuristic Find the root cause 36

Figure 6 Illustrations of (a) final solution generated from the interpreted problem statement discussed and (b) other solutions generated from the same presented problem 37

Figure 7 Demonstration of how the designer used the heuristic Define the characteristics of the setting 39

Figure 8 Demonstration of how the designer used the heuristic Describe the brand values 40

Figure 9 Demonstration of how the designer appeared to use the heuristic Describe an existing solution to use as conceptual inspiration 41

Figure 10 Illustrations of (a) final solution generated from the interpreted problem statement discussed and (b) other solutions generated from the same presented problem 42

Figure 11 Depiction of the role of problem framing in limiting or opening areas of the solution space 55

Figure 12 Illustration of the heuristic extraction process used in analyzing the data 63

Figure 13 Illustration of Problem Exploration Heuristics applied to a design problem 99

Figure 14 Protocol of Problem Exploration Heuristics application and the generation of a solution 100

LIST OF TABLES

Page

Table 1 Existing problem exploration techniques 17

Table 2 Summary of Problem Sources 21

Table 3 Application of Problem Exploration Heuristic Extraction Method using an example problem 24

Table 4 Problem exploration heuristics identified from the first 36 problems 27

Table 5 Problem exploration heuristics identified in the problem analysis of the entire set of 218 engineering design problems 30

Table 6 Synthesized definitions of problem finding, problem framing, and problem defining 54

Table 7 Descriptions of existing problem exploration strategies 56

Table 8 Participant Demographics 60

Table 9 Retrospective Interview Questions 62

Table 10 Summary of Procedure 62

Table 11 Engineer 1 Problem Statement 1 66

Table 12 Engineer 1 Problem Statement 2 67

Table 13 Engineer 1 Problem Statement 3 68

Table 14 Engineer 1 Problem Statement 4 69

Table 15 Engineer 1 Problem Statement 5 69

Table 16 Engineer 1 Problem Statement 6 70

Table 17 Engineer 2 Concepts, Interpreted Problems, and Heuristics 72

Table 18 Engineer 3 Concepts, Interpreted Problems, and Heuristics 76

Table 19 Engineer 4 Concepts, Interpreted Problems, and Heuristics 80

Table 20 Engineer 5 Concepts, Interpreted Problems, and Heuristics 83

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ABSTRACT

Looking beyond the provided or presented problem can allow new perspectives to emerge, revealing the potential for more varied and creative solutions. Current engineering and design research has primarily focused on the generation of ideas, and little research has investigated how engineering designers engage in identifying and refining problem definitions, a process called “problem exploration.” Past research has established that knowledge about how to perform problem exploration is important for improving our understanding of how presented problems turn into successful design solutions. However, existing problem exploration methods are not based on learning theory, and there is little empirical evidence about their effectiveness in education or practice. Therefore, the goal of this research is to investigate how engineering and industrial design students and practitioners explore problem spaces. The results characterize the cognitive strategies evident in finding, developing, and refining design problems.

This paper presents the results of two studies on the cognitive processes engineers and designers use to explore and define problems. Overall, the results demonstrated that problem exploration is associated with making shifts in design decisions. The first study focused on problem exploration strategies used by engineering and design practitioners through a content analysis of problem statements from web-based design competitions calling for novel solutions. The analysis resulted in an initial set of problem exploration strategies, or cognitive heuristics, extracted from the submitted solutions. The results also demonstrated that a single presented problem can be redefined by designers in a number of different ways. The second study examined individual cognitive processes through a think-aloud protocol study of five engineering design students (senior and graduate level) as they explored presented problems. The results of this study provided a more in-depth look at the problem exploration process, and

demonstrated that while common problem exploration heuristics emerged, each engineer displayed a distinct way of looking at the problem.

These results will support the development of instructional materials for dissemination in both educational and practice settings in order to assist students, educators, and practitioners in their problem exploration processes. The project findings will help to better prepare designers and engineers to develop problem descriptions that represent core needs, and to frame them in ways that facilitate innovative solutions, ultimately resulting in solutions that address the real problems of the 21st Century.

CHAPTER 1. INTRODUCTION

In today's world, the success and perhaps even survival of individuals, companies, and nations as a whole rests on the ability to think and act creatively and innovatively[1]. Creativity has been defined as the ability to produce new and unique ideas by looking at things from a different perspective, while innovation is the implementation of that creativity[2,3]. In engineering, innovation is the execution of a new idea in a tangible way through introducing process, system, or product solutions. Today, the value that creativity and innovation offer within engineering is their ability to facilitate the development of novel and effective solutions despite the increasing complexity of problems and the rapidly changing nature of technology[4].

The majority of new problems are characterized by novelty – new needs demand new solutions – and cannot be solved by replication[5]. For example, combatting climate requires fulfilling the world's energy needs through innovative technology; replicating an existing solution, such as burning coal, will not suffice. Creativity and innovation by engineers is an absolute requirement in order to generate novel solutions to challenging problems[5]. Despite this call for innovation, engineering education appears to lag behind in addressing creativity and innovation; according to Cropley, this stems from a resistance to change, overspecialization, and lack of knowledge about how to teach creativity and innovation in the engineering classroom[5]. Engineering instructional programs instead emphasize understanding narrow and deep technical specifications, and teach students to solve well-defined problems with convergent, analytical solutions. As a result, students receive little or no exposure to ill-defined problems, where the exact nature of the presented problem, solution paths, or expected solutions are unknown[6]. An ill-defined problem does not reduce to previously recognized methods; instead, creativity is required to identify potential solution paths using divergent thinking, invention, and other skills[5]. Traditional engineering problem solving methods have also been shown to be less efficient in arriving at "optimal" solutions[7] for more multifaceted problems, such as those encountered in practice.

Engineering practice shows evidence of this gap between traditional problem solving and the need for creative and innovative solutions to challenging problems[8,9]. A study conducted by Lyles and Mitroff found that the majority of engineering managers simply apply processes suited for well-defined problems to ill-defined problems[10]. When problems on the job require more creative problem-solving skills, engineers often fall back to traditional solution procedures not appropriate to the problem[10]. Creative skills are especially important when a problem is ill-defined or unknown, as are the majority of problems faced in current engineering practice. But which creative skills are needed to address challenging, ill-defined problems, and to uncover innovative solutions?

Problem Exploration in Engineering Design

In 1938, Albert Einstein and Léopold Infeld published their book, the *Evolution of Physics*, and asserted that, "The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science"[11] (p. 92). In theoretical physics, the structuring of the problem may be the true challenge; however, is problem formulation as critical for design engineers? The Gestalt psychologists developed a general theory of problem solving where the first step in the creative process is to explore and understand the problem at hand[12]. By considering ill-defined problems more deeply, routes to innovative solutions may be uncovered. As Max Wertheimer stated,

> "The function of thinking is not just solving an actual problem but discovering, envisaging, going into deeper questions. Often, in great discoveries the most important thing is that a certain question is found. Envisaging, putting the productive question is often a more important, often a greater achievement than the solution of a set question." (p. 123)

But problems also differ in many important ways that are relevant to their solution. According to Getzels[13,14], there are ten common types of problems defined by characteristics such as whether the problem exists or is created, whether the problem is suggested by the solver or another and whether a known solution exists or must be devised. Well-defined or well-structured problems are traditionally used in instruction, so people are most familiar with them and can solve them using specific methods. This is likely because well-defined problems have a definitive or "convergent" solution, so are amenable to instructional testing for knowledge of specific concepts, methods, and skills[15]. However, many problems encountered by engineers today are ill-defined, with vague or unknown parameters for potential solutions[15,16]. Some of these ill-formulated problems are referred to as *wicked problems*[17,18], where the information is confusing, many clients and decision makers express conflicting values, and ramifications of actions within a system are challenging to predict[17].

The most significant characteristic of a wicked problem is there is no single, 'right' way to represent them, opening up alternatives for designers to think and act divergently. An engineer's creative skills are called upon to frame the problem in such a way as to remove, or minimize, the "wickedness," and define a problem that can be solved. Consider the problem, "How can we dispose of plastics?" Engineers have designed new recycling methods; however a creative reframing of the problem might be, "How do we make disposable plastics?" Solutions to this reframed problem include a new generation of biodegradable plastics. When the problem is explored and refined to a deeper, more causal understanding, more creative and innovative solutions follow. Innovation may occur through asking *different* questions beyond the ones presented[19]. Problem definitions circumscribe the set of possible solutions; as a result, problem exploration is crucial in order to search for innovative solutions outside of the overly-constrained set.

The significance of exploring the problem space has been apparent for a lot longer than most people are aware. In 1961, the *The Evolution of Physics* was published asserting that "the formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science"[11] (p. 92). According to Einstein, the structuring of the problem is the true challenge and if designers are to be good at the solving of problems, they must be good at the exploration of problems.

Several modern studies have identified the creation or reframing of a problem as a key practice in design and design thinking[20–23], as well as creative work in general[24,25]. Innovative solutions are more likely to result when designers are more explicit about the way a problem is viewed, and choose to either work deliberately within that frame or to seek out alternative frames[19,26,27]. A study conducted by Cross[28] found that successful and experienced designers are proactive in problem framing, actively imposing their own specific perspective onto the problem to direct their search for potential solutions. Csikszentmihalyi[29] defined this exploration as *problem finding*, and demonstrated its importance in a variety of outcome measures, including the quality of a single work of art, reputation of eventual art portfolios, and career art sales 18 years later. Christiaans[30] study of designers also found that the more time spent defining and understanding the problem, the more creative the result. Even in elementary students, Okuda et al.[31] found that interest in exploring and redefining problems was the single best predictor of real-world creative activities[32].

These studies support the claim that posing the "right" problem to solve may be a significant step in the creative process[33]. However, most engineering research and instruction has focused on strategies for solving problems, rather than on ways to explore new problems or reframe existing ones[34]. To create innovation in engineering, we need to better understand the problem exploration process, and how expert engineers explore problems and find innovative solutions. By increasing our knowledge of how practitioners generate truly innovative designs, we can apply this knowledge to address the gaps in learning to innovate within engineering education. By understanding what advanced engineers have learned to do to explore problems, educators will be in a better position to develop ways to help beginning engineers develop more expert-like skills. Consequently, the present study focuses on the state of problem exploration skills in both engineering classrooms and industry settings.

Heuristic Use in Engineering Design

Formal approaches to solving well-structured problems begin with development of a theoretical search space including all possible operations (moves toward a goal) in all possible orders; then, this space is systematically searched until a solution is uncovered[35]. Ill-structured problems cannot be addressed in this way, since it is impossible to identify the solution search space for these problems[6]. Most design problems in engineering require novel solution paths because the search space cannot be constrained to specific, known "operators" moving toward solutions. With ill-defined problems, an exhaustive search for all possible pathways to solutions is, by definition, impossible[36].

This characterization of an (artificially) intelligent search process diverges from the observations of human reasoners at every level of expertise[35]. Human problem solvers solve problems through the use of "heuristic" strategies, or short cuts to solutions that do not guarantee the (or any) solution. The term "cognitive heuristic" refers to shortcuts in processing that people use in complex problem solving[37]. For example, the availability heuristic can be used to conclude that air travel is more dangerous than driving in a car because examples of publicized crashes come more easily to mind, and so are judged to be more frequent[38]. The heuristic in this case – the estimation of frequency of occurrence by determining how readily it comes to mind – is a default reasoning strategy seen in decision making that may sometimes lead to poor decisions[38].

In some circumstances, the use of heuristics may be harmful, as in the case of biases introduced by heuristics[39] (e.g. availability bias[38], representativeness heuristic[40]); however, heuristics exist because people find they provide a fast, easy guide to decisions that are often "good enough," and highly advantageous in most settings[41–43]. Many disciplines have identified specific domain heuristics comprising expertise, including mathematical problem-solving[44], education[45], artificial intelligence[46], user interface design[47], design for behavior change[48], cooperation in groups[49], behavioral economics[50,51], and decision research[52,53]. From a design perspective, where ill-defined problems are prevalent, the use of heuristics can prove valuable. Behavioral research shows that experts utilize heuristics effectively, and suggests that heavy use of heuristics by experts distinguishes them from novices[54]. Some research even suggests that heuristics can sometimes lead to optimal solutions when they focus on key variables in the problem space[55].

Previous research on engineering design has successfully utilized the theoretical framework of cognitive heuristics to identify "Design Heuristics" for idea generation[56–62]. Research on Design Heuristics shows that they help designers push past the initial, obvious solutions that come to mind and to generate more innovative solutions. This paper seeks to apply the same theoretical framework of "cognitive heuristics" to the process of problem exploration. How do expert designers use cognitive heuristics to explore and refine problems? Examining how engineers change problems to facilitate their solution may lead to the discovery of novel ways of approaching problems, and as a result, discovering innovative solutions may become more likely. If specific heuristics for exploring problems can be identified, they may assist current and future engineers in developing the necessary creative skills for finding and exploring problems, leading to innovative solutions.

Research Motivation

To summarize, because creativity and innovation are critical in design engineering, greater attention to the problem exploration process is required to identify specific strategies. Learning how expert designers explore problems will allow the identification of methods to improve these skills, and would benefit the field of engineering design. However, there is a lack of empirical studies investigating specific methods for framing and redefining design problems[63]. Some texts and popular books offer techniques, but they are not derived from empirical studies of engineering practice, nor is their effectiveness empirically validated. In addition, there is no evidence that the introduction of these methods successfully impacts problem exploration, or increases the likelihood of creating innovative solutions.

To address these gaps, the purpose of this research is to identify and document problem exploration as performed by expert and novice design engineers. The goal is to identify a set of empirically-based, cognitive heuristics to help find, develop, and refine design problems. By studying how engineers explore ill-defined problems, the impact of the problem exploration process on solutions can be appreciated. This paper reports the results of two separate empirical studies of problem exploration heuristics guided by the following research questions:

Q1. How do engineering students and practitioners explore and develop problems?

Q2. What are the common heuristics used in structuring design problems requiring innovative solutions?

Thesis Structure

To address these research questions, data was collected from two sources: (1) content analysis of existing design problems and solutions (Chapter 2); and (2) interviews and protocol studies with engineering students in classroom settings (Chapter 3). Specifically, Chapter 2 elaborates on the problem exploration processes of practitioners, and identifies an initial set of problem exploration heuristics that can be used to enhance one's ability to find, frame, and define a problem in order to generate novel solutions. Chapter 3 illustrates the problem exploration processes of five engineering students at the senior and graduate levels.

Both chapters contain an extensive literature review of research on problem exploration, including common definitions, importance, and existing strategies. Finally, Chapter 4 summarizes the conclusions drawn from the thesis, and details plans for future work. References for each chapter's contents are provided at the end of each chapter. Appendix A includes the IRB approval forms for the research studies reported in this thesis, Appendix B displays the full list of problem exploration heuristics extracted from the study in Chapter 2, and Appendix C contains the informed consent document provided to each participant for the study detailed in Chapter 3.

References

1. Badran I. Enhancing creativity and innovation in engineering education. *Eur J Eng Educ*. 2007;32(5):573-585. doi:10.1080/03043790701433061.
2. Mumford MD, Gustafson SB. Creativity syndrome: Integration, application, and innovation. *Psychol Bull*. 1988;103(1):27-43. doi:10.1037/0033-2909.103.1.27.
3. Amabile TM, Collins MA, Conti R, Phillips E, Picariello M, Whitney D. Creativity in context: Update to the psychology of creativity. *High Abil Stud*. 1996;2:100-101.
4. Pappas E. Creative Problem Solving in Engineering Design. In: *ASEE SE Section Conference*. ; 2002.
5. Cropley DH. Promoting creativity and innovation in engineering education. *Psychol Aesthetics, Creat Arts*. 2015;9(2):161-171. doi:10.1037/aca0000008.
6. Simon HA. The structure of ill structured problems. *Artif Intell*. 1973;4:181-201.
7. Lumsdaine E, Lumsdaine M. Creative problem solving. *IEEE Potentials*. 1994;13(5):4-9.
8. Allender JS. A study of inquiry activity in elementary school children. *Am Educ Res J*. 1969;6:543-557.
9. Getzels JW, Smilansky J. Individual differences in pupil perceptions of school problems. *Br J Educ Psychol*. 1983;531:307-316.
10. Lyles MA, Mitroff I. Organizational problem formulation: An empirical study. *Adm Sci Q*. 1980:102-119.
11. Einstein A, Infeld L. *The Evolution of Physics*. New York: Simon and Schuster; 1961.
12. Duncker K. On problem solving. *Psychol Monogr*. 1945;58:270. doi:10.1037/h0093599.
13. Getzels JW. Creative thinking, problem solving, and instruction. In: *Ernest R. Hilgard (Ed.), Theories of Learning and Instruction: The Sixty-Third Yearbook of the National Society for the Study of Education*. Chicago: University of Chicago Press; 1964:240.
14. Getzels JW. The problem of the problem. In: *R. Hogarth (Ed.), Question Framing and*

Response Consistency. San Francisco: Jossey-Bass; 1982:37.
15. Jonassen D. Instructional design models for well-structured and ill-structured problem-solving learning outcomes. *Educ Technol Res Dev*. 1997;45(1):65-94.
16. Hill A, Smith H. Practice meets theory in technology education: A case of authentic learning in the high school setting. *J Technol Educ*. 1998;9(2):29-45.
17. Rittel HWJ, Webber MM. Dilemmas in a General Theory of Planning Dilemmas in a General Theory of Planning. *Policy Sci*. 1973;4(2):155-169. doi:10.1007/BF01405730.
18. Buchanan R. Wicked problems in design thinking. *Des Issues*. 1992;8(2):5-21.
19. Csikszentmihalyi M, Getzels JW. Discovery-oriented behavior and the originality of creative products: a study with artists. *J Pers Soc Psychol*. 1971;19(1):47-52. doi:10.1037/h0031106.
20. Beckman S, Barry M. Framing and Re-Framing: Core Skills for a Problem-Filled World. *Rotman Mag*. 2015;(Winter):67-71. doi:10.1017/CBO9781107415324.004.
21. Dorst K. The core of "design thinking" and its application. *Des Stud*. 2011;32(6):521-532. doi:10.1016/j.destud.2011.07.006.
22. Drews C. Unleashing the full potential of design thinking as a business method. *Des Manag Rev*. 2009;20(3):39-44.
23. Paton B, Dorst K. Briefing and reframing. In: *DTRS8 Interpreting Design Thinking - Symposium Proceedings*. Sydney, Austrailia; 2010:317-336.
24. Hargadon AB, Bechky BA. When collections of creatives become creative collectives: a field study of problem solving at work. *Organ Sci*. 2006;17(4):484-500.
25. Schank R, Abelson RP. *Scripts, Plans, Goals, and Understanding: An Inquiry into Human Knowledge Structures*. Hillsdale, NJ: Lawrence Erlbaum; 1977.
26. Ecker DW. The artistic process as qualitative problem solving. *J Aesthet Art Crit*. 1963;31(3):283-290.
27. Dewey J. *How We Think*. Boston: D.C. Heath and Co.; 1910.
28. Cross N. Expertise in design: an overview. *Des Stud*. 2004;25(5):427-441.
29. Csikszentmihalyi M. The domain of creativity. In: Runco MA, ed. *Theories of Creativity*. Newbury Park, CA: Sage; 1990:190-212.
30. Christiaans H. Creativity in design. In: Technical University of Delft, Delft, Netherlands; 1992.
31. Okuda SM, Runco MA, Berger DE. Creativity and the finding and solving of real-world problems. *J Psychoeduc Assess*. 1991;9(March):45-53. doi:10.1177/073428299100900104.
32. Mumford MD, Reiter-Palmon R, Redmond MR. Problem construction and cognition: Applying problem representations in ill-defined domains. In: *Problem Finding, Problem Solving, and Creativity*. ; 1994:3-39.
33. Getzels JW, Csikszentmihalyi M. *The Creative Vision: A Longitudinal Study of Problem Finding in Art*. New York: Wiley; 1976.
34. Fogler SH, LeBlanc SE. *Strategies for Creative Problem Solving*. Massachusetts, USA: Pearson Education, Inc.; 2008.
35. Newell A, Simon HA. *Human Problem Solving*. Englewood, NJ: Prentice-Hall; 1972.
36. Simon HA. Problem forming, problem finding and problem solving in design. In: Collen A, Gasparski WW, eds. *Design and Systems: General Applications of Methodology*. ; 1995:245-257.
37. Nisbett RE, Ross L. *Human Inference: Strategies and Shortcomings of Social*

Judgment.; 1980. doi:10.1080/09658210244000603.

38. Tversky A, Kahneman D. The framing of decisions and the psychology of choice. *Science (80-)*. 1981;211(4481):453-458. doi:10.1126/science.7455683.
39. Thaler RH, Sunstein CR. *Nudge: Improving Decisions about Health, Wealth, and Happiness*. New Haven, CT: Yale University Press; 2008.
40. Kahneman D, Tversky A. Subjective probability: A judgment of representativeness. *Cogn Psychol*. 1972;3(3):430-454.
41. Gilli M, Maringer D, Winker P. Applications of Heuristics in Finance. In: *Handbook on Information Technology in Finance*. ; 2008:635-653. doi:10.1007/978-3-540-49487-4_26.
42. Goslar MD. Decision support systems: advantages in consumer marketing settings. *J Consum Mark*. 1993;3(3):43-50.
43. Zhou R, Hansen EA. Space-efficient memory-based heuristics. In: *19th National Conference on Artificial Intelligence*. ; 2004.
44. Polya G. Polya ' s Problem Solving Techniques. In: *How To Solve It*. ; 1945:1-4.
45. Papert S. *Mindstorms: Children, Computers, and Powerful Ideas*. New York, NY: Basic Books; 1980.
46. Newell A. The heuristic of George Polya and its relation to artificial intelligence. In: R. Groner, M. Groner & WFB, ed. *Methods of Heuristics*. Hillsdale, NJ: Lawrence Erlbaum Associates; 1983:195-243.
47. Nielsen J. 10 usability heuristics for user interface design. *Nielsen Norman Gr*. 1995;1(1).
48. Lockton D, Harrison DJ, Cain R, Stanton NA, Jennings P. Exploring problem-framing through behavioural heuristics. *Int J Des*. 2013;7(1):37-53.
49. Gardner R, Ostrom E, Walker J. Social capital and cooperation: Communication, bounded rationality, and behavioral heuristics. In: *Proceedings of the 3rd Conference for the International Association for the Study of Common Property*. Bloomington, IN: International Association for the Study of Common Property; 1992.
50. Gilovich T, Griffin D, Kahneman D, eds. *Heuristics and Biases: The Psychology of Intuitive Judgement*. New York, NY: Cambridge University Press; 2002.
51. Tversky A, Kahneman D. Judgement under uncertainty: Heuristics and biases. *Science (80-)*. 1974;185:1124-1131.
52. Gigerenzer G, Selten R. Rethinking rationality. In: Gigerenzer G, Selten R, eds. *Bounded Rationality: The Adaptive Toolbox*. Cambridge, MA: MIT Press; 2001:1-12.
53. Gigerenzer G, Todd PM, ABC Research Group. *Simple Heuristics That Make Us Smart*. New York, NY: Oxford University Press; 1999.
54. Klein G. *Sources of Power: How People Make Decisions*. Vol 52.; 1999. doi:10.1061/(ASCE)1532-6748(2001)1:1(21).
55. Dijksterhuis A, Bos MW, Nordgren LF, van Baaren RB. On making the right choice: the deliberation-without-attention effect. *Science*. 2006;311(5763):1005-1007. doi:10.1126/science.1121629.
56. Christian JL, Daly SR, Yilmaz S, Seifert CM, Gonzalez R. Design Heuristics to Support Two Modes of Idea Generation: Initiating Ideas and Transitioning Among Concepts. In: *Annual Conference of American Society of Engineering Education*. San Antonio, Texas; 2012.

57. Daly SR, Christian JL, Yilmaz S, Seifert CM, Gonzalez R. Teaching Design Ideation. *Am Soc Eng Educ pp 01372-22 2011*. 2011:1322-1372.
58. Daly S, Christian JL. Assessing design heuristics for idea generation in an introductory engineering course. *Int J Eng Educ*. 2012;Vol. 28(2):1–11.
59. Daly SR, Yilmaz S, Christian JL, Seifert CM, Gonzalez R. Design heuristics in engineering concept generation. *J Eng Educ*. 2012;101(4):601-629. doi:10.1002/j.2168-9830.2012.tb01121.x.
60. Kramer J, Daly SR, Yilmaz S, Seifert CM. A case-study analysis of design heuristics in an upper-level cross-disciplinary design course. *ASEE Annu Conf Expo Conf Proc*. 2014.
61. Yilmaz S, Daly SR, Seifert CM, Gonzalez R. A comparison of cognitive heuristics use between engineers and industrial designers. *Des Comput Cogn '10*. 2011:3-22. doi:10.1007/978-94-007-0510-4_1.
62. Yilmaz S, Daly SR, Seifert CM, Gonzalez R. Comparison of design approaches between engineers and industrial designers. In: *International Conference on Engineering and Product Design Education*. Dublin, Ireland; 2013.
63. Runco MA. *Problem Finding, Problem Solving, and Creativity*. New Jersey: Ablex Publishing Corporation; 1994.

CHAPTER 2. INVESTIGATING THE USE OF COGNITIVE HEURISTICS IN THE EXPLORATION OF ENGINEERING DESIGN PROBLEMS

Modified from a paper to be submitted to *Design Studies*.

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Abstract

The way a design problem is structured influences the types of solutions that can be generated and may have an impact on the creativity and innovation of those solutions. Thus, this paper explores cognitive strategies used by professional engineers and designers to identify and reframe design problems. A sample of 218 problem descriptions were collected from various sources and analyzed to see how the problem definitions evolved during design. The analysis resulted in the extraction of 42 problem exploration heuristics evident in designers' re-crafting of the presented problem to inform the development of instructional materials to help improve the problem exploration skills of both engineering design students and practitioners.

Introduction

Engineering creativity and innovation are, on the whole, the core of any competitive, industrial, and ever-progressing economy.[1] Innovative engineering and design solutions are rooted in the generation of ideas, which are built and iterated upon throughout the design process.[2–4] However, these ideas are impacted by the way the design problem is presented. A

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problem that is defined with incorrect presumptions concerning needs and opportunities can result in significant monetary losses as well as problem solving ineffectiveness.[5–7] Since engineering design problems are intentionally open-ended, there is often incomplete information about the problem, even less information about the solution, and very limited, if any, information about how to transition from the current problem state to the final solution. This limited information means that engineering design problems require a great amount of structuring by the designer[8] in order to create opportunities for innovative solutions.

According to Karl Duncker,[9] the process of finding a solution is more accurately seen as a continual restructuring of the problem. He states that over time this problem restructuring can lead to the discovery of "essential" properties of the solution that will, in turn, help dictate an appropriate solution to the problem. Therefore, creativity and innovation require looking beyond the provided or presented problem in order to discover the "real" problem worth solving, a process we refer to as *problem exploration*. One way to encourage this type of innovation is to facilitate engineers and support designers in taking different perspectives on design problems, and then generating possible solutions based on those differing perspectives. Supporting problem exploration requires evaluating and understanding the cognitive processes that professional engineers and designers use to define unique problems.[10]

Problem exploration has been highly researched in the field of psychology, however, little empirical research has been conducted on problem exploration as it relates to engineering design and scholars have not come to consensus on a common definition. Several sources define problem exploration as a research phase involving such things as data collection,[11–13] feasibility studies,[14] and market research.[15] However, these sources do little to explain how to use the research collected to effectively explore the problem in order to generate innovative solutions. For this paper, we define problem exploration as the first stage of the design process prior to idea generation encompassing three distinct processes: *problem finding, problem framing,* and *problem defining*. The definitions of these processes, synthesized from prior research, are provided in Figure 1.

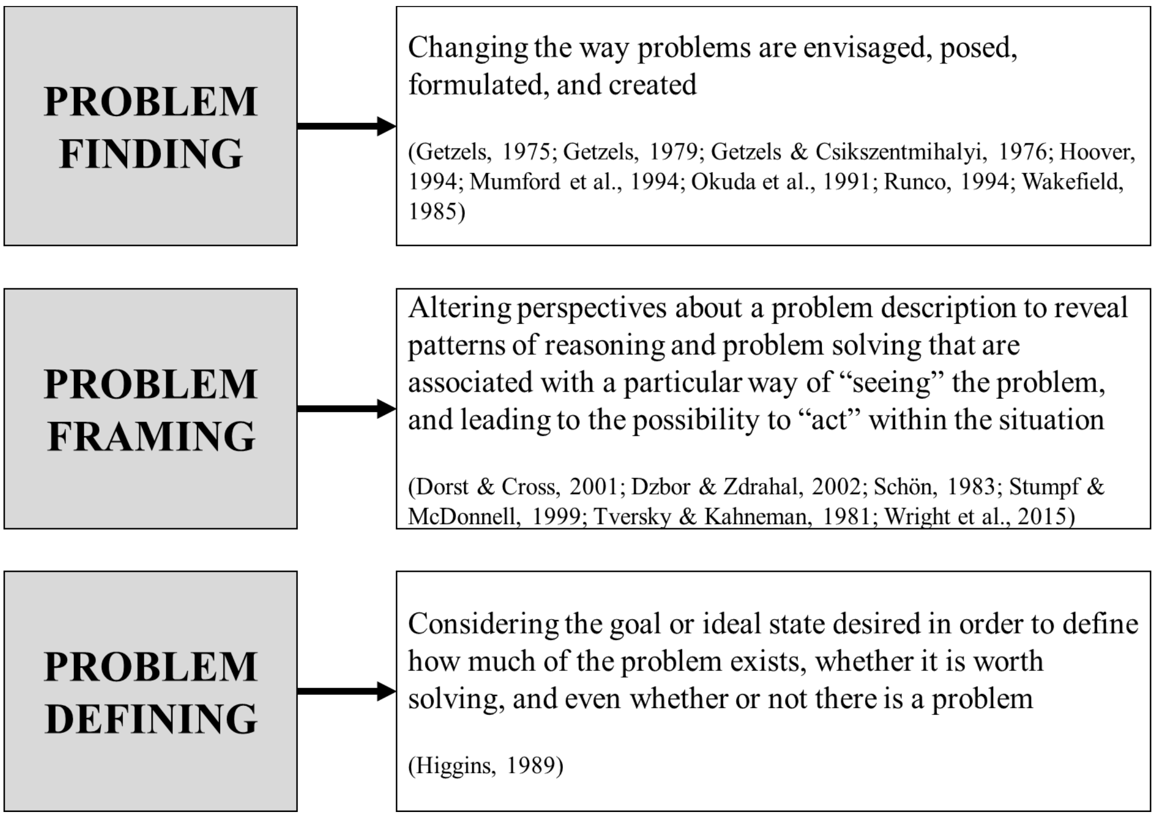

Figure 1. Synthesized definitions of problem finding, problem framing, and problem defining[10,16–29]

Problem finding has been suggested as the most crucial component of creativity and as initiation of thought toward solutions.[16,30,31] Problem framing provides avenues for non-standard and innovative responses to a problem.[32,33] This process allows the designer to "see", "think", and "act" to create a novel standpoint from which a problem can be tackled.[32] Problem defining is often used interchangeably with problem finding, which may justify the lack of research on the topic. Problem defining serves as the bridge between the problem exploration stage and the idea generation stage. After finding and framing the problem, the designer defines the problem that will serve as the basis for generating solutions.

Existing Problem Exploration Strategies

The importance of the problem exploration stage of design has been well established[34–36] and there are several documented strategies to help guide designers in framing and redefining design problems. Table 1 provides an overview of current problem exploration techniques in the literature. All these techniques propose trigger questions that may assist engineers in critically assessing the presented problem and further defining it. Several popular strategies were proposed by Fogler and LeBlanc[37] to assist in defining "the real problem" underlying a given engineering problem. These include: 1) employing critical thinking questions that will probe assumptions and explore different viewpoints; 2) using the present state/desired state analysis and the Duncker diagram[29] to analyze the differences between the current situation and end goal; 3) using Parnes' statement-restatement method,[38] which suggests triggers, or prompts, to help to evolve the problem statement (e.g. "placing emphasis on different words and phrases"); and 4) using the Kepner-Tregoe problem analysis technique[39] by focusing on four dimensions of the problem (identify, locate, timing, and magnitude) supported by prompted questions (e.g. "What is the problem versus what is not the problem?"). These strategies have been practiced in engineering curricula, although their effectiveness has not been empirically tested.

The problem exploration technique, "5 Whys"[40] is frequently used within the Toyota Motor Corporation and is one of the only methods proven to be applied in professional engineering design. This method repeatedly asks "Why?" in order to explore the cause and effect relationships underlying a problem. MacCrimmon and Taylor[41] identified complexity as a limitation in problem formulation, and provided a review of decision strategies to overcome it: 1) determining the problem boundaries, or examining the assumptions; 2) examining changes, or focusing on any alterations in the problem description; 3) factoring into sub-problems using methods such as morphological analysis[42] and attribute listing,[43] and 4) focusing on the controllable components, or selective focusing.[44] One of the more recent strategies was proposed by Spradlin[45] that included steps for defining problems that any organization can employ on its own. The steps were comprised of establishing the need for a solution (e.g. basic need, desired outcome, and benefits), justifying the need, contextualizing the problem, and writing the problem statement. Although there are a number of current problem exploration strategies existing today, these methods are not derived from empirical data nor the analysis of existing design problems. There is also little evidence of any of these methods, with the exception of "5 Whys", in use during professional engineering design or in engineering curricula. Most importantly, there is no existing evidence about whether the use of these techniques would increase the likelihood of creating innovative solutions. This paper sets out to fill these gaps in the current problem exploration strategies.

Table 1. Existing problem exploration techniques[46]

Technique	Description and Resources
Present state/desired state analysis and Duncker diagram	Means to determine the real problem by first describing the present state (where you are) and then describing the desired state (where you want to go)[9,29]
Critical Thinking Algorithm	Process to recognize underlying assumptions, scrutinize arguments, and assess ideas and statements using Socratic Questions to prompt the designer[37,47]
Parnes' statement-restatement method	Method to evolve the problem statement to its most accurate representation of the problem using different triggers such as "place emphasis on different words and phrases"[38]
Kepner-Tregoe problem analysis technique	Technique that determines the "four dimensions of the problem" including identify, locate, timing, and magnitude by determining the distinction between "is" and "is not"[39]

Table 1 continued

5 Whys	Technique that involves asking questions ("Why?") until you get to the root cause of the problem[40]
Attribute listing	Method that involves listing attributes of the problem space, considering the value of each attribute ("what does this give?"), and modifying attributes to increase value, decrease negative value or create new value[43]
Selective focusing	Technique that focuses on the problem components that can be manipulated[44]
Spradlin's Problem-Definition Process	Process that includes establishing the need for a solution, justifying the need, contextualizing the problem, and writing the problem statement[45]

Problem Exploration Heuristics

The aim of this paper is to introduce a new approach to identifying strategies in the problem exploration process. Following Newell and Simon's[48] definition of the solution space, we define the "problem space" as a bounding of the set of all problems that are possible perspectives on a presented problem. Problems that lead to creative solutions are rarely solved with systematic, linear approaches; instead, people often use *heuristics* to generate possible pathways to solutions.[49] Taken from psychology, a cognitive heuristic is a simple rule of thumb used to generate a judgement or decision.[49] Cognitive heuristics are not guaranteed to lead to a determinate decision, or to serve as a search algorithm; rather, they describe specific methods for best guesses at potential solutions. Heuristics capture problem situations that tend to occur in our experiences, along with solutions that tend to work.[50]

Recent work argues that heuristics are highly advantageous in most disciplines[51–53] and design in the idea generation phase.[54–61] Behavioral research shows that experts utilize heuristics effectively, and suggests that heavy use of heuristics by experts distinguishes them from novices.[62] Some research even suggests that heuristics can sometimes lead to optimal solutions when they are focused on key variables in the problem space.[63]

Designers may have general heuristics that they apply when exploring the problem space even when, or especially when they have little prior knowledge of the domain. Thus, we propose that problem exploration can take place through successfully applying different *problem exploration heuristics* to investigate the potential problem space of descriptions. We define *problem exploration heuristics* as cognitive strategies that help designers transition from a surface description of a problem to deeper, more novel problem understandings. These heuristics may help provide opportunities for surprising, uncommon views that lead to innovative solutions.

Research Questions

This paper takes an important first step in understanding how problems are explored and how that exploration impacts solutions by identifying specific ways engineering designers explore problems. In this study, we investigated problem exploration heuristics evident in existing engineering design problems taken from a variety of sources, and analyzed how the problem description impacted the final solutions generated. We focused on identifying heuristics that offer a means of generating new problem statements by guiding specific types of variations within the problem context. This paper reports the results of this analysis and is guided by the following research questions:

1. In order to specify the nature of problem exploration heuristics and the specific transformations they provide, can a method be created that does not rely on the verbal report of the designer?
2. Can the designed method be used by different coders to come up with similar results?

3. What are problem exploration heuristics and can they be extracted from existing, novel problems?
4. How often is each problem exploration heuristic observed and in what type of design problems?

Methods

The primary goal of the present study was to examine the way heuristics are used by professional designers in the problem exploration stage of the design process. The study reported here assesses problems from online innovation challenges, as well as published books that detail the design process of award-winning products. Each source contains the given problem description, or challenge, and most data sources also contain the solutions generated by professional designers in response to the problem presented to them.

Data Collection

We gathered a set of 218 engineering design problems from a variety of sources, including online innovation challenges and published books of award-winning successful products. The problem statements were selected based on clarity of the problem description and the accessibility of the subject matter for a range of audiences, including design and engineering students, researchers, and practitioners. Table 2 provides an overview of the sources used for this study including the source description, the data provided, and the number of problems gathered.

Table 2. Summary of Problem Sources

Source Name	Source Description	Data Provided	# of Problems
InnoCentive	Online crowdsourcing platform for innovative solutions working with organizations such as NASA, Booz Allen Hamilton, and Thomson Reuters (www.innocentive.com/ar/challenge)	• Problem background • Solution requirements	36
Unbranded Designs	Global community of designers that submit ideas to solve product design challenges (www.unbrandeddesigns.com)	• Introduction to the problem • Presented problem statement • Solution designs and descriptions for finalists and semi-finalists	102
IdeaConnection	Platform for crowdsourcing innovative solutions (www.ideaconnection.com)	• Presented problem statement	3
Design Secrets: Products: 50 Real-Life Projects Uncovered	Published book by the Industrial Designers Society of America (2001)	• Detailed description of the design process • Information on how the problem transitioned into a market-ready solution	29
Design Secrets: Products 2: 50 Real-Life Design Projects Uncovered	Published book by Lynn Haller and Cheryl Dangel Cullen (2006)	• Detailed description of the design process • Information on how the problem transitioned into a market-ready solution	48

Online Innovation Challenges

For this study, we selected three online innovation platforms to gather engineering design problems – InnoCentive, IdeaConnection, and UnbrandedDesigns. These platforms are used by institutions to crowdsource solutions from external solvers by initiating challenges, or specific problems that need solving. For InnoCentive and IdeaConnection, we selected only the challenges related to mechanical engineering, in order to narrow the scope to engineering product design. A total of 39 challenges, or presented problem statements, from both of these sources met this criteria and were added to the data set. The solutions to the InnoCentive and IdeaConnection challenges were not provided by the sources, and therefore not used in our study.

The challenges on UnbrandedDesigns concentrated on consumer product design and were selected if the challenge had been completed and winners had been chosen, in order to gather the full set of data for each challenge. Four challenges met these conditions and the presented problem statements for each were added to the data set. The solutions were also provided for each of these challenges, which included the reframed problem statements by the designer as well as the design that resulted from these problems. A total of 102 reframed, or discovered, problem statements were added to the data set.

Published Books

Two product design books (Design Secrets: Products: 50 Real-Life Projects Uncovered 1 and 2) were chosen for this study, because of the case study approach to each award-winning product described in the book. This provided a quality outlook on how the problem was initially outlined and what occurred in the reframing of the problem to create the finished product. The product description was used to extract the discovered problem through reframing. If the problem and the steps taken to reframe the problem were not apparent, the product was excluded. A total of 77 problems were extracted from the two books and added to the data set.

Problem Exploration Heuristic Extraction Method

Our method for extracting problem exploration heuristics is based on previous research on Design Heuristics,[55,61,64] which involved identifying major elements and key features of the products for functionality, form, user-interaction, and physical state. Once these features were identified, a content analysis of the needs, design criteria, and the solution was performed, which led to creating comparisons with the other products with similar features. We adapted this approach for this study in order to focus on the elements within a design problem statement and to compare the similar elements across problems.

For our study, the major elements of each of the engineering design problem statements were identified and the problems were then categorized based on these elements. Examples of the major elements identified include user criteria, environmental context, and primary stakeholders as they were identified in many of the problems. If both the presented problem and the discovered problem statements were provided, we analyzed the differences between the two statements to extract information about the transition and the reframing of the problem and then categorized these differences. After the elements were identified and the problems were categorized, the problems including the same element were compared with each other in order to explore the commonalities and discords. The heuristics and their definitions were then extracted from these elements. This entire systematic process will be referred to as the Problem Exploration Heuristic Extraction Method, which is illustrated in Figure 2.

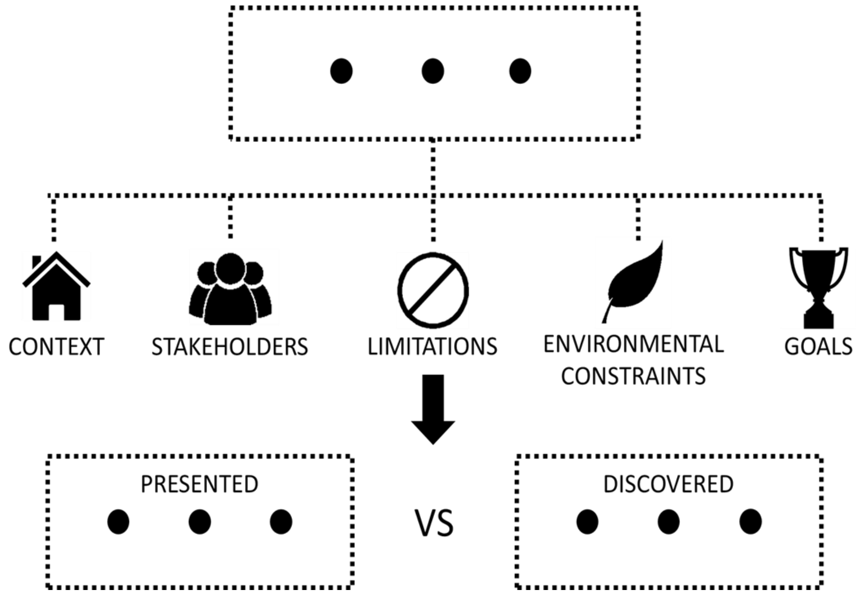

Figure 2. Illustration of the Problem Exploration Heuristic Extraction Method

Table 3 provides a detailed breakdown of each step of the Problem Exploration Heuristic Extraction Method as well as a demonstration of how each step was applied using example problem statements. This detailed extraction process was tested and refined using the first set of data from the InnoCentive website and then applied to the remaining set of data to ensure viability across data sources.

Table 3. Application of Problem Exploration Heuristic Extraction Method using an example problem

Step	Step Description	Application of Step
STEP 1	Select a problem statement from the source list.	**<u>Presented problem statement</u>** *"Oppressed, remote villagers need to be able to embrace clean water solutions and have access to them when in and around the home."*
STEP 2	Identify the major elements of the problem.	**<u>List of major elements</u>** • Primary stakeholders – oppressed, remote villages • Current state limitation – access to existing clean water solutions • Primary goal – provide access to existing clean water solutions • Environmental context – in and around the home

Table 3 continued

STEP 3	If a revised problem statement was provided, identify the major elements of the revised problem.	**<u>Revised problem statement</u>** *"Poor people that don't live close to water need to be able to obtain and store clean water when in isolated villages."* **<u>List of major elements</u>** • Primary stakeholders – poor people • Current state limitation – clean water • Primary goal – obtain and store clean water • Environmental context – isolated villages • Situational context – don't live close to the water
STEP 4	Analyze the differences between the two statements, if applicable.	**<u>Explanation of differences</u>** The limitation of the current state was changed from not being able to access existing clean water solutions to not getting clean water. This, in turn, changed the primary goal of the solution from providing access to existing solutions to obtaining and storing clean water. Also, a more specific environmental and situational context was added by specifying "in isolated villages" and "don't live close to water". Primary stakeholder was also changed from "remote villagers" to a broader demographic group: "poor people".
STEP 5	Derive heuristics both used by individual problem statements as well as heuristics used to reframe/restructure the problem	**<u>Heuristics observed in creating the original statement</u>** • Identify a primary stakeholder • Describe the principle limitation(s) of the current state • Specify the primary goal the desired solution is trying to achieve that will eliminate or reduce the principle limitation(s) • Identify a specific environment where the desired solution should be used • Identify a specific situation in which the desired solution should be used (final statement only) **<u>Heuristics observed in the comparison between the revised and the original problem statements</u>** • Change the principle limitation by analyzing the root cause of the problem • Change the scope of the primary goal • Provide a more specific environment in which the desired solution should
STEP 6	Select another problem that uses the same heuristic(s).	**<u>Alternative problem statements</u>** Presented Problem - *"School children in sub-Saharan Africa need to be able to adequately protect themselves against disease in primary/elementary schools."* Discovered Problem – *"School children need to be able to be clean as they transition from classrooms and other areas when they are in school."*

Table 3 continued

STEP 7	Determine how each problem used the heuristic to identify different ways of implementation.	**Explanation of differences** Both sets of problem statements changed the current state limitation by analyzing the root cause of the problem. The first set initially focused on how to use existing solutions, but ended up focusing on creating a new solution to solve the real issue. In the second set, they went from focusing on protecting against disease to preventing disease all together. Both sets also added a specific situation in which the final solution should be used with the first set focusing on where ("don't live close to water") and the second set focusing on when ("transitioning between classrooms")

Deriving a potential problem exploration heuristic from the problem definitions, especially when focusing on the problem transition, requires interpretation. The data provided no intermediate steps for the problem exploration process or a description of the designer's thinking progression during this process. The success of this extraction approach is not determined by the correctness of the derived heuristic. It is possible that the practicing engineers or designers may not agree with the characterization of the derived heuristic. However, the standard adopted for this analysis is whether the proposed problem exploration heuristic is observed in other design and engineering problems, and whether it appears to offer a transformation that can be successfully applied to problems that might lead to novel solutions.

Coding Analysis

For this project, 218 separate problem statements were gathered from the various sources and analyzed using our Problem Exploration Heuristic Extraction Method.

Preliminary Analysis

The first 36 problem statements gathered from InnoCentive were used to build the extraction method and gather the initial set of heuristics, or codes, which were further developed as more data were collected. An experienced engineer coded the first set of potential problem exploration heuristics due to the engineering focus of the problems collected from InnoCentive. The extracted heuristics are shown in Table 4.

Table 4. Problem exploration heuristics identified from the first 36 problems

#	*Observed Heuristic*	*# of Occurrences*	*Percentage*
1	Describe the principle limitation(s) of the current state	16	44%
2	Identify the primary goal	15	42%
3	Identify secondary functionality	14	39%
4	Identify a specific situation	11	31%
5	Identify specific cost and time constraints	11	31%
6	Add constraints on material used	7	19%
7	Specify manufacturing or supply chain constraints	6	17%
8	Identify user criteria	5	14%
9	Identify constraints of the specific environment	5	14%
10	Add criteria to benefit the environment	4	11%
11	Describe a specific environment	4	11%
12	Incorporate an existing concept into the primary goal in a novel way	3	8%
13	Specify a primary stakeholder	3	8%
14	Add criteria to allow for the user to reconfigure	2	6%
15	Add mobility to the context	1	3%
16	Incorporate an existing solution into the primary goal	1	3%
	TOTAL	**108**	**100%**

Using the first set of data, the coder analyzed each problem statement using the Problem Exploration Heuristic Extraction Method and identified potential heuristics used in framing the problem. Each heuristic identified captured a specific element of the problem statement that could impact potential solutions generated if added, modified, or removed. For example, in one of the problems, the designer decided to focus the solution to address needs of veterans by stating *"create ways to reassign motions and buttons on gaming controllers to provide alternative access for veterans…"* In a separate problem, the designer focused on women and children by stating *"allow families, particularly the women and children that are usually tasked with water collection, to spend less time walking distances to collect water and more time on activities that can bring in income and improve the quality of life"*. Both of these problems would be vastly different if the primary stakeholder was changed to represent a different population, which in turn would impact the type of solutions generated to solve these problems. This observation resulted in the heuristic *"Specify a primary stakeholder"* and both problems were coded to this heuristic. As the heuristics were being extracted, a general description was given to each to describe how the heuristic was used in the problem statement. Each heuristic was described so as to be readily observable as a new element within a given problem and applicable to many different engineering design problems. The heuristic description was further developed as the heuristic was observed in subsequent problem statements. Through this process, a total of 16 heuristics were identified from the first 36 problem statements from the InnoCentive data set. The frequency of use for each heuristic in the initial set of problems in shown in Table 4.

Next, a second independent coder with a background in Industrial Design analyzed the first 36 design problems using the same method as the initial coder. Before the analysis, each of the heuristics were verbally described to the second coder and written descriptions of each heuristic were provided for review as needed. The problem statements were provided to the second coder in the same order the data was collected. After completion of the analysis, the two coders met to compare their observations and refine the initial set of heuristics and descriptions to be utilized in coding the remaining data.

Final Analysis

Using the revised set of heuristics, the same two coders from the initial analysis worked independently to analyze the remaining 182 problem statements using the heuristic extraction method. The coders worked independently in order to validate the effectiveness of the heuristic extraction method and showcase the ability of two separate coders to extract heuristics from the problem statements. In the final analysis, a total of 26 new problem exploration heuristics were discovered and added to the coding list. The agreement between the two coders (an industrial engineer and industrial design student) in the final analysis was 90% overall. This number represents the percentage of observations in which both coders positively scored a given problem as containing a specific heuristic, or interrater reliability. The heuristic descriptions and title names were then further refined based on the new data as agreed upon by both coders. After completion of the analysis, a total of 42 problem exploration heuristics were identified including a brief title and a detailed description for each heuristic.

Results

Problem Exploration Heuristics

The main focus of this paper was to document ways in which professional designers explore problems. For this study, we observed how the designer transitioned from the presented problem (i.e. design challenges) provided to them to the problem interpreted by the designer to generate potential solutions. Using the seven step heuristic extraction method, 42 problem exploration heuristics were documented from the set of engineering design problems. Table 5 presents the identified problem exploration heuristics extracted from the dataset along with the identified title. Appendix B contains the full set of problem exploration heuristics with the detailed descriptions of how to use each heuristic effectively based on the observations. Each heuristic relates to a specific attribute within the discovered design problem and describes how the designer transformed the attribute after analyzing the problem statement, or challenge, that was initially presented to them.

The problem exploration heuristics were identified a total of 428 times in the 218 problem statements. This observation confirms our hypothesis that problem exploration heuristics do occur, in great numbers, in the work of professional engineers and designers. The observed counts for each heuristic are shown in Table 5. The table indicates that some heuristics were used frequently, including *Detail the required functions* (40 occurrences), *Prioritize use cases* (21), and *Find the root cause* (20), while others, including *List individuals or groups that are associated with the primary stakeholder* and *Describe secondary stakeholders*, were only seen in one problem each. Additional data is needed to confirm if the heuristics that were only seen in one or two problems are applicable to the field of design as a whole.

Table 5. Problem exploration heuristics identified in the problem analysis of the entire set of 218 engineering design problems

Rank	*Heuristic Title*	*# of Occurrences*
1	Detail the required functions	40
2	Include multiple ways to interact	39
3	Integrate mobility	24
4	Prioritize use cases	21
5	Find the root cause	20
6	State the desired outcome	20
7	Add potential limitations	19
8	Break down the addressed limitation(s)	19
9	Determine the end user and detail their needs	19
10	Determine the required cost	17
11	Describe secondary functions	17
12	Expand the setting	16
13	Break down the desired outcome	15

Table 5 continued

14	*Describe material characteristics*	*14*
15	Focus on eco-friendly solutions	14
16	Describe the desired visual attributes	13
17	Integrate existing products to address secondary functions	12
18	Describe an existing solution to use as conceptual inspiration	12
19	Define the characteristics of the setting	9
20	Substitute the individual primary stakeholder for a group	8
21	Describe the environmental conditions	7
22	Describe the required manufacturing process and its limitations	7
23	Incorporate user customization in manufacturing process	6
24	Substitute the primary stakeholder group for an individual	6
25	Describe the brand values	5
26	Expand the primary stakeholder group	5
27	Describe the primary stakeholder	4
28	Describe the required size and space attributes	2
29	Expand the scope	2
30	Consider existing solutions	2
31	Break down the primary stakeholder group	2
32	Shift focus to cultural issues	2
33	Examine assumptions	1
34	Brainstorm ways to eliminate the root cause	1
35	Brainstorm ways to eliminate environmental restrictions	1
36	Focus on education	1
37	Describe the required maintenance needs	1
38	Focus on economic growth	1
39	Incorporate more scenarios	1
40	Describe a future scenario	1
41	Describe secondary stakeholders	1
42	List individuals or groups that are associated with the primary stakeholder	1
	TOTAL	**428**

Examples of Heuristic Use

The problem exploration heuristics in Table 5 attempt to describe the designers' strategies evident in transforming the presented problem. To illustrate, two examples of a presented and an interpreted problem are provided, followed by a description of the problem exploration heuristic evident in the transformation, how the designer likely applied these heuristics to the presented problem description, and the final concept generated from the interpreted problem.

Example #1

Presented Problem Statement: Consider the mobile worker and define a concept to *facilitate individual work in a shared work environment*. Develop an innovative solution to a clearly defined problem, optimized for *today's mobile worker* that is both technically and visually appropriate for the workplace.

Interpreted Problem Statement: Working in open spaces fosters creativity and collaboration, yet this communal atmosphere possesses *security issues*. Mobile workers who utilize this type of space express concern about having their belongings stolen or losing their spot at the table when stepping away temporarily. Design a solution that allows *office workers, students, coffee shop goers, and anyone else that works in a communal space* to quickly *secure their belongings without having to pack up multiple items and lug them around*.

Observed heuristic #1: Break down the desired outcome

This heuristic focuses on the primary outcome of the solution. It is the cornerstone of the design and refers to the tangible goal you are directly trying to accomplish. The aim of this heuristic is to help narrow the scope of the problem to make it more manageable to solve. The steps for using this heuristic are:

1. Analyze the primary outcome the desired solution is attempting to accomplish.

2. Break the presented outcome into distinct subcategories.
3. Choose one of the subcategories to use as the new primary outcome to narrow the scope of the problem.
4. Detail the narrowed outcome in the problem statement.
5. Determine if the other subcategories identified can be used as secondary outcomes, or outcomes that you wish to accomplish but will forgo to achieve the primary outcome.
6. Detail the secondary outcomes in the problem statement (if applicable).

"Facilitate individual work in a shared work environment" is a very broad outcome. In order to make the problem more manageable, the designer selected a smaller outcome to focus the design on, *"secure their belongings"*. Figure 3 illustrates the use of this heuristic in Example 1 by breaking out the presented outcome into subcategories and selecting one to focus the final solution on.

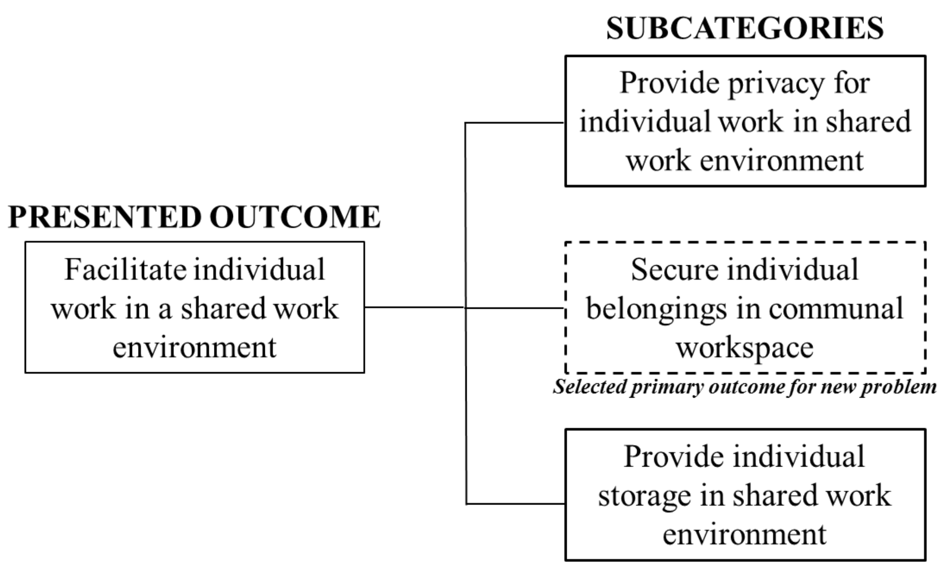

Figure 3. Demonstration of how the designer used the heuristic *Break down the desired outcome*

<u>Observed heuristic #2: Expand the primary stakeholder group</u>

This heuristic focuses on the primary stakeholders, an individual or group that will benefit the most from or will be significantly impacted by the final solution. Identifying the correct primary stakeholder is key to a project's success and getting the right people involved in the development of the solution. The goal of this heuristic is to broaden the primary stakeholder group to encompass more individuals. The steps for using this heuristic are:

1. Make a list of larger groups that the current primary stakeholder group is a part of and groups that are related to the primary stakeholder group.
2. Analyze the characteristics and interests of each group.
3. Select one or more groups to be the new primary stakeholder.
4. Detail these groups in the problem statement as the new primary stakeholder.

In Example 1, the presented problem focused on today's mobile workers as the primary stakeholder group. In the discovered problem statement, the designer decided to broaden the focus to not only include office workers, but also students, coffee shop goers, and anyone that works in a communal space. Figure 4 illustrates the use of this heuristic in Example 1 by brainstorming larger stakeholder groups the current stakeholder is a part of, selecting one or more of those groups to focus the solution on, and determining the primary needs of the group(s) selected.

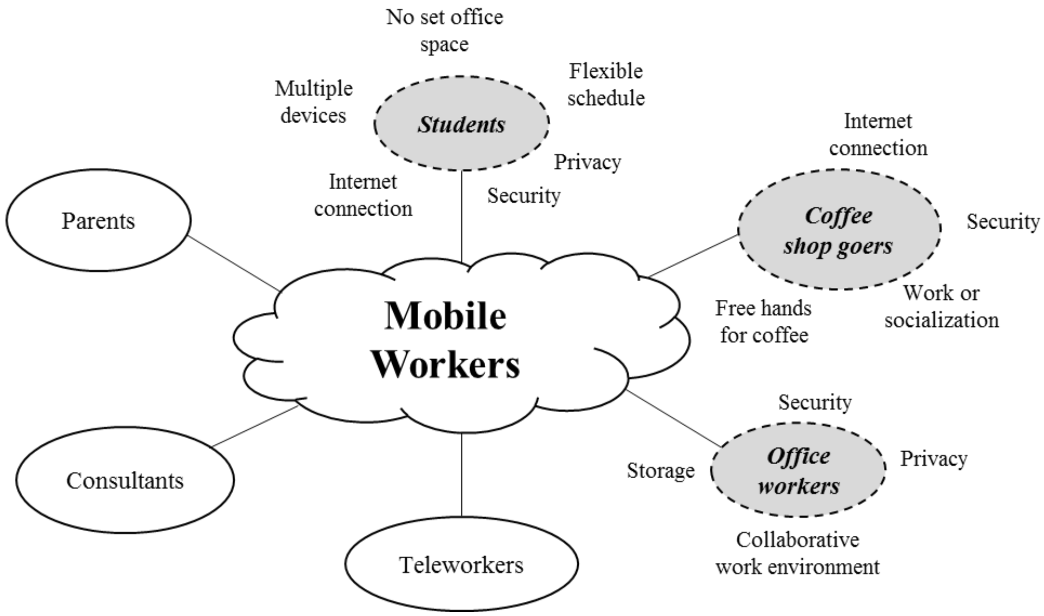

Figure 4. Demonstration of how the designer appeared to use the heuristic *Expand the primary stakeholder group*

Observed heuristic #3*: *Find the root cause

This heuristic focuses on examining the current state and the limitations that are producing the problem in the first place. This will allow the designer to identify the root cause of the problem instead of focusing on the symptoms, which will be more beneficial to all stakeholders involved. The steps for using this heuristic are:

1. Write down the limitations or flaws of the current state that are inhibiting people achieving the task at hand.
2. Select one of these limitations that the final solution should address.
3. Explore what is causing this limitation to determine the root cause of the problem.
4. Detail the limitation and the root cause of the problem in the problem statement.

The presented problem did not specify what limitation the solution is trying to solve. Instead it went with a general approach, by saying "develop an innovative solution to a clearly defined problem". It was up to the designer to explore the limitations of the current state and choose one to focus on. In this case, the designer determined that stolen belongings or having to lose a spot in a communal area was a current limitation for workers on the go. The designer then determined this limitation was due to workers not being able to secure their belongings in communal spaces without packing up and taking everything with them. Figure 5 illustrates the use of this heuristic in Example 1 by listing the current limitations, selecting one of the limitations to focus on, and determining the root cause of the limitation.

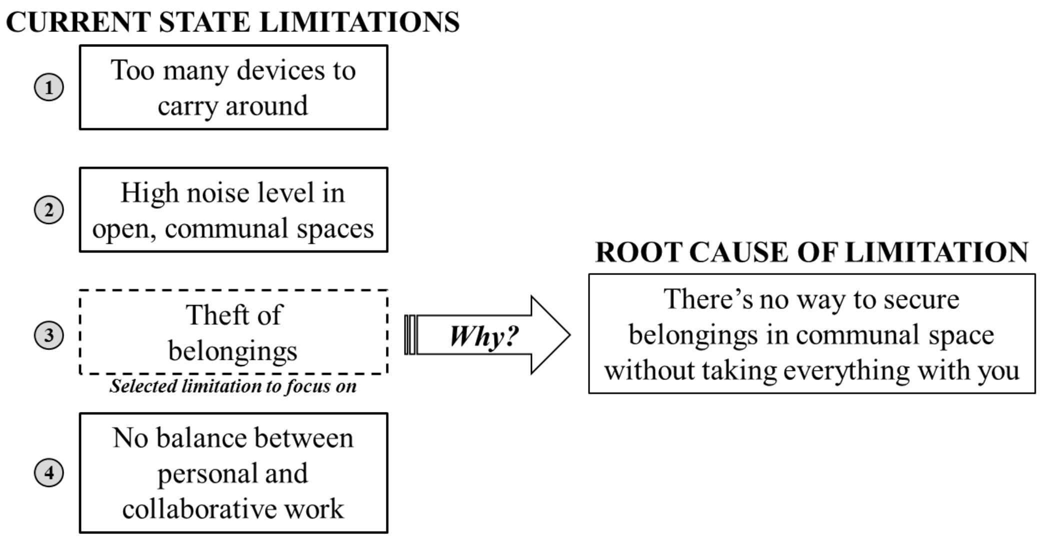

Figure 5. Demonstration of how the designer used the heuristic *Find the root cause*

The final problem statement included each of the three observed heuristics, and this led the designer to create a solution for a scroll top lock box that will allow the user to lock up their items in a communal space if they have to step away. Figure 6a demonstrates the scroll top lock box concept. Figure 6b shows alternative solutions to the same problem that were generated by other designers based on each of their individual interpretations of the presented problem. The diversity of solutions demonstrates that problem exploration heuristic use can create a multitude of varied design problems. Based on these designs being selected as semi-finalists and finalists in the given design challenge, this suggests that heuristic use may result in more innovative and creative solutions. This supports the claim that problem exploration heuristics may move designers to consider novel ways of approaching problems, and provide the opportunity for surprising, uncommon interpretations of the problem space.

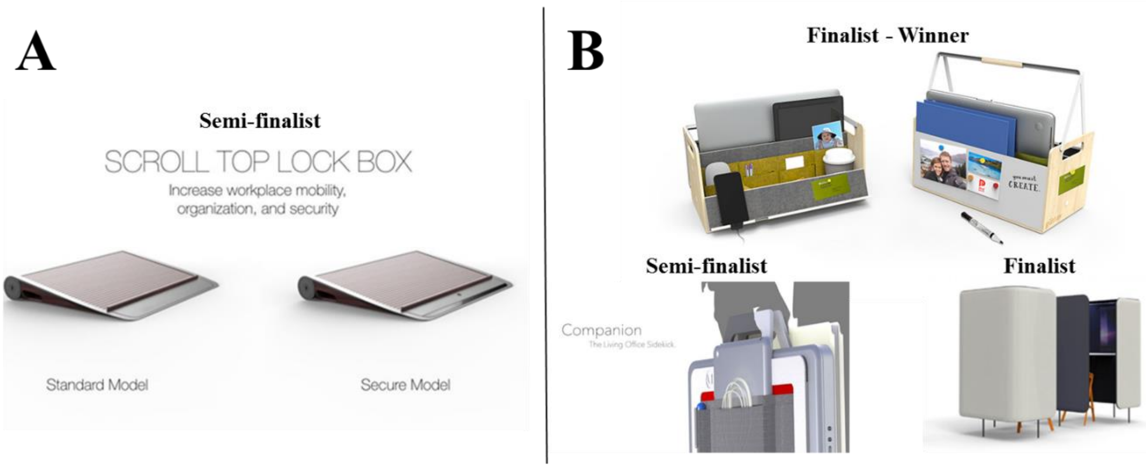

Figure 6. Illustrations of (a) final solution generated from the interpreted problem statement discussed and (b) other solutions generated from the same presented problem

<u>Example #2</u>

Presented Problem Statement: Motorola Mobility opened a new manufacturing facility in Dallas, Texas and needs a custom reception desk.

Interpreted Problem Statement: Design a custom reception desk for the new manufacturing facility in Dallas, Texas for Motorola Mobility. The <u>facility is eco-friendly with a lot of natural materials and the reception area is the focal point when entering the building</u>. The design should be no longer than 5’x7’ to fit in the space and be made of plywood. The Motorola brand represents innovation in technology and efficiency so the desk should reflect that while also being unique and telling a story. The desk should imitate louvres that are designed to give shade and protect the interior of a building.

Observed heuristic #1: Define the characteristics of the setting

This heuristic focuses on the positive and negative aspects of the setting to account for when designing the final solution. It is necessary to analyze potential spaces where the final solution may be implemented to ensure that it can be accommodated and used effectively. The steps for using this heuristic are:

1. If a setting is already defined in the presented problem, skip to step 4.
2. Make a list of potential settings in which the final solution could be used.
3. Select one setting to be the focus during problem solving.
4. Define the positive/negative characteristics of the setting and detail these characteristics in the problem statement.

In this case, the specific setting was already provided in the presented problem – the Motorola Mobility manufacturing facility in Dallas, Texas. The most suitable solution to this problem may have not been discovered without first analyzing the facility. The designer showcased knowledge of the facility by stating it is "eco-friendly with a lot of natural materials and the reception area is the focal point when entering the building". Figure 7 illustrates the use of this heuristic by the designer in Example 2 by making a list of potential settings in which the final solution will be implemented, selecting one to focus on, and describing the specific characteristics of the setting.

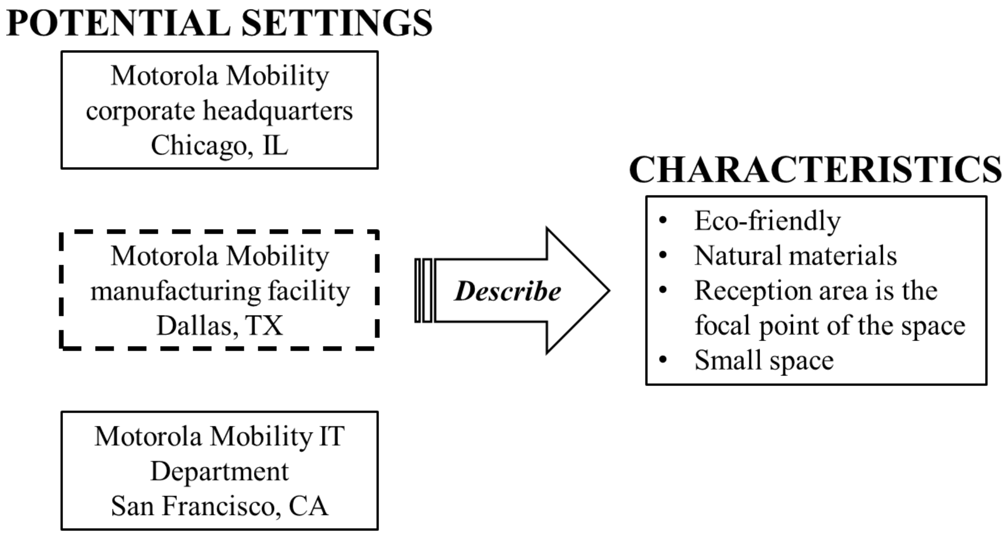

Figure 7. Demonstration of how the designer used the heuristic *Define the characteristics of the setting*

Observed heuristic #2: Describe the brand values

This heuristic focuses on how the company brand should be reflected in the final solution. By describing the brand values in the problem, the solution may better reflect the company and what it stands for. The steps for using this heuristic are:

1. Describe the values of the brand.
2. Determine how these values can be incorporated in the aesthetic of the final solution.
3. Detail these values and the desired aesthetic in the problem statement.

In this example, the designer specified that the Motorola brand "represents innovation in technology and efficiency". These represent values that the designer wished to incorporate in the final solution. Figure 8 illustrates the use of this heuristic in Example 2 by making a list of values the Motorola company has and evaluating how these values can be placed in the final design.

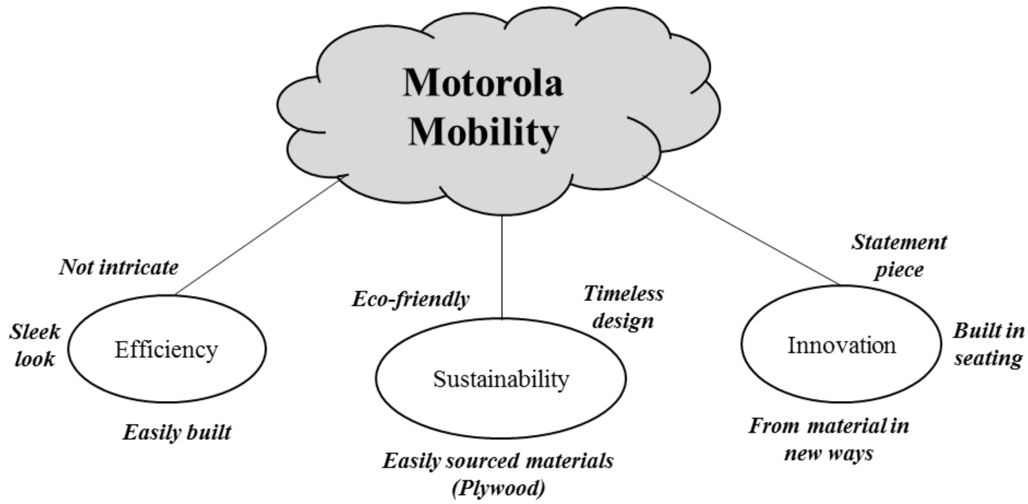

Figure 8. Demonstration of how the designer used the heuristic *Describe the brand values*

***Observed heuristic #3*: Describe an existing solution to use as conceptual inspiration**

This heuristic focuses on existing solutions and how they can be used as inspiration for the final solution. The inspiration does not have to come from a similar solution. The inspiration could also come from solutions that may have similar outcomes or functions. The steps for using this heuristic are:

1. Analyze the primary outcome of the desired solution and brainstorm existing products that may have a similar outcome.
2. Determine if any of the concepts could be used in a new way to solve the limitation you are addressing.
3. Select one concept as inspiration and detail the characteristics of it in the problem statement.

For this example, the designer was inspired by louvres and the way they give shade and protect the interior of a building. The designer incorporated these functions of the final solution in the discovered problem. Figure 9 illustrates the use of this heuristic in Example 2 by brainstorming areas of inspiration, narrowing it down to one idea, and specifying characteristics of that idea to be used in the final design.

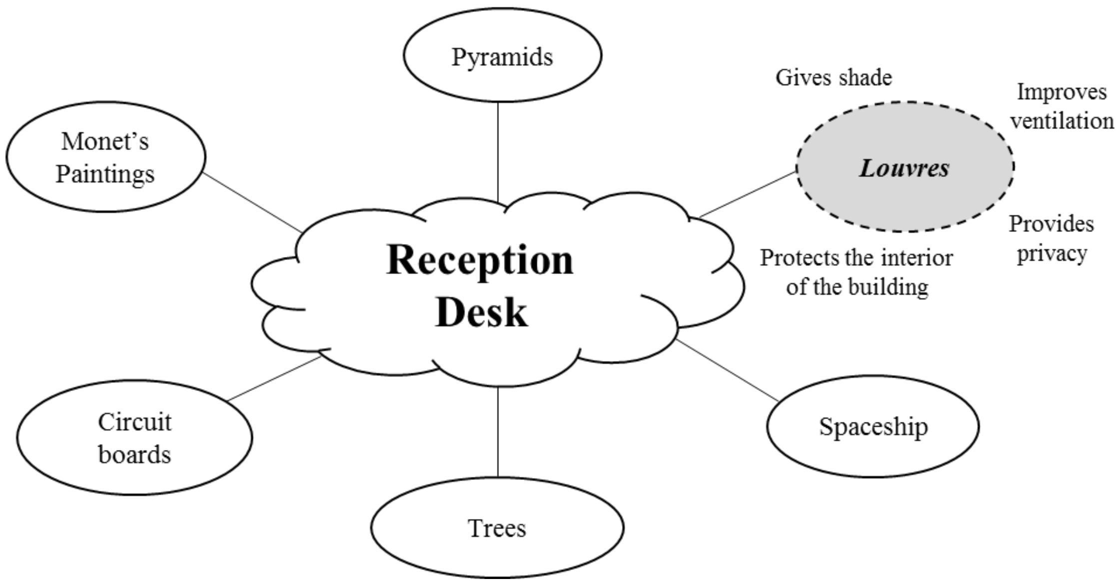

Figure 9. Demonstration of how the designer used the heuristic *Describe an existing solution to use as conceptual inspiration*

The final problem statement included each of the three observed heuristics detailed above as well as *Describe material characteristics*, *Integrate existing products to address secondary functions*, and *Describe the required size and space attributes*. This led the designer to create a solution for a plywood desk with attached seating. Figure 10a shows this solution and Figure 10b shows other solutions that were generated based on other designers' interpretation of the presented problem. Just like in the previous example, this demonstrates the generativity principle of problem exploration heuristics: A large number of problems can be generated from the presented problem through the application of a variety of heuristics which may result in more innovative and creative solutions.

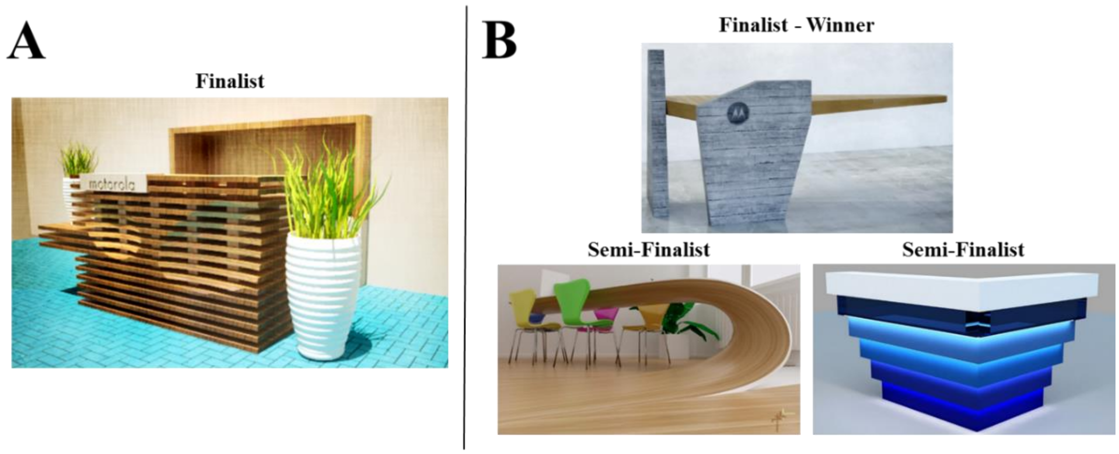

Figure 10. Illustrations of (a) final solution generated from the interpreted problem statement discussed and (b) other solutions generated from the same presented problem

Multiple Heuristic Use

The total number of heuristics extracted per problem ranged from 1 to 9, and in almost all of the problems (202 of 218), multiple heuristics were observed. The average number of heuristics used in each problem across the dataset is 3 heuristics, however, there are several problems that utilize 6 or more heuristics, punctuated by a problem that applied 9 heuristics. The observed problem definitions suggests the frequent application of *heuristic combinations*, rather than an approach where each problem demonstrates the application of a single heuristic. Heuristic combinations are evident in the provided example problems where at least three heuristics were observed in each example. For the problems with the most heuristics evident, 3 of the top 5 were selected as finalists by the design challenge judges in their respective online innovation design challenges, and the other two were semi-finalists. This finding suggests a relationship between the use of multiple problem exploration heuristics and the creativity of the final solution by the designer, which meets the expectation that using multiple heuristics may increase the likelihood of generating innovative solutions. However, further research is needed to validate this relationship.

Discussion

The primary objective of this study was to investigate how designers explore problems and how heuristic use during problem exploration impacts the solutions generated. To meet this objective, a new methodology was created to standardize the extraction of problem exploration heuristics from a diverse set of engineering design problems. The use of the extraction method resulted in a set of 42 problem exploration heuristics gathered from 218 problems. The problem exploration heuristics vary in that some identify constraints or address the primary stakeholders, while others explore desired outcomes or scenarios for the solution. As expected, the number of heuristics extracted indicates heavy use of heuristics by designers when exploring the problem space and demonstrates that heuristic use can be quantitatively documented using problem descriptions from a variety of sources. The prevalence of heuristic use suggests their importance when exploring the problem space. In addition, the variety of heuristics extracted indicates there are a number of different ways a problem can be interpreted and reframed, resulting in a diverse set of solutions to one given problem. Therefore, by using problem exploration heuristics, designers gain the ability to develop problem descriptions that represent core needs, and to frame them in ways that facilitate innovative solutions addressing real problems in the world.

The majority of the problem exploration heuristics identified in this study can be applied to a wide variety of design problems to support exploration of the problem space. However, a few heuristics extracted in this study may be domain-specific, depending on the type of design challenges selected in the study. For example, the heuristic "*Describe the brand value*" (extracted from a challenge involving the design of a new reception area for the Motorola Company), would be applicable only when designing for a specific brand and may not be relevant in all circumstances. In addition, the frequency with which each heuristic was seen in this study should mirror its frequency of use by designers in industry due to the comprehensiveness of the design problems selected. However, some heuristics may be more prevalent while others may be less common as additional data is collected to confirm the widespread use of these heuristics in design problems. The supplementary data may promote a more precise view through which problem exploration heuristics are used most frequently in engineering design.

Unlike existing problem framing strategies, the problem exploration heuristics identified provide an empirically based strategy for exploring the problem space prior to idea generation. However, some of the extracted heuristics show similarities to the previously identified framing strategies, including Spradlin's Problem-Definition Process.[45] Using Spradlin's process, the designer would answer the following questions when establishing the need for the solution: "What is the desired outcome?" and "Who stands to benefit and why?" These questions can be compared to the heuristics "*State the primary outcome,*" and "*Describe the primary stakeholder,*" respectively. The "5 Whys" strategy[40] is very similar to the heuristic "*Find the root cause*" in that both analyze the existing problem to find the underlying problem that requires a solution. When comparing the problem exploration heuristics to the majority of existing framing strategies, however, the identified heuristics offer more explicit guidelines of how to define the problem within a context. For example, using Parnes' statement-restatement method,[38] the designer may use the prompt of "placing emphasis on different words" to rethink the problem. This may allow the designer to focus, for example, on the desired outcome of the problem; however, the method does not provide clear directions on how to reframe a problem. Using the problem exploration heuristic

"*Break down the desired outcome*," the designer is told not only to focus on the primary outcome, or the goal state the designer is trying to achieve, but also is given explicit guidelines for breaking the outcome into smaller sub-goals and selecting a more manageable scope for the problem.

In addition, the results indicate that designers in the study generally used multiple heuristics simultaneously when reframing the provided problem. The results also suggest a correlation between the number of heuristics used and the creativity of the solution generated, as measured by the selection of the final design as a semi-finalist or finalist in the corresponding design challenge. This indicates design expertise may involve repeated experience with the simultaneous application of multiple heuristics. Those with more experience using heuristics could be more adept at exploring the solution space prior to attempting to solve the problem, and as a result, produce more innovative solutions. The application of heuristic combinations used to explore problems could be an indication of the designer's unique style in moving through the problem space. Alternatively, problem exploration heuristics could fall into categories that many designers learn with experience in various design domains. More research is required to determine which of these alternatives accurately reflects problem exploration heuristic use.

The findings from the present study are limited to the observation of heuristic use in the 218 problem descriptions gathered for this study. However, the design challenges were selected for their diversity, and were intended to provide a rich view of problems within the design community. The observed heuristics were studied through written problem statements and solution descriptions provided from each source, and may not reflect a designer's thoughts during the problem exploration process. However, the designer may not be aware of using heuristics when exploring the problem space and the methodology created for this study provided a reliable, consistent approach to extracting the problem exploration heuristics. Future research may investigate how designers approach problem exploration in real time and document their thought processes as they explore the problem space. Problem exploration heuristics could be examined through think-aloud protocol studies and interviews with both engineering and design practitioners and students to provide views of problem exploration as it occurs. It would also give us the opportunity to ask questions to better understand the evolution of the problem space. Although the results of the study did showcase a correlation between creative, novel solutions and heuristic use, we also plan to validate the effectiveness of problem exploration heuristics in design practice, and to determine which heuristics are shown to enhance innovation most effectively.

The results of this study, as well as future studies, will ultimately lead us to determine how problem exploration heuristics can be effectively taught in engineering design courses to better prepare engineers and designers for challenging problems. Many engineering and design undergraduates are provided with general instructions for finding, framing, and defining problems; however, it is less common to learn specific cognitive strategies for problem exploration that may lead to defining novel problems, and in turn, generating more creative solutions. By using problem exploration heuristics, a novice or expert designer can choose a heuristic, apply it to the current problem, and see where the resulting transformation leads. Exposure to a variety of heuristics, and experience in applying them to many different problems, may lead to the development of expertise in problem exploration and innovation. For many engineering design students and professionals, simply having an arsenal of heuristics to try might lead to improvement in problem exploration, and add to one's ability to generate multiple problem definitions for a given problem.

Conclusion

This research study suggests that there are specific strategies useful in understanding a presented engineering design problem. These problem exploration heuristics capture alternative perspectives and differing levels of problem scope that may lead to more varied and innovative solutions. The goal of this study was to compile a preliminary set of problem exploration heuristics from the problems and solutions created by professional engineers and designers. This study provides a base for comparison in future research, and the set of heuristics will likely expand with further development. Expanding the problems and solutions to other design sources will better reflect the engineering design community as a whole. These results, as well as the results of future research, will inform the development of instructional material for dissemination in educational and professional settings to assist engineering design students and practitioners in improving their skills in exploring problem spaces and producing creative solutions.

References

1. Badran I. Enhancing creativity and innovation in engineering education. *Eur J Eng Educ*. 2007;32(5):573-585. doi:10.1080/03043790701433061.
2. Brophy DR. Comparing the attributes, activities, and performance of divergent, convergent, and combination thinkers. *Creat Res J*. 2001;13(3-4):439-455. doi:10.1207/S15326934CRJ1334_20.
3. Liu YC, Bligh T, Chakrabarti A. Towards an "ideal" approach for concept generation. *Des Stud*. 2003;24(4):341-355. doi:10.1016/S0142-694X(03)00003-6.
4. Ottosson S. Dynamic product development - DPD. *Technovation*. 2004;24(3):207-217. doi:10.1016/S0166-4972(02)00077-9.
5. Granger CH. The Hierarchy of Objectives. *Harv Bus Rev*. 1964;42(May-June):63-74..

6. Kahn AJ. *Theory and Practice of Social Planning*. New York: Russell Sage Foundation; 1969.
7. Nadler G. *Work Systems Design: The IDEALS Concept*. Homewood, Illinois: Richard D. Irwin, Inc.; 1967.
8. Restrepo J, Christiaans H. Problem Structuring and Information Access in Design. *J Des Res*. 2004;4(2):0. doi:10.1504/JDR.2004.009842.
9. Duncker K. On problem solving. *Psychol Monogr*. 1945;58:270. doi:10.1037/h0093599.
10. Getzels JW, Csikszentmihalyi M. *The Creative Vision: A Longitudinal Study of Problem Finding in Art*. New York: Wiley; 1976.
11. Archer LB. *The Structure of Design Processes*. Springfield, USA; 1968.
12. Shneiderman B. Creating Creativity: User Interfaces for Supporting Innovation. *ACM Trans Comput Interact*. 2000;7(1):114-138.
13. Kruger C, Cross N. Solution driven versus problem driven design: strategies and outcomes. *Des Stud*. 2006;27(5):527-548. doi:10.1016/j.destud.2006.01.001.
14. Asimow M. *Introduction to Design: Fundamentals of Engineering Design*. New Jersey, 1968: Prentice-Hall; 1962.
15. Vasconcelos LA, Crilly N, Chen CC, Campos F, Kelner J. What's the benefit of problem exploration. In: *DS 84: Proceedings of the DESIGN 2016 14th International Design Conference*. ; 2016.
16. Getzels JW. Problem-finding and the inventiveness of solutions. *J Creat Behav*. 1975;9(1):12-18. doi:10.1002/j.2162-6057.1975.tb00552.x.
17. Getzels JW. Problem finding: A theoretical note. *Cogn Sci*. 1979;3(2):167-171. doi:10.1016/S0364-0213(79)80030-0.
18. Hoover SM. Scientific Problem Finding in Gifted Fifth-Grade Students. *Roeper Rev*. 1994;16(3):156-159. doi:10.1080/02783199409553563.
19. Mumford MD, Reiter-Palmon R, Redmond MR. Problem construction and cognition: Applying problem representations in ill-defined domains. In: *Problem Finding, Problem Solving, and Creativity*. ; 1994:3-39.
20. Okuda SM, Runco MA, Berger DE. Creativity and the finding and solving of real-world problems. *J Psychoeduc Assess*. 1991;9(March):45-53. doi:10.1177/073428299100900104.
21. Runco MA. *Problem Finding, Problem Solving, and Creativity*. New Jersey: Ablex Publishing Corporation; 1994.
22. Wakefield JF. Towards creativity: Problem finding in a divergent-thinking exercise. *Child Study J*. 1985;15:265-270.
23. Dorst K, Cross N. Creativity in the design process: co-evolution of problem–solution. *Des Stud*. 2001;22(5):425-437. doi:10.1016/S0142-694X(01)00009-6.
24. Dzbor M, Zdrahal Z. Design as interactions of problem framing and problem solving. *ECAI*. 2002;(c):210-214. http://eprints.aktors.org/300/.
25. Schon DA. The reflective practitioner. *Harv Bus Rev*. 1984;62:58-62.
26. Stumpf S, McDonnell J. Relating argument to design problem framing. In: *4th International Design Thinking Research Symposium (DTRS'99)*. Cambridge, MA; 1999.
27. Tversky A, Kahneman D. The framing of decisions and the psychology of choice. *Science (80-)*. 1981;211(4481):453-458. doi:10.1126/science.7455683.

28. Wright SM, Silk EM, Daly SR, Jablokow KW, Yilmaz S. Exploring the effects of problem framing on solution shifts: A case study. *ASEE Annu Conf Expo Conf Proc*. 2015;122nd ASEE(122nd ASEE Annual Conference and Exposition: Making Value for Society). doi:10.18260/p.24071.
29. Higgins JS, Maitland GC, Perkins JD, Richardson SM. Identifying and solving problems in engineering design. *Stud High Educ*. 1989;14(2):169-181.
30. Dillon JT. Problem finding and solving. *J Creat Behav*. 1982;16(2):97-111. doi:10.1002/j.2162-6057.1982.tb00326.x.
31. Getzels JW, Smilansky J. Individual differences in pupil perceptions of school problems. *Br J Educ Psychol*. 1983;531:307-316.
32. Dorst K. The Nature of Design Thinking. *8th Des Think Res Symp*. 2010:131-139. doi:10.1111/j.1948-7169.2005.tb00008.x.
33. Seevinck J, Lenigas T. Rock, paper, scissors: reflective practice for design process in the novice landscape architect. In: *Proceedings of the 2nd International Conference for Design Education Researchers*. ; 2013:2145-2159.
34. Csikszentmihalyi M, Getzels JW. Discovery-oriented behavior and the originality of creative products: a study with artists. *J Pers Soc Psychol*. 1971;19(1):47-52. doi:10.1037/h0031106.
35. Ecker DW. The artistic process as qualitative problem solving. *J Aesthet Art Crit*. 1963;31(3):283-290.
36. Dewey J. *How We Think*. Boston: D.C. Heath and Co.; 1910.
37. Fogler SH, LeBlanc SE. *Strategies for Creative Problem Solving*. Massachusetts, USA: Pearson Education, Inc.; 2008.
38. Parnes SJ. *Creative Behavior Guidebook*.; 1967.
39. Kepner CH, Tregoe BB. *The New Rational Manager*. Princeton, NJ: Princeton Research Press; 1981.
40. Bulsuk KG. An introduction to 5-why. 2011. http://blog.bulsuk.com/2009/03/5-why-finding-root-causes.html#axzz1WBoqfIV6.
41. MacCrimmon KR, Taylor RN. Decision making and problem solving. In: Dunnette MD, ed. *Handbook of Industrial and Organizational Psychology*. Chicago: Rand McNally College Publishing Co.; 1976.
42. Hall AD. *A Methodology for Systems Engineering*. New York: Litton Educational Publishing Inc.; 1962.
43. Rickards T. *Problem Solving through Creative Analysis*. Essex: Gower Press; 1975.
44. Shull FA, Delbecq AL, Cummings LL. *Organizational Decision Making*. New York: McGraw-Hill Book Co.; 1970.
45. Spradlin D. Are you solving the right problem? *Harv Bus Rev*. 2012;90(9).
46. Studer JA, Yilmaz S, Daly SR, Seifert CM. Cognitive Heuristics in Defining Engineering Design Problems. In: *Volume 7, 29th International Conference on Design Theory and Methodology*. ASME; 2016. http://dx.doi.org/10.1115/DETC2016-59942.
47. Paul R, Elder L. *The Thinker's Guide to the Art of Socratic Questioning*. Dillon Beach, CA: Foundation for Critical Thinking Press; 2006.
48. Newell A, Simon HA. *Human Problem Solving*. Englewood, NJ: Prentice-Hall; 1972.
49. Nisbett RE, Ross L. *Human Inference: Strategies and Shortcomings of Social Judgment*.; 1980. doi:10.1080/09658210244000603.
50. Clancey WJ. Heuristic classification. *Artif Intell*. 1985;27(3):289-350.

51. Gilli M, Maringer D, Winker P. Applications of Heuristics in Finance. In: *Handbook on Information Technology in Finance*. ; 2008:635-653. doi:10.1007/978-3-540-49487-4_26.
52. Goslar MD. Decision support systems: advantages in consumer marketing settings. *J Consum Mark*. 1993;3(3):43-50.
53. Zhou R, Hansen EA. Space-efficient memory-based heuristics. In: *19th National Conference on Artificial Intelligence*. ; 2004.
54. Daly S, Christian JL. Assessing design heuristics for idea generation in an introductory engineering course. *Int J Eng Educ*. 2012;Vol. 28(2):1–11.
55. Daly SR, Yilmaz S, Christian JL, Seifert CM, Gonzalez R. Design heuristics in engineering concept generation. *J Eng Educ*. 2012;101(4):601-629. doi:10.1002/j.2168-9830.2012.tb01121.x.
56. Kramer J, Daly SR, Yilmaz S, Seifert CM, Gonzalez R. Investigating the impacts of design heuristics on idea initiation and development. *Adv Eng Educ*. 2015;4(4).
57. Seifert CM, Gonzalez R, Yilmaz S, Daly S. Boosting Creativity in Idea Generation Using Design Heuristics. In: *Design Thinking: New Product Development Essentials from the PDMA*. ; 2015:71-86. doi:10.1002/9781119154273.ch6.
58. Yilmaz S, Daly SR, Christian JL, Seifert CM, Gonzalez R. Can experienced designers learn from new tools? A case study of idea generation in a professional engineering team. *Int J Des Creat Innov*. 2014;2(2):82-96. doi:10.1080/21650349.2013.832016.
59. Yilmaz S, Seifert CM. Creativity through design heuristics: A case study of expert product design. *Des Stud*. 2011;32(4):384-415. doi:10.1016/j.destud.2011.01.003.
60. Yilmaz S, Daly SR, Seifert CM, Gonzalez R. How do designers generate new ideas? Design heuristics across two disciplines. *Des Sci*. 2015;1(2015):e4. doi:10.1017/dsj.2015.4.
61. Yilmaz S, Seifert C. Cognitive heuristics in design ideation. *11th Int Des Conf Des 2010*. 2010;(1990):1-11. https://www.designheuristics.com/wp-content/uploads/2012/08/11_Design_2010.pdf.
62. Klein G. *Sources of Power: How People Make Decisions*. Vol 52.; 1999. doi:10.1061/(ASCE)1532-6748(2001)1:1(21).
63. Dijksterhuis A, Bos MW, Nordgren LF, van Baaren RB. On making the right choice: the deliberation-without-attention effect. *Science*. 2006;311(5763):1005-1007. doi:10.1126/science.1121629.
64. Yilmaz S, Seifert CM, Daly SR, Gonzalez R. Design Heuristics in Innovative Products. *J Mech Des*. 2015;138(July):1-12. doi:10.1115/1.4032219.

CHAPTER 3. CASE STUDIES OF PROBLEM EXPLORATION PROCESSES IN ENGINEERING DESIGN

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Abstract

Looking beyond the presented problem can allow new perspectives to emerge, opening up the possibility of more varied solutions. Little research exists about how engineering designers engage in this process, which we call *problem exploration*. In a study with engineering students, each student talked aloud as they worked to create design solutions; next, we asked them to explain their problem focus and to define the problem they addressed in each solution. The protocols revealed multiple cognitive strategies used to structure and frame the presented problem in alternative ways. Further research is aimed at empirically-based design tools to support problem exploration in engineering design.

Introduction

Creativity and innovation play a pivotal role in engineering, especially because of the complex, ambiguous, and varying contexts in which engineering design occurs. Creativity is defined as departing from norms through divergence, making unusual associations, and seeing unexpected solutions.[1] However, engineering education often focuses on solving

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convergent and well-defined analytical problems; even when divergent thinking is considered, there is limited attention to exploration of the problem space.[2] We define *problem exploration* as the generation of alternative views or perspectives on a problem in order to discover alternative solutions. Knowledge about how to explore problems is important for improving engineers' understanding of perceived problems, and turning them into successful design solutions.[3,4] Since problem exploration should occur in the early stages of design, it has the potential to affect the creative direction of all succeeding stages.[5]

Despite the significance of reformulating or reframing the problem to provide new opportunities for solutions, problem exploration methods are not generally offered in engineering classes. If taught, the focus is typically on information gathering techniques, such as competitive analysis feasibility studies, and heuristic evaluations, instead of concrete, actionable techniques to restructure the problem space.[6–10] Thus, this study investigated the cognitive processes engineers use to explore and redefine presented problems, with the ultimate goal of developing tools to support broader explorations of problems in engineering design.

Background

The importance of problem exploration is due, at least in part, to the strong relationship that exists between the representation of a problem and the domain of solutions and ideas that the representation can produce.[11,12] Duncker[13] described the process of finding a solution as a continual restructuring of the problem; over time, this problem restructuring can lead to the discovery of "essential" properties of the solution that will, in turn, help dictate an appropriate solution to the given problem. This simultaneous development of both a solution to the problem and an understanding of the problem itself is also called “problem-solution co-evolution”.[14,15] Design researchers have generally focused their attention on the design, implementation, and evaluation stages of a design process[16] rather than on how the dialog between problems and solutions could affect the solution space.

Identification, development, and pursuit of alternative problem definitions are skills that are rarely taught, developed, or assessed, but are essential to engineering excellence.[17] In a study by Cross and Clayburn,[18] each of the expert designers explored the problem from a particular perspective in order to frame it in a stimulating and productive way, challenging themselves to innovate. In another study, the time spent on problem definition – particularly at higher levels of abstraction - was positively associated with client satisfaction in students’ design projects.[19] This supports the claim by Adams and Atman[20] that problem scoping tended to be positively associated with performance, both in terms of design quality and efficiency in the design process. Although research conducted on problem exploration has showcased its importance in engineering design, very little is known about how problems are discovered and formulated.[21,22]

Prior research has used other language to define problem exploration processes -- problem finding, problem framing, and problem definition (defined in Table 6). Problem exploration, as a process, encompasses these overlapping terms. All three terms refer to the early identification of the problem space during problem solving.

Table 6. Synthesized definitions of problem finding, problem framing, and problem defining.

Process	**Description**
Problem finding	Changing the ways problems are envisaged, posed, formulated, and created[21,23–29]
Problem framing	Altering perspectives about a problem description to reveal patterns of reasoning and problem solving that are associated with a particular way of "seeing" the problem, and leading to a possibility to "act" within the situation[11,14,30–33]
Problem defining	Considering the goal or ideal state desired in order to define how much of the problem exists, whether it is worth solving, and even whether or not there is a problem[34]

By changing the understanding and formulation of the problem, a different space of possible solutions emerges. We propose that there is an initial search to "find the problem." [27,35] To illustrate, the white target shapes in Figure 11 below (Circles II and III) represent problem framing. As a consequence of the problem framing, the search space for solutions may be altered in differing ways, and will impact the number and types of solutions designers can identify. In the first diagram (Circle I), the same solution space depicted above appears. In Circle II, the problem space has been altered by the designer's *restructuring*, or *framing*, of the problem. The resulting problem frame has emphasized a portion of the solution space where the designer can envision potential solutions. This results in some solutions becoming no longer accessible because of the problem frame selected. In Circle III, the designer has redefined the problem again, resulting in access to a new, larger area of the solution space that includes novel designs not previously accessible.

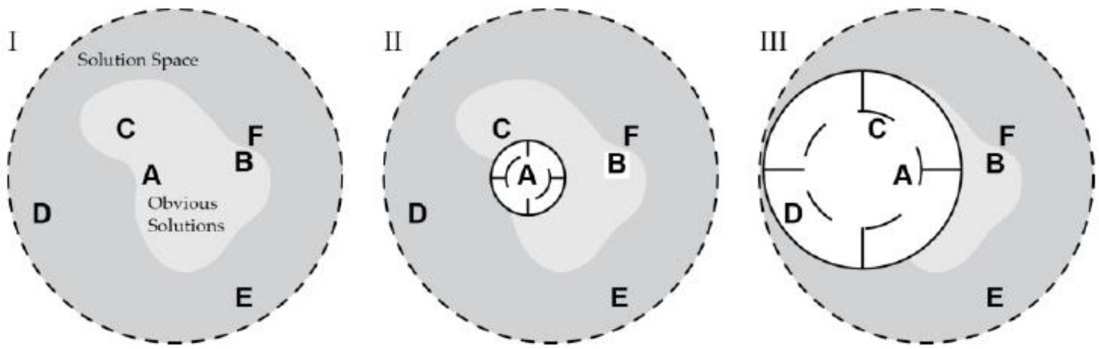


Figure 11. Depiction of the role of problem framing in limiting or opening areas of the solution space

Existing Strategies for Problem Exploration

Some existing techniques have been proposed to help guide engineers in framing and defining design problems. Table 7 provides an overview of current problem exploration techniques found in design literature. All of the techniques propose "trigger questions" that may assist engineers in critically assessing the presented problem and further defining it. One approach offered by MacCrimmon and Taylor identified complexity as a limitation in problem formulation, and provided a review of decision strategies to overcome it.[36] These include: 1) determining the problem boundaries, or examining the assumptions; 2) examining changes, or focusing on any alterations in the problem description; 3) factoring into sub-problems using methods such as morphological analysis[37] and attribute listing[38], and 4) focusing on controllable components, or selective focusing.[39]

Fogler and LeBlanc's[40] textbook on Engineering Problem Solving also proposed several strategies to assist in defining the "real problem" underlying a given engineering problem. These include: 1) employing critical thinking questions to identify assumptions and explore differing viewpoints; 2) using "present state/desired state" analysis and Duncker diagrams[34] to analyze the differences between the current situation and end goal; 3) using

Parnes' statement-restatement method.[41] which suggests prompts to help revise the problem statement (e.g., "place emphasis on different words and phrases"); and 4) using the Kepner-Tregoe problem analysis technique[42] focusing on four problem dimensions (identify, locate, timing, and magnitude) through prompted questions (e.g. "What is the problem versus what is not the problem?").

Two strategies, "5 Whys"[43] and Spradlin's Problem Definition Process[44], have been documented for their use in professional engineering settings. The "5 Whys" technique, documented in use within the Toyota Motor Corporation, repeatedly asks, "Why?" in order to explore the cause and effect relationships underlying a problem. Spradlin's[44] strategy has been used to help companies solve problems and includes steps for defining them. The steps include establishing the need for a solution (e.g. basic need, desired outcome, and benefits), justifying the need, contextualizing the problem, and writing the problem statement.

Table 7. Descriptions of existing problem exploration strategies[45]

Strategy	Brief Description
Present state/desired state analysis and Duncker diagram	Means to determine the real problem by first describing the present state (where you are) and then describing the desired state (where you want to go)[13,34]
Critical Thinking Algorithm	Process to recognize underlying assumptions, scrutinize arguments, and assess ideas and statements using Socratic Questions to prompt the designer[40,46]
Parnes' statement-restatement method	Method to evolve the problem statement to its most accurate representation of the problem using different triggers such as "place emphasis on different words and phrases"[41]
Kepner-Tregoe problem analysis technique	Technique that determines the "four dimensions of the problem" including identify, locate, timing, and magnitude by determining the distinction between "is" and "is not"[42]
5 Whys	Technique that involves asking questions ("Why?") until you get to the root cause of the problem[43]
Attribute listing	Method that involves listing attributes of the problem space, considering the value of each attribute ("what does this give?"), and modifying attributes to increase value, decrease negative value or create new value[38]

Table 7 continued

Selective focusing	Technique that focuses on the problem components that can be manipulated[39]
Spradlin's Problem-Definition Process	Process that includes establishing the need for a solution, justifying the need, contextualizing the problem, and writing the problem statement[44]

Problem Exploration Heuristics

Expert engineers usually explore problems in an intuitive and tacit manner; however, they may not be consciously aware of the strategies they employ in the problem exploration phase.[47] Thus, we propose that engineers use *cognitive* heuristics in order to produce varied perspectives during the problem exploration stage of design. Specific problem exploration heuristics may help the engineer to explore the problem space, leading to the generation of multiple problem frames to consider. Problem exploration heuristics may also support the engineer in generating novel approaches to presented problems, and provide opportunities for surprising, uncommon descriptions that lead to innovative solutions.

The term "cognitive heuristic" comes from the judgment and decision making literature, and refers to cognitive "short cuts" people use in complex problem solving.[11] Problems that lead to creative solutions are rarely solved with systematic, linear approaches; instead, people often use heuristics to "guess" at possible pathways to solutions.[48] Recent work argues that heuristic use is highly advantageous in most situations;[49–51] more specifically, in the idea generation phase of design.[47,52–58] Behavioral research also shows that experts utilize heuristics effectively, and that heavy use of heuristics distinguishes experts from novices.[59] Some research even suggests that heuristics can sometimes lead to optimal solutions when they are focused on key variables in the problem space.[60]

In a previous study, cognitive heuristics were extracted from the problem exploration processes of expert engineers and designers through their work on crowd-sourced design problems.[45] The results demonstrated that problem exploration heuristics are indeed evident and effective in problem definition either prior to, or in parallel with, idea generation. For example, the heuristic *Select a subgroup as the primary stakeholder* was extracted from several engineering design problems and solutions. Using this heuristic, an engineer would 1) brainstorm different subgroups within the given stakeholder group; and 2) select one of the subgroups as the new primary stakeholder to focus the intended solution. This paper will further examine problem exploration heuristics employed by engineers through protocol analysis.

Research Questions

Given the critical connection between the quality of design problems and innovative solutions,[14,15] we seek to establish how cognitive heuristics promote exploration of the problem space to increase innovative outcomes. In the present study, we were guided by the following research questions:

- How do engineers explore design problems, and what heuristics do they use in this exploration?
- To what extent are the student engineers conscious of their use of heuristics when exploring presented problems?

Research Methods

A think-aloud protocol and retrospective interviews were combined to gather data from engineering students of varying levels of expertise while they explored and defined problems. The "think-aloud" or verbal protocol is a research method in which subjects speak their thoughts aloud as they solve problems or perform a task. Think-aloud protocols allow researchers to gain an in-depth understanding of the cognitive processes of participants involved in the study.[61]. Ericsson and Simon[62] have demonstrated the validity of verbal protocol analysis, and argue that think-aloud procedures reveal a sequence of considered information without altering cognitive processes. The resulting data can be treated as objectively like other behavioral data. Thus, it is assumed that cognitive abilities such as memory, decision making, problem-solving, perception, and summarization are not altered when participants are asked to verbalize their thinking as they work on tasks. Participants were also asked a series of questions in a retrospective interview at the end of the session in order to uncover their own interpretation of their thought processes during problem exploration. Retrospective interviews have been used in previous studies analyzing expert designers' concept generation from differing perspectives,[53,63] and have provided an improved understanding of designers' strategies in solving engineering problems.[62]

Participants

Participants were recruited from the Mechanical Engineering undergraduate and graduate programs at a large Midwestern university. In the present study, we report findings from a set of five participants chosen from a larger study. These five participants were chosen based on both the quantity and the quality of the think-aloud data they provided. In addition, these five cases represent a range in domain experience, as well as a range of perspectives considered on the same design problem given. The demographics for the participants selected for this study are provided in Table 8.

Table 8. Participant Demographics

	Gender	Design-related experience
Engineer 1	Female	Senior Mechanical Engineering student
Engineer 2	Male	Senior Mechanical Engineering student
Engineer 3	Male	Senior Mechanical Engineering student
Engineer 4	Female	2nd year Mechanical Engineering graduate student
Engineer 5	Male	2nd year Mechanical Engineering graduate student

Materials

For the protocol studies, we chose an engineering design problem that was (1) novel (so that participants would not be biased by existing solutions) and (2) conceptual (so that it would not require advanced technical knowledge). The design problem was purposefully left open-ended to allow for the generation of multiple, diverse concepts. The problem as presented to each participant was stated as follows:

> "In areas recently stricken by natural disasters (tsunamis, earthquakes, hurricanes, floods, tornados, etc.), large populations are suddenly made homeless and lose access to electricity. Disaster relief efforts focus on rescue, and supplying food and shelter to victims, often meaning that electrical power can be inaccessible for a very long time. Your task is to design a deployable device(s) that can be used at the site of a disaster relief effort. They should be suitable for quick deployment and set-up, and should be operable by everyday citizens, including victims of disaster."

Procedure

Participants completed a one-page demographic survey at the beginning of the study to collect information regarding gender, classification (undergraduate/graduate), and major and were then instructed about the study procedure. For the first task, the participants were given the design problem and asked to generate as many possible solutions as they could think of in the 25 minutes allotted. They were asked to speak out loud, verbalizing any thoughts they had as they wrote notes and/or sketched solutions. Participants were provided with multiple sheets of blank paper to capture the concepts generated, and an audio recorder was on throughout the study. After 25 minutes passed, or the participants had exhausted their ideas (no more than five minutes early), they were asked to describe the problem statements from each of the solutions they generated on additional formatted sheets of paper. The specific prompt for this task was:

> *"For each of the solutions you generated, write a problem statement that would allow other students to come up with the same solution you developed. Imagine that what you write is the only thing the students would see (the given problem statement would not be available). Consider the background, the need and the constraints and criteria."*

Participants had a total of 15 minutes to write a problem definition for each of their solutions. Next, a retrospective interview took place where the participants were asked a series of questions to gather additional insight into their thoughts while defining their problem statements. At the end of the study, participants were also asked a series of questions regarding their previous experiences with problem exploration in both professional and educational contexts. The full set of questions is provided in Table 9. A summary of the tasks involved in the study as well as the time allotted for each task is provided in Table 10.

Table 9. Retrospective Interview Questions

	Interview Question
Thought Process in Defining each Problem	1. What part of the problem does this solution focus on?
	2. How is this problem different from the problem given to you?
	3. Why did you decide to pay attention to certain criteria/constraints/stakeholders/scenarios?* **Question varied based on the problems generated by the participant*
	4. Was there anything you decided not to pay attention to? Why?
Previous Experience in Problem Exploration *in the second retrospective interview only	1. Can you think of a time you changed the problem in one of your classes from the problem given to you? Explain. ○ What prompted the change? ○ What were the differences from the given problem?
	2. Do you typically focus on the problem given to you or do you take time to explore the problem first?

Table 10. Summary of Procedure

Task #	**Task Name**	**Time Allotted**
1	Demographic Survey	1 minute
2	Overview of Procedure	4 minutes
3	Idea Generation Task #1	25 minutes
4	Retrospective Interview #1	15 minutes
5	Idea Generation Task #2	25 minutes
6	Retrospective Interview #2	20 minutes
	Total Time	**90 minutes**

Data Analysis

First, the think-aloud data were transcribed for each of the five participants. The transcriptions, the generated concepts (notes and sketches), and the written problem statements were then simultaneously analyzed by two experienced coders with backgrounds in engineering. For the analysis, each solution was classified ("what was designed?"), and each problem statement was broken down into components (including who the intended solution was for, where the solution would be used, what conditions the solution would be implemented in, and any added constraints, criteria, or assumptions the participants stated in their defined problems). The verbal protocol data were then analyzed, and any additional verbal descriptions not explicitly stated in the problem statement were added. Each component of the problem statement was then compared to the presented problem, and brief descriptions of changes were documented. For example, one participant explicitly stated that a planned solution would be used during a tornado, which narrowed the scope to a specific, rather than general, “natural disaster” as specified in the presented problem. The coders worked independently, and then discussed any disagreements to come to consensus. Figure 12 provides an illustration of the data analysis process.

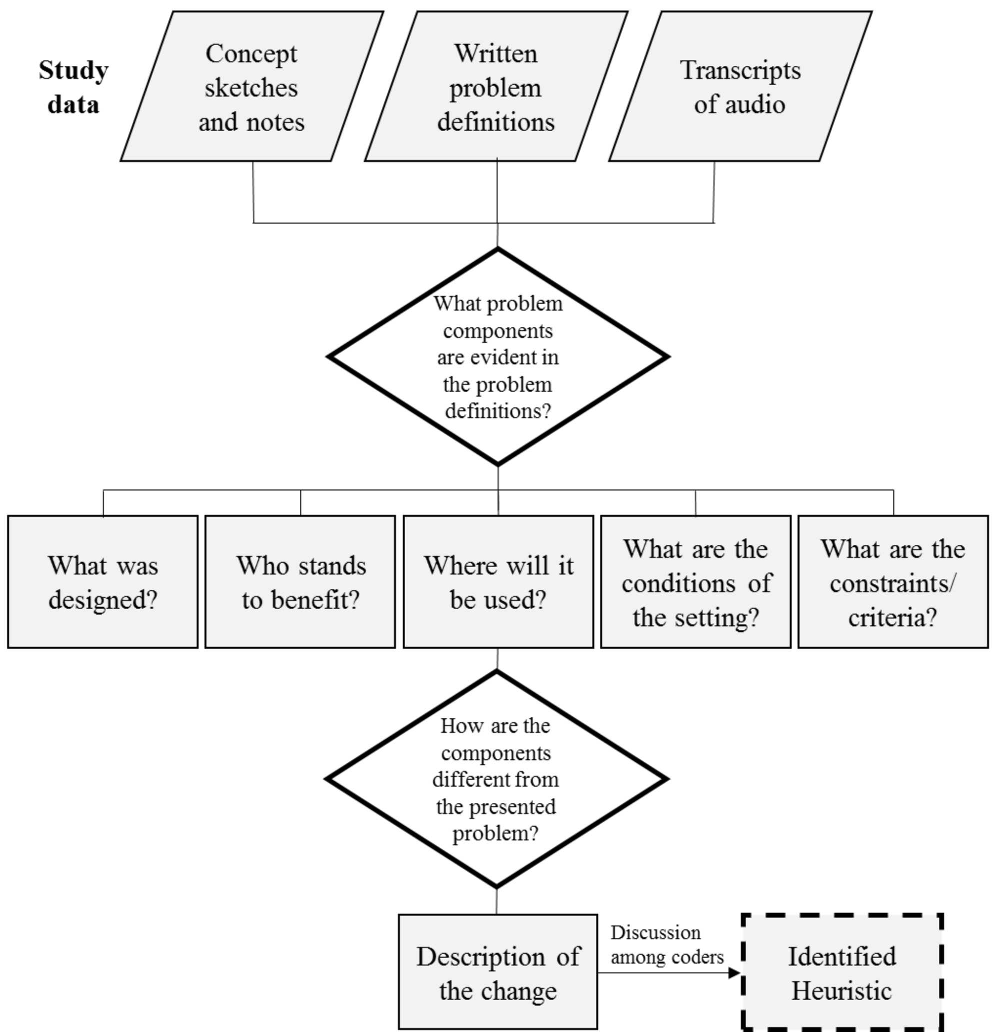


Figure 12. Illustration of the heuristic extraction process used in analyzing the data

Next, the two coders worked together to define a specific heuristic that matched each of the described changes from the interpreted problem statement. The 42 problem exploration heuristics extracted in a prior study[64] were used as a starting point, and new proposed heuristics were added and existing ones were modified as needed. The two coders compared their analyses and agreed upon a common set of problem exploration heuristics observed in the participants' descriptions.

This study captured the initial stages of both problem exploration and solution generation processes, and did not follow the designers through further idea development and iteration (such as stakeholder feedback, where the practicality and feasibility of the designs might be assessed). Therefore, for this study, we did not evaluate the concepts or revised problems with regard to the quality of the proposed solutions; instead, we focused on the ability of the participants to reframe the presented problem into alternative definitions.

Results

Each of the participants created at least four different solution concepts during the 25 minute idea generation task, along with matching revised problem statements during the later problem definition task. This resulted in a total of 28 distinct problem statements (N=5.6, with a range of 4 and 9).

Research Question 1: How do engineers explore design problems and what heuristics do they use in this exploration?

The use of problem exploration heuristics was evident in each of the problem statements defined by the engineering students. Each case is described below, including the heuristics applied within the context of the participants' defined problem statements. We present the results of the analysis of Engineer 1's protocol by detailing each generated solution and problem definition separately, for a total of six concept/definition pairs, to fully demonstrate our data analysis process. The remaining participants' concepts, problem statements and heuristics are summarized briefly and detailed in one consolidated table at the end of each case explanation.

Case 1

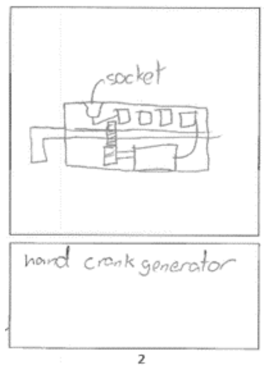
Engineer 1 focused all of her concepts on devices that victims can use after a disaster occurs. For the first concept, she developed a plywood house with a tarp/curtain door. Throughout her idea generation process, she significantly narrowed the problem by deciding to focus on providing shelter for disaster victims (*Break down the primary need*), selecting families as the main stakeholder group (*Break down the primary stakeholder*), and concentrating on tornado disasters instead of all types of disasters (*Focus on one scenario*). She also analyzed the setting where the solution would be used and focused on the part of the given problem statement that said electricity would be scarce *(Define the characteristics of the setting)* and added that only easily salvageable materials would be available *(Describe the material characteristics)*. Furthermore, she thought about the needs of the users, in this case, families, and added the need for privacy and comfort after the disaster takes place (*Determine the end user and detail their needs*). She also determined the operational requirements of the intended solution by stating the need for it to operate for an extended period of time (*Detail the operational requirements*). By examining the problem as a whole (the scenario, the setting, the users, etc.), the participants also determined that the solution needed to be cheap *(Determine the required cost).* Tables 11 through 16 show this participant's concept sketches and descriptions, interpreted problem statements, the heuristics identified from the transformation of the initial problem statement, and a description of the heuristics in the context of the problem.

Table 11. Engineer 1 Problem Statement 1

<table>
<tr><th>Concept Sketch and Description</th><th>Interpretation of Presented Problem</th><th>Heuristic Identified</th><th>Heuristic Use in Context</th></tr>
<tr><td rowspan="8">
</td><td rowspan="8">"Tornado torn through the town. Using easily salvageable components, create a single family shelter. Note that electricity will be scarce and families may be in this shelter for an extended period of time."</td><td>Break down the primary need</td><td>narrowed the focus to providing shelter for victims of a disaster</td></tr>
<tr><td>Break down the primary stakeholder</td><td>specified that the solution will be designed for families in a disaster area</td></tr>
<tr><td>Define the characteristics of the setting</td><td>stated that electricity is scarce in the area where the solution will be used</td></tr>
<tr><td>Focus on one scenario</td><td>selected a tornado as the primary scenario the solution will be used in</td></tr>
<tr><td>Describe the material characteristics</td><td>added the requirement to use easily salvageable materials only</td></tr>
<tr><td>Determine the required cost</td><td>added a solution requirement for it to be cheap</td></tr>
<tr><td>Determine the end user and detail their needs</td><td>added the need for privacy and comfort for the families that will be using the solution</td></tr>
<tr><td>Detail the operational requirements</td><td>stated that the solution must be able to be used for an extended period of time</td></tr>
</table>

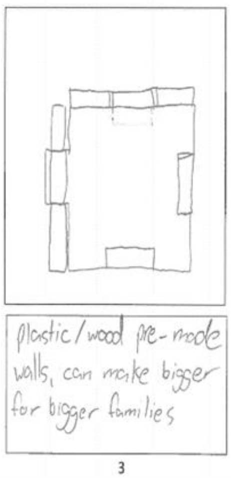
The second concept was a hand crank generator that can be used by every day citizens. Similar to the first problem statement, the engineer narrowed the focus of the problem by breaking down the primary need. In the second problem, she decided to focus on providing power/electricity to those in need, and providing power at little cost, again defining the cost requirements. She also expanded the number of scenarios the solution could be used in by not specifying that it needs to be used in a disaster area, but instead, stated that it could be used anywhere with limited or no power available. The problem and the extracted heuristics are represented in Table 12.

Table 12. Engineer 1 Problem Statement 2

Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"The client is in an area where electricity is scarce. Come up with a method to produce at least a small amount of power at a little cost with easy to find items."	Break down the primary need	narrowed the focus to providing power/electricity to those that need it
		Incorporate additional scenarios	generalized the setting to anywhere with limited or no power
		Determine the required cost	stated the need for the solution to provide power at little cost

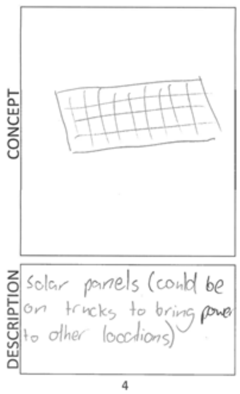
The third concept proposed pre-made walls that can be made "bigger for bigger families". Comparable to the first problem statement, the engineer narrowed the problem by focusing on providing shelter and selecting an earthquake as the primary scenario the solution would be used in. She also specified the need for the solution to be cheaper than a tent, providing a more specific cost requirement than the previous two problem statements. Again, she examined the needs of the end user and defined easily constructible and lightweight as new solution requirements in order for the users to be able to set up the shelter on their own. She also referenced Legos as conceptual inspiration. Like Legos, people should have the ability to easily put building block pieces together to create a shelter (Table 13).

Table 13. Engineer 1 Problem Statement 3

Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"Design an easily constructible and versatile shelter that is light weight and can be used by everyday citizens."	Break down the primary need	narrowed the focus to providing shelter for victims of a disaster
		Focus on one scenario	selected an earthquake as the primary scenario the solution will be used in
		Describe an existing solution to use as conceptual inspiration	referenced Legos as a source of inspiration for the solution
		Determine the required cost	specified the need for the solution to be cheaper than a tent
		Determine the end user and detail their needs	provided additional criteria to benefit the end user including easily constructible and lightweight to help the users in set up, and flexible sizing to assist larger families

The fourth concept presented solar panel trucks. The engineer focused the primary need on providing power/electricity to the victims of the disaster, and specified that electricity is hard to come by at the disaster site. The problem statement included the need for the solution to be mobile. She also thought about how the intended solution could be used by providing potential use cases including plugging in a fridge to save perishables (Table 14).

Table 14. Engineer 1 Problem Statement 4

Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"After a natural disaster, electricity can be difficult to come by. Create a method to bring power to locations where a natural disaster has happened."	Break down the primary need	narrowed the focus to providing power/electricity to victims of disaster
		Define the characteristics of the setting	specified that electricity is hard to come by
		Integrate mobility	added the need for the solution to be mobile
		Prioritize use cases	included a case for using the solution - can plug in the fridge with perishables

For the fifth concept, the engineer proposed a jack for lifting heavy objects. Similar to the preceding problem statements, she chose to concentrate on one aspect of the problem to solve, but this time shifting the focus to rescuing victims. She selected an earthquake or a tornado as the primary setting for the solution. She examined user needs and determined that safety of all users was an important requirement. She also detailed the notable characteristics of the disaster setting including that professionals (i.e. rescuers) would not be available (Table 15).

Table 15. Engineer 1 Problem Statement 5

Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"Create a device that would allow everyday citizens to assist in the aid or rescue of another person in an emergency when professionals are not near. Keep in mind the safety of all parties."	Break down the primary need	narrowed the focus to victim rescue
		Determine the end user and detail their needs	added the requirement for it to be safe for all users
		Define the characteristics of the setting	specified that professionals (i.e. rescuers) are not near the disaster or can't get to the victim
		Focus on one scenario	selected an earthquake or a tornado as the primary scenarios the solution will be used in

The final concept was a rainwater collector/purifier. Similar to the other five problems, the engineer narrowed the focus of the problem to providing clean water, and selected flooding as the primary scenario, analyzed the disaster site, and specified that the town's water supply was undrinkable (Table 16).

Table 16. Engineer 1 Problem Statement 6

Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"A flood has ripped through a town making most of the town's water undrinkable. Create a device that would aid in getting the town's people clean water to drink."	Break down the primary need	narrowed the focus to providing clean water
		Focus on one scenario	selected a flood as the primary scenario the solution will be used in
		Define the characteristics of the setting	specified that the town's water supply is undrinkable

Engineer 1 narrowed the problem by breaking down the primary need into sub-problems, including shelter, power/electricity, rescue, and clean water, and by selecting one or more natural disasters where the solution would be used. This narrowing influenced the types of solutions that she generated. By examining the setting of the disaster, Engineer 1 determined the characteristics necessary to solve the problem. For example, by first noting that the town's water supply was undrinkable (problem statement 6), it was evident that providing clean water was at the top of the priority list and that a solution was needed to solve that problem. Examining the setting also allowed her to examine the required materials, the need for mobility, the resources available, and the operational requirements of the solution.

"Analyzing the end users" was another strategy also frequently utilized by Engineer 1. By doing so, she was able to come up with criteria that the solution must adhere to in order to meet the needs of the user, including privacy, comfort, and safety. When describing the first problem statement, she stated, “It’s important to think about comfort when making it since 100 families just lost their houses and they may be there for a while.” Defining cost requirements was also used in several problem statements, though less specific, by stating the need for a solution that was “cheap,” “little cost,” and “less than a tent.” Problem statement 2 was the only statement in which the engineer expanded the problem from its original form. By stating that “the client is in an area where power is scarce,” she opened up the potential solution space to include solutions that might account for blackouts or underdeveloped countries where power is always scarce, not just after a natural disaster occurs.

Case 2

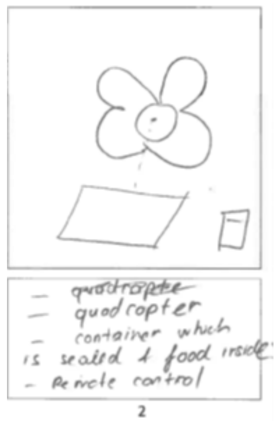
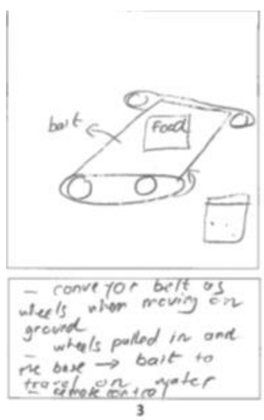
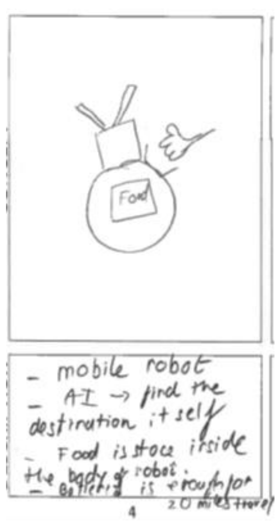
Engineer 2 generated four concepts and derived four distinct problem definitions. All of the problems interpreted by the engineer were similar in nature, with a few recognizable differences that influenced the type of solution generated. He first decided to narrow each of the problems by focusing on providing food to the disaster area, with the last problem also focusing on scouting the area for survivors first. He stated that he first thought about “the requirement for a deployable device, how mobile it should be, how far it needed to travel every day, and how much food or what kind of supply I need to carry.” In each of the problems, he also examined the disaster area, and added descriptions of the setting to the problem statements because “the given statement didn’t mention anything about the conditions.” This included adding detail on the condition of transportation and infrastructure (problem 1), stating that all roads are destroyed (problems 2 and 3), and stating that the level of damage and the number of injuries is unknown since the town is inaccessible to outsiders (problem 4). Problem 2 also noted that "the only way of transportation to the area is by air," which provided a focus on designing an aerial device.

Three out of the four problem statements focused on one particular natural disaster, with the first problem stated broadly, similar to the presented problem statement. The third problem focused on floods ("most of the area was filled with water"), which led the engineer to think about the requiring the device to be able to travel on both roads and water. All of the problem descriptions also contained detail on the operational requirements of the device. The first three problems specified that the device needed to be operated from a distance, while the final problem took it one step further and specified that the solution needed to be operable for at least 20 miles and to be autonomous (no user interaction while operational). By adding more descriptive requirements to the problem statement, the final generated solution was more distinct than the others. The heuristics extracted from each of the problem definitions and the description of the heuristic used in context are summarized in Table 17.

Table 17. Engineer 2 Concepts, Interpreted Problems, and Heuristics

Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"There was a disaster that damaged the road and regular cars can't travel thru. The road was covered in mud and a special transportation is needed to deliver food to the residents of the area."	Break down the primary need	narrowed the focus to transportation and food delivery to the disaster area
		Define the characteristics of the setting	added detail on the condition of transportation and infrastructure of the damaged area
		Detail the operational requirements	specified that the device needs to be operated from a distance

Table 17 continued

	"There was a tsunami happened that destroyed all of the roads and other accessibility to the area. The only way of transportation to the area is by air. The device needs to be accessible to the area."	Break down the primary need	narrowed the focus to transportation and food delivery to the disaster area
		Focus on one scenario	selected a tsunami as the primary scenario the solution will be used in
		Define the characteristics of the setting	stated that all roads are destroyed leaving air as the only option
		Detail the operational requirements	specified that the device needs to be operated from a distance
	"There was a horrible flood in a residential area. Some of the roads was damaged and most of the area was filled with mud/water. The transportation device should be able to deliver food and travel both on ground and water."	Break down the primary need	narrowed the focus to transportation and food delivery to the disaster area
		Focus on one scenario	selected a flood as the primary scenario the solution will be used in
		Define the characteristics of the setting	stated that all roads are destroyed
		Detail the operational requirements	specified that the device needs to be operated from a distance
		Detail the required functions	specified the requirement to travel both on ground and water
	"A horrible earthquake just happened and we don't know the level of injuries inside the town since all the access to the town were destroyed. We need a smart device that can travel through the area and be able to look for people who still survive and provide them with food a necessity."	Break down the primary need	narrowed the focus to scouting and food delivery to the disaster area
		Focus on one scenario	selected an earthquake as the primary scenario the solution will be used in
		Define the characteristics of the setting	stated that the level of damage or number of injuries is unknown; specified that the town is not accessible to outsiders
		Detail the operational requirements	added the requirement for the device to be able to travel at least 20 miles; added the requirement for the device to be autonomous

Case 3

Engineer 3 identified nine unique problem definitions and generated nine concepts. Similar to the first two engineers, he narrowed the problem by breaking down the need of the given description ("assist at the site of a disaster relief effort") into smaller sub-problems. Unlike Engineer 2, he focused on a variety of different aspects including providing shelter, water, and supplies (problems 1, 6), power (problems 2, 5), comfort (problem 3), communication (problem 4), survival (problem 7), and food (problems 8, 9). Also, in two of the nine problem descriptions, he decided to focus the solution on when a specific disaster occurs (problems 3 and 7), leaving others to incorporate all natural disasters. The engineer expanded the scenarios in which the solution could be used in problems 2 and 5 by stating that the device could be used anywhere electricity is not available and not necessarily when a natural disaster occurs. Problems 1-3 and 5 focused primarily on the mobility of the device to solve each of the corresponding problems interpreted by the engineer.

After narrowing the scope of the problem, the engineer examined the setting (the disaster area) and defined characteristics that he felt were important to know when designing the final solution. These characteristics included having no power available, possible rain showers (resulting in 'water-resistant' requirements), air as the only way to access the area, and people not being able to go in or out of the area. These descriptions provided a clearer direction for solving the problem, and ensured that all the conditions were taken into account. For example, problems 4 and 6-9 stated, "air is the only way to access the disaster area" in the problem description, which resulted in solutions that were airdropped from the sky. If this description of the setting was left out of the problem statement, a solution that needed to be transported by roads could have been generated which would not have been applicable for this scenario.

The engineer also specified primary uses of the solution in three of the nine problems in order to focus the set of potential designs. These uses included calling family or other help (problem 2), contacting other survivors (problem 4), and powering fridges to keep food safe and cell phones to call for help (problem 5). Cost was another aspect of the problem the engineer thought about when defining new problem statements which wasn't explicitly stated in the given problem. However, the cost requirements were left broad, only specifying the need for the solution to be "cheap". Problem 1 was the only problem where the engineer broke down the primary stakeholder group by specifying that the solution will be designed specifically for families. However, he did also explore the end user group and detail their needs by stating that the disaster victims will require privacy (problem 3), and a lightweight device so the users can construct the device themselves (problem 9). In problem 3, the engineer also explored a potential secondary function of the solution (not a must-have), adding that it could also collect rainwater in addition to providing a shower and bathroom to the disaster victims. He also showcased a new heuristic, *Determine the context of operation*. This heuristic refers to a condition that needs to be met in order for the solution to work. In the context of this problem, the engineer specified that sunlight is required to charge the device (problem 2) and heat the water (problem 3). The heuristics extracted from each of the problem definitions and the description of the heuristic used in context are summarized in Table 18.

Table 18. Engineer 3 Concepts, Interpreted Problems, and Heuristics

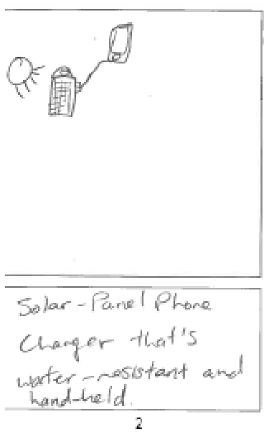
Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	"Create a mobile trailer for victims of disasters to live in with supplies inside."	Break down the primary need	narrowed the focus to providing shelter, water, and supplies to victims of disaster
		Integrate mobility	added the need for the solution to be mobile
		Define the characteristics of the setting	stated that no power was available and added the need for it to be water-resistant since it may be raining
		Break down the primary stakeholder group	specified that the solution will be designed for families in a disaster area
	"Create a method for charging a hand-held device that is portable, water-resistant and uses sunlight."	Break down the primary need	narrowed the focus to providing power to the disaster site
		Integrate mobility	added portability as a solution requirement
		Define the characteristics of the setting	stated that it could be raining so the solution needed to be water-resistant
		Determine the context of operation	specified the need for sunlight to charge the device
		Determine the required cost	specified the need for the solution to be cheap
		Incorporate additional scenarios	stated the device could be used anywhere electricity is not available, not necessarily for a natural disaster
		Prioritize use cases	specified the primary uses of the solution will be to call family or to call for help
	"Create a mobile trailer for victims of disasters to shower and go to the bathroom in."	Break down the primary need	narrowed the focus to providing comfort (a shower and bathroom) to the victims of disaster
		Focus on one scenario	selected a hurricane or flood as the primary scenarios the solution will be used in
		Integrate mobility	added portability as a solution requirement
		Determine the context of operation	specified the need for sunlight to heat the water

Table 18 continued

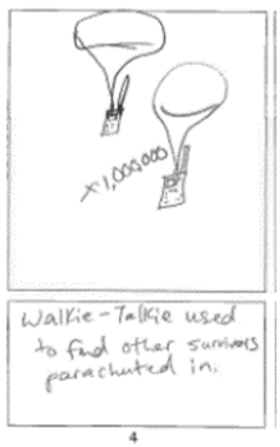
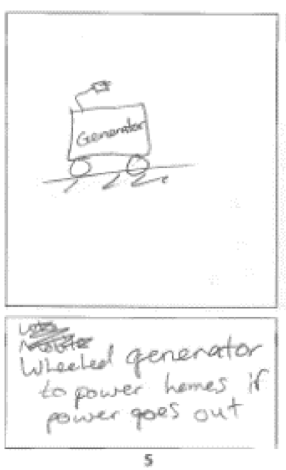
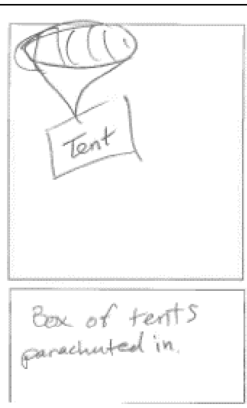
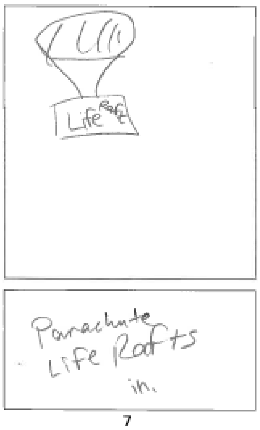
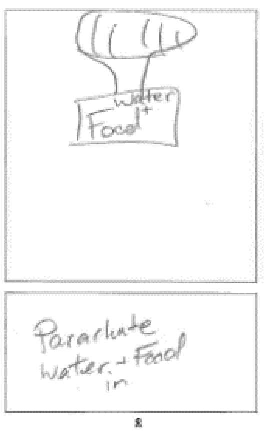
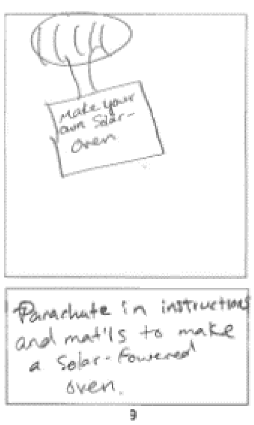
		Determine the end user and detail their needs	thought about the need for user privacy when in the showers and bathrooms
		Describe secondary functions	added rainwater collection as a secondary function
	"Create a method of delivering walkie-talkies to people on the ground from in the air."	Break down the primary need	narrowed the focus to communication and victim survival
		Define the characteristics of the setting	stated that air is the only way to access the disaster area
		Prioritize use cases	specified the primary uses of the solution will be to connect with other people and find survivors
	"Design a ground-mobile generator."	Break down the primary need	narrowed the focus to providing power to the disaster site
		Integrate mobility	added the need for the solution to be mobile
		Prioritize use cases	included cases for using the solution - can power fridge to keep food safe, power cell phone to call for help
		Incorporate additional scenarios	stated the device could be used whenever power goes out, not necessarily for a natural disaster
		Define the characteristics of the setting	stated that the area is inaccessible and that no person can go in our out
	"Create a method for delivering boxes of tents to people on the ground from the air."	Break down the primary need	narrowed the focus to providing shelter to disaster victims
		Define the characteristics of the setting	stated that the air is the only accessible point

Table 18 continued

	"Create a method for delivering life rafts to people on the ground from the air."	Break down the primary need	narrowed the focus to survival of disaster victims
		Define the characteristics of the setting	stated that the air is the only accessible point
		Focus on one scenario	selected a tsunami as the primary scenario the solution will be used in
	"Create a method for delivering food and water to people on the ground from the air."	Break down the primary need	narrowed the focus to providing food and water to the disaster victims
		Define the characteristics of the setting	stated that the air is the only accessible point
	"Create a method for delivering instructions and materials for making your own solar oven."	Break down the primary need	narrowed the focus to providing food and water to the disaster victims
		Define the characteristics of the setting	stated that the air is the only accessible point
		Determine the end user and detail their needs	added the requirement for it to be lightweight so users can construct the device themselves
		Determine the required cost	specified the need for the solution to be cheap

Case 4

Engineer 4 defined four unique problems and generated four concepts. All four of the problems related to one another in that the intended devices behaved similarly, but solved different needs. Problem 1 concentrated on providing electrical power for victims of disasters ("no electricity is available"), while the other problems focused on providing rescue, providing food, and providing shelter for disaster victims, respectively. In addition, all four problems focused on a device that would be used during natural disasters involving water. This distinction led the engineer to defining user criteria by stating "all these natural disasters, they involve water in some way, so the safety of the device (is important) to avoid electric shock". She also decided to focus all of the problems on designing a device that the rescuers could use, unlike the problem descriptions of the previous engineers, as well as the given problem, that focused on devices used by the disaster victims.

For problems 2-4, Engineer 4 outlined the required functions of the intended solutions after walking through each of the scenarios and determining what the device needed to do. She determined that the solutions would have to be able to navigate to a safe place after performing the primary functions of identifying and extracting victims (problem 2), carrying food (problem 3), and carrying items for shelter (problem 3). The engineer also determined that the last two solutions needed the ability to communicate with the rescue device (problem 1) for the purpose of navigating toward victims requiring food and shelter. The term "simplicity" was used often when generating the problem descriptions, and she stated the importance of "limiting the functions…so that we aren't complicating the functionality of it for the users" at the beginning of the task. This engineer also examined the operational requirements of the intended solution and determined that the solution of problem 3 needed to operate on its own in case communications were down at the rescue command center. She also specified in problem 1 that the device needs to last a long time without recharging or maintenance. Problem 3 also showcases a heuristic that was not seen in previous examples, called *Describe the required dimensions*. The engineer added a load requirement for the device, stating that the solution needed to be able to lift heavy objects (e.g., people). The heuristics extracted from each of the problem definitions and the description of the heuristic used in context are summarized in Table 19.

Table 19. Engineer 4 Concepts, Interpreted Problems, and Heuristics

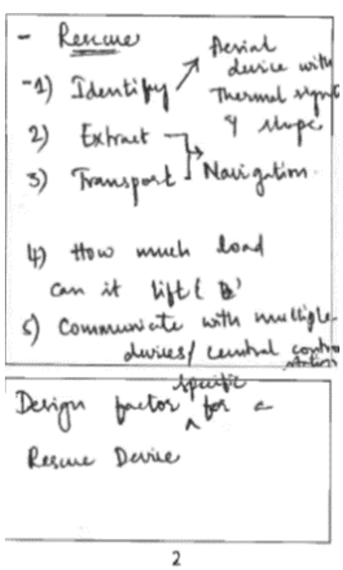
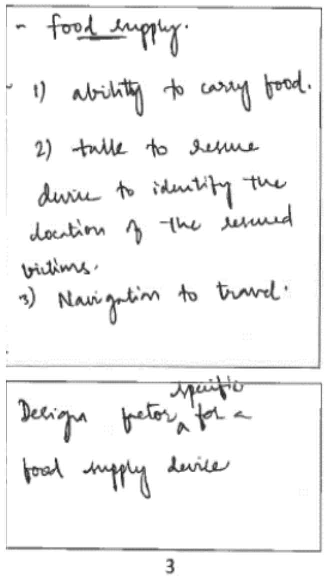
Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
	You have to come up with general design requirements for a deployable device that could be used for rescue efforts for victims of natural disasters (mostly involving water). Electric power is not accessible on the site, and lot of surrounding water. Should be operable by everyone.	Break down the primary need	narrowed the focus to providing electrical power for victims of disasters
		Define the characteristics of the setting	stated that no electricity is available and there is standing water
		Detail the operational requirements	specified that the device needs to last a long time (no recharging needed, no maintenance)
		Determine the end user and detail their needs	thought about the disaster victims and added the need for the device to be compact, simple, and safe for all users
		Focus on one scenario	selected water natural disasters as the primary scenarios the solution will be used in
	The device(s) should focus on rescue, food, and shelter. What are the specific design requirements for each of these functionalities? Assume you have three devices for each these functions, what are the requirements for the device?	Break down the primary need	narrowed the focus to providing rescue for victims of disasters
		Detail the required functions	specified the required functions of the device - identify victims, extract victims, and navigate to a safe place
		Describe the required dimensions	added a minimum load requirement of the device (needs to be able to lift heavy items, i.e. people)
		List individuals or groups that are associated with the given primary stakeholder	changed the primary user from the victims of the disaster to the rescuer

Table 19 continued

	What are the design requirements for a food supply device?	Break down the primary need	narrowed the focus to providing food for victims of disasters
		Detail the required functions	specified the required functions of the device - carry food (primary), communicate with rescue device, navigate to a safe place
		List individuals or groups that are associated with the given primary stakeholder	changed the primary user from the victims of the disaster to the rescuer
		Define the characteristics of the setting	stated that something could be wrong with the command center
		Detail the operational requirements	added the requirement that the device needs to operate on its own and communicate with other devices
	What are the design requirements for a shelter device?	Break down the primary need	narrowed the focus to providing shelter for victims of disasters
		Detail the required functions	specified the required functions of the device - carry items for shelter (primary), communicate with rescue device, navigate to safe place
		List individuals or groups that are associated with the given primary stakeholder	changed the primary user from the victims of the disaster to the rescuer

Case 5

Engineer 5 defined five distinct problems and generated five solution concepts, including two problems that solved different needs than those of the previous four engineers. Similar to the problem descriptions defined by the previous engineers, Engineer 5 narrowed the problem by breaking down the primary need into sub-problems, including providing power (problem 1), supplies (problem 2), and food (problem 4). However, he was able to come up with two other needs, including providing light to the disaster area during the night (problem 3) (even narrower than providing power), and providing medical care (problem 5) (narrower than providing rescue). In four of the five problems, the engineer decided to focus on one natural disaster where the solution would be used. In all but one of the problems, the engineer also specified that there is no electricity available, which was taken from the presented problem statement. The last two problems went further by stating that there's also no gas to cook food (problem 4) and that the local hospital is devastated (problem 5). The engineer also changed the primary user of problem 5 from the disaster victim to the medical team sent in to help victims, essentially taking away the requirement that the device needed to be operable by everyday citizens.

Engineer 5 added more detail to each of the problem descriptions in a variety of ways. In problem 1, he added operational requirements stating that the device needed to store a charge for 12 hours, and that the primary uses of the solution will be to charge laptop or mobile phone for communication. In problem 2, he added a secondary function of the device, "provide Wi-Fi," in addition to providing supplies (specifically, mobile batteries and dry goods). For problem 3, the engineer referenced glow sticks as a source of inspiration since they function similarly to the intended solution. The problem description also stated that solutions should consider using chemiluminescence as the material component. This engineer described the dimensional requirements in problem 4 by stating that the device needs to be small in order to be transported to the disaster site. In the final problem description, the engineer also stated that the primary function of the medical device is to check glucose levels of survivors, providing focus to the type of medical device designed. The heuristics extracted from each of Engineer 5’s problem definitions and a description of each heuristic used in context are summarized in Table 20.

Table 20. Engineer 5 Concepts, Interpreted Problems, and Heuristics used

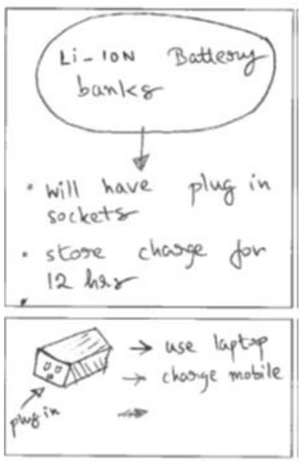
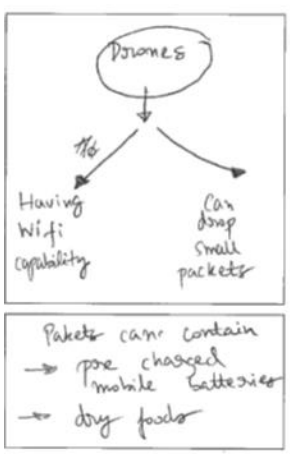
Concept Sketch and Description	Interpretation of Presented Problem	Heuristic Identified	Heuristic Use in Context
 1	Many people are trapped in a city which has faced a massive earthquake last day. They have run out of electric power. As the VP of a huge mobile battery manufacturing company you decide to help the victims in their hour of need. How many you help by using technology?	Break down the primary need	narrowed the focus to providing power to the disaster area
		Detail the operational requirements	specified the need for the device to store charge for 12 hours
		Focus on one scenario	selected an earthquake as the primary scenario the solution will be used in
		Define the characteristics of the setting	stated that there is no electricity available
		Focus on one setting	specified that the disaster area is in a city
		Prioritize use cases	specified the primary uses of the solution will be to charge laptop or mobile phones for communication
 2	How can airborne drones be used is establish communication in a disaster relief site where people have access is operational mobile/computer but no internet connection?	Break down the primary need	narrowed the focus to providing supplies to disaster victims
		Describe secondary functions	added a secondary function of the device-provide Wi-Fi
		Prioritize use cases	specified the primary use of the solution will be to provide mobile batteries and dry goods

Table 20 continued

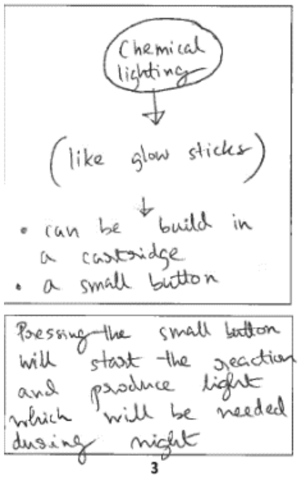
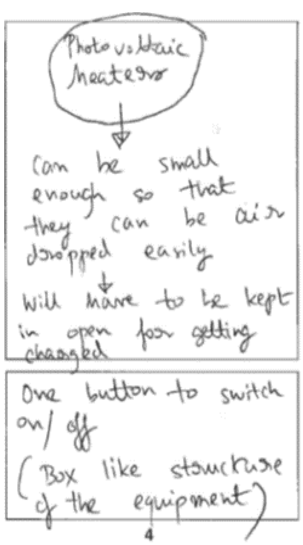
<table>
<tr><td rowspan="6">
</td><td rowspan="6">The recent flood has cut off the village's power supply and the survivors are having a hard time during night because of darkness. You recently came across a scientific article on chemiluminescence. Can you apply it to solve this problem of darkness?</td><td>Break down the primary need</td><td>narrowed the focus to providing light to disaster areas during the night</td></tr>
<tr><td>Describe an existing solution to use as conceptual inspiration</td><td>referenced glow sticks as a source of inspiration for the solution</td></tr>
<tr><td>Determine the context of operation</td><td>specified the need for it to be nighttime for the device to work as intended</td></tr>
<tr><td>Focus on one scenario</td><td>selected a flood as the primary scenario the solution will be used in</td></tr>
<tr><td>Define the characteristics of the setting</td><td>stated that there is no power supply available</td></tr>
<tr><td>Describe the material characteristics</td><td>specified that the solution should consider using chemiluminescence</td></tr>
<tr><td rowspan="4">
</td><td rowspan="4">Without electricity and gas connection the survivors of the recent tsunami are having a difficult time in preparing/making food. As the government representative from the renewable energy and resources department you are to come up with the action plan. What could it be? Hint: solar.</td><td>Break down the primary need</td><td>narrowed the focus to providing food to disaster victims</td></tr>
<tr><td>Focus on one scenario</td><td>selected a tsunami as the primary scenario the solution will be used in</td></tr>
<tr><td>Define the characteristics of the setting</td><td>stated that there is no electricity or gas available so there is no way to cook food</td></tr>
<tr><td>Describe the dimensional requirements</td><td>specified that the device needs to be small in order to be transported to the disaster site</td></tr>
</table>

Table 20 continued

	You need to have a quick and fast assessment about the health conditions of the tornado survivors. However there is no electricity to get up a small diagnostic center and the local hospital is devastated. What can you do now? Hint: Point-of-care diagnostics	Break down the primary need	narrowed the focus to providing medical care to disaster victims
		Focus on one scenario	selected a tornado as the primary scenario the solution will be used in
		Define the characteristics of the setting	stated that there is no electricity and the local hospital is devastated, therefore the device shouldn't use electricity or fancy equipment
		Detail the required functions	specified the primary function of the device - check glucose levels of survivors
		List individuals or groups that are associated with the given primary stakeholder	changed the primary user from the disaster victim to the medical team sent in to help victims

Research Question 2: To what extent are student engineers conscious of their use of heuristics when exploring presented problems?

The five engineers seemed to be aware of their use of heuristics when generating their problem definitions during the retrospective interview; however, it's not clear whether they were aware of using certain strategies during the task of defining the problems. Each engineer articulated at least a few transformations after being prompted to describe how their problem definition was different from the presented problem (e.g., "Mine is narrower because…"). For example, Engineer 1 was aware she was considering a more specific natural disaster than presented, and that she added the specification for easily salvageable materials in her first problem definition. She explained that she thought about what materials were available at the location; however, she was unable to explain why she decided to focus on one natural disaster instead of all disasters. Engineer 3 recognized that he was being more specific in his problem definitions ("fits inside of but doesn't explain the original problem statement"), but he stated a few times that he didn't know why he did [narrow the problem]. Engineers 1 and 2 were initially confused by the extensiveness of the presented problem, and immediately asked several questions to better define it, demonstrating their discomfort with broad definitions and most likely their inexperience in problem framing. In addition, all of the engineers expressed some confusion about what it meant to define the problem descriptions, suggesting that it is not common practice in their training.

Discussion

The analysis of the think aloud protocols from engineering students showed that problem exploration indeed occurs, and is associated with making shifts in design decisions. In particular, Engineers 2, 3, and 4 immediately addressed problem requirements and set boundaries for the problem space prior to beginning to generate ideas:

> Engineer 2: "First I would think about what the requirements are for the deployment device, how mobile it should be, how far it needed to travel every day, or how much food or what kind of supply it needs to carry whether it's water or just food. I will assume that [it's for] a hundred people, and it's going to make several trips a day, so it needs to carry at least a decent amount of food for each trip."
>
> Engineer 3: "I'm going to write down some requirements. Setup, it needs to be intuitive and needs to be deployable in areas of disaster, like where tsunamis, earthquakes, or floods. Large population is made homeless, access to electricity. I

don’t think it would have to be self-sustaining…The power is self-sustaining. Should probably be water resistant at least because most of those listed there include water. It needs to help a lot of people at a given time.”

Engineer 4: “Okay, based on the constraints that are given here, first I’m trying to come up with a list of all the things that need to be satisfied design-wise…First thing that as I said is like a power source, then how it should last long, and then it should be compact. The second thing is all these natural disasters, they involve water in some way, so the safety of the device, it shouldn't shock the victims apart from the shock of the natural disasters, I meant electric shock, so safety. The next thing is the quick deployment and setup. It would be good to have a device which is already programmed to do a specific function so that they don't need to do a setup dance… The whole thing is since it should be operable by every citizens, simplicity on how it is”.

After a preliminary exploration of the problem, Engineers 2, 3, and 4 added additional context and requirements for each interpretation of the presented problem. Engineers 1 and 5 did not set any initial boundaries, but proceeded directly to idea generation while considering the problem simultaneously. These findings document how problem descriptions change in character as new solutions are created; with each iteration, the resulting solution shifted. Prior research identified a “coevolution” of problems and solutions rather than discrete, separable stages in the creative design process.[14] Our findings confirm the merged stages in some protocols, such as when Engineer 1 quickly identified shelter as the primary need, calling it was the “easiest to solve…being a mechanical engineer,” and generated a solution with a plywood house with a tarp for the door. Engineer 1 also spoke about the need for "salvageable materials" in order for quick deployment of solutions.

The goal of this research was to identify heuristics for developing problems as employed in the 'fuzzy-front end' of the design process. To support this goal, three problem exploration heuristics were identified across all five cases described, suggesting common practices across engineering students at various levels. The heuristic, *Break down the primary need,* was seen in all 28 problem descriptions. This finding showcases the prominence of reducing, or narrowing, the scope of the problem during problem exploration. Previous research identified a similar strategy in the problem solving process ("defining a sub goal"), and it has proven to be effective in reducing the size of the problem space.[12,65] Reed and Abramson[66] also determined that the specification of a sub-goal may be a useful teaching technique for students who cannot solve a presented problem. The other two commonly observed heuristics, *Define the characteristics of the setting* and *Focus on one scenario*, were extracted from 22 and 14 different problem descriptions, respectively. This suggests that converging on one situation, in this case a particular natural disaster, and defining characteristics of the locations where it would take place (e.g., infrastructure damaged by flooding), were recurrent exploration strategies used among the five engineers.

The heuristics, *List individuals or groups that are associated with the given primary stakeholder*, *Describe the required dimensions*, *Focus on one setting,* and *Describe the required functions,* were used more often by the more advanced students. However, the majority of the heuristics were observed relatively evenly across all participants. In addition, *Focus on one setting* was observed only once in the problem definitions (Engineer 5, problem 1), suggesting that this heuristic was not common among the five engineers. This could be explained by the nature of the design problem; because the focus was on designing a device at the site of a disaster, identifying a more specific setting isn't necessary to solve the problem. However, in a problem such as designing a playground, the setting may be more important to specify in order to explore, for example, the current landscape, the materials that can be used, and who would use the playground on a regular basis. Nevertheless, the analysis of the protocols from all engineering students involved in the larger study is necessary to accurately gauge the frequency of heuristic use.

The engineers tended to narrow the problem space by focusing on one or more of the following: a particular need, a certain type of disaster, a specific stakeholder/user, the limitations of the environment (e.g. the town is inaccessible), the specific ways the disaster victim could make use of the device, and the requirements such as cost, functionality, dimensions, means of operation, and user needs. Existing research has focused on problem reduction as a rational and efficient approach for complex problem solving;[66,67] however, according to Maier,[68] the problem may never be fully understood or validated if focusing occurs too quickly. A solution may be to expand or broaden the scope of the problem in addition, or prior, to reduction. The heuristic *Incorporate additional scenarios*, extracted from three problem definitions (Engineer 1 and Engineer 3), demonstrates expansion of the problem space. The application of this heuristic allowed the two engineers to focus on solving a larger problem; in this case, providing electricity whenever and wherever electricity is not available. The solution could be useful in a disaster area, but it could also be valuable, for example, when a blackout occurs or in third world countries where power is not accessible at all times. Past research on problem exploration heuristics used by professional engineers and designers suggests evidence of both expansion and reduction strategies when exploring the presented problem.[45,64]

Excluding the three heuristics common to all five cases, each engineer seemed to have a particular pattern in exploring the presented problem. The engineers often used one or two heuristics prominently in each of their problem definitions that were not evident with the other engineers. For example, Engineer 1 focused on *Determine the required cost* in three of her five problem definitions; however, this heuristic was observed only twice in other cases. According to Shull et al.,[39] an individual's life experiences play a major role in determining how a problem is perceived and approached. For example, a few engineers referenced information from their classes; for example, Engineer 1 stated, "we made those in [ME] 270 so it would not be that hard to make." Differing perceptions of uncertainty, complexity or conflict can lead two individuals, even with similar experiences (all Mechanical Engineering students) to employ two very different strategies of problem identification and formulation.[36] This might also explain variations in heuristic use among graduate students (Engineers 4 and 5) and undergraduate students (Engineers 1, 2, 3) due to differences in their educational and professional experiences.

While the evidence from these protocols reveals a consistent picture of heuristic use in problem exploration, only a small sample of five engineers trained in the same university program was included. Most importantly, only one problem was considered, and the presented problem is more similar to design competition challenges than to classroom problems, which tend to have more explicit constraints. It is likely that more open-ended problems are more amenable to exploration heuristics; however, it is unclear whether even more specific problems would also benefit from greater consideration of alternative problem perspectives. Another limitation is that the participants were asked to "talk aloud" during their solution process, which may lead to feelings of self-consciousness and inhibition of their natural cognitive processes. Although, prior studies have documented the use of talk-aloud protocols as a method for studying problem solving processes, and have shown the solution results to be consistent with control protocols without speaking.[62] Further studies are needed to establish the prevalence of the problem exploration strategies identified in this study.

The results of this work have implications for engineering design education as well as practice. Learning about heuristics for exploring problems will provide better ways of teaching about design processes for more innovative outcomes, which in turn, could produce better-rounded, creative engineers and designers. The goal of this study was to provide an initial characterization of the cognitive processes behind problem exploration by engineering students at varying levels. Future work will provide a detailed comparison of the patterns of thinking and heuristic use evident in explorations of the problem space by professional and novice engineers and designers. The identification of differences in students' behaviors and outcomes will support the development of instructional materials for problem exploration. Their dissemination in educational and industry settings will better prepare both future and current engineers for the challenges of solving increasingly complex real-world problems.

Conclusions

The importance of exploring the space of problems in search of varied perspectives cannot be over-emphasized. While some problem finding methods exist, none are based on theory, and there is no empirical evidence about their effectiveness in education or in practice. This paper reports on a systematic examination of engineering practices to identify strategies used in exploration of the problem space. Exposure to problem exploration heuristics and experience in applying them to many different problems may lead to the development of expertise in intentional variations of problem perspective. For many engineering students, simply having an arsenal of problem exploration heuristics might lead to improvement in problem exploration processes, and lead to more innovative solutions. The problem exploration heuristics identified in this study have potential for improving the practices of engineering students and practitioners, providing a method for learning when and how to apply them in new engineering problems.

References

1. Cropley AJ. Fostering creativity in educational settings. In: *Creativity in Education and Learning: A Guide for Teachers and Educators*. ; 2001:202.
2. Cropley DH. Promoting creativity and innovation in engineering education. *Psychol Aesthetics, Creat Arts*. 2015;9(2):161-171. doi:10.1037/aca0000008.
3. Maiden N, Jones S, Karlsen K, Neill R, Zachos K, Milne A. Requirements engineering as creative problem solving: A research agenda for idea finding. *Proc 2010 18th IEEE Int Requir Eng Conf RE2010*. 2010:57-66. doi:10.1109/RE.2010.16.
4. Simon HA. Problem forming, problem finding and problem solving in design. In: Collen A, Gasparski WW, eds. *Design and Systems: General Applications of Methodology*. ; 1995:245-257.
5. Mintzberg H, Raisinghani D, Theoret A. The structure of “unstructured” decision processes. *Adm Sci Q*. 1976:246-275. doi:10.2307/2392045.
6. Archer LB. *The Structure of Design Processes*. Springfield, USA; 1968.
7. Shneiderman B. Creating creativity: user interfaces for supporting innovation. *ACM Trans Comput Interact*. 2000;7(1):114-138. doi:10.1145/344949.345077.
8. Kruger C, Cross N. Solution driven versus problem driven design: strategies and outcomes. *Des Stud*. 2006;27(5):527-548. doi:10.1016/j.destud.2006.01.001.
9. Asimow M. *Introduction to Design: Fundamentals of Engineering Design*. New Jersey, 1968: Prentice-Hall; 1962.
10. Vasconcelos LA, Crilly N, Chen CC, Campos F, Kelner J. What’s the benefit of problem exploration. In: *DS 84: Proceedings of the DESIGN 2016 14th International Design Conference*. ; 2016.
11. Tversky A, Kahneman D. The framing of decisions and the psychology of choice. *Science (80-)*. 1981;211(4481):453-458. doi:10.1126/science.7455683.

12. Newell A, Simon HA. *Human Problem Solving*. Englewood, NJ: Prentice-Hall; 1972.
13. Duncker K. On problem solving. *Psychol Monogr*. 1945;58:270. doi:10.1037/h0093599.
14. Dorst K, Cross N. Creativity in the design process: co-evolution of problem–solution. *Des Stud*. 2001;22(5):425-437. doi:10.1016/S0142-694X(01)00009-6.
15. Maher ML, Poon J, Boulanger S. Formalising Design Exploration as Co-evolution: A Combined Gene Approach. *Adv Form Des Methods CAD Proc IFIP WG52 Work Form Des Methods Comput Des*. 1996:3-30. doi:10.1007/978-0-387-34925-1_1.
16. McGuire WJ. The yin and yang of progress in social psychology: Seven koan. *J Pers Soc Psychol*. 1973;26:446-456.
17. Schon DA. Generative metaphor and social policy. In: *Metaphor and Thought*. ; 1993:137-163.
18. Cross N, Cross AC. Expertise in engineering design. *Res Eng Des*. 1998;10(3):141-149. doi:10.1007/BF01607156.
19. Jain VK, Sobek DK. Linking design process to customer satisfaction through virtual design of experiments. *Res Eng Des*. 2006;17(2):59-71. doi:10.1007/s00163-006-0018-2.
20. Adams RS, Atman CJ. Characterizing engineering student design processes: An illustration of iteration. In: *ASEE Annual Conference and Exposition, Conference Proceedings*. ; 2000:1271-1281.
21. Getzels JW. Problem-finding and the inventiveness of solutions. *J Creat Behav*. 1975;9(1):12-18. doi:10.1002/j.2162-6057.1975.tb00552.x.
22. Mitroff, Kilmann RH. *Methodological Approaches to Social Science*. (Josey-Bass, ed.). San Francisco; 1978.
23. Getzels JW. Problem finding: A theoretical note. *Cogn Sci*. 1979;3(2):167-171. doi:10.1016/S0364-0213(79)80030-0.
24. Hoover SM. Scientific Problem Finding in Gifted Fifth-Grade Students. *Roeper Rev*. 1994;16(3):156-159. doi:10.1080/02783199409553563.
25. Mumford MD, Reiter-Palmon R, Redmond MR. Problem construction and cognition: Applying problem representations in ill-defined domains. In: *Problem Finding, Problem Solving, and Creativity*. ; 1994:3-39.
26. Okuda SM, Runco MA, Berger DE. Creativity and the finding and solving of real-world problems. *J Psychoeduc Assess*. 1991;9(March):45-53. doi:10.1177/073428299100900104.
27. Runco MA, Chand I. Problem finding, evaluative thinking, creativity. In: *Problem Finding, Problem Solving, and Creativity*. ; 1994:40-75. doi:10.1080/19397030902947041.
28. Getzels JW, Csikszentmihalyi M. *The Creative Vision: A Longitudinal Study of Problem Finding in Art*. New York: Wiley; 1976.
29. Wakefield JF. Towards creativity: Problem finding in a divergent-thinking exercise. *Child Study J*. 1985;15:265-270.
30. Dzbor M, Zdrahal Z. Design as interactions of problem framing and problem solving. *ECAI*. 2002;(c):210-214. http://eprints.aktors.org/300/.
31. Schon DA. The reflective practitioner. *Harv Bus Rev*. 1984;62:58-62.

32. Wright SM, Silk EM, Daly SR, Jablokow KW, Yilmaz S. Exploring the effects of problem framing on solution shifts: A case study. *ASEE Annu Conf Expo Conf Proc*. 2015;122nd ASEE(122nd ASEE Annual Conference and Exposition: Making Value for Society). doi:10.18260/p.24071.
33. Stumpf S, McDonnell J. Relating argument to design problem framing. In: *4th International Design Thinking Research Symposium (DTRS'99)*. Cambridge, MA; 1999.
34. Higgins JS, Maitland GC, Perkins JD, Richardson SM. Identifying and solving problems in engineering design. *Stud High Educ*. 1989;14(2):169-181.
35. Csikszentmihalyi M and JWG. Creativity and problem finding in art. In: Farley F, Neperud R, eds. *The Foundations of Aethetics, Art, and Art Education*. New York, NY: Praeger; 1988:91-116.
36. MacCrimmon KR, Taylor RN. Decision making and problem solving. In: Dunnette MD, ed. *Handbook of Industrial and Organizational Psychology*. Chicago: Rand McNally College Publishing Co.; 1976.
37. Hall AD. *A Methodology for Systems Engineering*. New York: Litton Educational Publishing Inc.; 1962.
38. Rickards T. *Problem Solving through Creative Analysis*. Essex: Gower Press; 1975.
39. Shull FA, Delbecq AL, Cummings LL. *Organizational Decision Making*. New York: McGraw-Hill Book Co.; 1970.
40. Fogler SH, LeBlanc SE. *Strategies for Creative Problem Solving*. Massachusetts, USA: Pearson Education, Inc.; 2008.
41. Parnes SJ. *Creative Behavior Guidebook*.; 1967. http://books.google.co.uk/books?id=qshEAAAAIAAJ&q=Parnes,+S.J.+(1967)+Creative+Behavior+Guidebook.+Scribner,+New+York.&dq=Parnes,+S.J.+(1967)+Creative+Behavior+Guidebook.+Scribner,+New+York.&hl=en&ei=DrRyTM6eFNHJswbsgsS5Bg&sa=X&oi=book_result&ct=result&re.
42. Kepner CH, Tregoe BB. *The New Rational Manager*. Princeton, NJ: Princeton Research Press; 1981.
43. Bulsuk KG. An introduction to 5-why. 2011. http://blog.bulsuk.com/2009/03/5-why-finding-root-causes.html#axzz1WBoqfIV6.
44. Spradlin D. Are you solving the right problem? *Harv Bus Rev*. 2012;90(9).
45. Studer JA, Yilmaz S, Daly SR, Seifert CM. Cognitive Heuristics in Defining Engineering Design Problems. In: *Volume 7, 29th International Conference on Design Theory and Methodology*. ASME; 2016. http://dx.doi.org/10.1115/DETC2016-59942.
46. Paul R, Elder L. *The Thinker's Guide to the Art of Socratic Questioning*. Dillon Beach, CA: Foundation for Critical Thinking Press; 2006.
47. Yilmaz S, Seifert CM. Creativity through design heuristics: A case study of expert product design. *Des Stud*. 2011;32(4):384-415. doi:10.1016/j.destud.2011.01.003.
48. Nisbett RE, Ross L. *Human Inference: Strategies and Shortcomings of Social Judgment*.; 1980. doi:10.1080/09658210244000603.
49. Gilli M, Maringer D, Winker P. Applications of Heuristics in Finance. In: *Handbook on Information Technology in Finance*. ; 2008:635-653. doi:10.1007/978-3-540-49487-4_26.
50. Goslar MD. Decision support systems: advantages in consumer marketing settings. *J Consum Mark*. 1993;3(3):43-50.

51. Zhou R, Hansen EA. Space-efficient memory-based heuristics. In: *19th National Conference on Artificial Intelligence*. ; 2004.
52. Daly S, Christian JL. Assessing design heuristics for idea generation in an introductory engineering course. *Int J Eng Educ*. 2012;Vol. 28(2):1–11. http://www.researchgate.net/publication/259104145_Assessing_design_heuristics_for_idea_generation_in_an_introductory_engineering_course/file/3deec529fa6af1c6b4.pdf.
53. Daly SR, Yilmaz S, Christian JL, Seifert CM, Gonzalez R. Design heuristics in engineering concept generation. *J Eng Educ*. 2012;101(4):601-629. doi:10.1002/j.2168-9830.2012.tb01121.x.
54. Kramer J, Daly SR, Yilmaz S, Seifert CM, Gonzalez R. Investigating the impacts of design heuristics on idea initiation and development. *Adv Eng Educ*. 2015;4(4).
55. Seifert CM, Gonzalez R, Yilmaz S, Daly S. Boosting Creativity in Idea Generation Using Design Heuristics. In: *Design Thinking: New Product Development Essentials from the PDMA*. ; 2015:71-86. doi:10.1002/9781119154273.ch6.
56. Yilmaz S, Daly SR, Christian JL, Seifert CM, Gonzalez R. Can experienced designers learn from new tools? A case study of idea generation in a professional engineering team. *Int J Des Creat Innov*. 2014;2(2):82-96. doi:10.1080/21650349.2013.832016.
57. Yilmaz S, Daly SR, Seifert CM, Gonzalez R. How do designers generate new ideas? Design heuristics across two disciplines. *Des Sci*. 2015;1(2015):e4. doi:10.1017/dsj.2015.4.
58. Yilmaz S, Seifert CM, Gonzalez R. Cognitive heuristics in design: Instructional strategies to increase creativity in idea generation. *Artif Intell Eng Des Anal Manuf*. 2010;24(3):335-355. doi:10.1017/S0890060410000235.
59. Klein G. *Sources of Power: How People Make Decisions*. Vol 52.; 1999. doi:10.1061/(ASCE)1532-6748(2001)1:1(21).
60. Dijksterhuis A, Bos MW, Nordgren LF, van Baaren RB. On making the right choice: the deliberation-without-attention effect. *Science*. 2006;311(5763):1005-1007. doi:10.1126/science.1121629.
61. Atman CJ, Bursic KM. Verbal Protocol Analysis as a Method to Document Engineering Student Design Processes. *J Eng Educ*. 1998;87(2):121-132. doi:10.1002/j.2168-9830.1998.tb00332.x.
62. Ericsson KA, Simon HA. Verbal Reports as Data. *Psychol Rev*. 1980;87(3):215-251. doi:10.1037/0033-295X.87.3.215.
63. Yilmaz S, Seifert C. Cognitive heuristics employed by designers. *Des Sci*. 2009:4243-4246. https://www.designheuristics.com/wp-content/uploads/2012/08/13_IASDR_2009.pdf.
64. Studer JA, Seifert CM, Daly SR, Yilmaz S. Investigating the use of cognitive heuristics in the exploration of engineering design problems. *Unpubl Manuscr*. 2016.
65. Wickelgren WA. *How to Solve Problems*. San Francisco: W.H. Freeman; 1974.
66. Reed SK, Abramson A. Effect of the problem space on subgoal facilitation. *J Educ Psychol*. 1976;68(2):243-246. doi:10.1037//0022-0663.68.2.243.
67. Carroll JM, Thomas JC, Malhotra A. Clinical-Experimental Analysis of Design Problem Solving. *Des Stud*. 1979;1(2):84-92.
68. Maier. *Problem Solving and Creativity in Individuals and Groups*. Belmont, California: Brooks/Cole Publishing Co.; 1970.

CHAPTER 4. CONCLUSIONS

The research results presented in this thesis illustrate how differing problem perspectives can be created from a single problem description. In the content analysis study, existing design problems and solutions of professional engineers and designers were analyzed. From just four given problem statements (design challenges), 102 reframed, or interpreted, problems were observed. One of these challenges resulted in 55 different interpretations of the problem, leading to a varied set of solutions. For example, in a challenge asking for designers to "define a concept to facilitate individual work in a shared work environment," the top three designs represented very different interpretations of the given problem: The winner created a carrying case focusing on mobility, a finalist designed a cubicle focusing on privacy, and a semi-finalist came up with a scroll-top lockbox focusing on theft prevention.

In the protocol study with engineering students (Chapter 3), each student interpreted the given problem in a variety of ways, and each student's interpretations differed from those of other participants. For example, Engineer 3 from the protocol studies reframed the problem on disaster relief by thinking about the end user of the product (victims of a disaster), and determined the important need would be to provide them with a comfortable place to stay. This reframing led her to focus on solutions that not only provided shelter, but also provided amenities such as a bathroom or shower to make the victims as comfortable as possible. The same engineer also reframed the disaster relief problem to focus on providing power, and consequently created a completely different set of solutions, ultimately leading to the design of a mobile generator. Each newly-reframed problem statement led to a new and different set of potential solutions.

The varied interpretations of each of the presented problems suggest specific strategies, or heuristics, are used to understand a problem from differing perspectives, even though the designer may not be consciously aware of their use. This thesis presents a cumulative set of Problem Exploration Heuristics extracted from observations of designs by both professional (Chapter 2) and student (Chapter 3) engineers. Problem Exploration Heuristics appear to capture strategies used by designers to explore the space of possible problem formulations. These Problem Exploration Heuristics were observed across a wide variety of design problems and designers. These heuristics address a range of problem features, including constraints, requirements, stakeholders, current state limitations, primary goals or outcomes of the desired solution, user scenarios, problem settings, and many more.

The prevalence of problem exploration heuristics observed in these studies suggests they are an important method for exploring the problem space. A given problem exploration heuristic may not be applicable in every problem; however, the availability of multiple Problem Exploration Heuristics may result in greater flexibility in exploring problems and solutions. This suggests the potential for instructional interventions with novices about the observed heuristics, thus providing opportunity to gain the ability to discern differing problem descriptions, and learn to frame them in ways that facilitates innovative solutions.

The results of this research also showcase how problem descriptions change in character as new solutions are created. This is evident in the protocol studies when student engineers often reframed the problem after generating a solution. For instance, after designing a food delivery drone, one engineer stated, "…*that made me think that maybe* *shelter would probably be more important than food at first, and it should be simple enough for the victims to build themselves."* This process of revisiting of problem definitions after creating solutions echoes prior research on the "co-evolution" of problems and solutions.[1–3] In that work, a single, comprehensive problem ("create a concept for a 'litter disposal system in a new train") was addressed through the creation of sub-goals and partial solutions, leading to revision of the provided problem description; in particular, all nine of their participants added the notion that "newspapers should be collected separately." Dorst and Cross (2001) suggest that their protocols demonstrated that design problems are not viewed as "fixed," but are mutable, and unlike serial problem-solving models[4] where the problem space is defined and then a search for solutions occurs. The results from this thesis add to our understanding of the co-evolution process by showing that problems can be revisited and redefined with each completed solution.

Illustration of Problem Exploration Heuristics Use

The outcomes of this research include new knowledge about how engineers at several levels of experience use cognitive heuristics to explore and refine design problems. The ability to examine presented problems for their underlying characteristics appears critical in identifying successful and innovative solutions. In turn, these identified strategies may prove useful to other designers learning about how to explore problems. Consider the current, real world design problem to *"Develop a product that would assist citizens in Sub-Saharan Africa".* How might this presented problem be further explored through the use of *Problem Exploration Heuristics?* Figure 13 illustrates how problem exploration heuristics can be applied to this problem to generate numerous alternative perspectives.

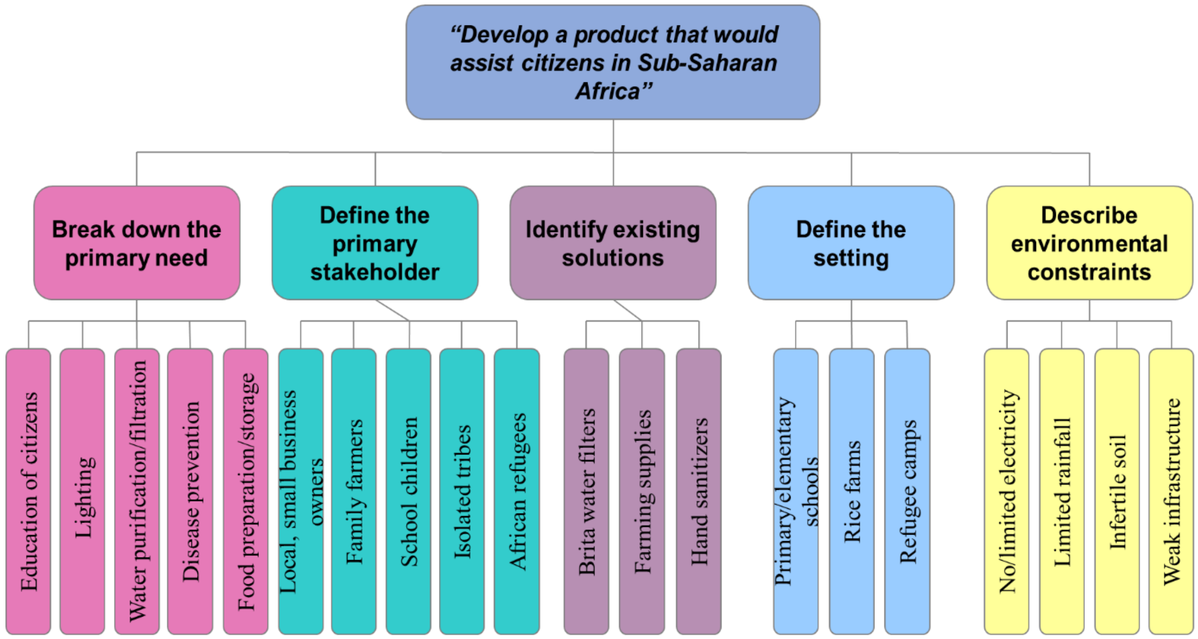


Figure 13. Illustration of Problem Exploration Heuristics applied to a design problem.

The five heuristics applied, as an example, to the presented problem explore a variety of attributes of the problem space. The Problem Exploration Heuristic, *Break down the primary need*, narrows the scope of problem to address one particular need that requires solving. In this example, areas of need in Sub-Saharan Africa include education, disease prevention, lighting, water purification, and food. The next heuristic, *Define the primary stakeholder*, focuses on the individual(s) that will benefit the most from the desired solution. These might include local, small business owners, family farmers, school children, isolated tribes, and African refuges. By applying the third heuristic, *Identify existing solutions*, the designer brainstorms existing solutions that can be used to address the primary need(s). Existing solutions could include Brita water filters, farming supplies, and hand sanitizers. The next heuristic, *Define the setting*, focuses the problem a specific place where the desired solution is to be implemented. In this case, the intended solution might be implemented in elementary schools, rice farms, or refugee camps. The final heuristic applied, *Describe the* *environmental constraints*, examines the limitations the environment imposes on the final solution, for example, limited electricity and/or rainfall, infertile soil, and weak infrastructure. Figure 14 illustrates one example of how the selection of problem heuristics led to reframing the presented problem and generating a solution. This designer (B.S. in mechanical engineering) reframed the presented problem to state, “School children need to be able to be clean to protect themselves from diseases as they transition from classrooms and other areas when they are in school.” This led to the implementation of sanitation zones for primary/elementary schools that children would use after using the restroom.

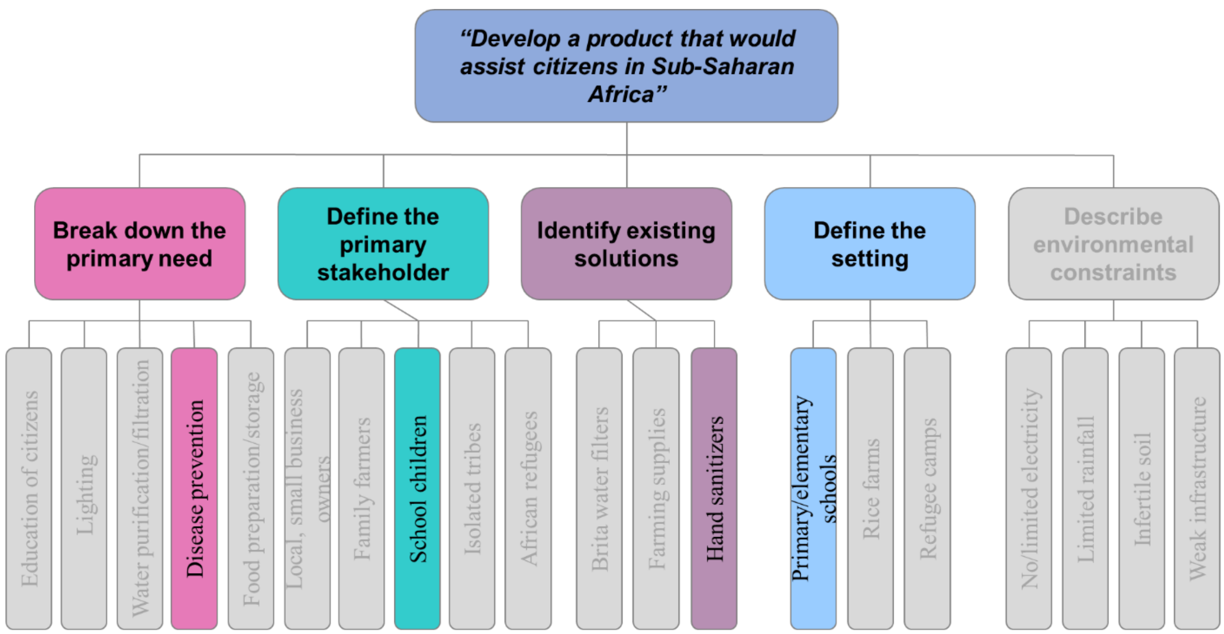


Figure 14. Protocol of Problem Exploration Heuristic application and the generation of a solution.

Each of these heuristics draws the designer’s attention to a new area of the problem space, and allows exploration of additional aspects beyond those evident in the original problem description. Therefore, by exploring the problem with an arsenal of problem exploration heuristics, uncommon and diverse solutions may result. Rather than getting fixated or “stuck” in a problem, one can choose a Problem Exploration Heuristic, apply it to the current problem, and see where the resulting transformation leads.

Limitations and Recommendations for Future Work

This thesis explores how both professional and student engineers search the problem space by generating alternative views toward the presented problem. The empirical findings lay a groundwork for future studies to determine a more definitive set of heuristics through a larger sample of problems and designs. While the content analysis study in Chapter 2 includes a variety of design problems and multiple solutions, no trace of the cognitive processes during design was available in that study. In addition, the protocol study presented in Chapter 3 examined just one problem across five participants. Additional protocol data would be helpful in determining whether expertise effects are evident in the use of heuristics. Comparisons of professionals and novices may identify differences in their patterns of heuristic use, which can be used to understand differences in underlying problem exploration abilities. These gaps may inform the development of a range of instructional strategies to enhance problem exploration skills, resulting in improved education of engineering and design students.

The protocol studies (Ch. 3) provide much more detailed data as each engineer ”talked aloud” while working on their solutions; however, the quality of the outcomes is not assessed in the study. Furthermore, these participants were asked to explicitly revise their problem statement to fit each solution. This task provides more explicit confirmation of how the engineer viewed the problem at each point; however, the task of reformulating an explicit problem description seemed challenging for some participants. Perhaps alternative problem perspectives are most typically captured only in solutions rather than in explicit revisions of the problem. Additionally, though protocol studies have been an important tool in design research, the short, one-time session is unlike typical design settings where progress might occur over days or weeks. Also, current design efforts frequently involve teams and feedback about designs; these aspects are not included in the protocol study, and not measurable in content analysis.

Now that these problem exploration heuristics have been identified, a key question remains: Can engineers benefit from learning about them? Ideally, future research would address how these heuristics might be effectively taught in engineering design courses. Evidence of their use in creating new, effective designs is important to establish their value as generative strategies. In addition, while the results of the content analysis (Ch. 2) showcased a correlation between creative, novel solutions and heuristic use, additional studies are needed to validate the effectiveness of problem exploration heuristics, and to determine whether heuristic use enhances innovative solutions.

The results presented in this thesis provide evidence of the problem exploration strategies available to engineering and design students and practitioners. With further refinement and development, engineering instructors may benefit from documented pedagogy aimed at training students to explore presented problems. In the words of an undergraduate engineer, “Coming from a family of engineers, I would have never imagined in my wildest dreams that ENGINEERING and CREATIVITY could even belong in the same sentence.” The results from this thesis demonstrate that creativity is indeed central to engineering design.

References

1. Dorst K, Cross N. Creativity in the design process: co-evolution of problem–solution. *Des Stud*. 2001;22(5):425-437. doi:10.1016/S0142-694X(01)00009-6.
2. Maher ML, Poon J, Boulanger S. Formalising Design Exploration as Co-evolution: A Combined Gene Approach. *Adv Form Des Methods CAD Proc IFIP WG52 Work Form Des Methods Comput Des*. 1996:3-30. doi:10.1007/978-0-387-34925-1_1.
3. Maher M Lou, Tang H-H. Co-evolution as a computational and cognitive model of design. *Res Eng Des*. 2003;14(2003):47-64. doi:10.1007/s00163-002-0016-y.
4. Simon HA. *The Sciences of the Artificial*. Cambridge, MA: MIT Press; 1969.

APPENDIX A. IRB APPROVAL

IRB ID: 15-435

INSTITUTIONAL REVIEW BOARD (IRB)
Application for Approval of Research Involving Humans

Title of Project: Tackling the 'right' problem: Investigating cognitive strategies used in understanding engineering problems

Principal Investigator (PI): Seda Yilmaz		Degrees: PhD	RECEIVED
University ID: 081255174 1 5	Phone: 5155090309	Email Address: seda@iastate.edu	
Correspondence Address: 146 College of Design			JUL 20 2015
Department: Industrial Design		College/Center/Institute: College of Design	By IRB

PI Level: ☒ Tenured, Tenure-Eligible, & NTER Faculty ☐ Adjunct/Affiliate Faculty ☐ Collaborator Faculty ☐ Emeritus Faculty ☐ Visiting Faculty/Scientist ☐ Senior Lecturer/Clinician ☐ Lecturer/Clinician, w/Ph.D. or DVM ☐ P&S Employee, P37 & above ☐ Extension to Families/Youth Specialist ☐ Field Specialist III ☐ Postdoctoral Associate ☐ Graduate/Undergrad Student ☐ Other (specify:)

FOR STUDENT PROJECTS (*Required when the principal investigator is a student*)

Name of Major Professor/Supervising Faculty:			
University ID:	Phone:	Email Address: @iastate.edu	
Campus Address:		Department:	
Type of Project (check all that apply):	☐ Thesis/Dissertation	☐ Class Project	☐ Other (specify:)

Alternate Contact Person:	Email Address:
Correspondence Address:	Phone:

ASSURANCE

- I certify that the information provided in this application is complete and accurate and consistent with any proposal(s) submitted to external funding agencies. Misrepresentation of the research described in this or any other IRB application may constitute non-compliance with federal regulations and/or academic misconduct.
- I agree to provide proper surveillance of this project to ensure that the rights and welfare of the human subjects are protected. I will report any problems to the IRB. See Reporting Adverse Events and Unanticipated Problems for details.
- I agree that modifications to the approved project will not take place without prior review and approval by the IRB.
- I agree that the research will not take place without the receipt of permission from any cooperating institutions when applicable.
- I agree to obtain approval from other appropriate committees as needed for this project, such as the IACUC (if the research includes animals), the IBC (if the research involves biohazards), the Radiation Safety Committee (if the research involves x-rays or other radiation producing devices or procedures), etc., and to obtain background checks for staff when necessary.
- I understand that IRB approval of this project does not grant access to any facilities, materials, or data on which this research may depend. Such access must be granted by the unit with the relevant custodial authority.
- I agree that all activities will be performed in accordance with all applicable federal, state, local, and Iowa State University policies.

7/20/15

Signature of Principal Investigator — Date

Signature of Major Professor/Supervising Faculty — Date
(*Required when the principal investigator is a student*)

- I have reviewed this application and determined that departmental requirements are met, the investigator(s) has/have adequate resources to conduct the research, and the research design is scientifically sound and has scientific merit.

7/20/15

Printed Name of Department Chair/Head/Director

7.20.15

Signature of Department Chair/Head/Director — Date

For IRB Use Only	Full Committee Review: ☐	Review Date: 7-21-15	
	EXPEDITED per 45 CFR 46.110(b): ǀ	Approval/Determination Date: 7-21-15	
Approval Not Required: ☐	Category 6, 7 Letter	Approval Expiration Date: 7-20-16	
Not Research: ☐	EXEMPT per 45 CFR 46.101(b):		
No Human Subjects: ☐	Not Approved: ☐	Risk: Minimal ☒	More than Minimal ☐

IRB Reviewer's Signature

APPENDIX B. PROBLEM EXPLORATION HEURISTICS

Rank	***Heuristic Title***	***Heuristic Definition***	***Total Occurrences***
1	*Detail the required functions*	Brainstorm specific functions that the final solution must have in order to solve the specific issue being addressed. Think about how the final solution will operate ideally and detail each function in the problem statement.	40
2	*Include multiple ways to interact*	Analyze how the user will use the desired solution. Add the ability of the user to reconfigure or customize the solution to meet the specific needs of each user and each situation in the problem statement including the ability to add, remove, or change different components.	39
3	*Integrate mobility*	Analyze the specific scenario in which the desired solution might be used and integrate the need for mobility (can be moved place to place) in the problem statement.	24
4	*Prioritize use cases*	Analyze potential scenarios in which the desired solution can be used (what is the user doing?). Define the positive/negative characteristics of the situations in which the solution will be implemented and prioritize them based on frequency. Select the top use case and detail it in the problem statement.	21
5	*Find the root cause*	Analyze the limitations to or flaws in achieving the task at hand in the current state and select one limitation to focus on. Explore what is causing this limitation to determine the root cause. Detail the root cause in the problem statement.	20
6	*State the desired outcome*	Determine the primary outcome of the desired solution, or what you are trying to achieve by solving the problem. Detail the primary outcome in the problem statement.	20
7	*Add potential limitations*	Analyze the limitation(s) to achieving the task at hand in the current state. Detail limitations that may be similar to or would benefit from a similar solution and select one or two to add to the problem statement.	19
8	*Break down the addressed limitation(s)*	Analyze the limitation(s) to achieving the task at hand in the current state. Make a list of all sub-limitations within the original one. Select one or two sub-limitations to replace the original limitation in your problem statement.	19

9	*Determine the end user and detail their needs*	Determine who the end users of the final solution will be. Define specific criteria that the solution must adhere to that will benefit these users and their experience with the final solution. This includes criteria for ease of use, ergonomics, and safety.	19
10	*Determine the required cost*	Analyze the economic status of the individuals, local communities, nations, etc. that will use the final solution. Define the maximum cost of the final solution.	17
11	*Describe secondary functions*	Analyze the environment and the situation in which the desired solution will be used. Examine the primary function of the final solution and brainstorm additional functions that could be added to benefit the final solution. Detail these functions in the problem statement.	17
12	*Expand the setting*	List additional settings in which the desired solution could be used to broaden the potential areas/spaces in which the final solution can be implemented. Detail each setting and add them to the problem statement.	16
13	*Break down the desired outcome*	Analyze the primary outcome of the desired solution and break it down into distinct pieces. Choose one of the subcategories to narrow the scope of the problem. Detail the narrowed outcome in the problem statement.	15
14	*Describe material characteristics*	Think about the specific material needs of the final solution and describe the necessary characteristics the material must have in the problem statement. The characteristics may include durability, elasticity, etc.	14
15	*Focus on eco-friendly solutions*	Evaluate the natural environment in which the final solution will be implemented. Detail specific criteria in the problem statement that the solution must adhere to that will benefit the environment - the ecosystem, the resources, etc. Think about issues such as material waste, climate change, use of natural resources, etc.	14
16	*Describe the desired visual attributes*	Describe the visual qualities needed to support the primary functions in the problem statement, in order to enhance the users' interaction with the outcome.	13
17	*Integrate existing products to address secondary functions*	Analyze the secondary functions of the desired solution and brainstorm existing products that could be incorporated in the desired solution to provide this additional functionality. Detail these products in the problem statement.	12

18	*Describe an existing solution to use as conceptual inspiration*	Analyze the primary outcome of the desired solution and brainstorm existing products that have a similar outcome. Use the concept of existing ideas as inspiration for your idea. Determine if the concept of the existing product could be used in a new way to solve the limitation you are addressing and detail it in the problem statement.	12
19	*Define the characteristics of the setting*	Analyze potential setting in which the desired solution could be used. Select a specific setting to focus on. Define the positive/negative characteristics of the setting in which the solution will be implemented in the problem statement. If a setting is already specified, provide more detail.	9
20	*Substitute the individual primary stakeholder for a group*	Make a list of the primary stakeholder's social groups. Select a specific group as the new primary stakeholder to include more individuals and detail the group in the problem statement.	8
21	*Describe the environmental conditions*	Analyze the environment in which the final solution will be implemented. Describe the conditions of the environment and the limitations that exist in the problem statement. This includes the climate, topography, labor force, and any existing products that may be used in the same environment.	7
22	*Describe the required manufacturing process and its limitations*	Analyze the current manufacturing capabilities and limitations including processes and machinery. Detail the capabilities and limitations in the problem statement.	7
23	*Incorporate user customization in manufacturing process*	Add criteria that require the ability for the final solution to be customized by the user before manufacturing. Detail the features that can be customized in the problem statement.	6
24	*Substitute the primary stakeholder group for an individual*	Make a list of individuals in the primary stakeholder group you identified. Select a specific individual and change the primary stakeholder to this individual in the problem statement.	6
25	*Describe the brand values*	Describe the aesthetic values desired by the solution or the brand in the problem statement	5
26	*Expand the primary stakeholder group*	Make a list of larger groups that the primary stakeholder group is a part of. Select one of these groups to encompass more individuals than the initial primary stakeholder group you identified. Change the primary stakeholder to this group in the problem statement.	5

27	*Describe the primary stakeholder*	Brainstorm all possible stakeholders (both internal and external) of the desired solution. Prioritize and select one stakeholder (individual or group) that will primarily benefit from the solution to add to the problem statement.	4
28	*Describe the required size and space attributes*	Analyze the setting and the use cases of the desired solution. Add a specific size limitation to the problem statement that the final solution needs to have in order to work effectively.	2
29	*Expand the scope*	Analyze the primary outcome of the desired solution and add scope to the goal (while still being manageable) to maximize the benefits of the final solution.	2
30	*Consider existing solutions*	Analyze the primary outcome of the desired solution and determine if an existing solution can be used to solve the problem. If not, describe the functions of similar solutions and identify which functions are applicable to the problem and add them to the problem statement. Address any gaps of the current solutions that still need to be filled and specify these gaps in the problem statement.	2
31	*Break down the primary stakeholder group*	Brainstorm the different groups within the initial stakeholder group you identified. Select a specific group as the new primary stakeholder to encompass more individuals and detail it in the problem statement.	2
32	*Shift focus to cultural issues*	Analyze the cultural issues present that impact the limitations of the current state. Change the primary outcome to reflect addressing these cultural issues to shift the focus from individual needs to broader needs. Detail the new primary outcome in the problem statement.	2
33	*Examine assumptions*	Identify potential assumptions you need to make for early-phase, preliminary solutions and add to problem statement.	1
34	*Brainstorm ways to eliminate the root cause*	Analyze the current limitations to achieving the task at hand. Determine if the object or situation causing the limitation can be moved in order to eliminate or reduce the limitation and modify the primary outcome to reflect this in the problem statement.	1
35	*Brainstorm ways to eliminate environmental restrictions*	Analyze the conditions and limitations of the environment in which the final solution will be implemented and determine if they can be modified, eliminated, or reduced. Change the primary outcome to resolving the environmental constraints in the problem statement.	1

36	*Focus on education*	Analyze the primary outcome of the desired solution and modify it to teaching individuals/group how to perform a task instead of the primary outcome being to perform a task in the problem statement.	1
37	*Describe the required maintenance needs*	Analyze how the desired solution may need to be maintained or serviced after implementation. Describe how or when the maintenance should occur and what tools/labor are required in the problem statement to suit the environment and situation of the desired solution. Add these details to the problem statement.	1
38	*Focus on economic growth*	Analyze the primary outcome of the desired solution and modify it to include benefiting the economic status of an individual, local community, nation, etc. in the problem statement.	1
39	*Incorporate more scenarios*	List additional use cases in which the final solution could be used. Detail each use case and add them to the problem statement. This will broaden the ways the final solution could be used.	1
40	*Describe a future scenario*	Brainstorm scenarios in which the desired solution could be used in the future. Think about the potential setting, the users, and the products available in the future. Detail one or two scenarios in the problem statement.	1
41	*Describe secondary stakeholders*	Brainstorm possible stakeholders that could benefit indirectly from the desired solution. These stakeholders would be involved in the final solution somehow, but may not be the main benefactors. Describe how these stakeholders will interact with the desired solution or the users of the desired solution in the problem statement.	1
42	*List individuals or groups that are associated with the primary stakeholder*	Brainstorm the individuals or groups that the initial primary stakeholder may interact with it on a regular basis. Select one of these individuals or groups as the new primary stakeholder in the problem statement.	1
		Total occurrences	**428**

APPENDIX C. INFORMED CONSENT DOCUMENT

INFORMED CONSENT DOCUMENT

Title of Study: Tackling the 'right' problem: Investigating cognitive strategies used in understanding engineering problems

Investigators: Seda Yilmaz, PhD
Jaryn Studer, Research Assistant

This is a research study. Please take your time in deciding if you would like to participate. Please feel free to ask questions at any time.

INTRODUCTION

The purpose of the study is to investigate problem exploration heuristics – strategies used to identifiy and refine problem definitions (also called problem finding or framing). You are being invited to participate in this study because you contacted us about your willingness in taking part in this research, where we explore cognitive heuristics used in defining design problems. You should not participate if you are under 18.

DESCRIPTION OF PROCEDURES

If you agree to participate, you will be given a problem statement describing a problem and its context in a written format, and asked to work on it for 25 minutes. The problem statement will be developed based on existing problems in engineering, inspired by the Grand Challenges. No interventions will be employed. After the problem statement is provided, you will be asked to reshape that problem into other potential problems, which may be more important or feasible to solve. We will, then, ask you to describe your thoughts as you form ideas for problems, and to explain why you think the defined problem is important. This task will then be repeated using a different problem statement.

After each 25 minute task, we will follow up with an interview addressing the types of design problems faced in practice, how problems change throughout the life of the project, what heuristics are used in framing problems and identifying new solution opportunities, and how problem space influences the solution space. These retrospective interviews will take about 10 minutes each to understand how you describe your own decision-making processes. These interviews will be audio-recorded and transcribed later for analysis.

The entire study will take about one hour and 30 minutes and you will not be asked to spend time on studies in addition to what you will be asked.

RISKS

While participating in this study you may experience the following risks: Minor psychological discomfort; however, we will provide a short think-aloud exercise at the beginning to minimize the discomfort of talking aloud while working on the task.

BENEFITS

If you decide to participate in this study there is no direct benefit to you. However, a possible benefit is that you will become more aware of your approach to problem exploration as we will ask specific questions about your behavior in how you think the design problem changed over time, during meetings and while you are working alone.

COSTS AND COMPENSATION

You will be compensated with $30 for participating in this study. This amount will be provided to you at the end of the session.

This information allows the University to fulfill government reporting requirements. Confidentiality measures are in place to keep this information secure. You may forego receipt of payment(s) and continue in the research study if you do not wish to provide your social security number and address. Information regarding documentation required for participant compensation may be obtained from the Controller's Department; 294-2555 or http://www.controller.iastate.edu.

PARTICIPANT RIGHTS

Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decided to not participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled. You can skip any questions that you do not wish to answer.

CONFIDENTIALITY

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: the coding of the data will be done by the researchers who will be blind to the project. Participants' information will be removed and replaced by ID codes. These ID codes will be matched by participants, but will only be available to the PI. No identifiers will be provided to researchers for data analysis. The identifiers will be kept in PI's office, in a locked cabinet. The data will also be kept there, and will be taken out when the researchers analyze them.

If the results are published, your identity will remain confidential.

QUESTIONS OR PROBLEMS

You are encouraged to ask questions at any time during this study.

- For further information about the study contact Dr. Seda Yilmaz at 515.294.716.
- If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa, 50011.

PARTICIPANT SIGNATURE

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (printed) ____

____ ____________________

(Participant's Signature) (Date)